Estuaries of the World

Ruben Kosyan *Editor*

The Diversity of Russian Estuaries and Lagoons Exposed to Human Influence

Springer

Estuaries of the World

Series editor
Jean-Paul Ducrotoy, The University of Hull, Hull, United Kingdom

More information about this series at http://www.springer.com/series/11705

Ruben Kosyan
Editor

The Diversity of Russian Estuaries and Lagoons Exposed to Human Influence

This book is endorsed by the International EMECS (Environmental Management of Enclosed Coastal Seas) Center in the context of their worldwide scientific and educational mandate. http://www.emecs.org.jp/englishver2/abouemecs_e.html

EMECS

Springer

Editor
Ruben Kosyan
P.P. Shirshov Institute of Oceanology
Russian Academy of Sciences (IO RAS)
Gelendzik, Russia

ISSN 2214-1553 ISSN 2214-1561 (electronic)
Estuaries of the World
ISBN 978-3-319-43390-5 ISBN 978-3-319-43392-9 (eBook)
DOI 10.1007/978-3-319-43392-9

Library of Congress Control Number: 2016952864

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG Switzerland

Preface

The economic, climatic and geopolitical processes of the modern world set a task for humanity for comprehensive study of the seas and coastal areas of strategic importance. The beaches and coastal areas of the Russian seas are its national heritage, the economic, environmental, recreational and aesthetic value of which is constantly growing. It should be recognized that, in the era of globalization and in the midst of the avalanche of technogenic intrusions into all spheres of nature, the seashores are a nonrenewable natural resource. To design a rational approach for the use of unique coastal landscapes so that problems may be fully resolved from a regional perspective, there must be complex research and analysis of the development of natural and socioeconomic processes in each region.

Russia is the largest country in the world by area, and it has the longest coast. This configuration determines the diversity of its coasts. Russian territory includes 12 coastlines along three oceans, located in different time, natural and climatic zones, with a total length of 37,653 km. These seas can be divided into four groups, according to their geographic position – Southern, Northwestern, Arctic and Far Eastern seas.

Southern seas. The Black and Azov Seas, by their geographical position, belong to this group. They are located at the same latitude (between 36 and 37 N) and are geographically close to each other, which gives them a certain similarity. Both of them have a tectonic origin, and their geological history is connected with the alternating uplift and subsidence of the crust all over the southern region, and the weakening or strengthening of the influence of salty oceanic and continental fresh waters. The geological past of the southern seas determined their most important modern natural peculiarities – almost complete isolation from the World Ocean and low salinity. Mainland stock is one of the most significant factors in the formation of the hydrological conditions and the most important component of the water balance of the southern seas. A variety of physical and geographical, hydrological and hydrochemical, and related biological conditions allow for distinguishing two regional types: the estuary-shelf and the oceanic. The first of these concerns the Azov Sea and the northwestern part of the Black Sea. They are characterized by shallow water, strong desalination, great influence by atmospheric processes and runoff. The second type, the oceanic, includes a deep part of the Black Sea. This type's characteristic feature is a large volume of water mass, creating a stable system, with relatively little exposure to external influences. The coastal landscapes and coastal forms of the southern seas are very diverse. The coast of the Russian part of the Sea of Azov in the north and east consists of clay and sand deposits and is subject to destruction as a result of active erosion. The beaches of the Taman Peninsula consist of solid limestone and are more resistant to abrasion. The surf zone represents sand and shell beaches. The coastal zone of the Black Sea, owned by Russia, is represented by different types of geomorphological shores, mainly abrasion, but accumulative forms are also present.

Northwestern seas. The northwestern group consists of the Baltic and White Seas. They occupy an intermediate position between the southern and Arctic seas, the first drawn to the south, and the second, to the Arctic. The Baltic and White seas are peculiar to large continental runoff. As a result of having a very weak connection with the neighboring seas, river water determines many of the essential features of these seas. They are characterized by a three-layer vertical structure of waters: freshened surface, intermediate saline water and deep saline water.

The observed vertical structure of the water column leads to their stable state, making it difficult for convective mixing to take place in the wind seas. However, the isolation of these seas, and the limited vertical mixing, does not entail a substantial permanent stagnation of the deep water in the Baltic and the White; they are renewed annually. Every year, both seas are covered by the winter sea ice. The shores of the White Sea are divided into several types: primary partitioned and little changed by wave processes, abrasion-denudation, accumulative and littoral, and abrasion-accumulative resulting in beaches with dead cliffs and modern marine terraces. The Russian Baltic Sea coast is indented with bays (Curonian, Kaliningrad, Vistula) and has an accumulative marine formation; the Curonian Spit and the Baltic Spit have spectacular Aeolian landscapes.

Arctic seas. This group is made up of marginal seas of the Arctic Ocean similar in nature: the Barents, Kara, Laptev, East Siberian and Chukchi Seas. All of them are within the Arctic Circle, limited in the south by natural boundaries, such as the coast of Eurasia, and widely and freely communicating with the ocean in the north, separated by conventional boundaries, such as lines drawn around the edge of the shelf. Between them, these seas are separated mainly by islands, as well as conventional lines. All are geologically young and of the same origin. The vast spaces of the Arctic seas lie in the region of relatively small (up to 200 m) depth, but the bottom topography is significantly different for each of them. The most complex and dissected relief is in the Barents and Kara Seas, simplified and leveled off to the east. On the northern outskirts of the Kara, Laptev and Chukchi Seas, relatively deep submarine trenches have been traced, penetrating far into the relatively shallow-water regions of these seas. The geological structure in the western segment is dominated by boulder loam, sand and gravel, and sandy material and in the east, by alluvial, lacustrine-marsh and fluvioglacial deposits. These materials are usually long-term frozen and perennially cooled, forming cryogenic shores (thermoabrasive, thermodenudation, abrasion-solifluction, etc.), occupying about 60% of the coastline.

Far-East seas. The fourth part of the coast of the Russian Federation is along the Pacific Ocean and its marginal seas – Bering, Okhotsk and Japan, combined into the group of Far East Seas. From a geomorphological point of view, these seas lie in the transition zone in the northwestern periphery of the Pacific Ocean. Here are the epicenters of earthquakes and the submarine areas of modern volcanism. One distinctive feature of the considered seas is a small continental runoff. A significant part of the water area of the Russian Far East freezes in winter. Variable in structure and external forms, the coasts of the Far East Seas belong to different geomorphological types. In general, they are scarp coasts, but there are accumulative ones as well. The shores are mostly rocky and steep, but there are valleys along certain parts of the coast.

Even these minimum characteristics of the Russian seas and coasts give an idea of their natural diversity and the peculiarities of each of them. And the first ones to notice that were sailors who worked in navigation. Farmers, manufacturers and traders who developed coastal areas also made notes on the natural landscape and climatic conditions. Later, these precious materials were used by coastal researchers.

The planning of economic activity on the coast should comply with requirements of environmental safety, rational use of natural resources, and economic feasibility. Meeting these requirements is especially important in areas with unique coast estuaries and lagoons of various types.

Among the water reservoirs of different genesis deeply protruding into the land, lagoons are of great interest, occupying one tenth of the coasts of the world and having considerable practical interest for many economic activities.

The physical and geographic features of lagoons – their relative shallowness, protection from storm surge of the open sea, large daily and seasonal variability of hydrodynamic and hydrochemical parameters, high biological productivity and circulation of nutrients, as well as rapid removal of metabolic products due to the influence of the tides – allow us to consider them as unique natural entities. Estuaries and marine lagoons are very common types along Russian sea coasts.

This book was created to summarize the knowledge and experience of economic activity along the Russian sea coasts accumulated to date. Description of estuaries of particular seas is divided by chapters. In Chap. 1, following the present preface, the main definitions of Russian sea lagoons and their classification and evolution in time are described.

Subsequent chapters examine individual regions.

Chapter 2 describes the most neglected lagoons of the Russian coast, those of the Arctic Seas.

Chapter 3 is devoted to lagoons and estuaries, which are widespread along the coasts of the Far Eastern Seas.

Chapter 4 represents two significant lagoon localities for the Russian sector of the Black Sea: the Kuban limans and the Imeretinskaya lowland

Chapter 5 is devoted to the lagoons of the eastern coast of the Sea of Azov.

The next two chapters describe lagoons of two Russian sectors of the Baltic Sea: the Curonian and Vistula Lagoons (Chap. 6) and a technogenic lagoon on the eastern gulf of Finland (Chap. 7).

Chapter 8 describes the structural organization of the White Sea as an estuarine system and the characteristics of the main factors forming the sea regime.

Finally, Chap. 9 synthesizes the primary information on the diversity of Russian sea estuaries

This book represents the first time a comprehensive description of the estuarine seas of Russia has been carried out and it required the use of data from different fields of earth sciences, economic sciences, and management areas. That is why a wide range of specialists (ecologists, oceanographers, geomorphologists, biologists) was engaged in the preparation of the book. We used materials derived mainly from specialists of the P.P. Shirshov Institute of Oceanology, RAS, and its branches located close to the various seas of Russia. Specialists from the Far Eastern Federal University and the A.P. Karpinsky Russian Geological Research Institute were also involved. Successful problem-solving was promoted by a comprehensive study of the natural and anthropogenic factors that determine the development of sea coasts, in all the complexity of their relationships, identification of common patterns, regional characteristics, and the analysis of the positive (negative) experience. The developed recommendations, constructed from data of natural observations and the analysis of published sources, will facilitate a more effective assessment of the impact of planned economic activity on these unique coasts and more rational environmental management of these peculiar geographical and ecological objects.

The monograph will be useful and interesting to a wide range of experts and professional scientists: to oceanologists, geologists, hydrotechnicians, researchers, environmental managers, and all of whom are engaged in questions of environmental protection and the developmental planning of coastal regions.

The book will also be useful to students, graduate students and teachers specializing in the natural sciences at institutions of higher education.

In the final words of the preface, I want greatly to thank Mrs. Svetlana Chayka and Mrs. Tatiana Podymova for their technical assistance in the creation of this book. I also want to give my special grand thanks to Dr. Jean-Paul Ducrotoy. It was on his recommendation that many authors agreed to participate in this monograph. His very valuable advice and assistance helped us very much in the completion of the book.

The collection of data and information for the monograph was carried out with the support of the Russian Scientific Foundation (grant no. 14-17-00547). The processing and analysis of literature and archive data were also supported by the Russian Scientific Foundation (grant no.14-50-00095).

Gelendzhik, Russia Ruben Kosyan

Contents

1 **Specific Features of Estuaries, Lagoons, Limans: Concepts and Terms** 1
Petr Brovko and Ruben Kosyan

2 **Estuaries and Lagoons of the Russian Arctic Seas** 13
Vyacheslav Krylenko

3 **Estuaries, Lagoons, and Limans of the Marginal Seas of Northeast Asia** 57
Petr Brovko, Yuri Mikishin, and Tamara Ponomareva

4 **Lagoons of the Black Sea** 93
Vyacheslav Krylenko and Marina Krylenko

5 **Lagoons of the Smallest Russian Sea** 111
Marina Krylenko, Ruben Kosyan, and Vyacheslav Krylenko

6 **Transboundary Lagoons of the Baltic Sea** 149
Boris Chubarenko, Dmitriy Domnin, Svetlana Navrotskaya,
Zhanna Stont, Vladimir Chechko, Valentina Bobykina, Vasiliy Pilipchuk,
Konstantin Karmanov, Anastasea Domnina, Tatiana Bukanova,
Victoria Topchaya, and Alexander Kileso

7 **Neva Bay: A Technogenic Lagoon of the Eastern Gulf of Finland (Baltic Sea)** 191
Daria Ryabchuk, Vladimir Zhamoida, Marina Orlova, Alexander Sergeev,
Julia Bublichenko, Andrey Bublichenko, and Leontina Sukhacheva

8 **The White Sea as an Estuarine System** 223
Evgeniy Ignatov, Oleksiy Kalynychenko, and Anatoliy Pantiulin

9 **The Diversity of Russian Estuaries** 265
Ruben Kosyan, Petr Brovko, and Jean-Paul Ducrotoy

Index 269

Contributors

Valentina Bobykina Atlantic Branch of the P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (AB IO RAS), Kaliningrad, Russia

Petr Brovko Far Eastern Federal University, Vladivostok (FEFU), Vladivostok, Russia

Andrey Bublichenko Zoological Institute of Russian Academy of sciences (ZIN RAS), St. Petersburg, Russia

Julia Bublichenko Saint-Petersburg Research Centre of Russian Academy of Sciences (SPbRC RAS), St. Petersburg, Russia

Tatiana Bukanova Atlantic Branch of the P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (AB IO RAS), Kaliningrad, Russia

Vladimir Chechko Atlantic Branch of the P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (AB IO RAS), Kaliningrad, Russia

Boris Chubarenko Atlantic Branch of the P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (AB IO RAS), Kaliningrad, Russia

Dmitriy Domnin Atlantic Branch of the P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (AB IO RAS), Kaliningrad, Russia

Anastasea Domnina Atlantic Branch of the P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (AB IO RAS), Kaliningrad, Russia

Jean-Paul Ducrotoy Institute of Estuarine and Coastal Studies, The University of Hull, Hull, UK

Evgeniy Ignatov Faculty of Geography, Lomonosov Moscow State University (MSU), Moscow, Russia

Oleksiy Kalynychenko Faculty of Geography, Lomonosov Moscow State University (MSU), Moscow, Russia

Konstantin Karmanov P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (IO RAS), Kaliningrad, Russia

Alexander Kileso Atlantic Branch of the P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (AB IO RAS), Kaliningrad, Russia

Ruben Kosyan P.P. Shirshov Institute of Oceanology Russian Academy of Sciences (IO RAS), Gelendzik, Russia

Marina Krylenko P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (IO RAS, Gelendzik, Russia

Vyacheslav Krylenko P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (IO RAS), Gelendzik, Russia

Yuri Mikishin Far Eastern Geological Institute (FEGI), Vladivostok, Russia

Svetlana Navrotskaya Atlantic Branch of the P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (AB IO RAS), Kaliningrad, Russia

Marina Orlova Zoological Institute Russian Academy of Sciences (ZIN RAS), St. Petersburg, Russia

Anatoliy Pantiulin Faculty of Geography, Lomonosov Moscow State University (MSU), Moscow, Russia

Vasiliy Pilipchuk Atlantic Branch of the P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (AB IO RAS), Kaliningrad, Russia

Tamara Ponomareva Far Eastern Federal University (FEFU), Vladivostok, Russia

Daria Ryabchuk A.P. Karpinsky Russian Geological Research Institute (VSEGEI), St. Petersburg, Russia

Alexander Sergeev A.P. Karpinsky Russian Geological Research Institute (VSEGEI), St. Petersburg, Russia

Zhanna Stont Atlantic Branch of the P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (AB IO RAS), Kaliningrad, Russia

Leontina Sukhacheva Research Institute of Remote Sensing Data for Geology (NIIKAM) Branch of FGUP TSNIIMASH, St. Petersburg, Russia

Victoria Topchaya Atlantic Branch of the P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (AB IO RAS), Kaliningrad, Russia

Vladimir Zhamoida A.P. Karpinsky Russian Geological Research Institute (VSEGEI), St. Petersburg, Russia

About the Editor

He is Doctor of Geographical Sciences, professor, Head of the Lithodynamics and Geology Laboratory of the southern branch of the P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, Academician of the Russian Ecological Academy, a member of the Krasnodar Regional Scientific and Technical Committee, a member of the Russian National Oceanographic Committee, expert IOC of UNESCO on the problems of the Black Sea, a member of the Association of Balkan Scholars, the American Association for the Development of Scientific Research, and the European Union for Coastal Conservation, and, since 2010, a member of the Scientific and Technical Committee of the International Center for Environmental Management of Enclosed Seas (Kobe, Japan).

R. Kosyan has more than 40 years of scientific and engineering experience. He is engaged in problems of physical oceanography, marine geophysics, ocean engineering and methods of dynamical processes' study in coastal regions. He has helped pioneer a number of methods and techniques for sediment transport measurement used in research works at many marine objects of different countries

A team of dedicated scientists from a number of Russian academic and branch institutes was created with his participation.

Supervising expeditions both on the ocean and near the coast, he was a member of four crews at the underwater laboratory "Chernomor," conducting numerous international experiments on the problem of "oceans." In 1987, he directed the research of radionuclides in the water of the Pripyat River after the accident at the Chernobyl nuclear power plant. For this work, he was awarded the Order of Carriage.

He is known as the head of 12 international and 40 Russian projects, all quite large. One of the most significant projects conducted under his leadership is the Ministry of Economic Development of the Russian Federation's scientific support for balanced planning of economic activities along unique sea coastal landscapes and suggestions for using said planning after the example of the Azov-Black Sea coast.

In 2012, the Intergovernmental Commission for the Protection of the Black Sea Against Pollution awarded R. Kosyan with the "Black Sea" Medal for his outstanding service in the protection of the marine environment of the Black Sea.

More than 400 scientific papers, including 11 monographs, have been published with his authorship.

He took part in the work of the steering committees of three international NATO programs dedicated to the Black Sea: the forecasting of wave climate, modeling of the ecosystem, and prediction and operational data management.

The scientific advances of Dr. Kosyan, R.D., in the study of dynamic processes of the coastal zone have gained international recognition and tremendous appreciation from the scientific community.

1 Specific Features of Estuaries, Lagoons, Limans: Concepts and Terms

Petr Brovko and Ruben Kosyan

Abstract

Lagoons and lagoon coasts are widely spread along the shores of the World Ocean (9.2 % of the total length of the coastal line). Modern world economic, climatic and geopolitical processes create a need for comprehensive study of the Russian seas and coastal areas of strategic importance. The physical and geographic features of lagoons – their relative shallowness, protection from storm surges from the open sea, the large daily and seasonal variability of hydrodynamic and hydrochemical parameters, and high biological productivity – allow us to consider them as unique natural objects. The main definitions of lagoons in the Russian seas, their classification, and time evolution are presented in this chapter.

Keywords

Conditions of estuaries formation • Economic use of lagoons • Estuarine system • Lagoon • Fjord • Liman

1.1 Introduction

The coastline of the World Ocean, with a total length of about 777,000 km, has an extraordinary morphological diversity. Along the oceanic coasts, we encounter the most unusual and complex combinations of private and industrial problems in regard to regional management, which are well known peculiarities of the coast as an object of nature. The coastal zone of the sea is not just "the arithmetic sum of the territory and waters. This is a holistic, very peculiar geographical and ecological entity that has unique properties and quite valuable qualitative features, which are found neither in the waters nor on land" (Bondarenko 2003).

Modern world economic, climatic and geopolitical processes create a need for comprehensive study of the Russian seas and coastal areas of strategic importance. It should be recognized that, in the era of globalization and strong technological introduction of mankind into all spheres of nature, the seashores remain non-recoverable natural resources. A comprehensive study and analysis of the development of natural and socio-economic processes in each region is a pressing need in the search for solutions to the problems of a rational approach to the use of unique coastal regions (Kosyan et al. 2012, 245). These problems are very variable even within the very similar climates, landscapes, and geomorphological structures of the sea shores. It is especially important in Russia, with its 13 coastal areas, connected to three oceans, located in different natural, climatic, and time zones.

1.2 Definitions

Leveled sites of coastline extended over hundreds of kilometers are interspersed with numerous bays, forming a rugged coastal circuit. The coastlines occupy different levels of ele-

P. Brovko (✉)
Far Eastern Federal University, Vladivostok (FEFU), 8, Sukhanova St, Vladivostok 690950, Russia
e-mail: peter.brofuko@yandex.ru

R. Kosyan
P.P. Shirshov Institute of Oceanology Russian Academy of Sciences (IO RAS), 1-g, Prostornaya, Gelendzik 353467, Russia
e-mail: rkosyan@hotmail.com

R. Kosyan (ed.), *The Diversity of Russian Estuaries and Lagoons Exposed to Human Influence*, Estuaries of the World, DOI 10.1007/978-3-319-43392-9_1

vation along hundreds of kilometers, forming an indented shore with numerous bays. Among the reservoirs of different formation deeply protruding into the land, the lagoons are of particularly great interest. They occupy one tenth of the world's coasts. Numerous economic activities are related to the practical application of lagoons.

The physical and geographic features of lagoons – their relative shallowness, protection from storm surges from the open sea, the large daily and seasonal variability of hydrodynamic and hydrochemical parameters, and high biological productivity – allow us to consider them as unique natural objects.

Other coastal waters, often united by a general concept, the estuary, have similar natural features. The term "estuary", when used generally in scientific papers, tends to cover all coastal waters: almost fresh or high saline (Safyanov 1987). In this case, the most commonly accepted definition was given by D. Pritchard: "Estuary is a semi-enclosed coastal body of water which has a free connection to the sea and within which sea water is to some extent diluted with fresh water flowing due to land drainage" (Pritchard 1967).

If we accept this definition, the estuary, unlike lagoons, has no distinct geomorphological boundaries; thus, this concept includes large bays and even certain seas, for example, the Azov and Baltic seas. The presence of the barrier (accumulative forms) is an essential feature that distinguishes a lagoon from an estuary.

Let us consider some meanings of the terms related to the above-mentioned reservoirs. The Encyclopedic Dictionary of Terms of Physical Geography (1980), written in four languages, gives descriptions as follows.

The LAGOON – a shallow part of the ocean (sea), separated from it by a bar, spit, or coral reef, and connected to it by a narrow strait or straits. Often found inside the atoll (Paffengolts 1978, 221).

The ESTUARY – an elongated bay with low shores, sinuous in formation. Formed by the flooding of the sea estuarine plain rivers or coastal depressions of the land. Estuaries are open to the sea and enclosed, separated from the sea by a spit or a bar. The majority of estuaries have significant salt content (Shchukin 1980, 233).

The FJORDS – narrow and deep (up to 1000 m and more), long (sometimes branched) bays jutting out into the land for tens to hundreds of kilometers. They are the result of glacier processing and the subsequent flooding of river valleys and tectonic depressions by sea water (Shchukin 1980, 476).

ESTUARY – funnel-shaped bay tapering towards the top, which is formed as a result of flooding of the lower reaches of the river valley and the influence of the converted wave, river and tidal factors (Shchukin 1980, 504).

The Terminology Guide to Marine Geomorphology, also released in 1980, gives a similar picture, with a few exceptions.

ESTUARIES (estuary) – extended funnel-shaped river mouth, representing a narrow and long bay. From a hydrological point of view, a boundary of the estuary towards the land is the beginning of the mixing of fresh and sea water; from a morphological one, the boundary is the line at which the river bed occupies the position below average sea level. Typical estuaries develop only in tidal seas (Kalesnik 1968, 194).

Long and narrow bays may genetically be rias or fjords.

FIRTH (LIMAN) – ingressive bay in the northwestern part of the Black Sea, which is the lower reaches of river valleys flooded by the sea. Most estuaries are fenced off from the sea by bars or spits (Kalesnik 1968, 186).

LAGUNA – water area, separated from the sea by a coast or island bar and elongated in the direction of the general strike of the coast (Kalesnik 1968, 105). In the broader geological sense of the term, a lagoon is any bay, totally or partially separated from the sea and having a different salinity (Kalesnik 1968, 106).

In general, many researchers agree that the separation of the Gulf by accumulative form is the main feature of the lagoon (Table 1.1).

Thus, taking into account the opinions of the above-mentioned authors and natural peculiarities of the reservoirs, we accept the following definition.

A laguna is part of the ocean, sea, or lake, separated by accumulative forms (reefs, artificial structures) with a hydrological regime that differs from the region of the water, specific conditions of relief formation and sedimentation, and development of unique biocenosis under the conditions of low or high salinity (Brovko 1990).

The problem of lagoon classification was raised over a half a century ago, by P.A. Kaplin. He wrote: "At the present time, there is a need for a more complete and accurate definition of the "lagoon" term, as well as the development of a rigorous geomorphological classification of lagoon formations. The classification must apparently be based, first of all, on the genesis of the bank, separating a lagoon from the main reservoir" (Kaplin 1957). The banks separating lagoons are divided by their origin into four types: bars, spits, bay-bars, and polygenetic forms. P.A. Kaplin identified seven types of lagoon on the coast of the Chukchi Sea, based on their geomorphological features: from merely separated by spits, to complex lagoon-estuaries and lagoon-limans (Ionin et al. 1971).

Zenkovich (1970) analyzed the conditions of formation of coastal strata of silt sediments and distinguished several types of "traps" for the fine particles: conventional lagoons,

Table 1.1 The definition of the lagoon, given by different authors

Name	Peculiarities					References
Isolated part of the sea	Separated by	Rocky or sandy isthmus	Connected	Straits		Nalivkin (1955, 322)
Reservoir original	Separated by	Coastal bar				Leontiev (1961, 128)
Reservoir shallow-water, natural	Separated by	Strip of alluvial dry land	Connected	Narrow strait		Kalesnik (1968, 192)
Shallow-water bay	Separated by	spit	Connected	Small strait	Stretched along the shore	Istoshin (1968, 31)
Former water area	Fenced by	Alluvial barrier			Stretched along the shore	Zenkovich (1970, 123)
Reservoir shallow-water, natural	Separated by	Strip of coastal bars	Connected (rarely)	Narrow strait		Paffengolts (1973, 383)
Nearshore shallow water	Separated by	barriers				Sheppard (1976, 166)
Shallow-watered part of the sea	Separated by	Not high narrow long strip of land	Connects with the sea		Often stretched parallel to the shore	Paffengolts (1978, 218)
Reservoir shallow-watered	Fenced by	Sand bars and bar-islands	Connected	Narrow girts	Situated parallel to the shore	Reinek and Singh (1981, 340)
Reservoir small, shallow-watered			Connected with the open ocean			Drake et al. (1982, 462)
Part of the sea	Separated by	Spit or bar				Lisitsyn (1982, 37)

lagoons with a torn barrier, estuaries, and raises, separated from bars, coral lagoons, deltas, and associated lagoons and lakes.

Three types of lagoons were established on the continental coast of the Sea of Japan (Korotky and Khudyakov 1990). The first type is related to large reservoirs separated by bars and spits, the second type includes narrow ingressive lagoons at the mouths of small rivers, and the third type is related to the mouths of large rivers. Lagoons are characterized by mixed facial composition of bottom sediments and rate of sedimentation up to 9 mm per year.

Kim Syn Chan, from Pyongyang University, in 1991 described deltas, bays, and tidal lagoons, as well as reservoirs inside polygenetic forms, connecting small islands with the continent on the coast of the Korea Peninsula.

Chinese authors have described bay-lagoons, semi-enclosed, and enclosed lagoons along the coast of China. All sedimentation processes have a broad connection with the sea in bay-lagoons, including biogenic sedimentation. Semi-enclosed lagoons are connected to the sea through tidal channels; salinity is either increased or decreased there. Fine bottom sediments dominate in such lagoons. Coastal vegetation develops intensely in enclosed lagoons with straits cut off by alluvium (Li Congxian and Chen Gang 1986).

Nichols and Allen (1981) distinguish four types of lagoon: lagoon-estuaries, opened lagoons, partially-enclosed, and enclosed lagoons. Connection with the sea decreases from the first type to the last, and the role of wave influence increases on the dynamics of accumulative forms separating lagoons from the sea.

1.3 Classification

Thus, different approaches to the allocation of types of coastal waters are presented in the above-discussed classifications depending on their morphology, topography, genesis, conditions of formation of bottom sediment, biocenosis, etc. These approaches can be taken into account in the classification of lagoons.

The first detailed classification of lagoons in Russia was compiled by Professor P.F. Brovko, who had experience in the study of these reservoirs on the banks of the Far Eastern seas, on islands in the Indian and Pacific oceans, and on the continental coast of East Asia (1990).

He suggested a classification that includes three classes of lagoon: coral, anthropogenic, and coastal. Coral lagoons form an independent class of separated water reservoirs; they are divided into two types: (a) between the shore and the fringing reef and (b) within the atolls (Preobrazhensky 1986). Anthropogenic (man-made) lagoons appear under the influence of the human activities that have continued along the coastal zones of the sea for hundreds of years. There are two main types of lagoon: (1) bay-bays, straits separated by

Fig. 1.1 Severnaya lagoon-fjord (Bering Sea)

hydraulic structures: dams and breakwaters, and (2) reservoirs formed on land and then connected to the sea through artificial channels.

Coastal lagoons are the most widely spread along the coast of the World Ocean, occupying, according to the estimates of different researchers, from 9 % to 15 % of the length of the shoreline. Depending on the origin of the water area, which is separated by an accumulative form, they form lagoon-estuaries, lagoon-limans, and lagoon-fjords (Fig. 1.1). The main part is related to the typical lagoons that appeared on the leveled accumulative or partitioned abrasive-accumulative shores. They are separated from the sea by bars, spits, and polygenetic forms.

Lagoons are characterized by the following properties:

By size (*square*): largest (larger than 1000 km^2), large (100–1000), medium (10–100), small (1–10), very small (smaller than 1 km^2);

By depth: very deep (more than 20 м), deep (5–20), medium depth (1–5), shallow (shallower than 1 м);

By salinity: very salty (более 35‰), salty (15–35), slightly salty (5–15), half-salty (0.5–5), fresh (less than 0.5 ‰);

By degree of isolation: opened, semi-opened, semi-enclosed, enclosed, separated.

Lagoon formation processes strongly differ under a wide range of climatic conditions: from tropical to polar regions. We specify the following zonal types for the location of lagoons: arctic, moderately humid, tropical humid, and arid

Fig. 1.2 Lagoon in an arid zone (Socotra Island, Indian Ocean)

(Fig. 1.2) (Brovko 1990). The largest lagoons in the world (8–18,000 km^2) are the Kara-Bogaz-Gol (Caspian Sea) (Fig. 1.3), the Wadden Sea in Western Europe, the Patos in South America and Pamlico Sound in North America. It was found that researchers' greatest interest is focused on the large and medium-size lagoons in the range of 10–500 km^2. More than a third of them represent the lagoons up to 30–40 km^2 (Nixon 1982). For comparison, the average area of 240 lagoons of the Far Eastern Seas in the 1–500 km^2 range is 31.3 km^2 (Brovko 1990).

The majority of the lagoons in the world have average depths of about 1–5 m (Zenkovich 1962; Nichols and Allen 1981; Nixon 1982; Schwartz 2005; Bird 2010). Depths shallower than 1 m are typical for small and very small lagoons, especially in arid zones. The deepest lagoons are lagoon-estuaries and lagoon-fjords; the size of the latter is relatively small. The other deepest lagoons are found in the Far East of Russia along the Koryak coast and Kamchatka.

The salinity of lagoons is an important hydrochemical and hydrobiological parameter, which is represented in the classification by their mean values. The majority of humid lagoons are salty and semi-salty; salinity may vary over a wide range, for example, during ebb-tide and rising-tide. The strait, connecting the reservoir with the sea, is an important element of the lagoon system. The origin and evolution of lagoon straits are influenced by many parameters. Their location depends on the morpho-structural horizontal shape of the coast, distribution of accumulative forms, topography of the underwater shore slope, physical and geographical peculiarities of the lagoon, river flow, relative changes of the sea level, character of the rising tide, etc. (Laser 1982; Brovko 1990; Wang Ying 1990; Schwartz 2005; Bird 2010).

Multiple investigations in different regions of the World Ocean have led to the direct reflection of waves or tide factor becoming important to lagoon research. Three types of straits have been distinguished: (1) formed mainly as a result of wave forcing (2) formed mainly by rising tides; (3) transit type of formation (Table. 1.2).

Besides these main types, straits are divided into constant and seasonal, periodically washing out during storms and forming tidy deltas, alluvial fans, etc. (Figs. 1.4 and 1.5).

1.4 Evolution of Lagoons

Lagoons separated from the sea by bars, spits, and sand bars tend to change the contour of the coast and lowland water covered areas by means of the filling the lagoons with river,

Fig. 1.3 Kara-Bogaz-Gol Lagoon (Caspian Sea)

Table 1.2 Types of strait along the Atlantic coast of the USA

Inlet morphologic variables			
Inlet types			
Variables	Wave-dominated	Transitional	Tide-dominated
Principal shoal locations	Inside the bay, as multi-lobate flood delta	In the throat	Seaward of the inlet as long linear channel margin bars
Ebb-tidal delta	Small and close to the beach	Variable	Large; extends far from shore
Flood-tidal delta	Large; lobate or digitate	Poorly developed or absent	Generally absent
Channel character	Poorly defined; often multiple	Variable; often one main channel and one or more secondary channels; unstable in shallower portions of 5–10 m depth	Tends toward stability; depths greater than 10 m
Width/depth ratio	Moderate	Very large	Small
Lagoon	Wide; open	Fringing marsh; marsh-filled	Marsh-filled and channelized
Swash bars	Poorly developed	Variable	Variable
Swash platforms	Poorly developed	Variable	Well developed
Channel margin bars	Absent	Variable	Large

Hubbard et al. (1979)

Fig. 1.4 Seasonal type of strait: closed with the tidal delta. Northern Sakhalin

sea, Aeolian, and other sediments. The evolution of water reservoirs may develop differently depending on the prevalence of one or another factor (Fig. 1.6).

In the lagoons elongated in the direction of wind and waves along the longitudinal axis of the lagoon, the protrusions of accumulative forms develop on their opposite banks; these are spits, which merge and divide the lagoon into separate pools (Figs. 1.6a and 1.7). This effect was first described by Zenkovich (1962) in the lagoons of the Chukotka Peninsula.

The biogenic factor has a strong influence on the dynamics of beaches and lagoon bottoms. Extensive development of algae, seagrass, and mangrove vegetation contributes to the creation of zones of accumulation of sedimentary material and the changing of coastal contours (Fig. 1.6b). The origin of oyster reefs is one of the clearest manifestations of biogenic factors (Nichols and Allen 1981; Brovko et al. 1988; Brovko 2002).

Strong winds permanently blowing from the sea under arid conditions form high dunes. Sandy trails stretch from them towards the lagoons, leading to a reduction in the lagoon water area (Fig. 1.6c).

A large proportion of solid river runoff forms the deltas in the lagoons, which can reach the opposite shore while they grow (Figs. 1.6d and 1.8). The speed of the extension of deltas and their growing area depends on the size of the liquid and solid flow, the size and depth of the lagoon, and the influence of the tides.

Under strong wave forcing at the open sea coasts, bars are moved to the coast, decreasing the water area of the lagoon. At the same time, marine sands cover the silt sediments of lagoons (Fig. 1.6d). This process is known to have occurred in the lagoons of Sakhalin and Kamchatka (Zenkovich 1962; Brovko 2002).

Fig. 1.5 Seasonal strait providing water flow into the sea. Northern Sakhalin

In a relatively short period of typhoon and hurricane propagation, bars in lagoons are eroded with the development of straits, channels and fan-like plumes of sediment (Fig. 1.6e) (Hayes 1967; Leatherman 1988; Brovko 2002).

In lagoons of low and medium tide, tidal deltas are formed that can lead to a significant reduction in the water area in small and narrow lagoons (Fig. 1.6g). In lagoons with high tides, the dissipation of tidal energy and the accumulation of sediments over the entire area of the lagoon occur. At the same time, lagoons may be completely drained owing to the outflow through the eroded channels (Figs. 1.6h and 1.9).

The evolution of lagoons generally leads to a reduction in their size and overall area within the existing coastal zone. However, if other factors remain the same (ceteris paribus), this trend continues only at a stable level. The modern rise in the global sea level suggests that the scheme can be different in each case. The erosion of coastal bars and spits, up to their disappearance and the formation of new straits in different regions, may lead to a different situation: a transition from separated reservoirs to a sea bay.

Fig. 1.6 Evolution of lagoon water basins (Brovko 1990): (**a**) restriction of reservoir growth towards opposite spits (After V.P. Zenkovich); (**b**) filling of the water with benthogenic forms: reefs; (**c**) accumulation of aeolian material; (**d**) growth of river deltas in the lagoons; (**e**) thrusting of the bar of the lagoon sediments; (**f**) the formation of salty puddles or pools when the storm breaks the bars; (**g**) growth of tidal deltas; (**h**) filling of active precipitation waters of tidal lagoons

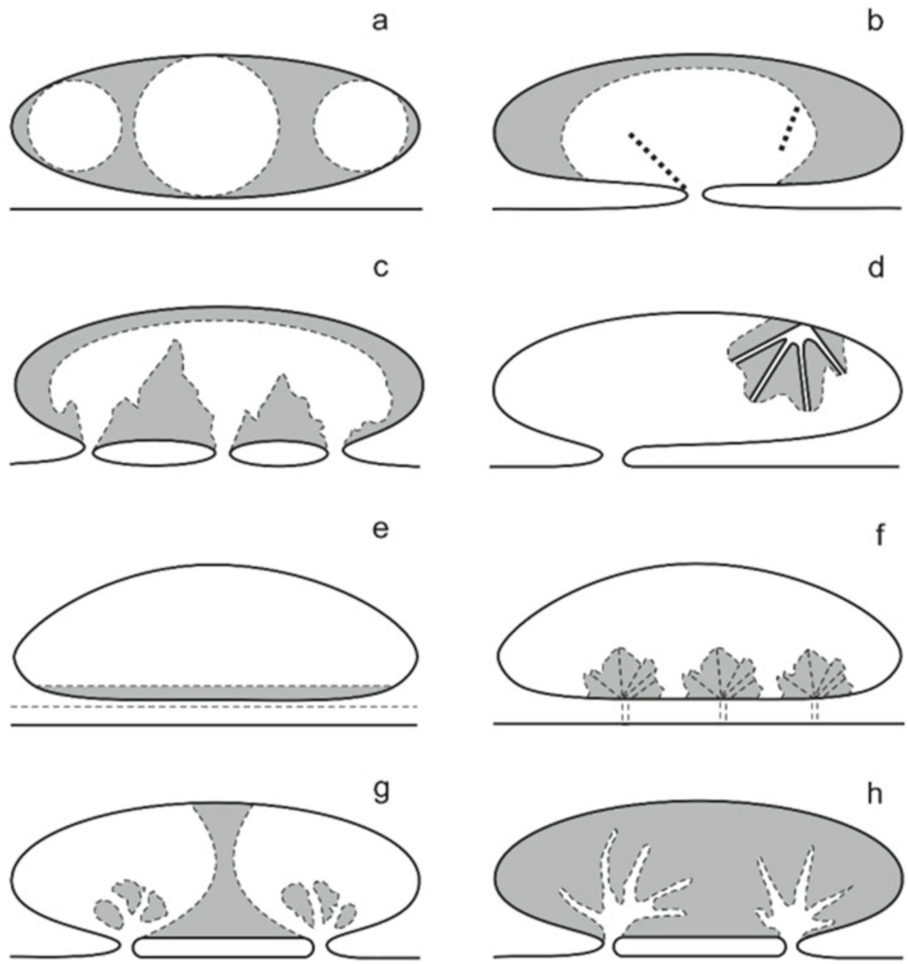


Fig. 1.7 Separation of the lagoon transverse spits. St. Lawrence Island (Bering Sea)

Fig. 1.8 Growing delta in the Semlachek Lagoon. East Kamchatka

Fig. 1.9 Lagoon formed by high tides (Sea of Okhotsk)

References

Bird ECF (2010) Encyclopedia of the world's coastal landforms, 1st edn. Springer, Dordrecht

Bondarenko VS (2003) Regional management of natural resource use in the coastal areas. Oikumena, Minsk (in Russian)

Brovko PF (1990) Development of coastal lagoons. Publishing house of the Far East University press, Vladivostok (in Russian)

Brovko PF (ed) (2002) Atlas of the coastal zone of Sakhalin island. Far Eastern National University, Primorsky Aerogeodetic Enterprise, Vladivostok (in Russian)

Brovko PF, Manuylov VA, Petrenko VS (1988) Geoecology lagoon complex of southern Primorye. In: Geography and natural resources, vol 2. Academic publishing Geo, Novosibirsk, pp 68–72 (in Russian)

Drake H, Imbrie J, Knauss J, Turekian K (1982) The ocean itself and for us. Progress, Moscow (in Russian)

Hayes MO (1967) Hurricanes as geological agents. In: Bulletin American Association of Petroleum Geologists, vol 51 (6, part_1). AAPG, USA, pp 937–942

Hubbard GK, Oertel GF, Nummedal G (1979) The role of waves and tidal currents in the development of tidal-inlet sedimentary structures and sand body geometry: examples from North Carolina, South Carolina and Georgia. J Sediment Petrol 49(4):1073–1091. Published GeoScienceWorld

Ionin AS, Kaplin PA, Leontiev OK, Medvedev VS, Nikiforov LG, Pavlidis YA, Scherbakov FA (1971) In: Kaplin PA (ed) Development of the landform and modern sediments in the coastal zone of the USSR Far Eastern seas. Nauka, Moscow (in Russian)

Istoshin YA (1968) Oceanology. Gidrometeoizdat, Lenigrad (in Russian)

Kalesnik SK (ed) (1968) Encyclopedic dictionary of geographical terms. Soviet Encyclopedia, Moscow (in Russian)

Kaplin PA (1957) On some peculiarities of the lagoons of the North-Eastern coast of the USSR. In: Bulletin of Oceanografic Commission of the USSR Academy of Sciences, vol 2. Publisher Academy of Sciences of the USSR, Moscow, pp 104–110 (in Russian)

Korotkiy AM, Khudyakov GI (1990) Exogenous geomorphological systems of seashores. Nauka, Moscow (in Russian)

Kosyan R, Kuklev S, Khanukaev B, Kochergin A (2012) Problems of the coasts erosion in the North–Eastern Black Sea region. J Coast Conserv 16(3):243–250. doi:10.1007/s11852-010-0115-2. Published by: Springer

Laser P (1982) Coastal lagoons. In: Nature and resources, vol 3. UNESCO, Paris, pp 24–43

Leatherman SP (1988) Barrier island handbook. Laboratory for Coastal Research, University of Maryland, College Park

Leontiev OK (1961) Fundamentals of geomorphology of the sea coast. Publishing house of Moscow state University, Moscow (in Russian)

Li Congxian, Chen Gang (1986) Postglacial transgression and regression and barrier-lagoon sedimentary system. Acta Oceanol Sin 5(1):82–89. Publisher The Chinese Society of Oceanography

Lisitsyn AP (1982) The avalanche sedimentation. In: Rostowski (ed) Avalanche sedimentation in the ocean. University Press, Rostov-on-Don (in Russian)

Nalivkin DV (1955) The doctrine of the facies. Publisher Academy of Sciences of the USSR, Moscow (in Russian)
Nichols M, Allen G (1981) Sedimentary processes in coastal lagoons. In: Coastal lagoons research, present and future, UNESCO, Paris, pp 27–80
Nixon SW (1982) Nutrient dynamics, primary production and fisheries fields of lagoons. Oceanol Acta SP. Published by Elsevier Science, pp 357–371
Paffengolts KN (ed) (1973) Geological dictionary (GD), 1st edn. Nedra, Moscow (in Russian)
Paffengolts KN (ed) (1978) Explanatory dictionary of geological terms. Mir, Moscow (in Russian)
Preobrazhensky BV (1986) Modern reefs. Nauka, Moscow (in Russian)
Pritchard DW (1967) What is an estuary physical view point. In: Lauff GH (ed) Estuaries, vol 83. American Association for the Advancement of Science (AAAS) Publisher, Washington, DC, pp 3–5
Reinek G, Singh I (1981) Terrigenous environment sedimentation. Nedra, Moscow (in Russian)
Safyanov GA (1987) Estuaries. Mysl, Moscow (in Russian)
Schwartz M (ed) (2005) Encyclopedia of coastal science. Springer, Dordrecht
Shchukin IS (1980) Four-language Encyclopedic dictionary of physical geography (FLED). Soviet Encyclopedia, Moscow (in Russian)
Sheppard F (1976) Marine geology. Nedra, Leningrad (in Russian)
Wang Ying (1990) Coast research in China. In: Recent development of geographical science in China. Science Press, Beijing, pp 183–96
Zenkovich VP (1962) Fundamentals of the theory about the development of the sea coast. Publisher Academy of Sciences of the USSR, Moscow (in Russian)
Zenkovich VP (1970) Formation of silt strata in the coastal area. In: Problems of geography. Digest, vol 84. Mysl, Moscow, pp 115–129 (in Russian)

2 Estuaries and Lagoons of the Russian Arctic Seas

Vyacheslav Krylenko

Abstract

The seas of the Arctic (Barents Sea, White Sea, Kara Sea, Laptev Sea, East-Siberian Sea, Chukchi Sea) wash over Russian territory from the North. Almost 70 % of Russian territory falls within the Arctic Ocean basin. Despite the necessity of monitoring instances of natural and technogenic changes in the Arctic, many segments of the Arctic coast are still "blank spots" for researchers. The main reason for the poor knowledge in regard to this region is its inaccessibility. Its lagoons and estuaries are among the most difficult for the study of natural geosystems, each of them distinguished by both natural features and their response to changes in external conditions.

The variations of accumulative shores (lagoon, delta) are widely spread within the Barents and Laptev Seas. They form a great many lagoons. The biggest estuaries are the Kola Gulf, situated near the city of Murmansk, and the Khatanga and Anabar estuaries. There are not that many full scale lagoons along the coasts of the Kara Sea, a fact which is related to the geological structure of the shores, the peculiarities of which do not facilitate the development of accumulative bodies. But the largest estuaries of the Russia Arctic coast are the estuaries of the Kara Sea: Obskaya Guba, Taz Guba, Yenisey Gulf, Baidaratskaya Guba and Gydanska Guba. A characteristic peculiarity of the East Siberian Sea is a long extension of the accumulative coasts (about 40 %), especially on the islands. The accumulative-lagoon systems are distinguished for their peculiar internal partition into a number of round basins. Accumulative bay-bars separating the shallow lagoons from the Chukchi Sea extend parallel to the continental coast over hundreds of kilometers. The bay-bar of the Tenkergynpilgyn Lagoon is approximately 100 km long, and the length of the Kuvetpilchin Lagoon exceeds 50 km. The abundance of coastal accumulative structures and the lagoons that they form is a consequence of the geological structure of the adjacent coast and the topography of the submarine slope.

The major portion of the lagoons of the Russian Arctic coast is formed by accumulative bodies: bars, bay-bars, and spits. The influence of the changes in external conditions on the accumulative coastal bodies is different depending on their type of feeding and formation. Over recent decades, changes in all climatic parameters have been observed throughout the planet, especially in the Arctic regions. This natural global process inevitably influences the state of geosystems along the entire Arctic coast, including lagoons and estuaries. At present, it is impossible to say with certainty how large the positive or negative consequences of the Arctic's climate changes will be. Human activities in the Arctic almost

V. Krylenko (✉)
P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (IO RAS), 1-g, Prostornaya, Gelendzhik 353467, Russia
e-mail: krylenko.slava@gmail.com

R. Kosyan (ed.), *The Diversity of Russian Estuaries and Lagoons Exposed to Human Influence*,
Estuaries of the World, DOI 10.1007/978-3-319-43392-9_2

always have a negative impact upon the environment. Environmental protection measures may decrease this impact but are not capable of preventing it in full measure. Fortunately, the severe natural conditions do not allow for a large scale development of the coast, as has happened in more favorable regions.

Keywords
Lagoon • Arctic seas • Ice conditions • Accumulative coast • Estuary

2.1 Introduction

The shore and continental slope of the Arctic are gradually being developed economically. In the course of this development, all the countries in the region have conducted research on the resources of the Arctic Ocean. Scientific researches of the coasts of the Arctic Seas represent an important part of this works (Dobrovolsky and Zalogin 1982; Alekseevsky 2007). In the twentieth century, large research institutes carried out researches in the Arctic Seas of Russia; these were the State Oceanographic Institute (GOIN), the Arctic and Antarctic Research Institute (AARI), and the Shirshov Institute of Oceanology (IO RAS). After the disintegration of the USSR, economic activity in the northern seas decreased by several orders of magnitude, which led to a sharp decrease in scientific researches, especially in the multidisciplinary researches. The actual available data, in both amount and time distribution, is not currently sufficient to serve as the basis for a comprehensive characterization of the geosystems of the coasts of the Arctic Seas. The greatest problem is extreme non-uniformity in the studies of the Arctic coasts, many parts of which still remain “white spots” for investigators (Dobrovolsky and Zalogin 1982).

The fundamental work by A.D. Dobrovolsky and B.S. Zalogin “Seas of the USSR” (Dobrovolsky and Zalogin 1982) became the basis for the physical-geographical description of the coasts of the Russian Arctic Seas. The resources of the global Internet also play a significant role in the information provision of the researches. Actual information on the state of the most remote and poorly studied coasts of Russia is located on the sites of state and public organizations (administrations of the regions, ministries and agencies, protected areas, WWF, etc.). We studied the data and analytically selected that which would determine the current state and dynamics of the lagoon coasts of the Russian Arctic Seas to the greatest extent.

The Seas of the Arctic (Barents, White, Kara, Laptev, East-Siberian, Chukchi) wash over Russian territory from the North. All these seas are marginal, with only the White Sea being enclosed. The total area of the Arctic Seas, adjacent to the coast of Russia, is more than 4.5 million km^2 and the sea water volume is 864,000 Km^3. Almost 70 % of Russian territory falls within the Arctic ocean basin.

The Arctic Seas are separated from each other, and from the Central Polar basin, by archipelagos and islands: Franz Josef Land, Novaya Zemlya, Severnaya Zemlya, Wrangel, Vaygach, etc. If there is no clear boundary, it is carried out conventionally. The greater portion of the seas is situated in a shelf and is therefore shallow. Mean sea depth is 185 m. Only the northern part of the Laptev Sea occupies the Nansen abyssal hollow. Its seabed goes down to 3385 m. Because of this, the average depth of the Laptev Sea is 533 m; it is the deepest sea of the Arctic Ocean (Dobrovolsky and Zalogin 1982). The Barents Sea (average depth of 222 m, maximum – 600 m) is in second place in terms of depth. The East Siberian (average depth 54 m) and the Chukchi (71 m) are the most shallow (Dobrovolsky and Zalogin 1982). The bottom of the seas is smooth. The Barents and Kara Seas are characterized by the greatest broken bottom relief.

All the Arctic seas are open. There is free water exchange between them and the center of the Arctic Ocean. In the west, the warm waters of the North-Atlantic Current flow in through the wide and deep strait between the Scandinavian peninsula and Spitsbergen in the Barents Sea, which annually brings in about 74 thousand km^3 in Atlantic water. In the northeast of the Barents Sea, the warm and salty (34.7–34.9 ‰) waters of the Atlantic fall below the cooler and less salty, and therefore less dense, Arctic waters. In the east, the Arctic Ocean is connected to the Pacific Ocean by the narrow (86 km) and shallow (42 m) Bering Strait, so the impact of the Pacific Ocean is much less than that of the Atlantic. The shallow depth of the strait complicates the deep water exchange. About 30,000 km^3 of surface water is received into the Chukchi Sea from the Pacific Ocean (Dobrovolsky and Zalogin 1982).

The Arctic Seas experience considerable river run-off from the mainland (2735 km^3 per year). The inflow of river water drastically reduces the salinity of the seas and forms currents from south to north. In summer, warm river water contributes to sea ice dissolution, and in autumn and winter, desalinating sea water promotes the formation of solid ice (Dobrovolsky and Zalogin 1982). The year-round presence of ice is the most vivid feature of the region. Most parts of the Arctic Ocean are icebound all year. In winter, only the western part of the Barents Sea is ice-free. Young stationary ice (fast ice) forms in the winter along the coast. It has its maximum width (several hundred kilometers) in the shallow East-Siberian Sea. Ice-holes become situated within fast ice. They are formed from year to year in the same places, to the extent that they even have their own names according to the geographical objects that are located nearby (Cheshskaya, Pechora, West Novaya Zemlya, Amderminsk, Jansky, Ob and Yenisei etc.). Drifting long-term ice (the Arctic pack) forms after the ice-holes. It consists of large ice floes, separated by fissures, sometimes by ice-holes. The average thickness of the Arctic pack is 2.5–3 m and up. The surface of the pack ice is smooth or wavy. Sometimes, there are ice hummocks with a height of 5–10 m. They form as a result of ice floe collisions. Ice hummocks up to 20 m occur on the border of the pack and first-year (Dobrovolsky and Zalogin 1982). In summer, the ice area of the Arctic Seas is reduced, but their edge does not go beyond marginal seas, even in August. Local blocks of drifting and fast ice are conserved in the marginal seas, except in the Barents Sea, during the summer. Besides, sea ice icebergs are found in the polar seas as well. They break away from the ice sheet of the archipelagos of Franz Josef Land, Novaya Zemlya and Severnaya Zemlya (Dobrovolsky and Zalogin 1982). Arctic sea ice conditions vary from year to year. In recent decades, a reduction in sea ice area has been due to a general warming of the Arctic. Ice cover on most of the seas significantly reduces wave action on the beaches.

The salinity of the sea water decreases from the northern to the southern sea borders. In the northwestern part of the Arctic basin, the salinity of the sea water is 34–35‰, in the northern and north-eastern regions, it is 32–33‰, and near the major river mouths, it reduces to 3–5‰. Salinity affects the formation and characteristics of the ice cover.

The severe climatic conditions of the northern seas, the polar night and the ice cover are all unfavorable for the development of phytoplankton and zooplankton, so the total biological productivity of the seas is not high. Organism and species diversity is relatively small. With the increasing severity in natural conditions from west to east comes a parallel change and decline in species composition in the same direction. In the Chukchi Sea, the diversity in animal species increases due to the penetration of warm Pacific Ocean waters, with the Pacific Arctic boreal species joining those indigenous to the area.

For the last several decades, changes in all climatic parameters have been observed throughout the planet, especially in the Arctic regions. The general Arctic “warming” is manifested by a decrease in the area of the ice cover and a change in the facets of its existence. The air and seawater temperature rises and the direction of prevailing air currents changes, influencing the formation and interaction of water masses. These natural global processes inevitably influence the state of geosystems along the entire Arctic coast, including lagoons and estuaries. At present, it is impossible to say with certainty how large the consequences, positive or negative, of the climate changes in the Arctic will be.

Unlike the natural influences, human activities in the Arctic almost always have a negative impact upon the environment. Environmental protection measures are only capable of decreasing this impact; they cannot prevent it in full measure. Fortunately, the severe natural conditions do not allow for accomplishing the sort of large scale development of the coast as has happened in more favorable regions. As a consequence of the permafrost and severe climatic conditions, there are no large cities along the Arctic coast of Russia. Most of the settlements were founded during the period of the USSR, when field development was carried out and military bases were established. After the disintegration of the USSR, economic activity in the northern seas stopped almost completely. Many people left the settlements after the closing of industrial enterprises, quarries, and military bases. At present, only economic activities yielding the highest return are conducted in the Arctic regions, which allow for compensation of the large expenses needed to “fight” against nature. As a rule, transportation (mainly hydrocarbon transportation, as well as extraction of natural minerals (also mainly hydrocarbons, i.e., oil and gas)) can be considered to be such an activity.

The Northern Sea Route connecting the northwestern and eastern regions of Russia and the mouths of the navigational rivers in Siberia runs along the seas of the Russian Arctic Ocean. In addition to transportation of loads providing for the economic development of the north of Russia, the development of international transportation of loads in the West – East – West direction will be possible in the future. Construction of a transport infrastructure (ports, roads, pipelines) will have the strongest and quickest effect on the coasts and coastal water areas including lagoons and estuaries.

In addition to transportation activities, exploration and production of raw hydrocarbon material on the coast and shelf of the Arctic Seas has become considerably more intense in recent decades. The activity results in strengthening the technogenic impact on the environment that has become evident in the transformation and pollution of the ecosystems. The coast and shelf of the Barents and Kara Seas, where considerable fields of oil and gas have been explored and their production carried out, have undergone the most severe impact.

Despite the necessity of monitoring occurrences of natural and technogenic changes in the Arctic, many segments of the Arctic coast are still “blank spots” for researchers. The lagoons and estuaries there are among the most difficult for the study of their natural geosystems, each of them distinguished by both natural features and their response to the change in external conditions.

2.2 Peculiarities of the Lagoon Coasts of the Russian Arctic Seas

Similarly to the other regions of the World Ocean, the appearance and development of the modern lagoons and the accumulative bodies of the Arctic that form them is related to the Holocene transgression. Nevertheless, these processes in the Arctic were significantly different, first of all, as the result of the climatic conditions. The presence of permafrost and thick ice cover along the entire coastline during a significant part of the year and seasonal variations in the discharge of rivers introduced significant changes in the shores and the processes that occur there. The natural factors facilitating the formation of the lagoon shores include the peculiarities of the tectonic-geological structure of the shore (configuration of the coastline, topography of the underwater slope, lithologic composition) and peculiarities of the coastal hydrodynamics (regime of wind and waves, thermal and ice regime, tides, and currents). Variety in the combinations of these factors led to significant diversity in the lagoons existing along the Arctic coasts. We can distinguish the following types of lagoon according to their origin, structure of the bay-bars, and the dynamics of the coastal processes (Kaplin 2010):

Ordinary lagoons, which appeared as a result of the separation of the basin by one or two spits.

Typical lagoons, formed in the curves of the coastline, which are separated from the sea by a bar that appeared as a result of the transversal transport of material.

Complex lagoons, formed as a result of flooding of hilly lowlands, and hence, having complex boundaries; they are separated from the sea by the remains of bedrock structures connected by accumulative multi-genesis crossbars.

Firth lagoons, separated by spits from the sea; they have the same configuration as the firths and are separated from the sea by accumulative bodies that originated as a result of the transport of deposits along the shore.

Typical firth lagoons, which have the configuration of the firths; they are separated from the sea by a bar that was formed owing to the transversal transport of material.

Complex firth lagoons, one part of their basins has a configuration of an ordinary lagoon and the other is a firth; they are separated from the sea by a bar or spit.

Lagoon bays, which are separated from the sea not by accumulative bodies but by bedrock land parts; according to their hydrological regime and configuration, they can be considered lagoons.

According to the combination of geological conditions (topography, lithology, lithodynamics), we can distinguish the most widely spread types of coast for which special properties of lagoon development are typical.

Bedrock Coasts of Hard Rocky Material The beaches of a portion of the Russian arctic coasts are formed of hard rocky material, which are stable in the face of wave forcing. Usually, the underwater coastal topography in such regions is distinguished by steep slopes and rapidly increasing depths. Such coasts include the Kola Peninsula, the Novaya Zemlya and Franz Josef Land archipelagos (the Barents Sea); the northwestern coast of the Taimyr Peninsula (the Kara Sea). The structure of the coasts does not facilitate the formation of large accumulative bodies, which evidently causes an almost complete absence of lagoons. Small lagoons are formed here only at the tops of deep shallow bays. The accumulative bodies separating these lagoons from the sea are frequently a result of the glacier, but not wave forcing. However, the area of Lake Mogilnoye located on Kildin Island at the Murmansk coast of the Barents Sea is only 0.09 km^2. This is actually a lagoon separated from the sea by a bar approximately 70 m wide, which is permeable for seawater (Fig. 2.1). This lagoon is similar to a miniature model of the Black Sea, owing to the presence of a few water layers of different salinity, from almost fresh at the surface (salinity does not exceed 3‰) to a salinity greater than 30‰ at the bottom; conditions for hydrogen sulfide formation exist in the bottom layer. Each water layer is characterized by its own set of organisms, including the endemic ones. The lagoon-lake Mogilnoye is recognized as a natural hydrological monument protected by the state.

Low shores are formed by loose deposits. The longest Russian Arctic coasts are swampy lowlands formed by loose deposits, with a greater or smaller proportion of fossil ice. Such deposits are rapidly destroyed, even under weak wave forcing. Two main types of beach are formed depending on the composition and grain size of the loose deposits and the inclination of the underwater slope: beaches with pronounced accumulative bodies and those without them.

Lowland Shores with a Barrier Beach A combination of lengthy sand accumulative beach bodies, clearly seen in Fig. 2.2, with lowland swampy beaches is a specific feature typical of many Arctic coasts (Ogorodov 2001). Such beaches with similar origin and structure are widely spread throughout the eastern part of the Barents Sea (the Pechora Sea) (Varandey Islands, Pesyakov, Gulyaevskiye Koshki). A common mechanism for the formation of such accumulative bodies caused their similar structure, as shown in Fig. 2.3. The frontal marine side terminates with a dune belt (foredune), which reaches the height marks of 4–10 m. The marine slope of the foredune is adjacent to the beach (20–100 m), which transforms into a regular foreshore. The rear part of accumulative bodies located beyond the dune belt is usually a laida

Fig. 2.1 Lagoon-lake Mogilnoye on Kildin Island in the Barents Sea (Modified from Kosyan 2013)

or setup/setdown foreshore with height marks within 2.5–3.0 m (Popov et al. 1988).

Aeolian processes play an important role in the formation and development of such accumulative coastal bodies (Ogorodov et al. 2003). The sand transported from the underwater slope is then transported by the wind from the beaches and foredunes and precipitates within the dune belt. Vegetation on the foredunes prevents deflation and facilitates intense Aeolian accumulation. As a result, a powerful dune ridge is formed at the surface of the primary bars.

As the shore recedes, the entire accumulative body rapidly advances on the coastal laidas, river valleys, and shallow bays (Popov et al. 1988). Lagoons are formed in the flooded river valleys, which most frequently do not lose their connection with the sea, being maintained by the motions of the ebb tide. The lakes that appear in the influence zone of the sea are gradually filled with the deposits transported over the bars during storms, and then disappear as the sea advances. Usually, a direct water exchange between such lakes and the sea does not occur.

Lowland Shores Without Formation of a Barrier Beach The accumulative coastal bodies are usually not formed in lowland regions of the gently sloping beaches where there is no transport of beach-forming deposits (abrasion products, solid discharge of rivers, or transport from the underwater slope). This usually happens on the descending parts of the coasts. An intermediate zone (laida) usually separates the tundra zone and the sea basin. Sometimes, it is a few kilometers wide. The laida is periodically flooded by the tides or setups. Specific vegetation (marshes) is typical of the laidas. Two levels are frequently distinguished in the laida morphology corresponding to the levels of low and high coverage, as one can see in Fig. 2.4 (Popov et al. 1988). Such conditions of shore development are not conducive to the formation of a real lagoon type. The existing lakes of river valleys are simply flooded by the sea.

Fig. 2.2 Extended accumulative body divides the lowland swampy tundra and the sea basin if the amount of deposits is sufficient. Eastern part of the Barents Sea (Modified from Kosyan 2013)

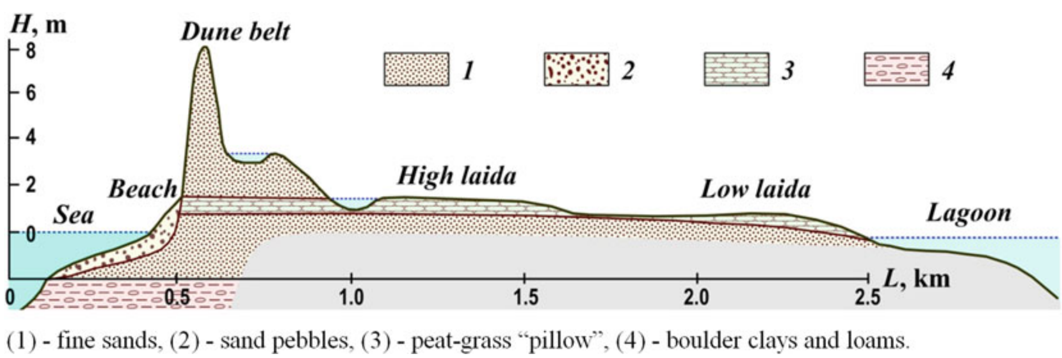


Fig. 2.3 *1* Fine sands, *2* sand pebbles, *3* peat-grass "pillow", *4* boulder clays and loams. Transversal geological geomorphological profile across the accumulative body on Pesyakov Island (Popov et al. 1988)

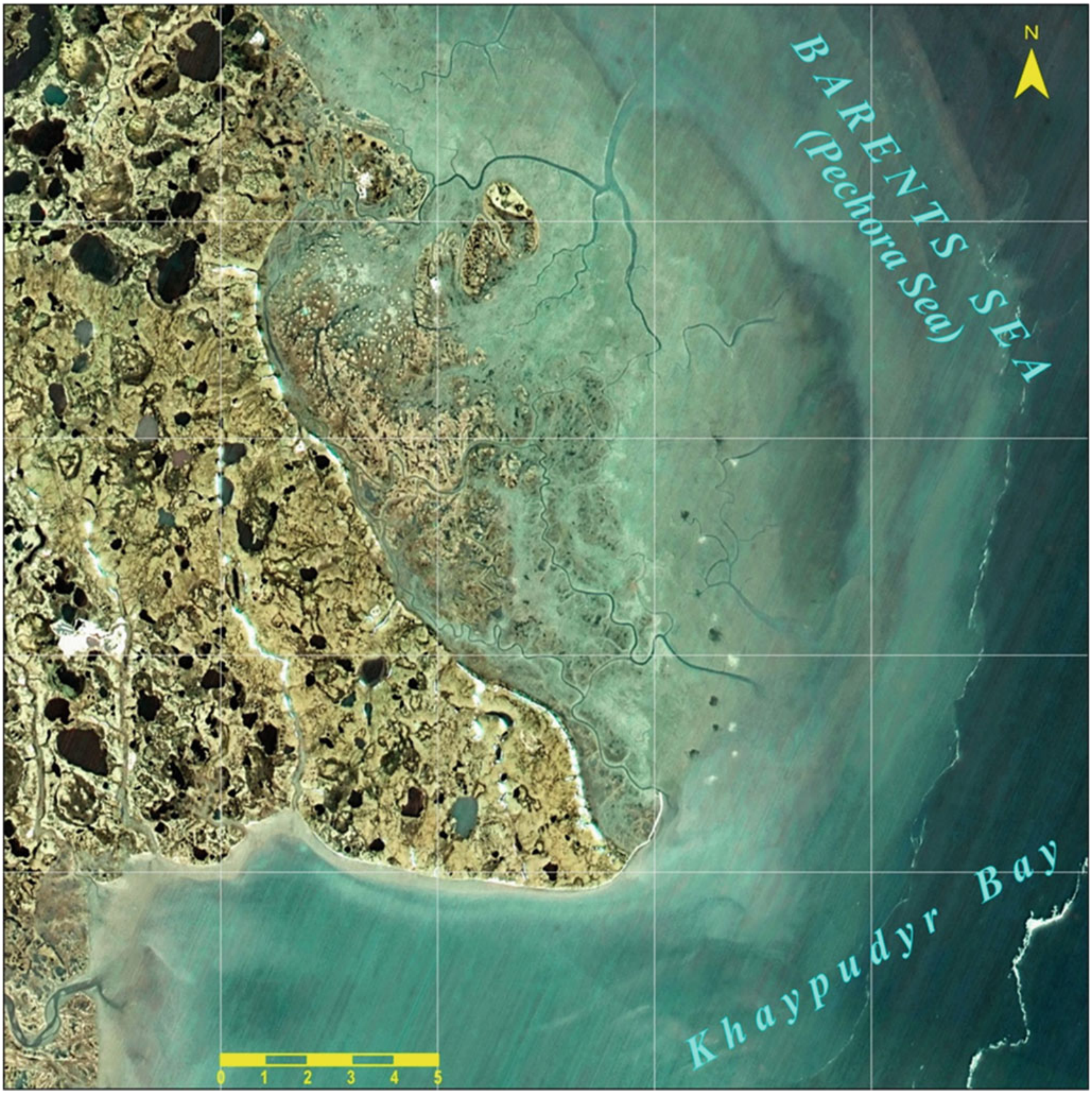


Fig. 2.4 If the amount of deposits is not sufficient for the formation of accumulative bodies, an intermediate zone (laida) separates the low wetland tundra and the sea basin. A laida is formed by tidal setup/set-down fluctuations of the sea level. It can be a few kilometers wide. Eastern part of the Pechora Sea (Modified from Kosyan 2013)

Low Shores Without Formation of a Barrier Beach with Foreshore Zone An intermediate shore structure is formed when deposits accumulate in the coastal zone but their grain size and amount do not provide for formation of an entire thick accumulative body of a bay-bar or spit. Usually, such a shore structure is observed in regions where wave forcing at the bottom and shore is low (as a result of a very gently sloping bottom or when the ice cover period is long). Such shores are characteristic of the western part of the East Siberian Sea and the eastern part of the Laptev Sea (Fig. 2.5).

Accumulative Bodies of Freezing Wave Origin If wave forcing is low, the rapid modern freezing of the deposits accumulated in the coastal zone facilitates stabilization of accumulative bodies formed under wave forcing, even if the amount of deposits is not high. Frozen organic remains,

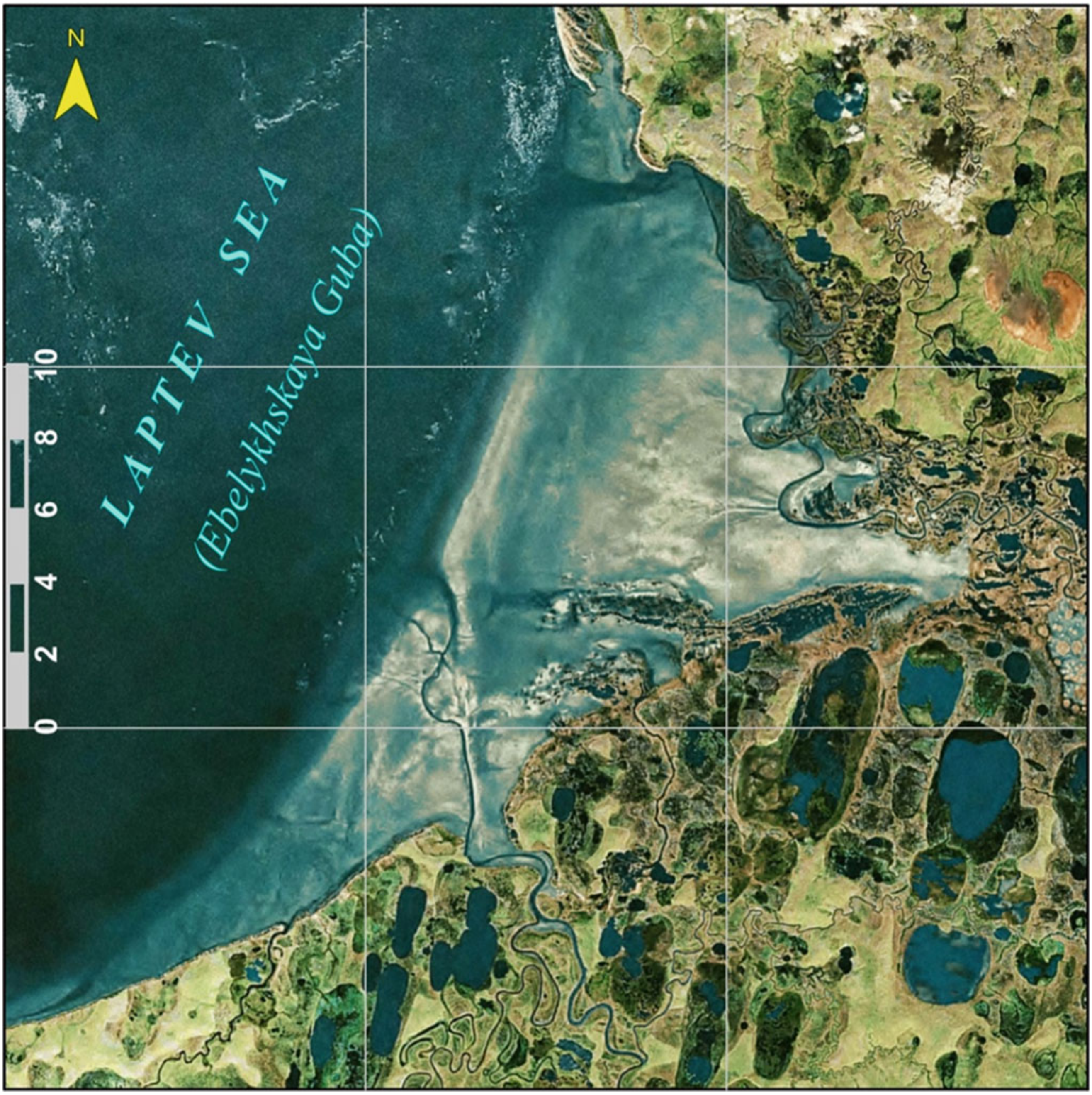


Fig. 2.5 Silt foreshore in the eastern part of the Laptev Sea (Ebelykhskaya Guba) (Modified from Kosyan 2013)

mixed with sand and silt, sometimes serve as the material for the formation of accumulative bodies. Such conditions are favorable for the appearance of lengthy accumulative bodies, which separate large water reservoirs from the sea. The Mogotoevo lagoon-lake, located along the coast of the East Siberian Sea (Fig. 2.6), is an example. This is a large (323 km^2) brackish (13–19.5‰) reservoir formed by a large accumulative body located to the northwest of the Indigirka River mouth in Yakutia.

«Typical» Bars and Bay-Bars The largest accumulative bodies and lagoons are formed when the conditions of relatively steep bottom slopes, strong wave forcing, and an abundance of deposits of large granulometric size are combined. Such conditions are characteristic of a significant part of the shores of the East Siberian Sea and the Chukchi Sea. The inclinations of the bottom slopes there are usually 0.01–0.02 (reaching 0.08), which makes possible the development of powerful waves capable of transporting sandy pebble material from the underwater slope to the beach. The traces of wave impact at

Fig. 2.6 The East Siberian Sea. Accumulative body is located to the northwest of the Indigirka River mouth. Several large lagoons are formed, together with numerous small lagoons. Lake Mogotoevo is the largest of them (Modified from Kosyan 2013)

the bottom are sometimes observed up to depths of 35–40 m. However, the main condition for the development of high accumulative bay-bars is the abundance of mobile sandy pebble deposits on the submarine slope (Fig. 2.7). Usually, the material of the modern abrasion is not enough for the formation of large and stable accumulative bodies at the open coast. The discharge of the major part of the northern rivers is usually represented by deposits of sand-silt size. The major part of it precipitates in the deep bays (flooded river valleys). Therefore, the only possible sources of the material applicable for the formation of large bars are silt and fluvio-glacial sediments on the shelf transported by water streams during the melting of mountain and valley glaciers flooded during the Holocene regression. Under the conditions of transgression and domination of the transversal motion of the sediments, part of these deposits formed a lengthy coastal ridge, which was slowly displaced to the coast during the transgression. This process slowed down simultaneous to the decelera-

Fig. 2.7 Lagoon coasts of the Chukchi Sea (Modified from Kosyan 2013)

tion of the transgression, but in some regions, where a relative increase in the sea level exists, the bars continue their inland motion (for example, the bay-bar of the Inchoun Lagoon in the Chukchi Sea). This process leads to an alignment of the coastline along a significant length of the shore, as one can see in Fig. 2.7. As the bar approaches the regions of the coast that are stable in the face of abrasion (mountainous massifs of hard rocks), protruding capes are formed. Accumulative arcs supported by the abrasion capes will be formed as the bars displace to the lowland beach.

2.3 Estuaries of the Russian Arctic Seas

The features of the tectonic-geological structure of the continental margin determined the configuration of the modern coastline of the Arctic seas. After completion of the Holocene transgression, the coastline of the Arctic coast was considerably indented. Flooding of sea river valleys that had been greatly deepened during the previous regression formed deep ingressive bays.

The subsequent arrival of the river solid runoff and abrasion products changed the coast's configuration. Many bays were completely filled by river solid run-off or blocked by mouth bars. They transformed, respectively, into deltas or lagoons. However, some ingressive bays were preserved, forming special natural features – estuaries, where the combined influence of river runoff and sea is exhibited. The tectonic subsidence of near-coastal land or the deficiency of solid material to form deltas or estuary bars contributed to the preservation of the estuaries.

In modern scientific literature, the definition of an estuary is "a semi-closed water body, which is part of the river mouth area and characterized by active processes of the sea and river water mixing" (Mikhailov and Gorin 2012). The main feature of the estuary (besides a semi-closed form) is the existence of a mixing zone for fresh river and salty sea waters and the existence within it of the “estuarine barrier” where salinity varies within 1–8‰ (Mikhailov and Gorin 2012).

Researchers have isolated a number of different types of estuary. The following are the usual criteria for determining estuary type: morphologic (shape and origin of the estuary); characteristics of the longitudinal changes in water salinity; characteristics of the salinity’s vertical distribution; tidal level oscillations; characteristics of the water circulation. In accord with the morphological and genetic features, all estuaries can be classified into four main types: sea type, river bed type, lagoon type and liman type (Mikhailov and Gorin 2012).

Semi-enclosed bays in which “estuarine barriers” (the mixing zones of river and sea water masses with changes in salinity from 1 to 8‰) are formed under the influence of river runoff are marine type estuaries. A close relationship with the sea and a relatively weak effect of river run-off are distinctive features of marine estuaries. The deep bays of the Barents and Kara Seas (Gydansky, Baidaratskaya, Khaipudyrskaya and the like) can be attributed to this type of estuary. Many small rivers flow into these bays. River run-off has little effect on their hydrological and hydrochemical regime. Perhaps the little-known fjords of the Novaya Zemlya archipelago are like estuaries.

River bed estuaries are formed in the lower parts of river beds under the influence of the opposite flows of river and sea water. Two subtypes of river bed estuary are determined according to features of the hydrological mode (Mikhailov and Gorin 2012): those with widening mouths and those without. Hydrological processes in the river bed estuaries without widening mouths proceed under the primary influence of river run-off. Often, there is estuarine water circulation when river water moves to the sea in surface layers and sea water moves towards the river at the bottom. Along the Russian Arctic coast, this type of estuary is available at the mouth of the river Yana. In river bed estuaries with widening mouths, their hydrological processes are characterized by the action of sea tides; river and sea waters actively mix, causing delicate water stratification in these objects. Estuaries of this type prevail on the coasts thanks to the presence of strong rocks, for example, the Kola Peninsula in the Barents Sea.

The origin and form of estuaries of the lagoon type are mainly related to waves and sediment motion in the mouth zone, where accumulative sea bodies (spits, coastal bars, barrier islands etc.) are formed. The main difference between lagoon estuaries and standard lagoons is the presence of river run-off in them. On the featureless coasts, the lagoon estuaries are water bodies extended or waterways flowing along the sea coast, “pressed” by bay-bars to the land. Most lagoon estuaries are located at the mouths of small and medium rivers, a type quite prevalent along the Arctic coast. The main difference between lagoon estuaries and other types is that their hydrological processes are related to the dynamics of the accumulative form, separating these estuaries from the sea. This type of estuary is predominant along the coast of the East-Siberian and Chukchi Seas. Other types of estuary are practically absent, because the majority of river mouths are blocked by accumulative bodies or have deltas (Fig. 2.7).

Liman estuaries often form near the mouths of medium and large rivers and have an elongated form along the axis of the river valley. Liman estuaries are either unblocked on their seaside or are partially blocked by accumulative forms (spit, bay-bar, barrier islands). The water regime of liman estuaries is determined by river runoff. Liman estuaries’ salinity increases closer to the sea. In estuaries of this type, the majority of solid runoff settles near the mouth, forming deltas. In Russia, estuaries of the liman type are called “liman” or “guba”. In English language papers, such estuaries are called “coastal plain estuaries” or “drowned river valleys”. The largest estuaries of the Russian Arctic coast are of this type, in particular, those of the largest rivers of Russia – the Ob and the Yenisei Rivers, which flow into the Kara Sea, and the Khatanga and Anabar Rivers, which flow into the Laptev.

Estuaries are very interesting objects, scientifically speaking, because they are unique centers of biological activity in the system between the sea and the river. They have original hydrological, hydrochemical and hydrobiological conditions. Here, river runoff interacts with the salty waters of the sea, this interaction affecting the composition, distribution, quantitative indicators and living conditions of the biological organisms in the estuary. Furthermore, estuaries are often areas of human activity, as they have favorable locations for transport and other infrastructure. High sensitivity to natural and anthropogenic impact and slow reducing processes are features of the estuarine ecosystems of the Arctic Seas.

The intensity of interaction in the “river – sea” system is determined by the amount of river run-off (and its seasonal fluctuations), tidal processes, and surge phenomena. The influence of the Russian polar seas on inflowing rivers can be estimated from the data in Table 2.1.

It should be noted that poor knowledge of the Arctic coasts of Russia, including estuaries, creates difficulties for their economic use and protection. Most Arctic estuaries are of interest, not the least for their valuable natural objects, and need further study.

Table 2.1 Tide and surge influence on the regime of the Russian Arctic rivers

River	Run-off, km³/год	Max tide, m	Max surge, m	The maximum range of intromission of:		
				Tide, km	Surge, km	Salinity water, km
Pechora	128.4	1.0	2.4	180	160	10
Ob	357	0.7	3.0	51	358	200
Pur	28.4	–	1.5	–	100	0
Taz	33.5	–	1.8	–	180	0
Yenisei	624.4	0.7	3,0	566	990	253
Hatanga	104.5	0.8	2.5	227	–	–
Lena	521	0.4	2.5	25	56	–
Jana	35.1	0.2	1.5	10	133	60
Indigirka	49.5	0.3	2.0	24	137	–
Kolyma	123	0.1	2.5	–	283	–

Modified from Mikhailov (1997)

2.4 Lagoon Coasts and Estuaries of the Russian Arctic Seas

2.4.1 The Barents Sea

General Characteristics of the Sea

The Barents Sea is the westernmost sea among the seas of the Russian Arctic sector. In modern boundaries, the sea is located between latitudes 81°52′ and 66°44′ N and between longitudes 16°30′ and 68°32′ E. The sea has natural borders in the south and, to an extent, in the east. In the other parts, its boundaries are conventional lines (Dobrovolsky and Zalogin 1982). In the west, the Barents Sea borders the Norwegian Sea along the following line: Southern Cape (the southern tip of the Spitsbergen Archipelago) – Bear Island – North Cape (Cape Nordkapp). The southern boundary of the sea is the continental coast and the following line: Cape Svyatoy Nos – Cape Kanin Nos, which separates it from the White Sea. From the east, the sea is limited by the western coast of Vaigach and the Novaya Zemlya islands, and then by the line along the straits bordering the Kara Sea: Cape Zhelaniya – Cape Kohlsaat. In the north, the border is located along the northern edge of the Franz Josef Land archipelago and then from Cape Mary Harmsworth (Alexandra Land Island) through the Victoria and Belyi islands to Cape Leigh Smith on Nordaustlandet Island (Spitsbergen Archipelago).

The Barents Sea is one of the largest Russian seas; its area is 1424 th. km² (according to the other data 1405 th. km²), and its water volume is 316 th. km³ (Arctic and Antarctic Research Institute).

The southeastern part of the Barents Sea between Kolguev Island and the southwestern coast of Novaya Zemlya is called the Pechora Sea. The Kara Gates Strait and Yugorsky Shar Strait are not related to the Pechora Sea (Dobrovolsky and Zalogin 1982; Pavlidis et al. 2007). There are many islands in the Barents Sea, and large archipelagos are its boundaries. Small islands are located near the coasts or close to larger islands; they are frequently joined into small archipelagos.

Characteristics of the Barents Sea Shores

The length of the coastline of the Barents Sea is 6645 km (Dobrovolsky and Zalogin 1982). Individual regions of the shores are related to different morphological types, which can be seen in Fig. 2.8. The Barents Sea is characterized by a wide variety of shores, which are strongly determined by the structural geological formation of the coast (Alekseevsky 2007). The main types of shore and their characteristics are presented in Table 2.2.

The variations in accumulative shores (beach, lagoon, delta, and foreshore) are widely spread within the Barents Sea (Alekseevsky 2007). Large accumulative marine bodies of different types are characteristic of these shores. The accumulative bodies are represented by the forms of transversal transport of sediments (including the relict bars) and by the forms of alongshore motion. The forms of transversal sediment transport are generally represented by bars and bay-bars (blocking the river estuaries or shallow-water bays) on the shores, formed by loose or easily eroded rocks. Elongated accumulative bodies are formed as a result of the alongshore transport of sediments on gently sloping low coasts of the Pechora Sea formed by loose rocks. These are shown in Fig. 2.9. The most interesting are the tombolos forming the Svyatoy Nos Peninsula, which has a double side supply of material and a large coastal bar (Timansky bereg) with a total length of 200 km. It separates a number of lagoons from the sea and continues to exist as partly flooded islands in the current period: Gulyaevskiye Koshki.

Tombolos are found on the shores of Vaigach Island (including double tombolo), connecting individual islands to each other or with the main coast, as one can see in Fig. 2.10. These tombolos frequently separate lagoons of small area from the sea.

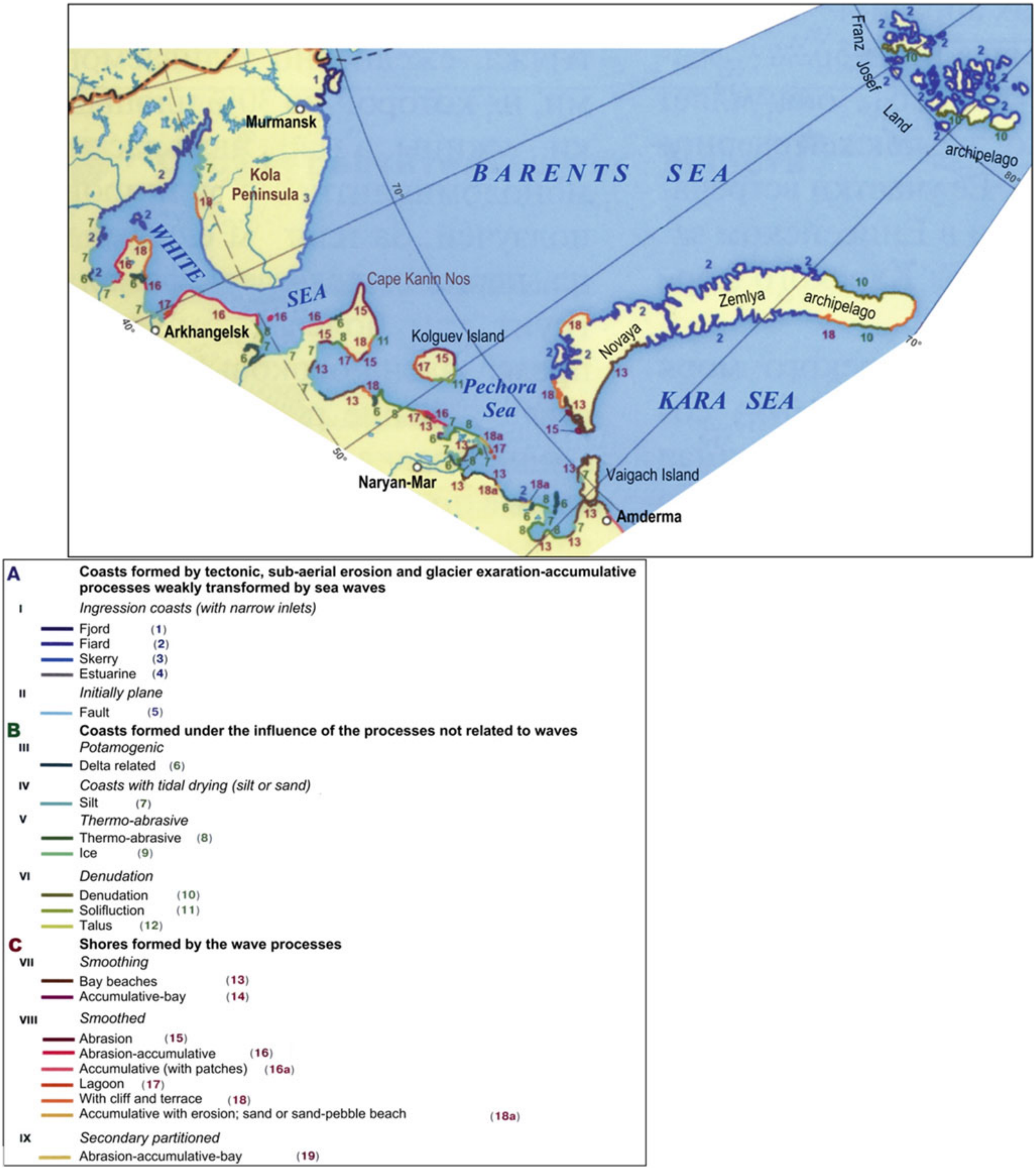


Fig. 2.8 Morphological types of the Barents Sea coasts (Spiridonov et al. 2011), *A*, *B*, and *C* are types of sea shore, *I–IX* (*Roman numerals*) subtypes of shore partitioning, *1–19* (*Arabic numerals*) primary causes of the initial partitioning of the shoreline

The city of Murmansk is situated in the deep Kola Gulf of the Barents Sea (Fig. 2.11). The gulf is 47 km in length and from 1 to 7 km in width and has a tectonic origin, i.e., it is a fjord and not a flooded river valley. The depths at the gulf entrance are between 200 and 300 m. According to its geomorphological features, the Kola Gulf is conditionally divided into three parts: the south, the middle, and the north. The small Tuloma and Kola Rivers run into the southern part

Table 2.2 Proportion of the shore types in the Barents Sea (%)

Shore type	Continental coast	Islands	Total
Not affected by the sea	29.6	29.5	29.6
Abrasive-denudation	–	7.4	4.9
Abrasive	11.3	5.0	7.2
Abrasive fossil	1.7	7.6	5.6
Thermo-abrasive	16.0	43.2	34.0
Abrasive-accumulative	0.7	2.9	2.1
Accumulative: beach	5.0	2.0	3.0
Lagoon	14.0	2.4	6.3
Foreshore	16.7	–	5.6
Delta	5.0	–	1.7

of the gulf. The hydrological and hydrochemical processes in the Kola Gulf concurrently have features of marine, riverbed, and liman estuaries. This kind of structure and regime is characteristic of many fjord-like gulfs of the Kola Peninsula and the Novaya Zemlya archipelago.

The Kola peninsula is characterized by a great diversity of hydrological conditions. Tides in the gulf are semidiurnal, up to 4 m.

The salinity regime in the Kola Gulf is determined by the degree of desalination of the water of the Barents Sea when mixed with fresh waters. Salinity varies depending on river runoff, spring snow melting, liquid fallout, intensity of water exchange and mixing. The salinity degree quickly decreases with depth. Salinity at all levels beginning at 100 m remains within the range of 34.0–34.5‰ throughout the whole year. At a depth of 50 m in the middle of the Kola Gulf, desalination up to 33.8‰ can be observed. In the middle and northern parts at depths from 10 to 25 m, salinity is about 34‰ in winter and decreases to 32‰ in summer. At a depth of 5 m, salinity is from 32 to 33‰ in winter and decreases to 25‰ in summer. Salinity in the surface layer varies very much throughout the gulf, being no less than 30‰ in winter, and decreasing to a range of 15–20‰ in early summer. The most significant desalination is observed in the southern part of the Kola Gulf, with summer salinity in the surface layer decreasing at a rate of 10–15‰. At the 5 m level, salinity varies from 28 to 32‰ for the better part of the year; from June to August, it decreases to a range between 15 and 20‰. At the 10 m level, salinity remains fixed at no less than 25‰.

Ice phenomena in the Kola Gulf change significantly from year to year. In some years, ice is only observed in the Gulf from February to March; there are years when the southern and middle parts are entirely covered with ice of up to 30 cm thickness. In the most severe winters (1935–1936, 1965–1966, 1978–1979, 1997–1998, 2010–2011, 2014–2015), a complete freezing of the gulf has been observed.

The Kola Gulf coast is home to the largest cities and ports of the Russian Region of the Arctic: Murmansk and Severomorsk. The main sources of gulf water pollution are industrial, agricultural, and the result of transport enterprises, marine vessels, and settlements. Wastewaters are discharged into the Kola Gulf by 60 large enterprises, about 1000 vessels are attached to the sea ports, and about 4000 port calls are registered every year. Since 2004, the largest Russian off-shore oil shipment terminal, holding 360 thousand tons of oil, has been functioning in the Kola Gulf. One hundred and twenty seven sunken vessels considered to be sources of pollution have been registered in there. Thus, the Kola Gulf ecosystem undergoes extremely severe technogenic pollution.

2.4.2 The Kara Sea

General Characteristics of the Sea

The Kara Sea is a wide open portion of the Arctic Ocean. The major part of the sea is located on a shallow continental shelf. It is related to the continental marginal sea type. The Kara Sea is one of the largest Russian seas. Its square is 883 th. km^2, the volume is 98 th. km^3, the mean depth is 111 m, and the maximum depth is 600 m (Dobrovolsky and Zalogin 1982; Arctic and Antarctic Research Institute 2015).

The western boundary of the sea goes from Cape Kohlsaat (the Frantz Josef archipelago) to Cape Zhelaniya (Desire) (the Novaya Zemlya archipelago) and then along the eastern shores of the archipelago, stretching from the western boundary of the Kara Gates Strait from Cape Kusov Nos (the Novaya Zemlya archipelago) to Cape Rogaty (Vaigach Island) and then along the eastern shore of the island, and finally from the western boundary of the Yugorsky Shar Strait to the continent. The northern boundary goes from Cape Kohlsaat (the Frantz Josef archipelago) to Cape Arctichesky on Komsomolets Island (the Severnaya Zemlya archipelago). The eastern boundary goes along the western coasts of the Severnaya Zemlya archipelago and eastern boundaries of the Krasnoi Armii, Shokalsky, and Vilkitsky straits. The southern boundary goes along the continental coast. Within these limits, the sea occupies the basin between

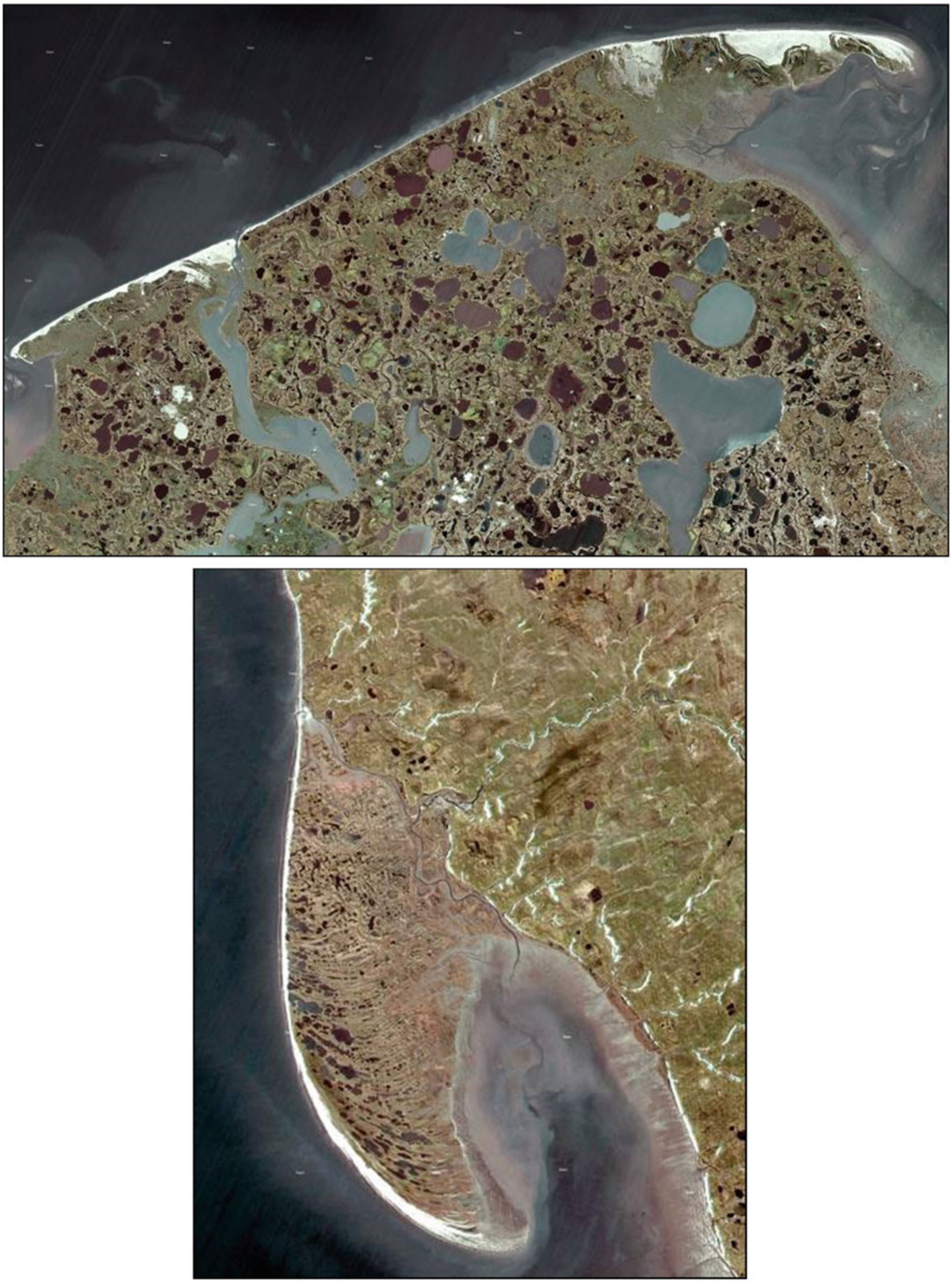


Fig. 2.9 Sand silts in the Pechora Sea (Modified from Kosyan 2013)

Fig. 2.10 Accumulative bodies; southern coast of Vaigach Island (Modified from Kosyan 2013)

the 81°6′ and 66°0′ N latitudes and the 55°2′ and 104°1′ E longitudes.

There are many islands in the Kara Sea. Most of them are small and located along the continent. The large islands are solitary and the small islands are grouped into archipelagoes.

Characteristics of Shores of the Kara Sea

The coastline length of the Kara Sea is 9790 km. The length of the continental part is 6025 km, and the island part is 3765 km. The abrasion and accumulative shores are almost equally developed. Abrasion shores slightly dominate (mostly thermal abrasion shores), as seen in Table 2.3 and Fig. 2.12.

Accumulative and abrasive-accumulative shores are widely spread in the bays and along the open coasts. They are frequently subject to strong wave erosion.

There are not that many full scale lagoons along the coasts of the Kara Sea, a fact related to the peculiarities of the geological structure of the shores, which does not facilitate the development of accumulative bodies. The domination of alongshore sediment transport, which facilitates the formation of unclosed accumulative bodies (spits), is another possible cause. We note the existence of several large bays along the western coast of the Yamal Peninsula, partly separated from the sea by spits. The largest is the Sharapov Shar Gulf, separated from the sea by the Sharapovy Koshki Islands, which are accumulative bodies (Fig. 2.13). Strong tides prevent the formation of continuous accumulative shores.

Lagoon shores are widely spread along the northern part of Belyi Island (Fig. 2.14), as well as the Olenyi, Shokalskogo, and Sibiryakova Islands, and on the Gydansky Peninsula. These lagoons are not large. Usually, they are the flooded valleys of small rivers separated from the sea by accumulative spits and bay-bars created out of the erosion material of low bedrock shores made up predominantly of sands, loams, and clays with numerous ice veins.

The largest estuaries of the Russia Arctic coast are the estuaries of the Kara Sea. Here are situated the liman type estuaries of the Ob River (with the adjoining estuary of the river Taz) and the Yenisei River (Fig. 2.15). In addition, the Baidaratskaya Guba and Gydanska Guba ("guba" – the local name for a deep sea bay) can be considered estuaries of the sea type. About 40 % of the Kara Sea water area is influenced by river runoff. The rivers carry 1290 km^3 of fresh water per

Fig. 2.11 Kola Bay of the Barents Sea (Modified from Kosyan 2013)

year into the sea, 80 % of which comes in during the period from June to October. The Yenisei brings 600 km^3 of water per year, the Ob, 450 km^3, the Pur and Taz, 86 km^3 together, the Pyasina, 80 km^3, and the others, about 74 km^3 all together.

Ob River Estuary

The Ob River estuary (the Gulf of Ob, the local name of the Obskaya Guba) is the largest gulf of the Kara Sea. The gulf separates the coasts of the Gydan peninsula in the east and

Table 2.3 The types of the Kara Sea shores (%)

Shore type	Continental coast	Islands	Total
Lightly or weakly transformed by sea	16.3	35.0	23.5
Abrasive as a whole, including:	24.8	32.4	27.7
Abrasive	4.3	8.6	5.9
Thermo-abrasive	19.3	19.3	19.3
Abrasive-denudation	–	1.7	0.7
Abrasive with fossil cliff	1.2	2.8	1.8
Abrasive-accumulative	23	11.7	19.3
Accumulative:	25.4	20.9	23.6
Beach	10.5	14.9	12.2
Lagoon	3.2	6.0	4.3
Setup (foreshore)	11.7	–	7.2
Delta	10.5	–	6.4

the Yamal in the west (Fig. 2.15). The estuary is about 800 km in length (many researchers consider it to be the longest estuary in the world). The width of the estuary ranges between 30 and 80 km, the total area is 20,800 km^2, and its volume is 400 km^3. The lowest depth of the estuary reaches 25 m, but throughout most of its area, it varies within a range of 10–15 m. Between the estuary and the main sea, there is the Ob bar, a sand-bar in the most active part of the estuary runoff cone resulting from river sediments deposited in the area where the river flows into the sea. The Ob estuary bottom is of firm mud, and only along the coast are there some sand banks.

The Tazovskaya Guba, i.e., the estuary of the Taz and Pur rivers, is on the same side as the Ob estuary in the east (Fig. 2.15). Besides the Ob and Taz Rivers, several small rivers run into the Ob estuary, sometimes forming island archipelagos near the estuaries. The Ob estuary coasts are steep in the west and flatter in the east. Islands only occur in the small river mouths, and there are few gulfs and bays. The Ob estuary coast is woodless, being dominated by marshy Arctic tundra.

The current look of the Gulf of Ob came about during the Holocene transgression, when the Kara Sea waters flooded the bed and floodplain of the lower Ob. Coastal thermoabrasion and erosion caused a significant widening of its lower valley, and the estuary deepening took place as a result of the river's thermic impact upon the bed permafrost. At present, these processes are still going on in the gulf.

The Ob estuary's hydrological regime is determined by the river Ob delivering 75.8 % of the river runoff, i.e., 530 km^3. The main feature of the Ob basin is a huge watershed of 2,770,000 km^2, 75 % of which is a heavy wetland. A minor slope of the river basin in its flat area leads to a high degree of natural regulation of the runoff. The Ob River has a prolonged high water in the spring and summer. Starting in October and continuing throughout the entire winter, the river runoff sharply decreases. During the high water period, the greater part of the estuary has a hydrologic regime similar to that of a river; in the lower water period of winter, the regime is similar to that of a lake, and the importance of meteorological components, i.e., winds and related positive and negative setups, the amplitude of which can reach from 3 to 4 m, grows sharply at that time.

A tidal wave 0.5 m in height in the Kara Sea would first grow to two or three times its initial size when entering the estuary (the tide amplitude reaches 1.85 m), and then gradually decrease to zero in the Ob estuary. Positive setups in the Gulf of Ob are caused by the north, west, and northwest winds. Slight level rises can be observed under the southwest winds. Negative setups are caused by the east, south, and southeast winds.

The currents in the Ob estuary are generated by interaction between permanent, tidal, and windy currents. The permanent currents are formed by the Ob river runoff; they are directed to the north at a rate of 0.05–0.1 m/s. The tidal current at the estuary's entrance is semidiurnal, with reverse motion in the tidal cycle. The highest rates are observed in the northwest part of the Gulf of Ob and reach 0.6–0.7 m/s. In the surface layer, the rate of summary currents can reach 1.4 m/s, and at the bottom level (20 m), the maximum rate to have been observed is 0.5 m/s.

The Ob estuary stretches from the south to the north, a fact that has a significant effect on its ice regime. The greater part of the Gulf of Ob, excluding its southern part, freezes up in October. The estuary becomes completely free of ice in July.

In accordance with modern scientific classification, the Gulf of Ob is a microtidal, vastly stratified estuary of the liman type. The water in the greater part of the Ob estuary is fresh and contains a large amount of suspended matter. The area bordering the salt waters of the Kara Sea (the frontal

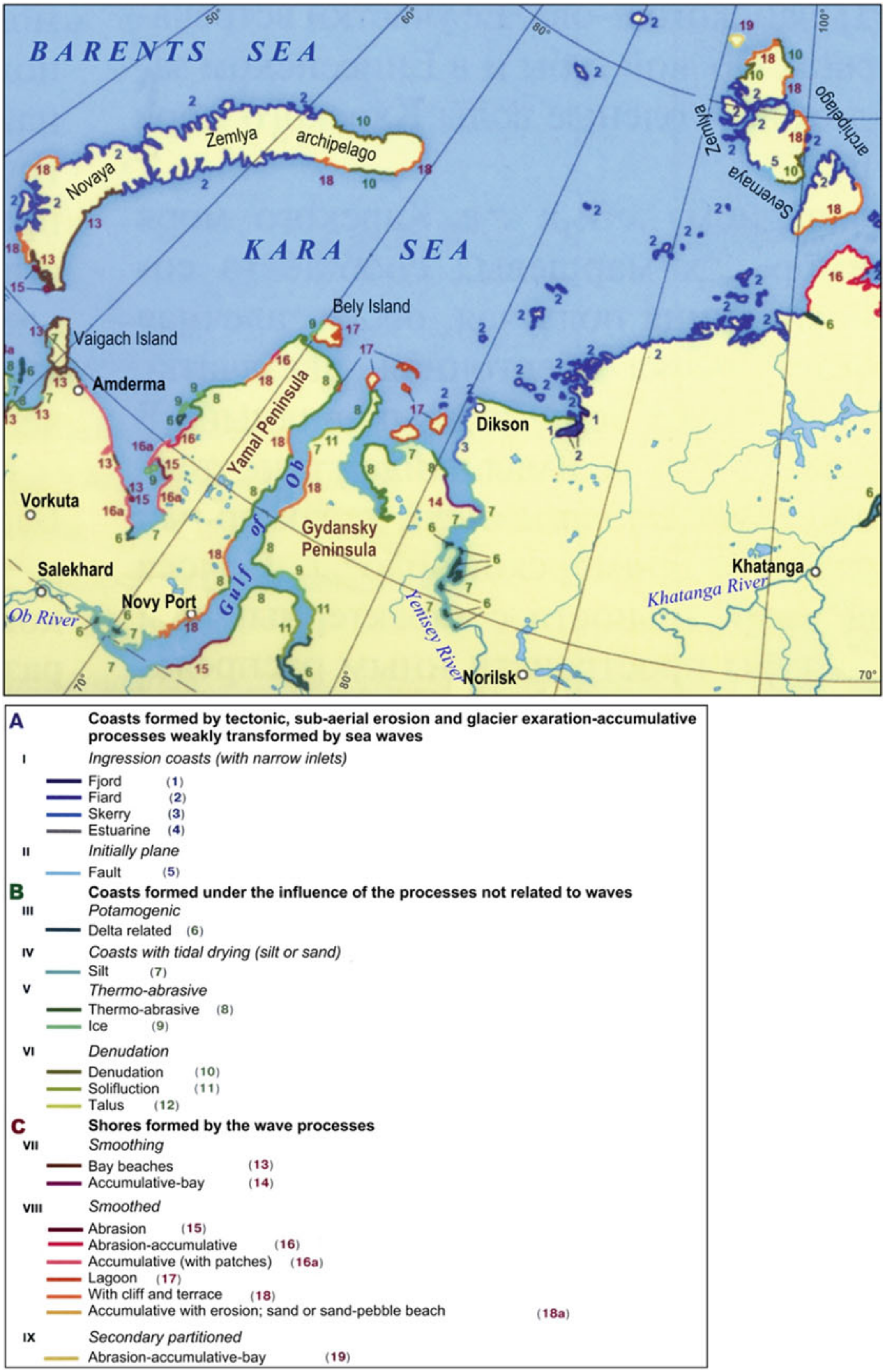


Fig. 2.12 Morphological types of the Kara Sea coasts (Spiridonov et al. 2011), *A*, *B*, and *C* are types of sea shore, *I–IX* (*Roman numerals*) subtypes of shore partitioning, *1–19* (*Arabic numerals*) primary causes of the initial partitioning of the shoreline

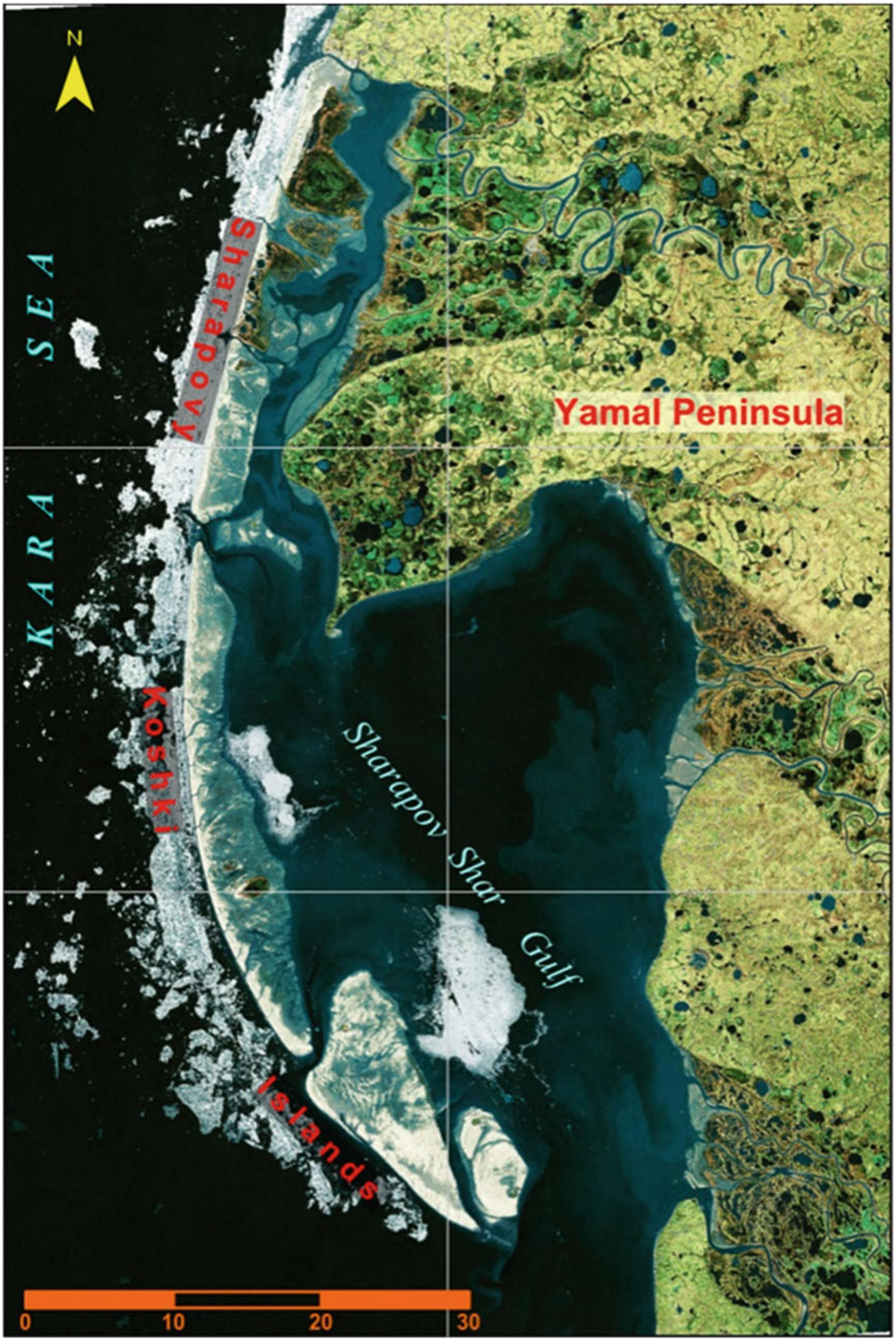


Fig. 2.13 Sharapovy Koshki Islands formed by accumulative processes and the Sharapov Shar Gulf (the Kara Sea, Yamal Peninsula) (Modified from Kosyan 2013)

Fig. 2.14 Belyi Island and the adjacent coast of the Kara Sea (Modified from Kosyan 2013)

zone) is flexible: during the high water period, it is located at 50 km from the sea, and by the end of winter, it moves up to 300 km to the south. The complicated dynamic interaction between the fresh runoff and the Kara Sea salt waters takes place in the north gulf; and the physicochemical, biochemical, and biological processes occurring on the boundary between the fresh water biocenosis and that of the marine area also intensify here. The bioproductivity of the Ob estuary is higher than that of the Ob River itself. The Ob estuary ichthyofauna includes more than 60 sea and freshwater species and subspecies.

In the flood-land of the Gulf of Ob lies the Nizhne-Obsky reserve, with a total area of 128,000 ha. The reserve territory is included on the list of wetlands of international importance ("Islands of the Kara Sea Gulf of Ob", Ramsar Convention). The reserve was organized for the purpose of maintaining the safety of rare species of animals, as well as protecting the nesting places and habitats of the indigenous birds.

Some small settlements, such as Novy Port, Yamburg, and Mys Kamenny, are situated on the Ob estuary coast.

The water areas of the Ob and Taz estuaries, as well as the Ob River, are used for navigation. These waterways facilitate cargo delivery to and from the area of the northern regions of West Siberia (Yamalo-Nenets Autonomous Okrug) to the Taimyr peninsula and Krasnoyarsk Krai. Similar delivery and removal of necessities for the West Siberian oil and gas basin are accomplished through the Taz estuary to the Pur and Taz rivers. Navigation and cargo transportation are pro-

Fig. 2.15 Estuaries of the Kara Sea: *1* Obskaya Guba, *2* Tazovskaya Guba, *3* Yenisey Gulf, *4* Baidaratskaya Guba, *5* Gydanska Guba (Modified from Kosyan 2013)

vided by the Enisey ship company. This cargo transportation is realized by special vessels which have a permit to work under the coastal conditions of the Kara Sea. The terms of cargo transportation are determined by the ice conditions. The navigation in this region usually takes place from August until the end of September.

Over the last few decades, a large number of oil and gas fields were discovered on the coast close to the Ob estuary and on its bottom. The Novy Port field is located within 30 km of the Gulf of Ob coast. The recoverable reserves of the Novy Port oil and gas condensate field exceed 230 million tons of oil and 279 billion cubic meters of gas; it is one of the largest fields of the Yamal. By 2020, it is estimated that 6–9 million tons of oil will be extracted there per year. The field is located far from the existing overland transport infrastructure, so it is necessary to transport the oil by waterway. For loading ships, by the end of 2015, OJSC "Gazprom Neft" plans to put the marine terminal Novy Port in the Ob estuary near the cape of Kamenny into operation. By 2019, the marine terminal will ship 8.5 million tons of oil per year. The port is planned so as to be able to receive tankers of Arc6 ice class with maximum deadweight up to 55 thousand tons, draught up to 9 m (fresh water), and maximum width from 32 to 34 m. The tankers will accomplish year-round cruises for the purpose of transporting oil to the ports of Murmansk and Rotterdam (the Netherlands).

Port Sabetta is already being built on the west coast of the Ob estuary. Port Sabetta, with an annual freight turnover of 30 million tons, will become one of the largest in the Russian Arctic. When the port is put into operation, the freight flow through the Gulf of Ob and Northern Sea Route will grow. Port Sabetta will become a key element in the transportation infrastructure of the Yamal LNG project, which provides for starting up a liquefied natural gas plant (LNG) on the resource base of the Yuzhno-Tambey field. Terminals for loading LNG and gas condensate will be built. The plan provides for dredging in the area of the Ob estuary, including laying a marine canal through the Ob bar of 49 km length, 295 m width, and 15.1 m seabed level. The general volume of the dredging is about 70 million cubic meters. Port Sabetta will function all year round, despite the severe ice conditions in the Ob estuary. As the Ob estuary is free of ice for only 3 months a year, it is supposed that the year-round oil removal can be accomplished using icebreakers. The nuclear-powered icebreakers "Yamal" and "Taimyr" are already working on the route to provide for navigation. The open-sea icebreaker "Yamal" brings ships to the Ob estuary, where the shallow-draught nuclear-powered vessel "Taimyr" accompanies them to Port Sabetta. The nuclear-powered icebreaker "Vaigach" will lay and renew channels for vessels going from Port Sabbetta to Port Dudinka in the Yenisei estuary.

Gas production is also planned in the Ob estuary water area. The Kamenny Mys field is located in the southern part of the Ob estuary between the Kamenny and Parusny Capes. Specialists estimate its reserves to be around 534.7 billion cubic meters. Gas production, with drilling planned in 42 wells, will begin here in 2021. For the main multiwell pad, they will use an ice-resistant platform, a metallic construction of 100 m length and 60 m width. The platform will be fixed on piles to the bottom of the Gulf of Ob; there will be a drilling installation on it, and after drilling, there will be gas conditioning equipment. In addition to that, a living settlement and gas conditioning installation are planned for construction on the Parusny Cape in the Nadymsky District. The objects will be connected to the Yamburg settlement infrastructure by the 80 km gas pipeline. By 2030, the Gasprom company will produce, in total, 50 billion cubic meters of gas per year in the Ob and Taz estuaries.

Thus, the Ob estuary and its coasts will eventually become a busy navigable and oil and gas production zone. Human interference will adversely affect the ecology of the Ob estuary. A marine canal of 50 km length and 300 m width will be laid through the Ob bar, located in the area adjacent to the main sea. The canal is necessary for high capacity tankers to pass into the ports. The Ob bar (a shallow area of the Gulf of Ob at the river-sea boundary) is a natural obstacle for the Kara Sea salt waters on their way to the south towards the freshwater estuary area. The canal construction will lead to an increase in the penetration of salt seawaters deep into the estuary and to changes in the Gulf of Ob's ecosystem. As a result, the volume of the Ob estuary's fresh water portion, which forms the basis for biological productivity in the ecosystem of the entire Ob basin, will decrease.

Yenisei River Estuary

The Yenisei estuary has a total length of 500 km and its width at the entrance is about 200 km. According to the geomorphological features, the estuary is divided into the silt delta, the Yenisei liman, and the Yenisey Gulf (Fig. 2.15). The Yenisei delta is about 180 km in length and includes the river segment from the settlement of Ust-Port on Nasonovsky Island. The liman, at a length of 115 km, begins at the north part of Nasonovsky Island; its external boundary is the Sopochnaya Karga Cape. The north part of the Yenisei estuary is called the Yenisei Gulf; its marine border is a line between the Mattesal Cape (Yavai peninsula) and the Severo-Vostochny Cape (near the Dikson settlement). The marine boundary of the estuary is not exactly defined; some researchers draw it along the straits to the east and to the south of Sibiriakov Island. Others set it as the entire water area within the line marked by the Shokalsky, Vilkitsky, and Dikson Islands, including the vast Gydan Gulf.

The depth of the Yenisei Gulf is 6–15 m; to the east of Sibiriakov Island, the gutter of the flooded Yenisei River valley, with a depth of 20–35 m, can be observed. Tides are semidiurnal, up to 0.4 m. The thermic and salinity regimes are determined by the volume of the Yenisei river runoff. The frontal zone has seasonal dynamics; the deepest penetration of seawater into the estuary is observed from February to March. In winter, the gulf is covered with fast ice and with drift-ice in the north. The Yenisei Gulf water freezes in October and the ice starts to break in June.

Sea routes to the ports of the lower Yenisei Dudinka and Igarka pass through the Yenisei Gulf. Port Dikson, providing navigation along the Northern Sea Route, is located on the eastern coast near the entrance to the Yenisei Gulf.

Within the northern part of the Gydan Peninsula and on the islands of the west Yenisei estuary, the Gydansky State Natural Reserve is situated. The reserve was established in 1996 to protect the undisturbed tundra ecosystems of West Siberia, and the coastal and marine ecosystems of the Kara Sea, as well as places of mass bird nesting.

2.4.3 The Laptev Sea

General Characteristics of the Sea

The Laptev Sea, in its modern boundaries, is characterized by the following measures: the area is 662 th. km^2, the volume is 353 th. km^3, the mean depth is 533 m, and the maximum depth is 3385 m. The western boundary runs along the eastern coasts of the Severnaya Zemlya archipelago from Cape Arctichesky (Komsomolets Island) and then along the Krasnoi Armii Strait, then follows the eastern coast of Oktyabrskoi Revolyutsii Island to Cape Anuchina, through the Shokalskogo Strait to Cape Peschanyi on Bolshevik Island and along its eastern coast to Cape Vaigach, then spans the eastern boundary of the Vilkitskogo Strait and up the continental coast to the top of the Khatanga Gulf. The northern boundary of the sea goes from Cape Arctichesky to the crossing of the meridian of the northern edge of Kotelnyi Island (139° E) with the conventional edge of the continental shallow bank (79° N, 139° E). The eastern boundary goes from the above-mentioned point (79° N, 139° E.) to the western coast of Kotelny Island and then along the western boundary of the Sannikov Strait, turning around the western coasts of Bolshoi and Malyi Lyakhovskiye Islands, and then continuing along the western boundary of the Dmitry Laptev Strait. The southern boundary goes along the continental coast from Cape Svyatoi Nos to the top of the Khatanga Gulf.

Within these boundaries, the sea is located between 81°16′ and 70°42′ N latitudes, and 95°44′ and 143°30′ E longitudes. According to its geographical location and hydrological conditions, which are different from those of the ocean, despite the sea being openly connected, the Laptev is related to the continental marginal sea type (Dobrovolsky and Zalogin 1982).

Characteristics of the Shores of the Laptev Sea

The length of the coastline of the Laptev Sea is 5900 km. The length of the portion along the continent is 3880 km, and the portion along islands is 2020 km. The coasts are related to different morphological types, which can be seen in Table 2.4 and Fig. 2.16.

Abrasive and accumulative shores in the Laptev Sea are almost equally numbered, with a slight domination of abrasive shores, as seen in Table 1.3 (Alekseevsky 2007). To the greatest degree, this is characteristic of the continental shores. Low shores are only a small part of the total length of the coastline of the sea.

A large amount of terrigenous material transported to the coastal zone from the rivers, as well as from the shallow submarine slope, facilitates the development of accumulative shores that form the edges of the plane. The rapid modern freezing of the sediments accumulated in the coastal zone and the intense formation of frozen columns facilitate stabilization of the sea shores, even if the relative amounts of the transported sediments is not high. Sea basins separated from

Table 2.4 The types of the Laptev Sea shores (%)

Shore type	Continental coast	Islands	Total
Lightly or weakly transformed by sea	1.7	20.5	8.2
Abrasive as a whole, including:	33.9	38.3	35.3
Abrasive	12.5	12.6	12.5
Thermo-abrasive	13.9	19.8	15.9
Abrasive-denudation	2.8	5.9	3.9
Abrasive with fossil cliff	4.7	–	3.0
Abrasive-accumulative	13.6	14.4	13.9
Accumulative:	32.8	26.8	30.8
Beach	9.2	9.7	9.3
Lagoon	6.7	8.9	7.5
Setup (foreshore)	17.0	8.2	14.0
Delta	17.9	–	11.8

Alekseevsky (2007)

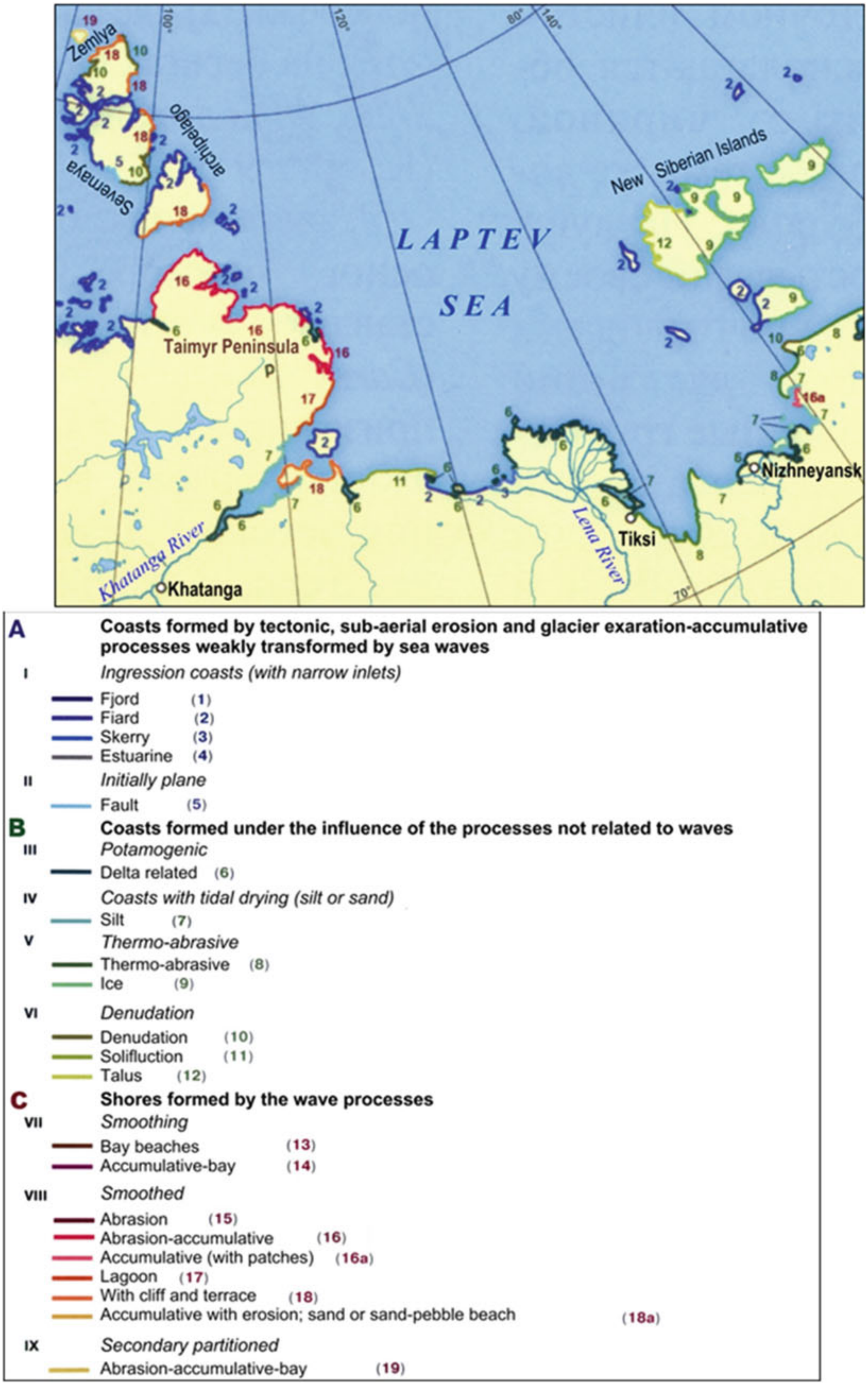


Fig. 2.16 Morphological types of the Laptev Sea coasts (Spiridonov et al. 2011), *A*, *B*, and *C* are types of sea shore, *I–IX* (*Roman numerals*) subtypes of shore partitioning, *1–19* (*Arabic numerals*) primary causes of the initial partitioning of the shoreline

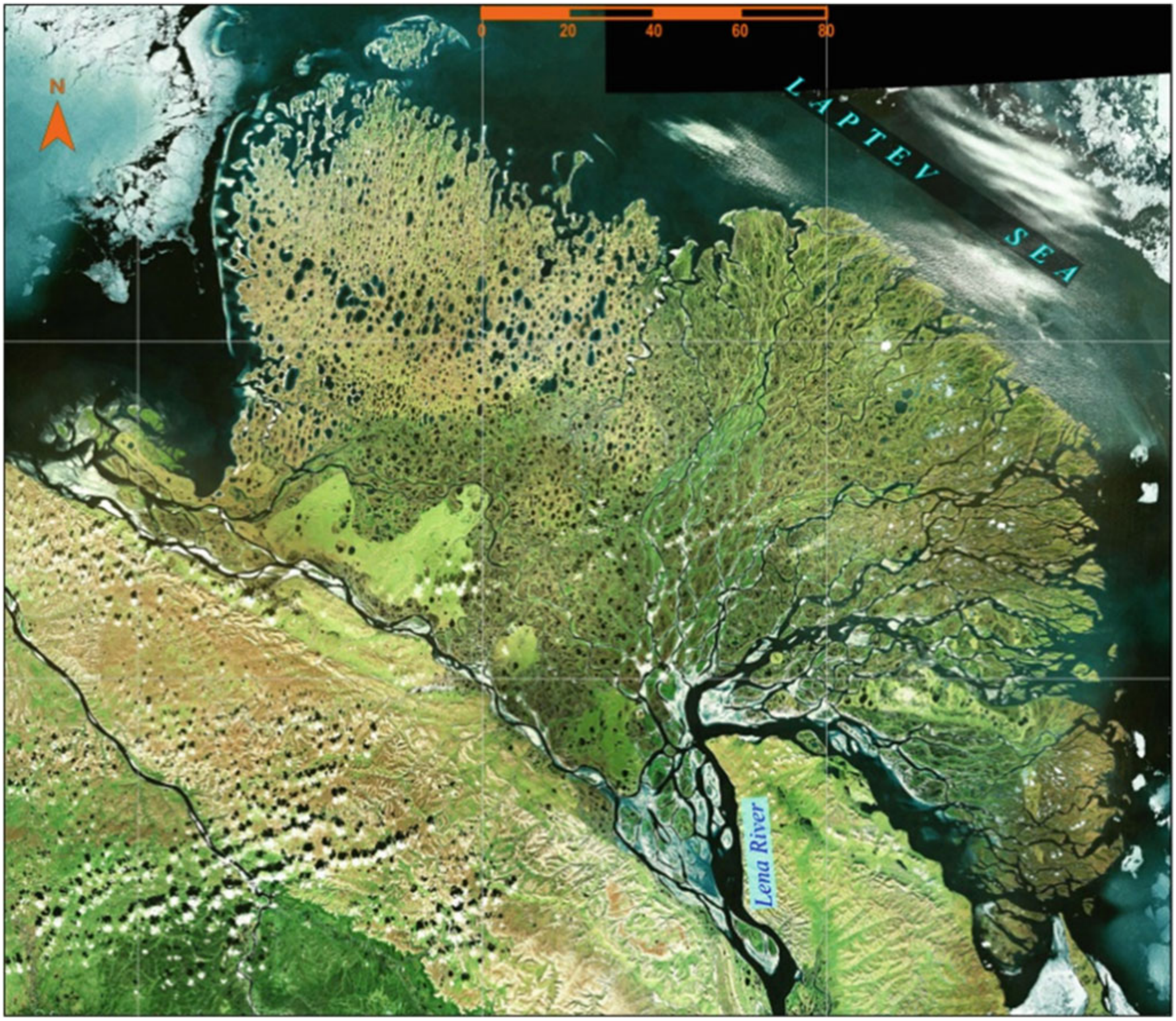


Fig. 2.17 The Laptev Sea, the Lena River delta (Modified from Kosyan 2013)

the sea occur under specific conditions, appearing in the deltas of the Lena and Yana, in shallow bays (Yana, Khromskaya Guba). In particular, the stable condition of a long sandy barrier that borders the northwestern part of the Lena River was recorded during the period 1969–2001 (Fig. 2.17) (Alekseevsky 2007).

Abrasive regions alternate with accumulative bodies along the eastern coast of the Taimyr Peninsula, where coastal steps are eroded in the sand-stone, schists, and also in loose Quaternary deposits. Edge bars formed of sand and pebble material separating small lagoons from the sea are observed most frequently (Alekseevsky 2007). Lagoons at the mouths of rivers are widely spread along the low shores of Khatanga Bay and the Begicheva Islands.

Several lagoons are located on the northwestern coast of Kotelny Island (the Novosibirskiye Islands archipelago) (Fig. 2.18), including the Stantsii, Reshetnikova, Eselyakh, Nerpalakh, and Durnays lagoons.

Khatanga and Anabar River Estuaries

The Khatanga river estuary (Khatanga Gulf) is in the southwest portion of the Laptev Sea. The gulf is about 230 km in length, and its maximum width is about 50 km (Fig. 2.19). The water exchange with the sea is realized via the Vostochny (8 km in width) and Severny (13 km in width) straits, separating the large Bolshoy Begichev Island. The Khatanga estuary includes the Kozhevnikov Bay and the Nordvik Bay situated in the west Khatanga Gulf. Throughout most of the

Fig. 2.18 Lagoons on Kotelny Island (the Novosibirskiye Islands archipelago) (Modified from Kosyan 2013)

gulf, the depths are from 8 to 20 m, while its central part features a gutter with a depth from 20 to 30 m that stretches towards the Severny strait, marking the location of the Khatanga river valley flooded by the sea.

The Anabar river estuary (Anabar Gulf) is located to the east of the Nordvik peninsula. The gulf is conical, widening in the direction of the sea, a shape similar to that of the "classic" estuary. The gulf goes 70 km into the continent and its width near the entrance is 76 km. The greater part of the Anabar Gulf is less than 10 m in depth, but the flooded bed of the Anabar River can be seen as a gutter with a depth of up to 17 m.

The coasts of the Khatanga and Anabar Gulfs are mainly high and indented, destroyed as a result of thermoabrasion. Tides are semidiurnal, up to 1.4 m. For much of the year (from October to July), the Khatanga and Anabar gulfs are covered with ice.

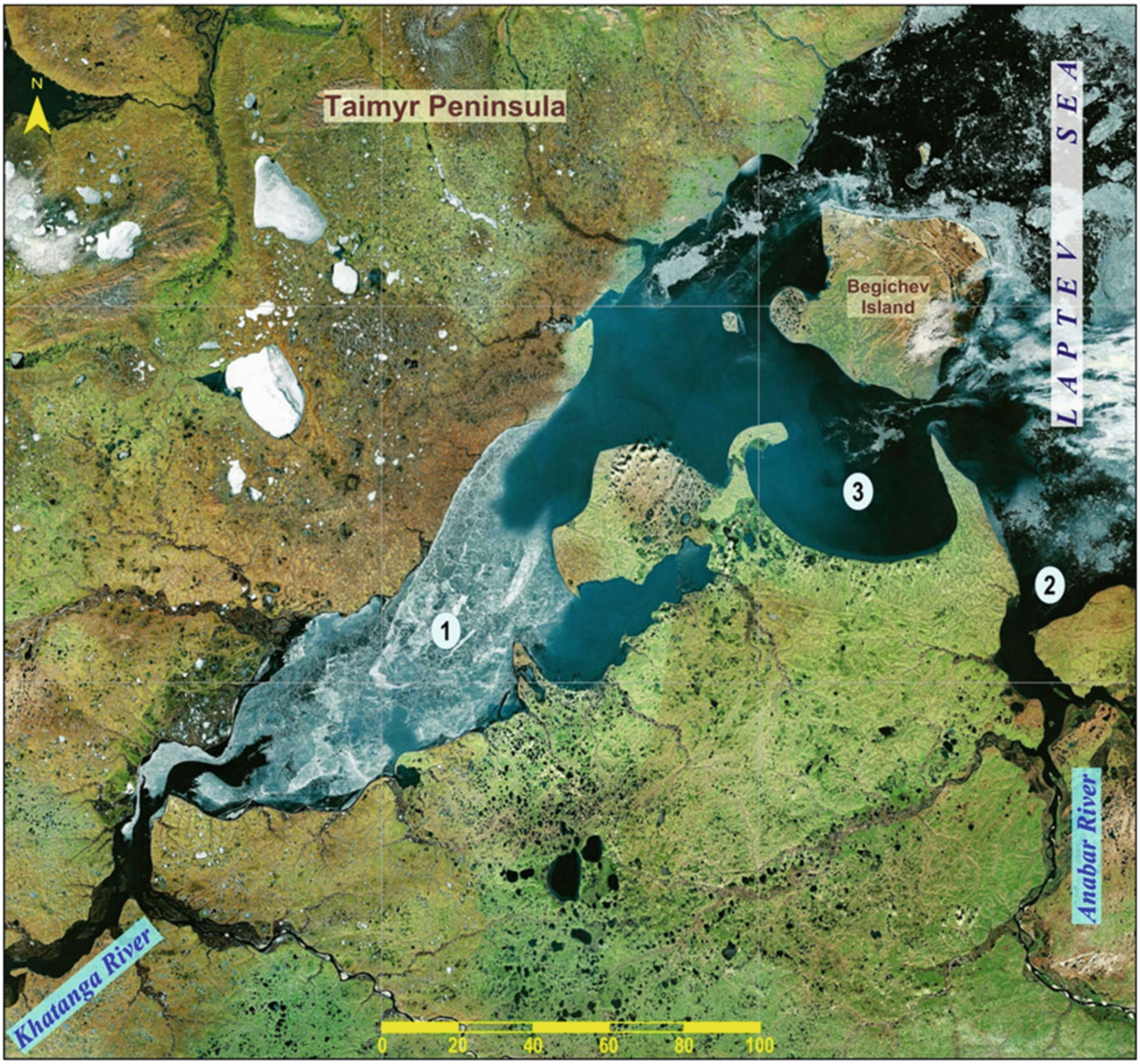


Fig. 2.19 Khatanga estuary (*1*) Anabar estuary (*2*) and Nordwik Bay (*3*) (Modified from Kosyan 2013)

2.4.4 The East Siberian Sea

General Characteristics of the Sea

The East Siberian Sea, in its modern boundaries, is characterized by the following measures: the area is 913 th. km^2, the volume is 49 th. km^3, the mean depth is 54 m, and the maximum depth is 915 m. The western boundary goes from the crossing of the meridian at the northern edge of Kotelnyi Island with the edge of the continental shallow bank (79° N, 139° E) to the northern edge of this island (Cape Anisii) and then follows along its western coast to the eastern boundary of the Laptev Sea. The northern boundary goes along the edge of the shallow continental bank from the point with coordinates 79° N, 139° E to the point with coordinates 76° N, 180° E. The eastern boundary goes from the point with coordinates 76° N, 180° E along the 180° meridian to Wrangle Island and then along its northwestern coast to Cape Blossom and further to Cape Yakan on the continent. The southern boundary goes along the continental coast from Cape Yakan to Cape Svyatoi Nos (the western boundary of the Dmitry Laptev and Sannikov straits).

According to its geographical location and hydrological conditions, the sea is related to the continental marginal seas (Dobrovolsky and Zalogin 1982).

Table 2.5 The types of the East Siberian Sea shores (%)

Shore type	Continental coast	Islands	Total
Not transformed by sea	–	–	
Abrasive-denudation	3.3	5.1	
Abrasive	4.8	15.2	
Abrasive fossil	1.9	1.0	
Thermo-abrasive	21.9	29.9	
Abrasive-accumulative	5.6	8.2	
Accumulative beaches	4.6	26.0	
Lagoon	3.3	1.0	
Setup (foreshore)	35.0	13.1	
Delta	19.6	0.5	

Alekseevsky (2007)

Characteristics of the Shores of the East Siberian Sea
The length of the coastline of the East Siberian Sea is 5090 km. The length of the portion along the continent is 3145 km, and the portion along islands is 1945 km (Alekseevsky 2007). A characteristic peculiarity of the sea is a long extension of the accumulative coasts (41.8 %), especially on the islands, which can be seen in Table 2.5 and Fig. 2.20.

Processes of setup-setdown accumulation, together with thermo-abrasion processes, dominate in the western (greater) part of the East Siberian Sea. In the eastern (smaller) part of the sea, the processes of wave accumulation, combined with abrasion, dominate (Alekseevsky 2007; Kaplin et al. 1991). The development of absolutely different forms within one sea were a consequence of the differences in the submerged slopes of the coastal zone, existence of the resources and sources of sediments, and peculiarities within the wind-wave regime.

Sediments of low granulometric size (fine grain sands and clays) dominate in the western part of the region. Such sediments are not capable of remaining within the coastal zone in the major part of the shores of the other seas, and are transported to the deep sea. The East Siberian Sea, among the other Arctic seas, is characterized by the greatest shallowness. The depths in many regions at a distance of 3 km from the coast hardly reach 1–2 m, while the slopes of the bottom within 0.0003–0.0004 continue up to a distance of 18 km from the coast (Alekseevsky 2007). A low gently sloping lacustrine-alluvial plane approaches the sea from the land side. The wave impact on the shore is decreased due to the low slopes of the bottom and the ice cover during the better (80 %) part of the year. Under such conditions, the main factor forming the coast becomes the setup-setdown phenomena. Wide (up to 4–5 km) silt foreshore regions were formed along the coastline of the sea (Fig. 2.21). The water edge within these regions migrates, depending on the synoptic situations. Vegetation is not formed here. Low current velocities facilitate the accumulation of clay particles. Fine sediments are transported along the surface of the foreshore regions by setup currents, gradually filling them (Alekseevsky 2007).

Large volumes of loose material (silt and fluvio-glacial) on the submarine slope in the eastern part of the sea and wave forcing that intensifies in the eastern direction facilitate intense accumulation.

Many of the accumulative lagoon systems are distinguished for their peculiar internal partition into a number of round basins. A complex bay-bar near Cape Billings, shown in Fig. 2.22, is the most interesting accumulative body of such type. The bay-bar of Cape Billings separates the basins of several oval lagoons from the sea: the Valkakinmanka-1 (western) and Valkakilmanka-5 (eastern) lagoons. The marks of the storm ridge reach 5.4 m and even 6.8 m, together with the dune (Alekseevsky 2007; Kaplin et al. 1991). V.P. Zenkovich suggested that such accumulative bodies were formed as a result of the formation of "mirror" series of spits of the Azov type (Kaplin et al. 1991). However, there is no commonly accepted opinion about the formation mechanism of such natural structures. Different researchers consider this accumulative body to be a spit, a double bar with remains of edoma in the rear part (Tarakanov et al. 1981).

Small lagoons are located at the southern edge of Wrangle Island: the Popova, Davydova, and Predatelskaya lagoons. The entire territory of Wrangle Island and the adjacent sea basin are natural state reserves.

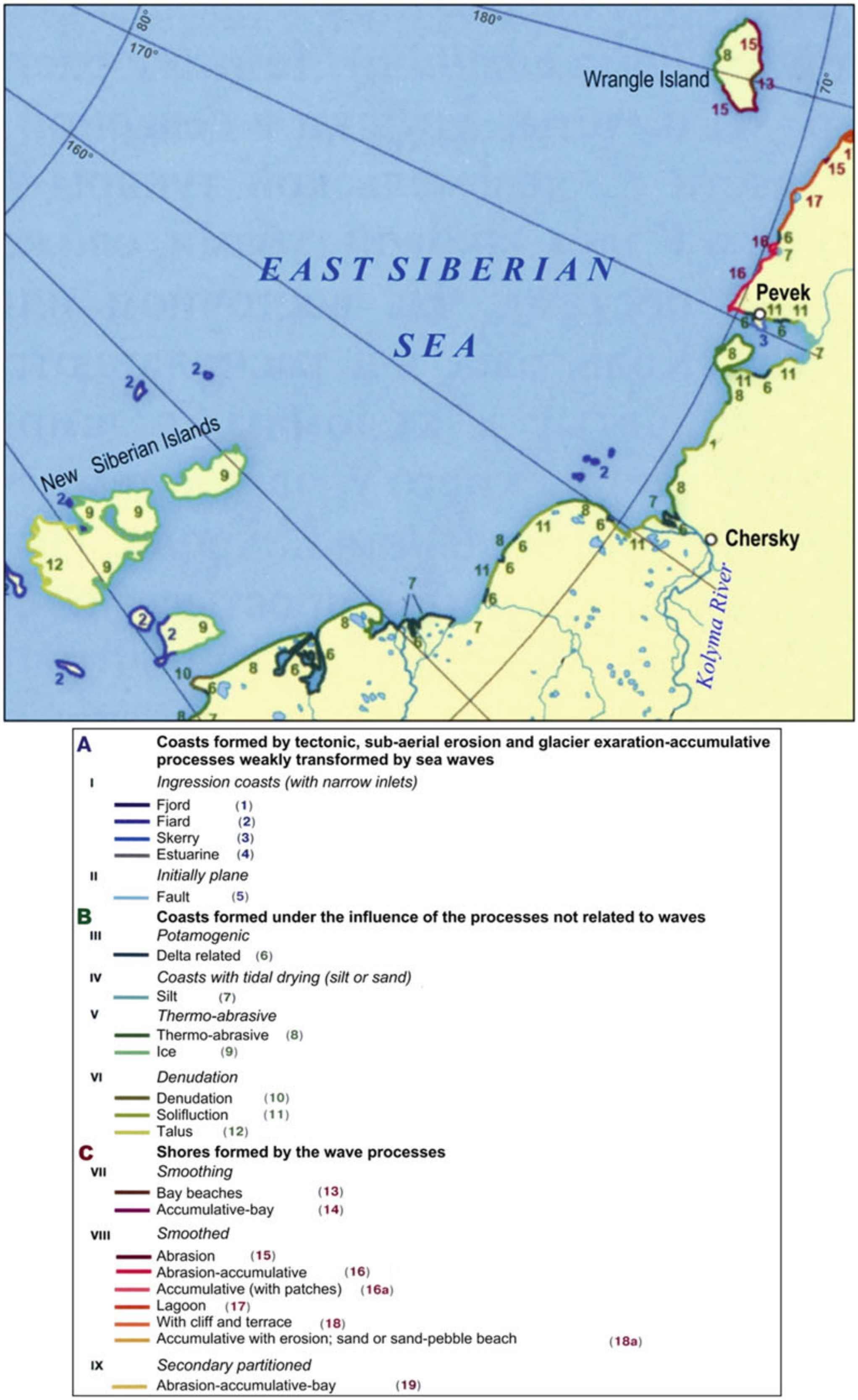


Fig. 2.20 Morphological types of the East Siberian Sea coast (Spiridonov et al. 2011). *A*, *B*, and *C* are type of sea shores *I–IX* (*Roman numerals*) sub-types of shore partitioning *1–19* (*Arabic numerals*) primary causes of the initial partitioning of the shoreline

Fig. 2.21 Silt foreshore regions in the western part of the East Siberian shore (Modified from Kosyan 2013)

Fig. 2.22 East Siberian Sea, complex bay-bar near Cape Billings separates the Innukay Lagoon (*left*) and Valkakinmanka-1 – Valkakinmanka-5 lagoons (*round*) (Modified from Kosyan 2013)

2.4.5 The Chukchi Sea

General Characteristics of the Sea

The Chukchi Sea is partly limited by land and partly by conventional lines. The western boundary goes from the point that crosses meridian 180° with the edge of the continental shallow bank (76° N, 180° E) along the 180° meridian to Wrangle Island and then along the eastern boundary of the East Siberian Sea. The northern boundary goes from the point with coordinates 72° N, 156° E to Cape Barrow in Alaska. The eastern boundary goes along the continental coast of Alaska to the southern entrance cape of Sishmarev Bay (Cape Seward). The southern boundary of the Chukchi Sea goes along the northern boundary of the Bering Strait from the southern entrance cape of Sishmarev Bay (Cape Seward) to Cape Unikan (Chukchi Peninsula) and then along the continental coast up to Cape Yakan. The Longa Strait is also related to the Chukchi Sea, its western boundary stretching from Cape Blossom to Cape Yakan. The eastern boundary of the strait goes from Cape Pillar (Wrangle Island) to Cape Schmidt.

Within these boundaries, the sea occupies the basin between 76° and 66° N latitudes and 180° E and 156° W longitudes. The area of the sea is 595 th. km^2, its volume is 42 th. km^3, the mean depth is 71 m, and the maximum depth is 1256 m. According to its geographical location and free connection with the Arctic Ocean, the Chukchi Sea is related to the continental margin sea type (Dobrovolsky and Zalogin 1982). The majority of Wrangle Island and the entirety of Herald Island are related to the basin of the Chukchi Sea.

Characteristics of the Shores of the Chukchi Sea
The length of the coastline of the Chukchi Sea is 1705 km. The length of the portion along the continent is 1300 km, and the portion along islands is 405 km. Accumulative processes dominate on the shores of the Chukchi Sea. Lagoon shores are in great abundance here. They occupy more than 49 % of the Asian continental coast and the coast of Wrangle Island, as seen in Fig. 2.23 and Table 2.6 (Alekseevsky 2007).

Accumulative bay-bars (dominating height is 0.5–3.5 m and width ranges from 0.1 to 1.5 km) separating the shallow lagoons from the sea extend parallel to the continental coast over hundreds of kilometers. The bay-bar of the Tenkergynpilgyn Lagoon is approximately 100 km long, and the length of the Kuvetpilchin Lagoon exceeds 50 km. Widely spread lagoon shores in the Chukchi Sea are related to the specific combination of natural factors.

First of all, the abundance of accumulative coastal structures and the lagoons that they form is a consequence of the geological (lithological) structure of the adjacent coast. The bay-bars are formed of sand and gravel-pebble material, whose composition is closer to the rocks of the internal portion of the continent than to those of the neighboring abrasion ledges (Kaplin et al. 1991). The modern abrasion regions are comparatively short and could hardly supply sufficient amounts of debris material to the coastal zone. It is likely that the resources of alluvial and fluvio-glacial sediments on the shelf were previously transported by water flows during the melting of the mountain and valley glaciers that subsequently flooded in during the Holocene regression. They could be the sources of transported material. Thus, the majority of the Chukchi Sea bay-bars are standard bars, i.e., the result of transversal sediment transport (Kaplin et al. 1991). During strong storms, the debris material is washed over the crest of low bars in the direction of land, which leads to the gradual displacement of the bar on the lagoon. A characteristic peculiarity of many bars in the Chukchi Sea is the inclusion of the remains of coastal edoma in their body, which are formed from frozen loamy sediments (Alekseevsky 2007).

The topography of the submarine slope is very important. Here, the inclinations of the submarine slope notably increase owing to the approach of the spurs of the Chukchi Rise towards the sea. The bottom slopes are usually 0.01–0.02 (in the eastern part, they are as steep as 0.08), which makes possible the development of high waves capable of transporting sandy-pebble material from the submarine slope to the shore. The traces of the wave impact on the bottom are seen up to depths of 35–40 m. The abundance of submarine sediments on the shelf provides for the development of high accumulative bay-bars.

The increase in the duration of the ice-free season owing to the influence of warm Pacific waters propagating through the Bering Strait is important for the formation of the lagoon-bar complex. The proportion of ice-free time increases in the eastern direction, from 10 % near Cape Billings (the Longa strait) to 27 % near Cape Dezhnev (Kaplin et al. 1991). The waves from the northern and northeastern directions, which sometimes are as high as 6–7 m, transport sedimentary material from the coastal submarine slope and play a primary role in the formation and displacement of accumulative bay-bars in the direction of land.

Depending on the formation mechanism, we distinguish between long and narrow (cord-shaped) lagoons (Kuvetpilchin, Maaminpilgyn), bay-lagoons (Neskynpilgyn), firth-lagoons (Amguema, Pyngopilgin), and others. Many of these are distinguished by their peculiar internal partition into a number of round basins as a result of the formation of a series of spits belonging to the Azov type (Kaplin et al. 1991).

Unlike the overwhelming number of lagoons and accumulative bodies of the Arctic coast of Russia, the Chukchi Sea lagoons have been well studied (Kaplin 2010). Since many features of the structure and appearance of the accumulative bodies and lagoons of the Chukchi Sea are also found on the shores of the other Arctic Seas, the book we have cited is a reasonable source of information. The data from the investigation of the shores and lagoons of the Chukchi Sea (adopted from Kaplin et al. (1991)) are presented below.

Five coastal regions have been distinguished in the Chukchi Sea (Kaplin et al. 1991):

1. Dezhnev region (between Capes Dezhneva and Unikan), including the Uelen and Inchoun lagoons (officially, this coastal region is part of the Bering Strait coast (IHO 23-3rd 2002).
2. Cape Serdtse-Kamen region (between Capes Unikan and Serdtse-Kamen), with well-pronounced abrasion forms.
3. Genretlen region (from Cape Serdtse-Kamen to the eastern edge of the Serykh Gusey Islands), which is distinguished by its peculiar lagoons and the zonal orientation of the coastline.
4. Vankarem region (from the islands of Serykh Gusey to Cape Vankarem), including various accumulative bodies and adjacent abrasion regions of different structure.

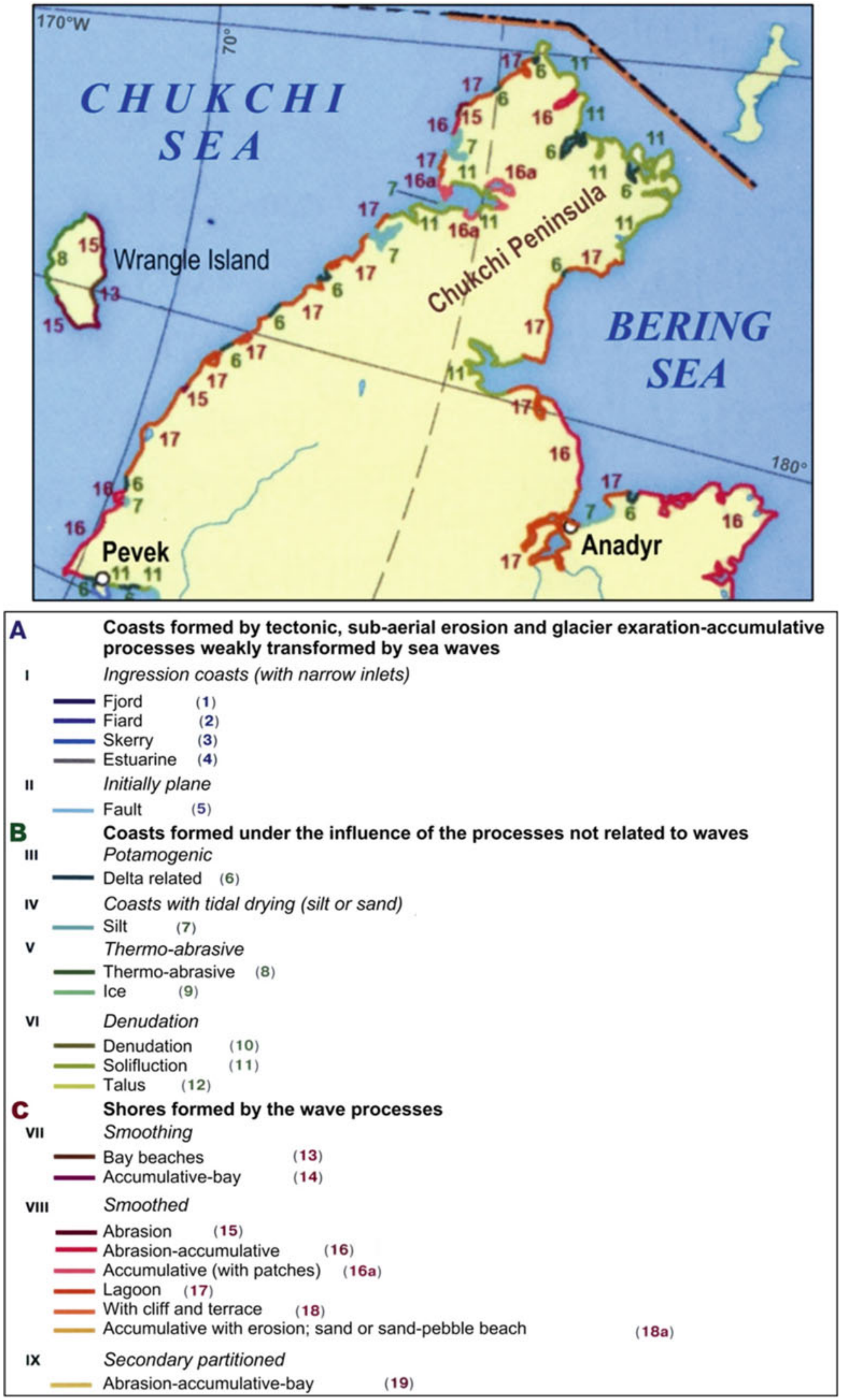


Fig. 2.23 Morphological types of the Chukchi Sea coasts (Spiridonov et al. 2011). *A*, *B*, and *C* are type of sea shores. *I–IX* (*Roman numerals*) sub-types of shore partitioning *1–19* (*Arabic numerals*) primary causes of the initial partitioning of the shoreline

Table 2.6 The types of the Chukchi Sea shores (%)

Shore type	Continental coast	Islands	Total
Not transformed by sea	–	–	
Abrasive-denudation	6,2	12,3	
Abrasive	9,6	17,3	
Abrasive fossil	–	4,9	
Thermo-abrasive	12,7	11,2	
Abrasive-accumulative	11,5	–	
Accumulative beaches	–	4,9	
Lagoon	49,2	49,4	
Setup (foreshore)	10,8	–	
Delta	–	–	

Alekseevsky (2007)

5. Schmidt region (between Capes Vankarem and Yakan), which is characterized by thick accumulative bodies, including the remains of bedrock. There are no lagoons of this size in the other regions of the Chukchi Sea.

The *Dezhnev coastal region* includes adjacent abrasion shore regions, in addition to the Uelen and Inchoun lagoons (Fig. 2.24). The lagoons are located in the lowlands, which join together and form a vast coastal plane. The height of individual hills reaches 100 m. They are confined to the mountainous regions (the Dezhnev massif, the Inchoun mountain massif, etc.) Basement rocks pierced by quartz veins form the foundation of the hills (chloritic and clayey schists). They are covered by a layer of loose Quaternary deposits, which include marine blue clays and loams. Sands, loams, clays, pebbles, and boulders of glacial and water-glacial origin form the upper part. Several rivers cross the coastal plane. They meander wildly and split into a multitude of creeks. They also flow into the lagoons, therefore only slightly influencing the dynamics of the sea shore. Numerous lakes are spread widely across the lowlands.

The Uelen and Inchoun Lagoons have many common morphological features. They combine the properties of lagoons and firths. The configurations of the Inchoun Lagoon are simpler. Their formation is related to the flooding of the estuary-valley of the Inchoun River during the Holocene transgression of the sea. The firth that appeared here is separated from the sea by a bay-bar. The Uelen Lagoon consists of two heterogeneous regions: its southwestern part is a firth and the region stretched along the sea coast is a classical example of a lagoon.

The bay-bar of the Inchoun Lagoon is a thick accumulative structure. This bay-bar not only crosses the entrance part of the lagoon but continues along the low shore as a coastal bar. In some places, this bar is adjacent to the land, and in other places, a series of shallow-water lagoons remain after the bar. It is likely that the bay-bar in this region gradually displaced the coastal plane. A series of lagoons is a relict structure of a large lagoon similar to the Uelen Lagoon. Some indicators provide evidence of the displacement of the bay-bar of the Inchoun Lagoon in the direction of the land: it is eroded from the sea side, and at the same time, its rear part displaces in the direction of the secondary accumulative bodies of the Azov spit type.

The bay-bar of the Uelen Lagoon has no indicators of displacement. This bay-bar consists of two thick coastal bars. Its structure resembles the accumulative bodies, which V.P. Zenkovich called double bars. The first one (from the sea side) has a significant height and occupies almost the entire bay-bar along its width. The second bar of smaller height is located parallel to the first. It is likely that it was formed by the waves inside the lagoon. A series of secondary lagoons exists between the bars. Creeks connect it with the main lagoon basin.

The petrographic composition of the pebble forming these bay-bars points to the main source: the transport of sediments from the underwater slope. Here, we find syenite pebbles as well as pebbles of various erupted rocks, although the neighboring abrasion regions are formed of schists. Pebbles cannot be transported along the coast from distant regions, owing to the existence of the capes protruding into the sea. It is likely that the Quaternary water-glacier columns forming the coastal valley and the bottom were the source of such material. During the transgression of the sea, these sediments formed a large bar, which gradually displaced the coast and became the basis of the modern bay – bars.

Sediments are transported in the lagoons along bedrock coasts and the rear parts of the bay-bars. The shores of their basins change as a result of the formation of double crescent bars, accumulative ledges, and other accumulative bodies. Owing to these processes, the coastlines of the lagoons dismember first and then later align, while the lagoons are divided into a number of basins of the oval form.

The *region of Cape Serdtse-Kamen* is the result of the development of Paleozoic rocks that form the mountainous coastal ridge. The youngest set of rocks, which is represented

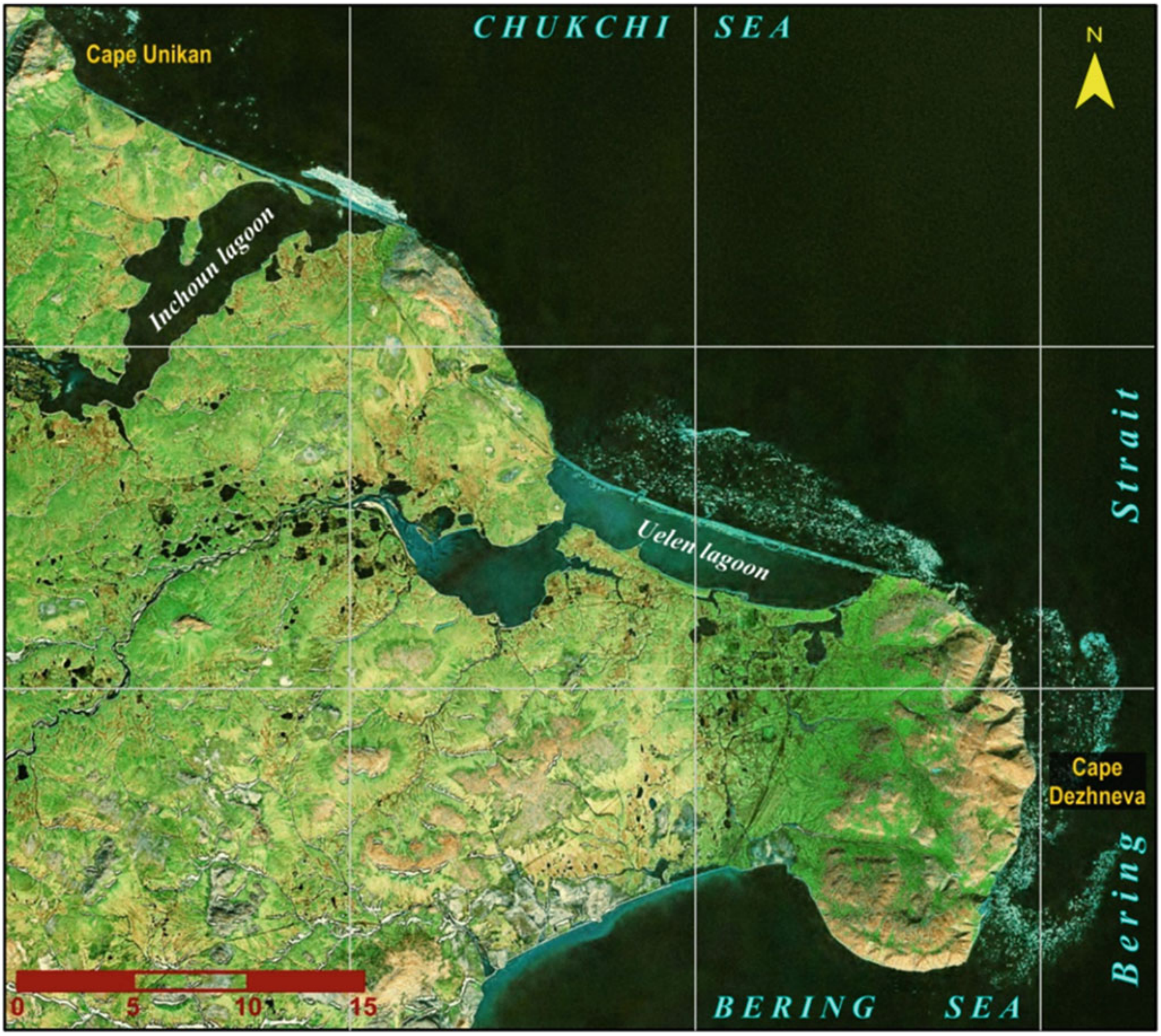


Fig. 2.24 The Inchoun (*upper left*) and Uelen (*middle*) Lagoons and the Dezhnev Cape (Modified from Kosyan 2013)

by sandstone and schists of the Middle and Upper Carboniferous, is located close to the sea. The rocks forming the coast are strongly dislocated and separated by the intrusions of granitoids. Numerous tectonic cracks predetermined the formation of erosion intrusions, talus troughs, and surge niches.

The mountains at the shore form steep coastal cliffs almost everywhere, the sole exception being the bays in the region of the Serdtse-Kamen massif. The mean heights of the coastal ridge in this region are 400–600 m. Most of the rivers cross the slopes of the ridge through narrow, poorly developed valleys and fall into the sea through hanging mouths. In general, the coastline is aligned, with only the granite intrusion massifs Inkigur and Serdtse-Kamen protruding far into the sea. There are not many accumulative structures above water in this region. Even a river as large as the Chegytun has a comparatively small lagoon separated by a bay-bar from the sea. This lagoon is only a widening of the river valley when it debouches into the sea. The bay-bar near the mouth of the river is formed as a result of the accumulation of the material transported along the coast.

In the *Genretlen coastal region*, the shore becomes low west of the Serdtse-Kamen massif. The mountains retreat far to the south, and only near Cape Genretlen does a spur of the mountainous ridge protrude into the sea. The Genretlen massif and Idlidlya Island are the only outcrops of the bedrocks in the region of the shore. The remainder of the shore is formed of a loose sand column, sandy loam, and loams with

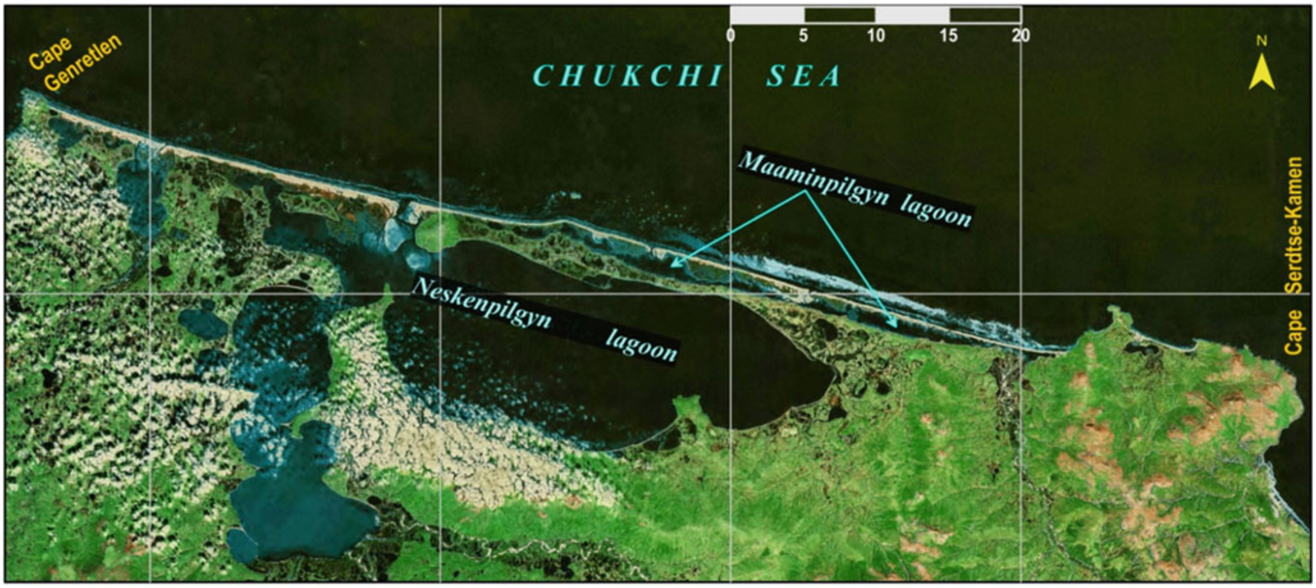


Fig. 2.25 Large Neskenpilgyn Lagoon is not a classical lagoon but a sea gulf (Modified from Kosyan 2013)

layers of peat. The plain approaches the sea only in the region from Cape Genretlen to the Belyaka Spit. The rest of the shore is rich in the lagoons separating the coastal plane from the sea. These lagoons are very specific, both in morphology and in their origin.

The Neskenpilgyn is not a classical lagoon. This is a large marine gulf with a narrow and shallow entrance. It is separated from the sea, and from the real Maaminpilgyn Lagoon (Fig. 2.25), by narrow bands of low tundra, which resemble the usual bay-bars of lagoons. The coasts of the gulf are abrasive.

The Maaminpilgyn Lagoon is very specific in its morphological peculiarities. It extends along the shore over double digit kilometers as a narrow band (Fig. 2.25). The bay-bar of this lagoon has a complex structure. The coastline of the sea side is aligned, while on the lagoon side, it is strongly dismembered. In some places, the bay-bar widens and protrudes into the lagoon basin over hundreds of meters, while in other places, it narrows to roughly 20–30 m. Peat formations outcropping on the cliffs of bedrock remain included in the bay-bar of the Maaminpilgyn Lagoon. These layers alternate with sand layers 5–8 cm thick. A low ridge of dunes is located above these deposits along the sea shore. After the dunes, the bar bay surface becomes lower closer to the lagoon where there is further outcropping of peat formations. It is likely that the layered deposits on the sea side appeared due to the long-term transport of sand from the bottom to the shore. Ridges of dunes were formed from this sand. Intervals in the sand supply occurred in certain periods, possibly related to the increase in the ice cover of the sea, during which the dunes were partly eroded by the wind and partly covered with vegetation. Thus, their surface became covered with peat. A new ridge of dunes was formed on the surface of the peat structures and the process was repeated many times.

Several lagoon-lakes are located between the Neskenpilgyn Gulf and Cape Genretlen, among low tundra. These lakes are confined to the mouths of the river valleys. The valleys of the rivers are wide; therefore, the lagoons that appear when the valleys are flooded are wide and shallow. The Einenekvyn Lagoon has a different form, which extends along the valley in the estuary of the river with the same name. It is separated from the sea by a bay-bar, which includes the bedrock remains of the land.

A thick accumulative structure (the Belyaka Spit) is located in the western part of the region (Fig. 2.26). It consists of two branches, between which there is a lagoon of the same name. The research in this region shows that the branch of the spit separating the Belyaka Lagoon from Kolyuchinskaya Guba is not an accumulative structure, but rather a low peninsula formed by loose clayey and sandy-loam deposits whose column outcrops at the northern coast of Kolyuchinskaya Guba. Thus, the southern part of the Belyaka Spit, similarly to the bay-bar of the Neskenpilgyn Lagoon, is a part of the coastal valley. The northern part of the Belyaka Spit is an accumulative structure of a free type. Its distal end is wide and turned to the southwest, while the base part consists of one narrow sand bar, over which the waves gush in stormy weather. The width of the wide end of the spit reaches a few kilometers. Ancient shore bars covered with vegetation, whose direction coincides with the configuration of the coastline, are seen on its surface. Small lagoons are located between the bars.

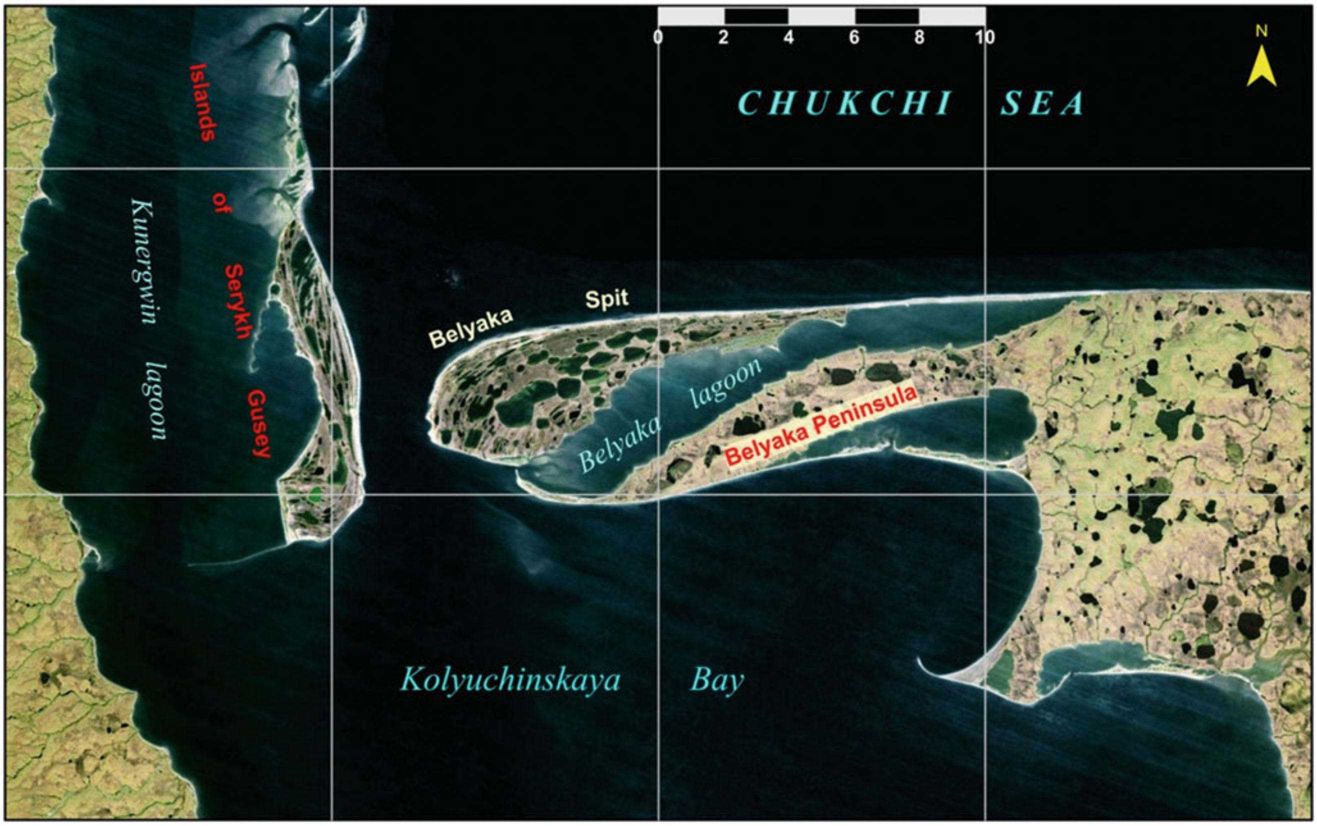


Fig. 2.26 The Belyaka Spit (*right*) and Yuzhny Island (the Islands of Serykh Gusey) (Modified from Kosyan 2013)

Vankarem Coastal Region The mountains closely approach the coastline here. In the region of Cape Onmai, their ridge protrudes into the sea. A loose Quaternary column forming the coastal lowland plane consists of peat, sands, and clays, with inclusions of vein ice. Significant regions of the coastal lowland plane are formed of loans, also with inclusions of vein ice. The coastal cliffs formed by a loose column break intensely under the influence of sub-aerial processes. During storms, the waves erode and transport material away from the coastal cliffs, cutting their basements, which facilitates the activation of slope processes and hinders stabilization of the equilibrium on the slopes.

The majority of accumulative structures of the Vankarem coastal region are represented by bay-bars and spits separating the lagoons of different size from the sea. A number of lagoons separated from the sea by spits, which appeared as a result of the accumulation of sediments from the abrasion shores, are found in the region from Cape Onman to the Vankarem Lagoon. The Eikuy Lagoon, itself separated from the sea by two small spits, is an example of these.

The Islands of Serykh Gusey are a peculiar accumulative structure (Fig. 2.26). This series of islands resembles a spit in its morphological structure. It has grown due to the accumulation of sediments transported along the coast from north to south and then separated by the straits into individual parts. However, it is possible that this spit has never been a single accumulative body. Setup-setdown currents at the entrance to Kolyuchinskaya Bay prevented this. It has an extremely narrow entrance, which is frequently blocked by ice. During setdowns, the pressure of water collected from the vast basin of the guba (bay) can be extremely high. Owing to this, the islands did not unite into one accumulative body but formed a bar torn into individual parts. It is possible that if the northern (accumulative) part of the Belyaka Spit had not been protected by the bedrock Belyaka Peninsula, a single accumulative body could not have been formed here.

The bay-bar of the Vankarem Lagoon (Figs. 2.7 and 2.27) is an interesting accumulative structure. It is located at the mouth of the river with the same name; therefore, it has a configuration characteristic of the firths. The lagoon is separated from the sea by two spits: a smaller one in the southeast and a longer one in the northwest.

The *Schmidt coastal region* includes the shore from Cape Vankarem to Cape Yakan. The bay-bars extend across the region, excluding Cape Schmidt. They separate a series of vast lagoons from the sea. A coastal plane with hills occupies a wide band between the lagoons and the marine mountain ridge. The elevation marks of this plane do not exceed

Fig. 2.27 The lagoon coast of the Chukchi Sea between Cape Schmidt and Cape Onmyn (Modified from Kosyan 2013)

20–30 m. Numerous lakes are located between the hills. The marine mountain ridge that extends over a large distance removed from the coast closely approaches the sea near Cape Schmidt and then recedes again, only veering back near Cape Yakan, where it breaks to the sea in the form of steep rocks.

In general, the coast of the region considered here is of the lagoon type. The Nutauge and Tynkurginpilgyn Lagoons are the largest on the coast of the Chukchi Sea (Fig. 2.27). The majority of the lagoons are connected by the channels, forming a single series with a total length of more than 100 km. The Kuvetlilchin Lagoon extends along the coast as a narrow band. Its length exceeds 50 km. All the lagoons of the region are shallow.

Lagoons and bay-bars of different morphology in the Schmidt coastal region have developed in approximately equal conditions under the influence of the same shore-forming factors. Over the entire length of the coast, the resultant wave vector is directed from northwest to southeast. In this relation, the debris material also has a tendency to be transported in the same direction. The configuration of shore bars on the bay-bars of the lagoons and the outlines of the secondary accumulative structures in their basins provides evidence that this is true. It is likely that at present, when the coastline is aligned and almost no abrasion regions are left on the shore, only the bottom gravel-pebble material participates in the motion of sediments. There are no other sources of sediment supply, because the rivers debouche into lagoons, in which the terrigenous material transported by them is accumulated.

Significant alongshore displacements of sediments also occur from the rear side of the bay-bars. The accumulative structures that are formed in the lagoon basins are related to the Azov type of spit. The abundance of such spits in the lagoons of the Chukchi Sea corresponds to the hypothesis of V.P. Zenkovich, according to which their basins tend to take on an oval shape in the process of their development and frequently divide into individual round parts owing to the opposite growth of accumulative capes at the opposite coasts. Hence, the narrower the lagoon and the stronger it is extended along the shore, the greater number of accumulative structures that are formed on its shores, which tend to divide the basin.

Each of the lagoons in the region considered here has its own peculiarities and differs from those that neighbor it (Fig. 2.28). For example, the Amguema Lagoon and certain other smaller lagoons can be considered typical firths, formed during flooding of the estuarine parts of the river valleys and separated from the sea by bay-bars. The Ekiatap, Tenkergynpilgin, and Kuvetpilchin Lagoons were also formed as a result of the flooding of negative topographic forms, but these depressions were not developed by the river valleys. Therefore, the outlines of the lagoons are various and complex. The narrow Kinminyakily Lagoon, the creek between the Ekiatap and Tenkergynpilgin Lagoons, and certain regions of the other lagoons appeared at the basements of ledges eroded by rivers or sea due to the separation of narrow basins from the sea by a bar. Depending on the formation process, we distinguish long and narrow (cord-shaped) lagoons (R'ypil'gyn, Er'okynmanky lagoons), bay-lagoons (Kanygtokynmangky lagoon), and firth lagoons (western R'ypil'gyn lagoon) (Alekseevsky 2007; Kaplin et al. 1991).

Fig. 2.28 The western part of the Chukchi Sea coast is characterized by the abundance of accumulative bodies and lagoons of different type (Modified from Kosyan (2013))

2.5 Conclusion

The majority of the lagoons of the Russian Arctic coast are formed by accumulative bodies: bars, bay-bars, and spits. The influence of the changes in the external conditions on the accumulative coastal bodies is different depending on their type of feeding and formation.

Accumulative bodies of longitudinal motion of sediments are usually formed through the drift of material from breaking bedrock shores or through transport by rivers. The transport of solids in rivers within the Arctic coast is insignificant (related to the transport of sediments by the wave field). Therefore, abrasion material is the main source for the formation of accumulative structures. If there is a region of abrasion shore that supplies beach-forming material to the coastal zone and under the conditions for the formation of alongshore transport of sediments, wide beaches or bay-bars are formed at the adjacent concave regions of the coast; spits are formed at the convex regions of the shore. The increase in sea level usually causes more rapid destruction of abrasion shores; therefore, it can lead to an increase in the rates of growth of associated accumulative bodies. An increase in the depths in the coastal region can induce the intensification of wave impact on accumulative bodies and lead to their transformation or destruction.

The increase in wave impact under the condition of an increasing ice-free period and length of the wave fetch cause intensification of the rate of abrasive coastal destruction; therefore, it can lead to the growth of the associated accumulative structures.

A change in the dominating wave direction can significantly change the configuration of similar accumulative bodies. An increase in the transversal to the shore wave component can lead to a decrease in the amounts of alongshore transport of sediments, which inevitably will lead to the degradation of accumulative structures. In this case, conditions can be formed in the erosion region of the bedrock shore for the accumulation of sediments. An increase in the alongshore component will lead to an increase in the growth of the distal end of the accumulative structure and local erosions along the accumulative body.

The main sources of sediments for an accumulative body of transversal sediment motion can be either the abrasion material from the neighboring parts of the shore or debris from the underwater slope. Relative sea level rise (resulting from tectonic motions of the Earth's surface and a global rise in the ocean level) can lead to the reconstruction of these accumulative bodies (their displacement in the direction of the land). If the amount of sediment is insufficient, some regions can be flooded. In general, taking into account the small values of sea level rise (compared with the amplitude of tides, setup-setdown fluctuations of the level, and similar short-period processes), nothing threatens the integrity of the majority of them.

An increase in wave impact related to the changes in the synoptic situation, an increase in the duration of the ice-free period, or changes in the wave fetch can cause intensification of the displacement of such accumulative structures in the direction of the land. A strong storm at the Uelen bay-bar and near the settlement of the same name, as shown in Fig. 2.29, which continued for 93 h in October 1969, caused a displacement of the bar in the direction of the land by 5 m (Alekseevsky 2007). The composition of beach sediments can also change. If the intensity of wave impact increases, sediments of larger size would be required for beach formation. If they are lacking, the sediments would be transported to deep places, causing gradual degradation of the accumulative structure, eventually resulting in its compete destruction.

Fig. 2.29 The Uelen settlement is located on the spit (bay-bar) of the same name (the Chukchi Sea)

Simultaneously, the increase in the height and length of the waves would facilitate further transport of sediments from the underwater slope if they are still deposited there.

The most threatening factor for the stability of bars and bay-bars formed out of the material from the underwater slope would be an increase in the sea level with a simultaneous increase in wave forcing. At a specific moment in time, the wave forcing would no longer be compensated by the increase in the height of the bar and it will be flooded. Correspondingly, the hydrological regime of the lagoon would be distorted up to its complete merging with the sea.

A change in the direction of the dominating waves can lead to an increase in the amounts of alongshore sediment transport, which will lead to redistribution of the material between different parts of the accumulative structure. Conditions can be formed in some regions for the complete degradation of the accumulative body.

The slopes of underwater topography are very small in many coastal regions of the Arctic Seas, and no transport of sediments from underwater slopes occurs. Beach-forming sediments are only supplied from the erosion of bedrock shore or with river outflow. An elongated accumulative structure (beach-barrier) is formed along the entire shore if the amount of sediment is sufficient (Fig. 2.30). According to their structure and evolution, these bodies are closest to bay-bars, which means that the transversal motions of sediments and Aeolian processes play a great role in their dynamics (Sivintsev et al. 2005). If the positive balance of sediments remains, small fluctuations in the sea level would not lead to significant changes in such accumulative bodies. Aeolian bodies develop intensely if the sea level remains constant. If the sea level rises, accumulative bodies gradually displace towards the land. In this case, the transversal structure almost remains the same. The situation is different if wave forcing increases or wave parameters change. If the intensity of wave forcing increases, larger grain size sediments would be needed for beach formation. If they are lacking, the sediments will be transported to the deeper water regions and degradation of the accumulative body would gradually occur up to its complete destruction. Variations in the direction of dominating waves can lead to an increase in the volumes of alongshore transport, which would inevitably lead to the redistribution of the sediments between different regions of the accumulative body. Erosion of the accumulative body would be observed in some regions of the body, while in the other regions, intense accumulation of sediments would occur.

Shores of a special type are formed under the conditions of low wave forcing (most frequently in deep bays or in regions with long ice-covered periods) in the regions of gently sloping coastal topography (usually in the zones of the modern tectonic subsidence of the Earth's crust) with a lack of beach-forming sediments. In such regions of shores similar to the one shown in Figs. 2.4, 2.5, and 2.21, the tundra zone and the sea basin are usually separated by a zone of tidal or set-down foreshore, which is sometimes a few kilometers wide. Several levels are frequently distinguished in the morphology of such zones (ru.wikipedia.org). Both sea level rise and changes in the synoptic characteristics (increase in wave height or setup levels) are hazardous for such shores. An increase in sea level leads to the flooding of new land regions (which can be catastrophic during setups). The development of abrasive or accumulative processes can be observed in some regions. The volume of sediments participating in these processes are small and do not have any significant influence on the evolution of the shore.

Lithologic structure, coastal topography and, most of all, natural peculiarities facilitate the appearance of an intriguing situation. Many settlements, industrial, and transport objects on the coasts of the Russian Arctic Seas are located at the most dynamic part of the sea shore: accumulative coastal bodies (spits, bay-bars, and bars) (Fig. 2.31). Therefore, human industrial activity has a permanent place in the influence zone of hazardous natural processes and simultaneously impacts the ecosystems of the sea and lagoons.

How strongly does anthropogenic activity influence the state and dynamics of the Arctic lagoon shores? In general, the technogenic factor only slightly influences the coastal development of the Russian Arctic Seas. To a greater degree, this depends on the low industrial and economic importance of the regional shores, which, in its turn, is influenced by difficult natural conditions. The existing and future technological transformation of the shores of the Arctic Seas are actually limited by the following:

1. Construction of hydro-technical structures and military ports. The majority of such constructions has been built or is planned for closed bays or gulfs and do not have a significant impact on the lithodynamic conditions of the adjacent coastal regions. The negative influence of such constructions is limited by the immediate zone of their location and the zone of the actual or potential (in the case of accidents) pollution of the neighboring shores. An opposite situation appears when attempts are made to interfere with the lithodynamic links. Distortions of alongshore fluxes of sediments (during the construction of protection for the ports) can lead to changes in or even the destruction of the accumulative bodies and lagoon formations over a significant extension of the shore.
2. Construction of pipelines (including underwater pipelines). Currently, construction and projection of long pipelines for oil and gas transport is being carried out in the region. They are designed to transport hydrocarbons to processing locations, for consumption or for reload onto sea tankers. Usually, the impact of such objects on coastal ecosystems is limited by the width of the corridor

Fig. 2.30 If the amount of sediments is sufficient, the accumulative body separates the low-land tundra and the sea basin. The development regime of the accumulative body is determined by the configuration of the shore. The Pechora Sea is shown on the *left* and the Laptev Sea is on the *right* (Modified from Kosyan 2013)

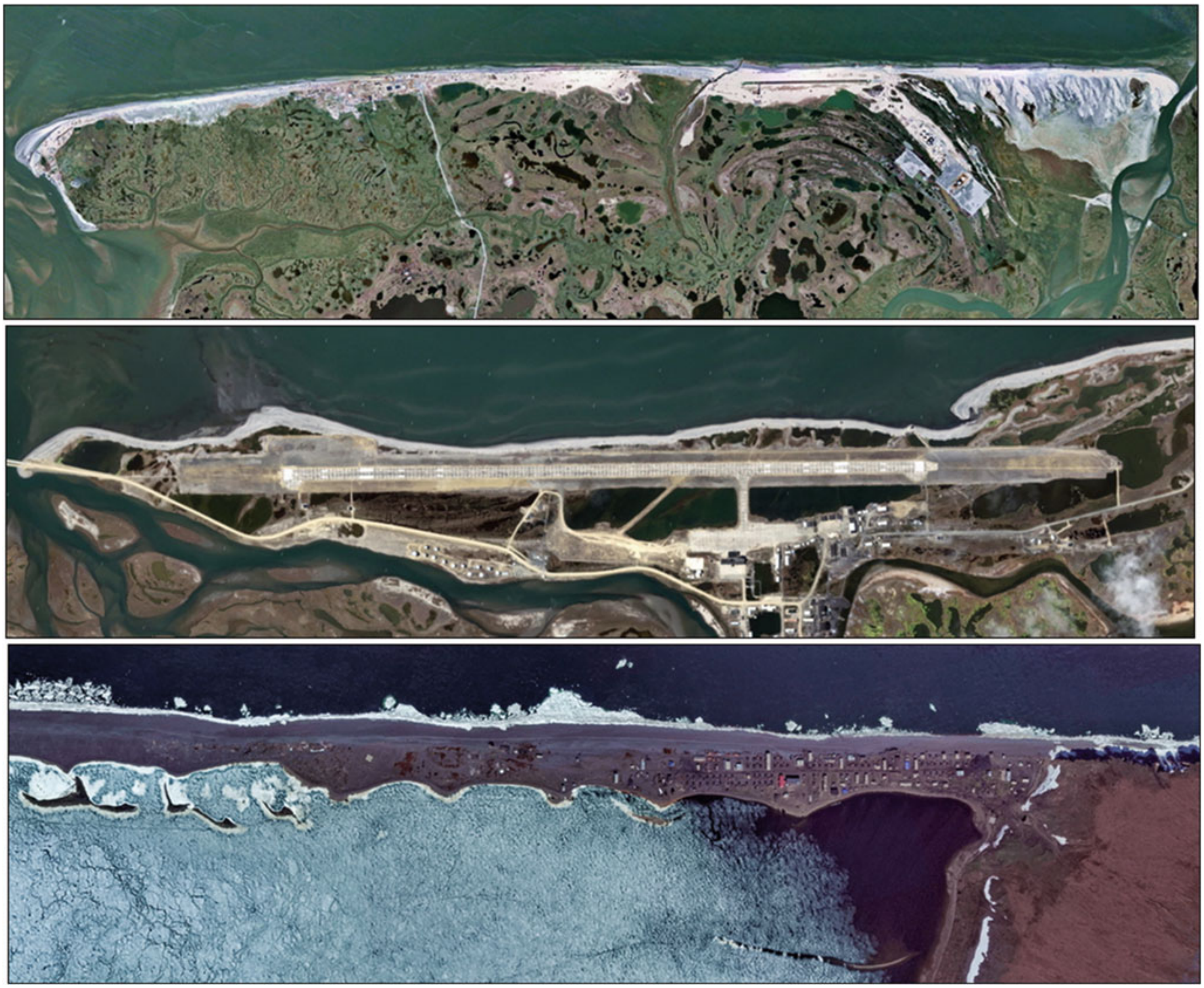


Fig. 2.31 Many settlements, industrial, and transport objects on the coasts are located on accumulative coastal bodies (spits, bay-bars, and bars). From *top* to *bottom*: Varandey (Barents Sea), Pevek (East Siberian Sea); Uelen (Chukchi Sea) (Modified from Kosyan (2013))

for this construction or by the width of the zone of negative consequences of possible accidents. Pipeline construction under permafrost conditions can provoke intensification of thermal erosion and thermal abrasion, which inevitably will result in the evolution of the adjacent part of the shore. The existence and motion of large ice masses is another factor, as it influences the bottom up to sufficient depths. Construction of underwater pipelines should provide for their reliable protection from ice forcing. Usually, underwater pipelines do not prevent the alongshore transport of sediments; therefore, there is no hazard to the stability of accumulative bodies.

3. Construction of roads for automobiles under permafrost conditions. This can provoke intensification of thermal erosion and thermal abrasion. Frequently, roads for automobiles are constructed immediately on the surface of the accumulative bodies. Under such conditions, the road can play the role of a wave rake, which would lead to the erosion of beaches and the loss of beach-forming material. In addition, construction of roads for automobiles can induce distortions in the evolution of Aeolian processes, which would also decrease the stability of accumulative bodies.
4. Construction of power stations (thermal, tidal, hydroelectric plants). While designing such objects, it is necessary to take into account their significant influence on the hydrological and microclimatic conditions of vast regions. Variations in the hydrothermal regime would inevitably influence the ice and (indirectly) the wave regimes of the adjacent basins and can strongly change the evolution of

lithodynamic processes. It is especially important to take into account the direct and indirect influence of power stations on the hydrothermal regime of lagoons, which is extremely important for the hydrochemical and biological processes that develop there.

References

Alekseevsky NI (ed) (2007) Geoecological condition of the Arctic coast of Russia and environmental management safety. GEOS, Moscow (in Russian)

Dobrovolsky AD, Zalogin BS (1982) Seas of the USSR. Publishing House of the Moscow University, Moscow (in Russian)

Federal State Budgetary Institution “Arctic and Antarctic Research Institute”. www.aari.nw.ru. Accessed 5 Sept 2015 (in Russian)

IHO 23-3rd: Limits of oceans and seas, special publication, vol 23, 3rd edn, 1953, published by the International Hydrographic Organization. http://www.marineregions.org/gazetteer.php?p=details&id=4310. Accessed 11 Oct 2015

IHO PUBLICATION S-23: limits of oceans and seas (Draft 4th edn, 2002). http://www.iho.int/mtg_docs/com_wg/S-23WG/S-23WG_Misc/Draft_2002/Draft_2002.htm. Accessed 12 July 2015

Internet portal of the Federal Agency of Sea and Inland Water Transport. www.morflot.ru/sevmorput. Accessed 17 Sept 2015 (in Russian)

Kaplin PA (2010) Problems of the geomorphology and paleo-geography of the sea coasts and shelf: selected publications. Geographical Faculty of the Moscow State University, Moscow (in Russian)

Kaplin PA, Leontyev OK, Lukyanova SA, Nikiforov LG (1991) Coasts. Mysl, Moscow (in Russian)

Kosyan RD (ed) (2013) Scientific support for the balanced business planning on the unique coastal landscapes and proposals for its use by the example of the Azov-Black sea coasts. Research report. SB SIO, Gelendzhik (in Russian)

Mikhailov VN (1997) The hydrological processes in estuaries. GEOS, Moscow

Mikhailov VN, Gorin SL (2012) New definitions, zoning and typing river near-mouths and their parts – estuaries. Water Resources 39(3):243–257. Moscow: IAPK Nauka/Interperiodica

Ogorodov SA (2001) Morphology and dynamics of the Pechera sea coast, vol 3. Proceeding of the Institute of Oceanology BAS, Varna, pp 77–86

Ogorodov SA, Polyakov EI, Kaplin PA (2003) Evolution of the Pechora Sea coastal bars. Reports of Academy of Sciences 388(3):392–394. Moscow: RAS (in Russian)

Pavlidis YA, Nikiforov SL, Ogorodov SA, Tarasov GA (2007) Pechora Sea: last, real and future. Oceanology 47(6):927–939. Moscow: IAPK Nauka/Interperiodica (in Russian)

Popov BA, Sovershayev VA, Novikov VN (1988) Research of stability of the North geosystemse. Publishing House of MSU, Moscow, pp 176–201 (in Russian)

Sivintsev YV, Vakulovskiy SM, Mazokin VA (2005) Technogenic radionuclides in the seas washing Russia. White Book-2000, vol 8. AT Publishing House, Moscow (in Russian)

Spiridonov VA, Gavrilo MV, Krasnova ED, Nikolaeva NG (eds) (2011) Atlas of the Russian Arctic seas and coasts biological diversity. WWF of Russia, Moscow (in Russian)

Tarakanov LV, Novikov VN, Birykov VY (1981) Morphogenesis of Valkakimanka lagoon (Cape Billings, East Siberian Sea). Geomorphology 3:77–85. Moscow: Nauka (in Russian)

Wikipedia – the free encyclopedia. Franz Joseph Land page. https://en.wikipedia.org/wiki/Franz_Josef_Land. Accessed 22 Oct 2015

Estuaries, Lagoons, and Limans of the Marginal Seas of Northeast Asia

3

Petr Brovko, Yuri Mikishin, and Tamara Ponomareva

Abstract

Lagoons and estuaries are widespread along the coasts of the Far Eastern Seas. These lagoons and estuaries became objects of active research only in the second half of the twentieth century.

On the shores of the Japan, Okhotsk and Bering Seas are located 240 lagoons, ranging in size from 1 to 1000 km^2. A large portion of them are shallow lagoons, with depths of up to 5–6 m. Deep lagoons, with a depth of over 20 m, occur on the coasts of fjords.

For the last 25 years, the research has been complex and comprehensive. It involved studying the hydrological, hydrochemical and ice regimes of the lagoons, as well as the mechanical and chemical composition of bottom sediments, bottom biological communities, etc.

Estuaries can be divided into three types based on human impact: (1) – estuaries and lagoons that are still relatively pristine; (2) – estuaries and lagoons in the process of being degraded; and (3) – estuaries and lagoons that bore the full pressure of historical developments. For type (1), the case studies focus on the Nabyl Lagoon; for type (2), the case studies focus on the Amur Liman and the Busse Lagoon; for type (3), the case studies focus on Peter the Great Bay.

The major economic activities in these regions include oil and gas exploration, and the harvesting and processing of fish and marine products. Lagoons, estuaries, and limans play a significant role in transportation infrastructure: ports, channels, harbors, etc.

Keywords

Lagoons • Estuaries • Sea coasts • Bottom sediments • Far eastern seas • Amur Liman • Peter the Great Bay • Sakhalin Island

3.1 Introduction

Lagoons and estuaries are widespread along the coasts of the Northeast Asia Seas. They are either located as separate bodies of water amongst abrasive-bay, ria and fjord coasts or form accumulative coasts which are hundreds of kilometers long. The lagoons and estuaries have a number of geographical peculiarities, such as separation from the sea by sand ridges (песчаная коса), connection with the sea via one or two straits, and shallow depths. Fine sediments – silts and aleurites – prevail at the bottom. The salinity of the lagoons

P. Brovko (✉) • T. Ponomareva
Far Eastern Federal University, Vladivostok (FEFU),
8, Sukhanova St, Vladivostok 690950, Russia
e-mail: peter.brofuko@yandex.ru; ptamara24@gmail.com

Y. Mikishin
Far Eastern Geological Institute (FEGI),
159, 100-letiya Vladivostoka, Ave., Vladivostok 690022, Russia
e-mail: yurimikishin@fegi.ru

R. Kosyan (ed.), *The Diversity of Russian Estuaries and Lagoons Exposed to Human Influence*,
Estuaries of the World, DOI 10.1007/978-3-319-43392-9_3

is lower than that in the sea; it can often vary within a period of 24 h due to the influence of tides. The biological community represents a great variety of flora and fauna, often including commercially important species of plants and animals.

The lagoons and estuaries of the Northeast Asia Seas only became objects of active research in the second half of the twentieth century. The very first research data appeared in the middle of the nineteenth century, in the reports of Russian ocean hydrographic expeditions; this information dealt with the regions suitable for navigation – the Amur Liman, Peter the Great Bay, and the coastal waters of Sakhalin. At the same time, the first navigation charts of the Amur Liman and the lagoons of Busse, Nyivo and Nabil were compiled.

Geomorphological studies of the lagoons and estuaries have been conducted since the 1940s by the RAS USSR Institute of Oceanology, Lomonosov Moscow State University, the Laboratory of Aeromethods within the USSR Ministry of Geology, the State Oceanographic Institute, and other institutions.

For the last 30 years, the research has been complex and comprehensive. It involved studying the hydrological, hydrochemical and ice regimes of the lagoons, as well as the mechanical and chemical composition of bottom sediments, bottom biological communities, etc. The major volume of research work has been conducted by Far Eastern Federal University, Sakhalin State University, the Sakhalin Research Institute of Fisheries and Oceanography, the Institute of Marine Geology and Geophysics, and the Pacific Institute of Geography within the FEB RAS.

3.2 Morphology and Dynamics of the Shores of Northeast Asia

3.2.1 The Bering Sea

General Description

The Bering Sea is the largest and deepest sea in Russia, and one of the largest and deepest in the world. Its surface is 2315 thousand km^2, its volume, 3796 thousand km^3, its average depth, 1640 m, reaching 4151 m at its deepest point. The shoreline of the Bering Sea is very complex and dissected, with major gulfs – the Anadyr, Karaginsky, Olyutorsky – and many bays, peninsulas, capes, lagoons, and estuaries.

The continental shelf occupies about 40 % of the sea area; its upper border is the shoreline; its lower border is marked by the continental slope shoulder at a depth of 120–165 m. The average depth of the Bering Sea shelf is about 150 m.

The shelf surface consists of relics of a subaerial landscape, submerged shores and ice forms of relief (beach bars, sand bars, cliffs, and troughs) (Zenkevich et al. 1967).

The salinity of the surface layer generally decreases northward, from 33.0 to 33.3‰ – down to 31–32‰. The maximal salinity (33.2–33.3‰) on the surface is registered near the Medny Island, the minimal salinity (20–25‰) in the gulfs and bays. The surface layer shows slight annual fluctuations of salinity. In the lagoons, estuaries, and limans, these fluctuations can reach 10–15‰.

Complex interaction of winds, water inflows through the straits of the Aleutian Islands, tides and other factors creates the major pattern of permanent currents in the sea. Velocities of the permanent currents range between 5 and 22 cm/s in the Anadyr Gulf to 9–120 cm/s in the Kamchatka Strait.

The biggest sea level fluctuations are registered in the Bristol Gulf at over 8 m, the smallest – near the Bering Strait – about 0.5 m. The tides at the entrance to the Anadyr Liman can reach 2.5 m. The velocity of reverse tidal currents in the narrow shallow straits varies between 1–2 and 4–6 m/s (Aibulatov 2001).

Throughout the entire year, waves in the Bering Sea can reach 2 m at 6-s intervals. In summer, the frequency of such waves is 80–90 %; in winter, 70–80 %.

For a significant part of the year, the majority of the Bering Strait is covered by ice. In winter, the whole northern part of the sea is filled with heavy, impassable, up-to-6-m thick ice. The bays, lagoons and estuaries provide for more favorable ice-forming conditions than the open sea due to the desalinating effect of the river runoff.

Floating ice in the northern areas of the Bering Sea, together with the shore ice, protects the shore from the direct influence of waves for many months of the year. The alongshore ice barrier serves as a natural wave breaker (Ionin 1959).

Geological and Geomorphological Structure of the Coast and Dynamics of the Shoreline

The coast of the Bering Sea consists of some of the most diverse formations – of different age and lithological composition – of sediment, effusive and intrusive rock. Soft Quaternary formations of glacier, sea, lake and alluvial origins are abundant; they form shores and accumulative coastal plains (Ionin 1959).

Among the least abrasion-resistant formations are soft Quaternary deposits, mostly clays, rubbly clayish soils, pebbles, sands, etc.

Quaternary deposits include ice lenses or layers of cavern-load ice, for example, on the southwest and northwest coasts of the Anadyr Bay where the abrasion rate is higher, reaching 1–2 m/year.

Among the most abrasion-resistant examples are sandstone, shale, conglomerates and other formations, which compile high cliffs. The rate of abrasion is a few centimeters per year.

Thus, a geological structure of the coast has a very significant influence on the development processes and morphology of the shore. On the one hand, major formations determine the type of shore development; on the other hand, such factors as lithology and jointing determine the rates of shore development, peculiarities of the upper shelf topography, and the mechanical and mineralogical composition of the sediments.

The western coast of the Bering Sea mostly consists of mountains of very complex geological composition; small-size lowlands are situated on their outskirts and in their river valleys. The land surface is noticeably tilted towards the Pacific Ocean.

The whole eastern part of Chukotka is occupied by the Chukotka Mountain Ridge. The maximum altitude is 1500–1800 m. Alpine types of topography are not uncommon there: circuses, kars, and deep through ice valleys.

Lowlands are situated in the coastal zone. The shoreline is very rugged, with many deep, fjord-like gulfs, for example, Provideniya Bay. In the Quaternary period, glaciers descended into the sea through these gulfs (Zenkevich 1967).

The Anadyr Lowland is the most significant in size in Chukotka. Its topography is mostly plain. The altitude of the majority of its surface does not exceed 50–100 m above sea level. There are many lakes in the Anadyr Lowland. Liman-lakes are most common near the seashore; nowadays, they are not connected to the sea.

The Koryak mountain ridge, with its Alpine-type topography, borders the Anadyr Lowland in the south. The mountains consist of parallel chains of 1000–2500 m high, separated by intermountain depressions (Fig. 3.1).

Originally, the contours of the Bering Sea shoreline were formed by the eustatic sea level rise in the Late Glacial Period (Ionin 1959). The landscape was formed through river erosion and the influence of glaciers. With few exceptions, the entire shoreline had been exposed to icing; its traces are found in the land topography and glacier deposits.

Sea level rise in the Holocene period caused flooding of the lower part of the trough valleys, which turned into narrow, deep, rectangular or twisting bays – fjords. Unlike classic Scandinavian fjords, which have almost perpendicular 1000–2000-m-high precipices, significant lengths (up to 220 km) and depths (down to 800–1200 m), the Bering Sea fjords have relatively low shores and smaller lengths. Their depths comprise 50–100 m, reaching 156 m only in rare cases (Provideniya Bay).

During the Late Glacier sea level rise, the plains were flooded, together with the lower parts of the trough valleys in the coastal mountain areas. Seawater penetrated into the wide valleys, developed by rivers, as well as into all depres-

Fig. 3.1 The Koryak coast (Bering sea) (Photo by I. Shpilenok)

sions of the coastal landscape of Glacier origin. This phenomenon was typical of several parts of the Chukotka coast, within southwest shores of the Anadyr Gulf, etc.

Thus, the initial ruggedness of the shoreline and diversity of the Bering Strait bay shores led to icing in the Holocene period and the subsequent sea level rise.

3.2.2 The Sea of Okhotsk

General Description

The Sea of Okhotsk is a marginal sea in the northwest of the Pacific Ocean. The sea is bounded by the eastern coast of Asia from the Lazarev Peninsular to the Penzhina River mouth, the Kamchatka Peninsula, the Kuril Islands, and the islands of Hokkaido and Sakhalin. The sea is connected to the Pacific Ocean through the Kuril Straits, and to the Sea of Japan through the Straits of Nevelskoy and La Perouse. The length of the sea from the north to the south is 2445 km; its surface area is 1583 thousand km^2; its average water volume is 1365 thousand km^3, and its average depth is 177 m, with the deepest point being 3372 m.

The shoreline of the sea is 10,460 km long. The largest gulfs are as follows: Shelikhov, Sakhalinskiy, Udskaya Guba, etc. They also include Aniva Bay and Terpeniya Bay, near the southwest coast of Sakhalin Island. Major rivers fall into the Sea of Okhotsk: the Amur, the Uda, the Okhota, the Gizhiga, and the Penzhina.

The cyclonic water pattern (counterclockwise) along the borders of the basin is the main characteristic feature of the system of currents in the Sea of Okhotsk. Straits play a significant role in the system of general water circulation; these straits connect the sea with the Pacific Ocean and the Sea of Japan (in the south).

Along the western Kamchatka coast, the velocity of the currents reaches 10–20 cm/s; in the Sakhalin Strait, 30–45 cm/s; in the Kuril Straits, 15–40 cm/s; in the Soya current near Hokkaido, 50–90 cm/s.

Periodic tidal currents are significant in the Sea of Okhotsk; they have a reverse pattern in the offshore areas. In lagoons, estuaries and between islands, the velocities of these currents reach extremely high values: 1.2–2.6 m/s in the lagoons of Sakhalin, 2.3 m/s in the Amur Liman, and over 4 m/s near the Shantarsk Islands.

Maximal height of the tide ranges between 0.8 and 1.2 m near the Sakhalin shores, up to 9.7 m in Udskaya Guba, and 13.9 m in Penzhinskaya Guba.

Ice in the Sea of Okhotsk is of local origin only. Its severe conditions are comparable with the Arctic Seas. The average annual continuity of the ice season in the northwest part of the sea is 260–270 days, 190–200 days in the northern areas and near the shores of Sakhalin, and 110–120 days in the south. In the northwest part of the sea, the icing season lasts until July.

In severe winters, the ice reaches maximal width (90–160 cm) in the Sakhalin Gulf. Ice ridges in the open sea do not exceed 1 m in height; in some gulfs, they can go up to 1.5–3.0 m.

Geological and Geomorphological Structure of the Coast and Dynamics of the Shoreline

Western Kamchatka is a swampy coastal lowland with multiple lakes. Away from the sea, it turns into a hilly steppe plain stretching to the foothills of the Sredinny Mountain Range. Absolute plain altitudes are 0–200 m; in the foothills, they reach 500 m. There are two types of coastal terraces of 9–10 m and 20 m, respectively (Zenkevich 1967).

The Western Kamchatka shore has a relatively simple structure – a combination of valley walls and extended bars with long and narrow lagoons behind them. The bars mostly consist of one beach bar, and less often, of a generation of beach bars.

Along the shore, there are wide sand foreshores with signs of swells on the surface; at the river estuaries, there are muddy-sandy foreshores with deep washouts and effluent launders. In the area of the head of Penzhinskaya Guba, the shores show fewer traces of sea impact. Denudation sea cliffs are more common here; foreshores become rocky, with a lot of boulder and block material carried by ice.

In general, development of abrasive and bay shores in the north of Western Kamchatka has slowed down nowadays (Ionin et al. 1971). It has achieved the stage of geomorphological maturity, though its shoreline contour has never levelled.

The relief of Severnoye Priokhotie is a semicircle facing the Sea of Okhotsk, with its highest altitudes in the western part (Mus-Khaya Mountain, 2959 m) and others. Southward and eastward, the relief is lower, falling to middle altitudes of 1500–2000 m; near the seacoast, lower mountain ridges prevail, separated by valleys and intermountain depressions: Nizhne-Okhotskaya, Kava-Tuiskaya and others (Ivashinnikov 2010).

The peninsulas far advanced into the sea (Lisyanskiy, Staritskiy, Koni, Pyagina, Taigonos, and others) are intermitted by bays and gulfs.

Some of them have complex unique contours; others, contrastingly, have rectilinear contours, like the fjord bays of the Chukotka coast (Bays of Luzhina, Nagayeva, etc.).

The heads of wide, open gulfs and bays consist of thick accumulative formations (bay-bars and bars), which separate lagoons, or of alongshore estuarine portions of rivers (Amakhtonsky Bay, Ola, Yamskaya Guba, and others). These coastal formations appeared in the past when the sea level was lower; they slowly moved towards the land, together with the Global Ocean level rise.

During the last icing period, the northern coast of the Sea of Okhotsk was a vast piedmont plain, with rivers that flowed into the sea and created lagoons; fine-grained sediments with turf layers accumulated there. Alongshore plains were bounded by pebble and sand-pebble beaches and numerous major bars.

Abrasive levelled, abrasive-bay and abrasive-accumulative types of shores can be found along the northwest coast of the Sea of Okhotsk. Vast accumulative sections are found in the bay heads where large rivers fall. Rocky cliffs with narrow benches and beaches, compiled by coarse deposits, prevail in the peninsulas (Fig. 3.2).

The shoreline is very indented between the Uda River mouth and Amur Liman with numerous gulfs, peninsulas, and straits (Brovko 2010).

The geomorphological composition of the shores between Udskaya Guba and Sakhalin Gulf is mostly determined by the differentiated tectonic movement of the Earth's crust (Kulakov 1980). Gulfs, deeply advanced into the shoreline, are trenched faults intermitted by peninsulas- blocks-horsts of various size and structure. The coast southward from the Shantar Islands is indented especially deeply.

The surface area of the Shantar Islands is 2412 km^2; they consist of 15 big and small islands with numerous rock-ice ramparts and above-water ridges. The topography of the islands and the adjacent mainland is low mountainous. The

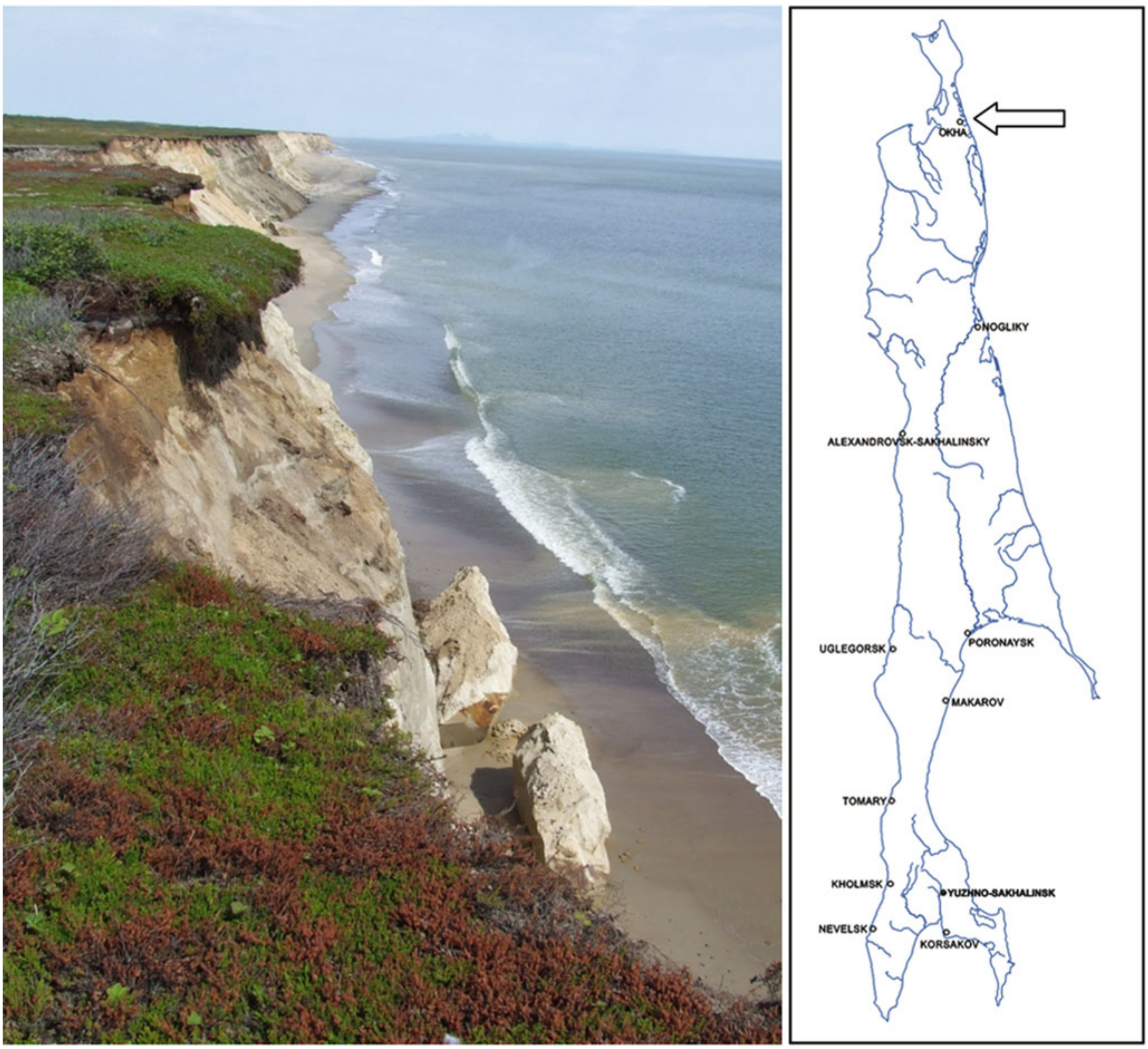


Fig. 3.2 Rocky cliff with narrow beach (Sea of Okhotsk) (Photo by P. Brovko)

islands are mostly composed of Paleozoic formations – silicon and argillaceous slates, sandstone, limestone, conglomerates, and tuffs. River valleys and seashores mostly consist of Quaternary deposits of various geneses.

Ice pattern is a significant factor of shore formation. Tidal foreshores in the island bays show evidence of the wedge work of ice. Tidal sand-muddy foreshores are widely spread.

The Sakhalin Bay shores are more levelled due to the high number of bay-bars and beach bars of various contours and geneses. In the Amur Liman, as in the Shantar Archipelago straits, tidal currents have a considerable impact on the formation of seabed topography and subsoil distribution.

3.2.3 The Sea of Japan

General Description

The Sea of Japan is situated in the northwest part of the Pacific Ocean between the continental coasts of Asia, Sakhalin and Japan. The Straits of La Perouse and Nevelskoy connect it with the Sea of Okhotsk; the wide Sangarskiy Strait (Tsugaru) connects the Sea of Japan to the Pacific Ocean. Maximum depths in the Nevelskoy Strait comprise 8 m; in the Sangarsky Strait, over 200 m. The surface area of the sea is 1062 thousand km^2; the volume of the water body is 1631 thousand m^3.

The continental shoreline is insignificantly indented, the only exception being the Peter the Great Gulf. The total length of the shoreline is 7531 km. Water salinity exceeds 34‰ in winter and 31–33‰ in summer. In the coastal area, the salinity decreases to 25–30‰ in the bays and to 12–25‰ in the lagoons and estuaries.

Tides in the majority of the coasts do not exceed 0.5 m. In the Korea Strait, they comprise 3 m; in the head of the Tatar Strait, 2.3–2.8 m. Velocities of tidal currents in the Strait of La Perouse are over 1 m/s. The continuity of the icy season is maximal in the Peter the Great Gulf (120 days) and in the north of the Tatar Strait (170 days).

In summer and fall, storm pileups caused by typhoons play an increasing role on the coast. The coasts are also exposed to tsunami waves, which periodically occur in the Sea of Japan.

Geological and Geomorphological Structure of the Coast and Dynamics of the Shoreline

The coast of the Sea of Japan runs parallel to the direction of geological formations along a considerable length; only in the south of Primorye is it almost perpendicular to the infolded formations (Ivashinnikov 2010). Therefore, the considerable diversity of the geological structure of the shores here is due to the varied composition of the geological zones.

The coast of the Peter the Great Gulf is mostly indented, with many lagoons and estuaries.

The geomorphological features of the Primorye coast are different in two coastal areas: Southern Primorye and Northern Primorye (Petrenko 2009).

Southern Primorye This territory is located within the Peter the Great Gulf from the Tumen River mouth to Cape Povorotny. The southern border of the gulf is 205 km; the indented area is 96 km deep into the land. The continental coast of the gulf stretches for 1040 km; thus, the articulation coefficient equals 5.0 (Petrenko 2005), which is twice as much as the average articulation of the Global Ocean coasts. The total shore length of the islands is 350 km; the total length of the gulf shores is 1390 km.

The shoreline of the Peter the Great Gulf is of an erosive-tectonic (ria shoreline) type (Korotkiy and Khudyakov 1990). The gulfs of Amursky, Ussuriisky, Nakhodka and Vostok were created by sea ingression into river valleys in the Early and Middle Holocene. The eastern and western coasts of these gulfs are, as a rule, formed by steep cliffs up to 20–40 m high. The cliffs and benches consist of formations of different age and composition. The heads of the gulfs and bays consist of 1–2 m high alluvial sea terraces (Fig. 3.3).

The west coast of the Amur Bay is the only area in the Peter the Great Gulf coast where a coastal lowland stretches alongshore 50 km southward from the Amba River mouth. The lowland is expanding due to the formation of accumulative forms, which connect former islands with the mainland. There are relict lakes and lagoons, such as Tsaplichya, Lebyazhya, and Melkovodnaya, which are gradually being filled by micro-fragmental debris and organogenic rock.

Abrasive coasts in the Peter the Great Gulf have mostly developed on the peninsulas, capes and islands. Almost all abrasive coasts consist of coherent rock; therefore, wearing by waves is insignificant and slow. The cliffs are 30–70 m high; sometimes they rise up to 100 m.

The beaches of the gulf belong to two morphological types: attached one-bar and two-bar beaches of full profile of balance.

Attached beaches are adjacent to accumulative terraces and ridges of dead or semi-active cliffs. In the first case, the beaches are mostly up to 20–40 m wide, and consist of sand or sand and pebble materials, with an absolute elevation of 1.5–2.5 m and a 5–6° tilt towards the sea. The beaches attached to cliffs are narrower and steeper, consisting of pebbles and boulders.

The beaches of full profile are widespread in the areas where lagoons, girts and other topographic depressions are situated at their rearmost parts. Their width can reach 100 m,

Fig. 3.3 The shoreline of the Peter the Great Gulf (Photo by P. Brovko)

with a 5–7° tilt towards the sea and a 2° tilt towards the mainland (reverse slope). These beaches have the thickest layer of storm erosion (Petrenko 2009).

Eastern Primorye The shores of this area stretch for 950 km from Cape Povorotny to Cape Tumanny on the border with Khabarovsk Krai. A relatively even contour of the shores in Eastern Primorye is slightly indented by ria bays and gulfs (the bays of Kiyevka and Sokolovskaya, the gulfs of Olga, Rynda, and Vladimir) and other small bays (Medvedev 1961).

Abrasive and abrasive-denudation shores prevail there. Domination of abrasive processes over accumulation of shores is determined by the significant wave activity of the Sea of Japan and their openness to the prevailing waves, as well as by the steep underwater coastal slope. Cliffs and benches, well developed in rocks, are the topographic shore forms of abrasive beaches. The cliffs are mostly upright, 50–100 m high, rarely reaching 200 m or more (Krasnaya Skala Cape, Cape Zolotoy).

The accumulative parts of the coast are, as a rule, developed in bays and gulfs, and mostly consist of 2–5 km-long levees (Bays of Zerkalnaya, Dzhigit, Rudnaya and others). They are formed out of various types of debris, ranging from fine sand to boulders. The coast of the Tatar Strait to the south of Cape Zolotoy is the only extended accumulative area (Korotky and Khudyakov 1990).

The slightly indented coasts of Eastern Primorye and the west coasts of the Tatar Strait (articulation coefficient equals to 1.3) do not provide many bays convenient for port construction. Only the Vladimir Gulf and the Bay of Preobrazheniye are completely protected from storms from all directions.

The contemporary look of the Primorye coast is primarily the result of anthropogenic influence on its natural landscapes. The scale of this influence is already comparable to that of natural processes. It is possible to reduce the negative anthropogenic effects by conducting comprehensive research on the shores, both at the design stage and during construction of hydrotechnical or other facilities.

3.2.4 Lagoons and Estuaries of the Northeast Asia Seas

Straightened abrasive-accumulative coasts with lagoons – fjords are common on the western coast of the Bering Sea. Fjords, separated by bay-bars and beach ridges, are found on the coasts of the Chukotka Peninsula, the Koryak Mountains and in the Olyutorskiy Gulf. Hydrographic maps show them as lagoons, lakes or estuaries. The bay-bars, which separate the fiords, are formed by the abrasion of capes or by the input of sea and morainic materials. This happens via the transversal transport of sediments from the seabed towards the shore. The formations of transversal transport are called barrier beaches. They mostly consist of pebbles and boulders. Barrier beaches usually include one beach ridge; bay-bars normally consist of several beach ridges and can reach a significant width of a few kilometers.

Bay-bars and barrier islands separating the fjords from the sea have turned them into lagoons, such as Imtuk, Arinai, Amayam, Srednyaya, Orianda and others (Ionin 1959). The biggest barrier island, called Meyechkin, is located in the northern part of the Anadyr Gulf. It is 76 km long, 4–5 m high, and between 200 and 1000 m wide.

Several straightened parts of the coast are exposed to alongshore sediment flows, which extend for kilometers in the double digits. These flows form major accumulative formations – spits, such as the Ruddera Spit, the Russkaya Koshka Spit, etc. (Zenkevich 1967).

A major estuary is situated in the Anadyr River mouth and is called the Anadyr Liman. The Liman's shores are exposed to tides and storm surge. The biggest tide in the estuary reaches 2.5 m. The continuity of the pileups is 3–6 days. The biggest of them was registered on November 8, 1982, when the water level went up to 1.8 m and caused significant damage to the city of Anadyr. The water salinity at the Liman seabed is 15–18‰, even during the spring flood; on the surface, it varies between 0 and 30 ‰.

The peninsulas of the eastern Kamchatka, which extend into the Pacific Ocean, are intermitted by open wide gulfs. The gulf shores are sea and alluvial-sea plains with extensive alluvial formations – terraces, spits, barrier islands and beach ridges. They reach 4–5 m in height (with up to 10–15-m dunes) and separate river mouths and shallow lagoons from the sea, for example, the Semlyachek Lagoon. This lagoon is about 1 m deep, reaching 5 m in the lagoon's strait (Brovko et al. 1998b). Terrigene sediments prevail in the lagoon. Its northern part is abundant in aleurites and pelites; its southern part – closer to the strait – in sands (53 % of the seabed surface). Fine sand is brought into the lagoon by tidal currents and winds from the ocean side of the spit.

A big sand-pebble spit separates the Kamchatka River mouth and a major lagoon – Nerpichye Lake – from the ocean. The spit is formed by storm waves and river runoffs. From the eighteenth to the twentieth centuries, the coastal relief in the Kamchatka River mouth underwent significant changes (Gorin 2014).

The Shipunskiy Peninsular has small lagoons-fiords separated by bay-bars from the Kronotskiy Gulf – Malaya Medvezhka, Bolshoi Kalygir, and others. They have higher and steeper shores than the lagoons of Chukotka, but are shallower.

All estuaries of Kamchatka fall into five groups, among which the most common are river bed-lagoons and lake-lagoons (Gorin 2007). The first type is widespread along the western coast of Kamchatka; the second is more typical of the eastern coast. This classification of estuaries reflects the physical-geographical features of different parts of the Kamchatka coast (relief, river runoffs, tides, and sea waves) (Fig. 3.4).

The major difference between these two lagoon groups is defined by the interaction and proportion of the river and sea factors. This, in turn, determines the hydrological structure of the estuaries and the transformation processes of water masses. The main factors that limit the existence and development of biocenosis in riverbed lagoons include water salinity; in lake-lagoon estuaries, it is the content of dissolved oxygen. In both cases, the hydrological structure of the estuaries develops under the influence of tidal water level fluctuations (Gorin 2007).

Lagoons and estuaries are less common on the coast of the Sea of Okhotsk. Among the biggest, there are Perevalochnaya, Ola, Bolshaya, and Schastya. The barrier beaches, which separate the lagoons from the sea, mostly consist of gravel and pebbles. The longest barrier beach is over 9 km; it separates the lagoon-estuary complex of the Okhota and Kukhtui rivers from the sea.

The Okhota River lagoon is relatively small; its area is under 4.5 km^2, though the runoff of this river is twice as big as the runoff of the Kuktui River, comprising on average 5.19 km^3 a year. The Okhota River bed falls into several branches in the lower reaches and forms a delta. The Kukhtui River lagoon is much bigger; its area is 15 km^2 and it extends into the land by 10 km. When the Kukhtui River falls into the lagoon, it also splits into several branches, arms and dead river arms.

There are not many lagoons on the northwest coast of Primorye. They have small sizes and are mostly located near bay heads where rivers fall (Petrenko 2009). The spits, which separate lagoons from the sea, are 2–5 km long; they consist of various types of debris, ranging from sand to pebbles. Spit configuration changes under the influence of storm waves in the Sea of Japan and sudden water level rises in rivers during tropical cyclones. In the last hundreds to thousands of years,

Fig. 3.4 The lagoon-estuary coast (Western Kamchatka) (Photo by R. Kultaev)

many smaller lagoons have been filled by river drifts and thus no longer exist (Korotkiy and Khudyakov 1990).

In the southwest part of Primorye, the shoreline is significantly indented: there are many shallow straits, bays, and lagoons. The biggest, the Ekspeditsiya Lagoon, is about 80.9 km^2. Its average depth is 2.9 m. The majority of the lagoon is filled with aleurites and pelites. A narrow section of sand with pebbles and gravel stretches along its western and eastern shores. Sand-shell deposits with growths of seaweed – Zostera and Gracilaria (a valuable commercial seaweed) – can be found in the southern part of the lagoon (Brovko et al. 1988a, b).

The Novgorodskaya Lagoon stretches alongshore from the west to the east; its area is 30.7 km^2. The lagoon seabed is covered by alluvia of homogenous granulometric composition. The percentage of pelite in the bottom sediments is 42–63 %. The eastern part of the lagoon is covered by seaweed – Zostera with a biomass of 2.1 kg/m^2. Organic reefs are also found in the lagoon. They are small topographic formations, rising 1–3 m above the alluvial plain of the lagoon seabed. The reefs are compiled of oysters, scallops and mussels. Oyster reefs are always highly bioproductive: one hectare can yield between 1 and 25 tons of valuable proteins per year (Brovko et al. 1988a, b).

In summer, the sea is very warm near coasts with lagoons; from June through September, thousands of tourists from Primorye and other regions of Russia use these beaches. Thus, this coast ensures favorable conditions for developing various economic activities.

3.3 Lagoons of Sakhalin Island

3.3.1 Geomorphological Structure of the Coast and the Conditions of Lagoon Formation

Sakhalin and the Kuril Islands are situated within the only island territory in Russia – the Sakhalin region (Sakhalin Oblast). There are also about 30 smaller islands in this region, including certain unique ones – Moneron (30 km^2) and Tyuleniy (0.54 km^2). The total area of Sakhalin Oblast is 87.1 thousand km^2 (0.51 % of the Russian territory).

Sakhalin Island is in the heart of the region; it is the largest island in Russia (76.6 thousand km^2), stretching along the meridian for 948 km, with the widest part being 160 km. and the narrowest part 26 km (the Poyasok Neck). Sakhalin is separated from the mainland by the Strait of Tatar of the Sea of Japan, the Nevelskoy Strait (7.5 km. at its narrowest part), the Amur Liman and the Gulf of Sakhalin. In the south, the island is separated by the La Perouse Strait (41 km. at its narrowest part) from the Japanese Island of Hokkaido; in the south, it is bounded by the Sea of Okhotsk (Fig. 3.5).

Thus, the island is situated near the eastern shores of the Eurasian continent in the transition zone between the continent and the Pacific Ocean. The substantial length of Sakhalin Island provides for its diverse landscapes, natural conditions, resources and options for human economic activity.

3.3.1.1 Hydrodynamics of the Coastal Waters

Seaways Wind patterns of the sea are defined by the dominant atmospheric pressure fields and seasonal sign reversals of the predominant air pressure systems over the land and sea. The diagram below (Fig. 3.6) shows the distribution of mixed waves by seasons. By winter, the contribution of waves over 3 m increases (in summer, their frequency is 73 %; in winter, 46 %).

Whenever waves exceed 8 m in height, the wind velocity goes over 10–15 m/s. In some cases, storms last for several periods. Even during weak winds, the wave height can reach 3 m; when the wind is 15–19 m/s, the waves range between 0.4 and 5 m. The velocities of 10–14 m/s and 15–19 m/s cause waves 1–2.9 m high. Five-meter waves and higher (storm waves) with relative frequency over 2 % are registered during winds of 15 m/s and more. Such waves do not occur during less intensive winds (Brovko 2002).

Fig. 3.5 Sakhalin Island

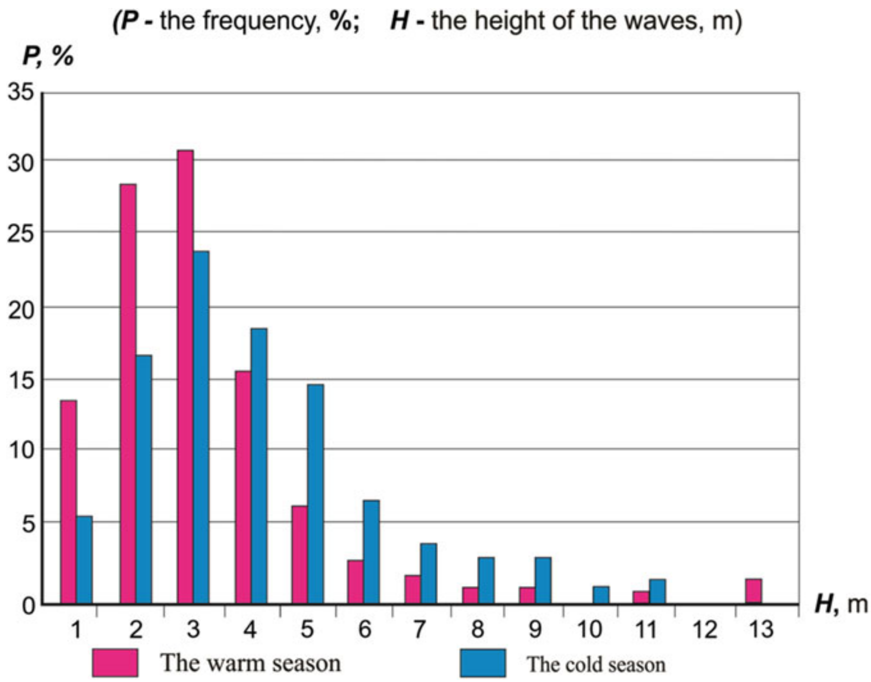


Fig. 3.6 Seasonal distribution of wave heights

Currents The east and southeast coast of Sakhalin are bounded by the cold East-Sakhalin current; its southward velocity can reach 20 cm/s. The extreme velocity of the summary current can reach 1.8 m/s on the surface and 1.3 m/s at the bottom (Pischalnik and Bobkov 2000).

The Tsushima Current enters the Strait of Tatar in the south. Water outflows northward along the west coast of Sakhalin around the latitude of Uglegorsk: this is the West Sakhalin Compensatory Current. Between Uglegorsk and the Poyasok neck, the West Sakhalin Current can reverse its direction by seasons; southwards from Poyasok, the current is more stable in terms of direction. The velocity increases in the direction from north to south: from 5 to 9 cm/s near the Lamanon Peninsular up to 15–19 cm/s near the town of Nevelsk. According to Kantakov (2002), the velocity of the West-Sakhalin Current near Nevelsk is 40 cm/s in August, and 75–80 cm/s near the Cape Krilyon.

Northward from Uglegorsk, there is a north alongshore current. However, there is no intensive northward sediment inflow within the coastal area, since it is interrupted by the peninsular ridges (Medvedev 1961). The inflow results in the accumulation of sediments in the southern part of the peninsula, where they form wider beaches (up to 25–35 m) consisting of fine gravel, sand and, less often, pebbles; these beaches are wider than those in the northern part, where boulder and pebble material prevail (up to 5–10 m wide) up until the Joniker Peninsula.

In Aniva Bay, the system of currents moves in a slow clockwise circulation (anticyclone character). The water velocity in the flow increases: 18–20 cm/s in spring and 26–28 cm/s in the fall. The center of circulation shifts southward. However, along the coast of the Tonino-Aniva Peninsula, the alongshore flow of sediments travels from the south to the north. Near the Krilyon Peninsula, the alongshore current is congruent with the direction of the current.

The anticyclone circulation of water is typical of Terpeniya Bay in all seasons. The maximal velocity reaches 8–10 cm/s, and occurs in the spring and summer seasons (Arkhipkin and Pischalnik 1999).

Tides Tidal variations are inconsistent in space and time. The rate depends on the extension and sinuosity of the shore, as well as the width of the coastal zone. Thus, the tide increases from 0.5 to 2.3–2.8 m along the west coast from the south to the north, caused by the narrowing of the Strait of Tatar and the decreasing of its depth. The tides can reach 2.8 m in the lagoons on the north side of the island (Brovko 2002). The tides are especially strong in the La Peruse Strait, where maximal tidal velocity can reach five knots (2.6 m/c). Reversal currents (0.1–0.5 m/s) can occur in the estuarine parts of rivers.

Storm Pileups Traditionally, pileup waves have mostly affected the coast of the Sakhalin Strait and the Amur Liman, where their height has occasionally exceeded 2 m. Though the pileups are lower – up to 1 m – on the south side of the island, they have caused major economic damage there. The worst consequences were on November 10–11, 1990 and November 8–9, 1995, when the pileup waves damaged the berths in the ports of Korsakov, Kholmsk, and Nevelsk; other hydro-technical structures were also damaged there, as well as port machines and equipment; several vessels sank or were cast ashore. The fishing industry suffered the worst damage: several fish-processing facilities and camps were washed away; a canning factory was damaged (Brovko 2002).

The railway near Korsakov, Moskalvo, Gornozavodsk, Vostochny-Novoye, and Kholmsk-Sortirovochnaya was also washed away; in the port of Kholmsk, the reception facility of the ferry line was damaged. The roads for automobiles, which, like the railway, pass along the coast, were washed away near Prigorodny, Chekhov, Uglegorsk, Vzmorye, and Vostochny.

Tsunami A tsunami is a catastrophic natural phenomenon that destroys settlements and industrial facilities along the coast and kills many people. In Russia, the most destructive tsunami to date occurred on November 5, 1952, when giant waves almost completely wiped out the city of Severo-Kurilsk on the Island of Paramushir.

Sakhalin has not experienced such catastrophic waves, since tsunamis lose much of their power while moving from the Pacific through the Kuril Straits. According to witnesses, the Kamchatka (November, 1952) and Chile (May, 1960) tsunamis partially flooded the ports of Korsakov and Pronaisk. The Moneron tsunami (September, 1971) also casued some damage to the economic infrastructure on the southwest coast of Sakhalin, because the area of the underwater earthquake was not far from the island.

Ice Regime Ice has been instrumental in forming the landscape and sediments of the Sakhalin offshore area. Ice protects the coast from waves in cold seasons, transfers debris, and transforms the landscape of the underwater offshore slopes. This ice has different origins, forms, and dynamic features.

Shore ice is the ice that stays near the coast. It can be of two kinds: stable, i.e., existing for a month or more, and unstable. Along the Sakhalin coastal zone, both types are found throughout the cold season from November through May.

Stable shore ice is formed in the Alexandrovsk, Severniy and Sakhalin Bays, Amur Liman and the Lagoons of Piltun, Nyivo, Lunskaya and others. The width of stable shore ice can reach hundreds of meters. Sometimes, stable shore ice is formed in Mordvinov and Lososey Bays.

There is no shore ice, even the unstable variety, in the north of the Strait of Terpeniya, the east of Aniva Bay or the southwest coast of Sakhalin (Nevelsk and Kholmsk districts). Shore ice ridging varies; on average, it comprises 2–3 points; however, strong pileup winds can bring it to the maximal value of 5 points. While touching the seabed, ice ridges move sediments and substantially transform the seabed topography (Brovko 2002).

3.3.1.2 Geological and Geomorphological Structure of the Coast

Sakhalin Island has a unique combination of mountain ridges and intermountain basins. The majority of the island is separated by two parallel mountain systems. Northern Sakhalin has a combination of high plains and swampy lowlands, with protruding brows of Neogene structures drowned under the unconsolidated quaternary deposits. Some low-mountain rises – the Dagi Mountains in the east and the Vagis Mountains in the west – are the northern stretch of the East-Sakhalin and West-Sakhalin mountain ridges.

The outskirts of Northern Sakhalin also have swampy coastal lowlands intermitted by bays, lagoons, and lakes. The Amur estuary brings in terrigenous sediments, which form offshore shallows (the bank of Zotov, for example) and coastal dunes advancing towards the internal areas of Northern Sakhalin.

A combination of narrow zones of compression and extension as trenched faults and depressions with multiple lakes and lagoons (Tunaicha, Busse, etc.) is typical of the East-Sakhalin and Tonino-Aniva mountain ridges and the Muravyev lowland. A significant area is occupied by the East-Sakhalin mountain ridge, with the highest peak being the Sakhalin–Lopatina Mountain (1609 m). These mountains have well-preserved paleo-seismic dislocations made up of settlement ditches caused by high seismic activity.

The volcanogenic topography includes a shield layer of dacitic andesites, which form the Lamanon Plateau. Volcanogenic formations also include modern mud gryphons in the Daga River valley in the northern part of the island, the Pugachevsk Volcano, and the Yuzhno-Sakhalinsky Volcano, which is situated 25 km northwestward of the regional center and which periodically erupts with splashes of liquid mud, steam and hot water. A new source of mud volcanism was discovered on the western coast of Tunaicha Lake in the lower reaches of the Ochepukha River.

The modern landscape of Sakhalin was formed in the context of intensive wave abrasion and the modern genesis of rifts, which provide for the island's high amount of seismic activity.

3.3.1.3 Morphology and Dynamics of Shores

The majority of island coasts are subjected to abrasive processes (Brovko 1979). Since 1955, the rate of abrasion has increased by 1.5 times along many portions of island coasts due to sea level rise (Mikishin 1998). Extreme processes are often confined to local areas, where their intensity is more obvious against the general background.

Abrasive processes are insignificant in the southwest of Sakhalin. Abrasion of accumulative terraces is found only in river mouths where the bench is disrupted. However, the filling of new territories has caused significant changes in the landscape of the shore on the southwest side of the island. The largest filling was created for the second part of the ferry line in the Kholms-Polyakovo section. Soil filling beyond the bench, where the depths increase dramatically, resulted in the abrasion of the "artificial" terrace and required coastal protection measures (Brovko 2002).

Wide tidal benches and narrow beaches lie along the western shores of the island. The abrasive effects of waves occur only during storm pileups and tides. However, the shores of this area have been intensively destroyed, as shown by the deformation of coastal protection structures. Accumulative forms are destroyed faster. Ice washed-up onto the steep abrasive shelves of the west Sakhalin coast is a factor, causing rapid destruction of the shores. Ice-formation on poorly lithified formations during catastrophic storms (with waves up to 5–7 m high) creates instability of the rock formations and results in their fast movement and a retreat of the shore in winter by 3–4 m/year (Korotkiy and Khudyakov 1990).

In the middle part of western Sakhalin, intensive seawater abrasion is constantly cutting the ridges compiled by fractured sediment formations. Landfalls here are not significant; however, their constant yearly occurrence is a major factor in the progressive destruction of the cliff. The major landfalls are observed in the areas where sediment formations abruptly fall towards the sea.

The length of the washed-out coasts in the northwest of Sakhalin is 40.3 % of the total coastal line of the region. Intensively abraded ridges are found on the shores of the Amur Liman and Sakhalin Bay. The velocity of retreat of the shore compiled of poorly consolidated or soft sediments is 2–5 m per year.

Peninsulas are most intensively washed out in the Strait of Nevelskoy. The rate of washout of their southern segments is much higher than that of the northern segments, due to the character of the alongshore transport of sediments. In the system of bay-bars of the Azov type in the Amur Liman, under the conditions of level changes in tidal water, northern waves play a predominantly destructive role in the development of the upper part of the coastal profile. The most powerful northern waves of the fall season mostly result in washouts of the coastal ridges in abrasive areas and accumulation of material in accumulative areas (Brovko 2002).

Three alongshore lows of sediment travel along the shores of Sakhalin Island. The abrasion of Neogene formations as a source of debris entering the offshore zone plays a significant role in the northern and southern regions. Currently, there is an insufficiency of sediments in certain parts of the shore, which causes abrasion of accumulative forms. Washout of accumulative forms occurs at a rate of 2–22 m/year, but not along the entire sea front; it occurs along individual 1–23 km-long shore ridges (Brovko and Mikishin 1999).

The offshore zone in the northwest of Sakhalin is an area of challenging ice conditions, which impede human economic activity. The straightness of the shoreline and a lack of deep bays prevent the stable shore-ice from forming. In winter, the shore ice is often broken. Many ice ridges and hummocks build up. In the zones of contact between hummocks and seabed, sand bars (up to 2 m) and stretches (down to 1.13 m) are found, caused by seabed gorging (Tambovsky et al. 2001). Ices gorge the surface of beaches, breaking off prominent parts of abrasive outliers, benches and cliffs. Ices also protect the shore from the impact of waves by regulating the wave regime.

The shores of Terpeniya Bay stretch for over 500 km. away from the Terpeniya Peninsula up to the Starodubskoye settlement. The significant size, openness and over-50-m depths of the majority of the Bay have created a favorable environment for wave acceleration. In Terpeniya Bay, the shore is intensively abraded near the Soimonov Peninsula. The rate of abrasion reaches 3–3.5 m/year, which is in many cases caused by anthropogenic factors. Construction of the water intake basin for the Sakhalin Hydroelectric Power Plant near the Vakhrushevo settlement in the area of alongshore sediment transport has disrupted its pattern of moving from the south to the north along the shores. A zone of material accumulation has appeared to the south of the water intake basin; to the north, there is an abraded shore compiled of relatively stable pebbles on argillaceous and ferruginous cements. In the course of 8 years, it has lost 20–25 m and continues its retreat at present (Buzlaev 1993).

The rates of cliff destruction along the shores in the south of the Tonino-Aniva and Krilyon Peninsulas do not exceed several centimeters per year. Abrasive shores in soft depths are found in the northwestern part of Aniva Bay. A stretch of sand and sand-argillaceous materials lies at the bottom of the intensively abraded, almost vertical cliffs. Landslide formations are also found there. The shore retreat rate is 0.1–1.0 m/year (Brovko 2002).

3.3.1.4 Anthropogenic Effect on the Shores and Shelf

The coastal zone of Sakhalin is an area of dynamic economic activity. Development of sea transport, construction and reconstruction of ports, installation of roads, railways, and power lines, offshore fishing and the formation of recreational zones – all of this has caused dramatic changes in the topography of the coast. Human economic activity, to one extent or another, has transformed about 20 % of the coast.

Significant changes in the topography of the shore have been caused by the filling of new territories in the southeast of Sakhalin. The biggest filling was constructed (for the second part of the ferry line) in the section between Kholmsk and Polyakovo. Landfilling beyond the bench, where the depth increases abruptly, resulted in a washout of the "artificial" terrace and required coastal protection measures. Coastal protection through tetrapods, rock blankets, and metallic and wooden structures is applied in the places where railways and automobile roads have been destroyed.

Environmental problems have been aggravated in several areas of coastal zone development. Thus, levelling of the 12–20 m high terrace surface widely spread along the lagoon coast of the Northern Sakhalin allows for travelling practically without roads. This option, which is mostly favorable, is used unrestrictedly. In some areas, the alongshore transportation zone is almost 100–120 m and consists of three to six parallel lanes. Frequent usage has almost completely destroyed the soil and vegetation cover and has exposed soft quaternary deposits, subjecting them to blowing-out and erosion (Fig. 3.7).

In the late 1980s, the port of Kholmsk was reconstructed in order to increase cargo turnover; the entrance into the water area of the port was widened; bottom-dredging works were conducted. Smaller port basins were reconstructed to be used by small fishing boats in the settlements of Pravda and Yasnomorskoye. Near the settlement of Pionery, an open-cut sand mine is in operation. Practically untreated sewage from housing and utilities is dumped into the sea along the entire shore. Benched vessels become an additional source of heavy metals entering the sea environment.

A basin protected by two breakwaters was constructed on the low sand bay-bar near the settlement of Shakhtersk. Northward of the basin, the shore retreated by 40–60 m over the course of 50 years. It had to be enforced by concrete blocks and protective wooden walls, since there was a risk of destruction of the airport runaway, which lies perpendicular to the coastline.

In the Strait of Nevelskoy, the intensity of the washout is much higher in the southern segments of the peninsulas than in the north, due to the character of the alongshore transport of sediments. However, south of the Pigibi Peninsula, construction of a dam has changed the situation. A coastal ridge in the south has been stabilized; a northern segment has been exposed to more intensive abrasion.

Fig. 3.7 Old roadbed destruction as a result of abrasion. North-Eastern Sakhalin

The anthropogenic impact on the Tunaicha Laguna has increased dramatically over the last decade. Forests were logged in many water-intake areas; this will undoubtedly result in the decrease in the water transparency and an increase in the rate of sediment accumulation due to the increased particle content in the inflowing streams. Additionally, in the mid-1970s, a bridge was constructed across the estuarine part of the Krasnoarmeisk tribute near the settlement of Okhotskoye. Much of the tribute was filled with ground, leading to dramatic shallowing of the estuarine zone and complete blockage of seawater entry into the lake. The lake water was somewhat desalinated. Open sand mines have been developed on the bay-bar, which separates the Laguna from the sea.

The port of Korsakov, like the southwest coast of the island, is exposed to strong storm pileups caused by deep cyclones passing by the settlement. Environmental damage has to be considered in addition to economic losses. For example, the pileups of November 10–11, 1990 and November 8–9, 1995 sank several vessels, damaged the shore facilities and destroyed the piers; they also washed away a lot of coal, cellulose, and scrap metal, etc., from the piers (Kovalev et al. 2001).

The Sakhalin-2 project operated by Sakhalin Energy involved the construction of an LNG plant in the settlement of Prigorodnoye. Liquefied gas is stored in reservoirs until the arrival of liquefied gas tankers. The LNG is shipped to the buyers from the offshore mooring. Construction of the mooring and seabed deepening disrupted the natural lithic-dynamic balance. Construction of facilities and increased intensity of navigation resulted in a higher contamination of the water with oil products.

Biocenosis is very diverse in the Busse Lagoon. The Ahnfeltia seaweed is the most valuable, being in a satisfactory condition. Its resources were seriously depleted in the period from the 1920s to the 1960s. Since Ahnfeltia takes a long time to grow, reproduces only in a vegetative way and is vulnerable to changes in environmental conditions, intensive and uncontrolled production of it inevitably results in a dramatic reduction in its amount. Currently, the fields of Ahnfeltia are slowly recovering (Brovko 2002).

Pollution of the lagoons has increased dramatically over recent years due to the economic influence of humans on nature. This includes the coastal lagoons, many of which are contaminated with oil products (Ekhabi, Odoptu, Nabil), sewage and industrial waste (Busse, Urkt, Lebyazhya). Additionally, the seashore of Southern Sakhalin is a popular recreational area for many inhabitants of the island. However, crowds of tourists pollute the beaches with food leftovers, plastic bags, plastic and glass bottles, tin cans, etc.

The development of environmentally-unfriendly industries in Sakhalin without proper measures of environmental protection aggravates the ecological condition of the coastal zone. The oil and gas industry poses the greatest danger to nature, with its drilling units at sea and on shore, its oil refinery, LNG plant, and pipelines. Protection of the coast from waves and pollution has been the greatest challenge so far. The majority of the problems are caused by irrational natural resource management while ecological risks, i.e., the possibility of harmful anthropogenic influence, are only increasing for the ecosystem and humans.

3.3.1.5 Geomorphological Monitoring and Economic Use of Lagoons

The observation of natural and anthropogenic facilities, together with analysis of trends and the processes that bring about change, is defined as environmental monitoring. An important place in the system is taken up by the geomonitoring aimed at studying geological and structural bases of landscapes of various geneses. It involves the formation of different shore types – abrasive, denudation, accumulative, biogenic, lagoon, etc. Lagoon shores occupy 10 % of the coasts of the Global Ocean. There are many of them within the temperate zone of the Northern hemisphere – the shores of the USA and Canada, Denmark and the Netherlands, Poland and Latvia, Russia (Brovko 1990).

In Sakhalin, as in Kamchatka and Japan, the lagoon shores are the most developed. One fifth of the 2670 km. of the coastline consists of bay-bars and bars, which separate lagoons from the sea.

The Sakhalin lagoon shores are shown on the geographical maps below, based on the results of hydrographic works starting from the middle of the nineteenth century (the expedition of G.I. Nevelskoy); however, real outlines were drawn only in the 1930s. Since then, the maps have been used as an instrument for geomorphological monitoring (Fig. 3.8).

The monitoring of natural processes on the complex lagoon shore is a comprehensive procedure. It involves observations of the morphology and dynamics of the landscape topography as a basis of the coastal landscape. Cross-spectrum analysis of asynchronical different-scale topographical and navigational maps, along with aero- and space pictures, is a major method of geomorphological monitoring. Reliable maps and data for the Sakhalin lagoons have existed since 1952. Field observations involve the following: plane surveying and geodesic profiling of various types of accumulative forms, as well as the creation of a network of benchmarks for recurrent surveying in equal time intervals (a month, a season, a year). Such surveying has been conducted on the shores of the Sakhalin Lagoon since 1973 (Fig. 3.9).

The morphology and dynamics of individual topographic forms can have common or local differences. The morphological system of the shore of the Sakhalin Lagoon includes a number of elements, which reflect the morphology and genesis of the landscape, as well as the character of

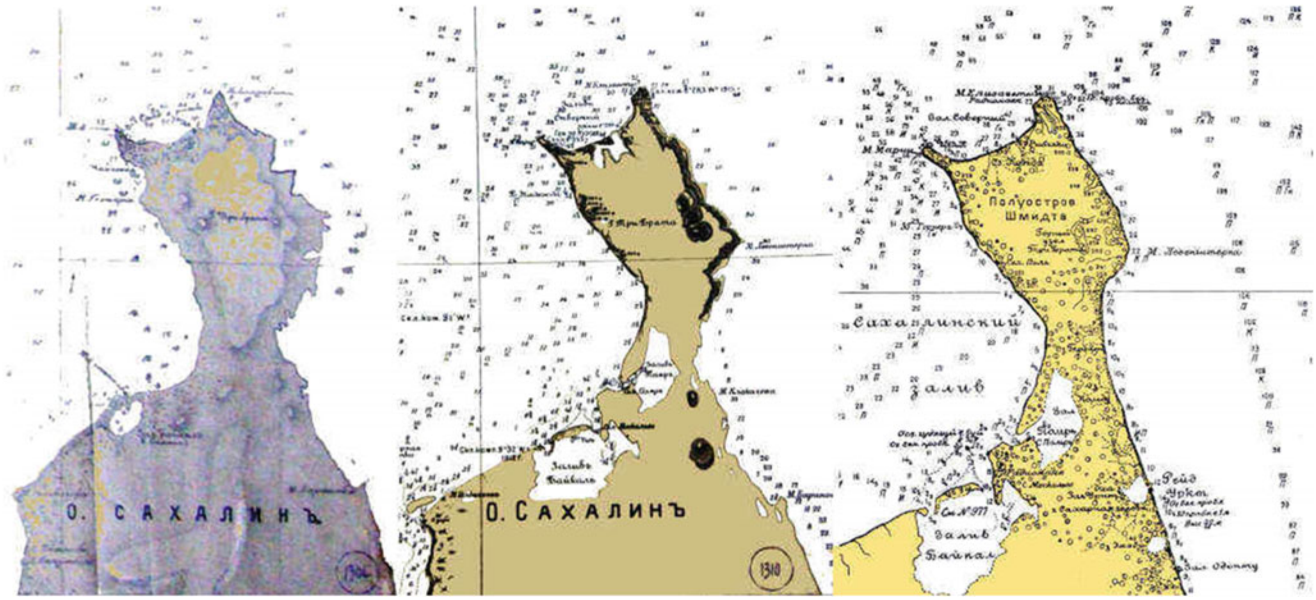


Fig. 3.8 Northern part of the Sakhalin Island on the maps, dated 1887, 1914 and 1936

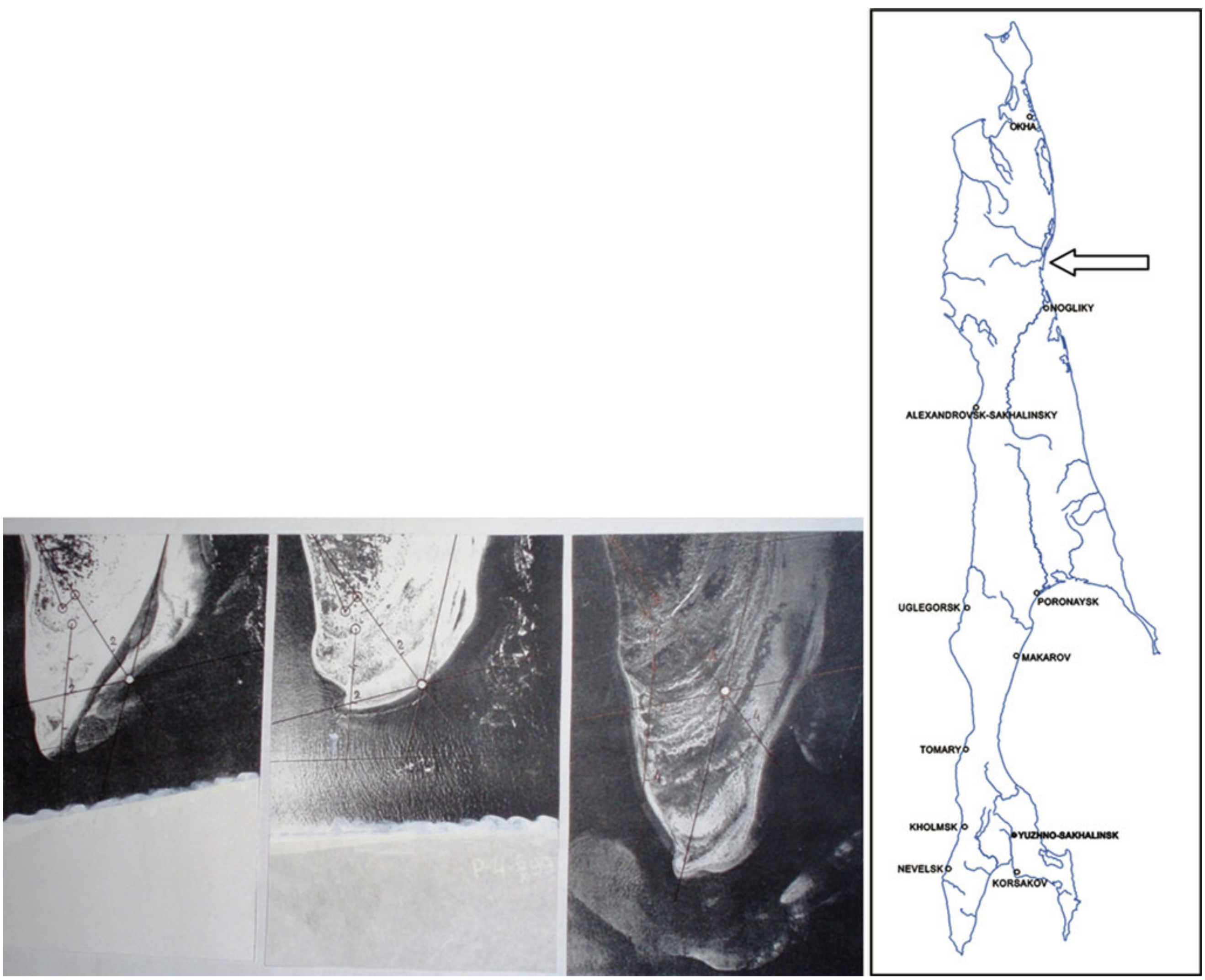


Fig. 3.9 Dynamics of the Chayvo Lagoon foreland (growth to south direction) according to aerial photos, dated 1980, 1983 and 1989

coast-forming processes. It is most obvious in the northeast of the island. They include the following: an accumulative underwater coastal slope, bars and bay-bars, accumulative plains of lagoon seabed, lagoon and sea terraces, lagoon straits and abrasive ridges between the lagoons.

The *accumulative underwater coastal slope* is a slightly wavy, tilted plain with submerged coastal sand-and-gravel bars. The upper part of the slope has a series of underwater bars, influenced by the joint effect of the waves, tidal and wavy alongshore currents. Recurrent surveys show that the bar tends to shift towards the shore. Narrow gravel and pebble deposits lie along the shoreline. Large and average-grain sands cover the slopes and crests of underwater bars.

Bars and bay-bars separate lagoons from the Sea of Okhotsk and consist of accumulative formations of various morphological type and size. The surfaces of bars – major formations 20–30 m long and 6–8 m wide – have multiple generations of offshore bars cutting into each other at different angles. The location of these bars shows multiple transformations of the shoreline.

The Piltun Lagoon is separated from the Sea of Okhotsk by a very complex bar. Its body includes the original residual hill, which used to be an island in the time of maximal development of the Holocene transgression; later, it was connected to the shore by accumulative formations.

The smaller lagoons, the Urkt, Ekhabi, Keutu and others, are separated by bay-bars, with one wide bar being up to 3 m high. Lagoon muds in the horizontal section that is also exposed along the submerged slope under the poor layer of modern sand, gravel and pebble sediment give us an indication of the shifts of bay-bars towards the shore and the advancing of sea sediments onto the lagoon sediments. The *accumulative plains of the lagoon seabed* consist of three levels of sub-horizontal and slightly tilted surfaces. The upper level is occupied by the tidal foreshores along almost the entire coastline. Slightly tilted accumulative plains of the middle level occupy up to 50 % of the lagoon seabed area. Central parts of the lagoon seabed (lower level) are taken up by the sub-horizontal accumulative plains at depths of 2–4 m. They consist of fine aleuritic and clayed silts. Alluvial and Aeolian materials are instrumental in forming the bottom sediments (Archikov 1986).

Lagoon and sea terraces of the middle-late Holocene are widely spread along the shores and line up the internal shores of the lagoons. The estuaries of major rivers – the Paromai, Piltun, Evai and others – have well-developed terraces with flat horizontal swampy surfaces and cryosolic torfhuegels. The majority of terrace coasts is subject to abrasion and rarely gradually transfers into beaches or sand-muddy unwatered areas.

Lagoon straits are the most dynamic forms; by the time they come into existence, they are divided into two types: permanent and seasonal. Permanent straits are the straits of major lagoons with bigger areas of transverse currents – the Piltun, Kleye, Anuchin, and Aslanbekov. Their sizes and expected outlines allow for judging the predominant direction of sediment transport. Thus, the Strait of Aslanbekov is actively shifting towards the north, while the Strait of Piltun does so to the south (Fig. 3.10).

Seasonal straits of smaller lagoons have a different structure. The predominant direction of the alongshore transport of sediment out of the shore is established in accordance with the morphology of accumulative forms, such as land tongues, which deflect the strait bed in any direction. The typical feature of the strait beds is in their seasonal changes: during the fall storms, they are completely obstructed by sediments. The straits recover in spring when a higher level of water in the lagoons caused by rivers and ice-melt results in disruption of the barricades (Fig. 3.11).

Abrasive ridges are situated between the lagoons and stretch for 1–14 km. The cliff is an abraded ridge of the abrasive-accumulative terrace of 12–22 m. height. The foundation of the terrace consists of the sand and clay deposits of the Nutovo formation of the Pliocene (Fig. 3.12). Long-term observation of the cliff dynamics allowed for establishing a seasonal rhythm of its development.

In winter (November–April), the coastal ridge and beaches have been "canned' by the ice-shore with a thick snow cover. Snow does not stay on the vertical walls of the cliff exposed to strong winds. In spring, temporary water flows form ravines and gulleys, which are transit ways for transporting the soft covers of the terrace to the beach.

In summer (July–August), the coastal ridges experience intensive landslides, forming the tail areas of soft and long accumulations. The active period of shore development finishes in the fall. Fall storm winds wash out, carry onto the slope and redistribute along the shore the debris accumulated during the spring and summer periods. Abrasion occurs only in the second half of the fall, when the layer of soft sediments near the cliff bottom disappears.

Constant remote observation of the new materials led to the opening of a new island near the lagoon shore of Sakhalin; this island was formed when water broke through the bay-bar of the Dagi Lagoon during a storm (Figs. 3.13 and 3.14). This island is subjected to constant geomonitoring via space pictures.

The anthropogenic effect on the shore of the Sakhalin Lagoon involves anthropogenic violation of the natural landscape and disruption of the natural chemical composition of river and lagoon waters, which cause negative changes in the structure of highly efficient biocenosis of closed shallow waters.

The anthropogenic effect is mostly related to the development of open sand mines for construction purposes on the bay-bars and surf zones. In recent years, over 20 authorized and unauthorized open sand mines have been operating on the Sakhalin shores; half of them are on the lagoon bay-bars (Fig. 3.15). In some cases, insufficiency of sediments in the coastal area results in a more intensive abrasion.

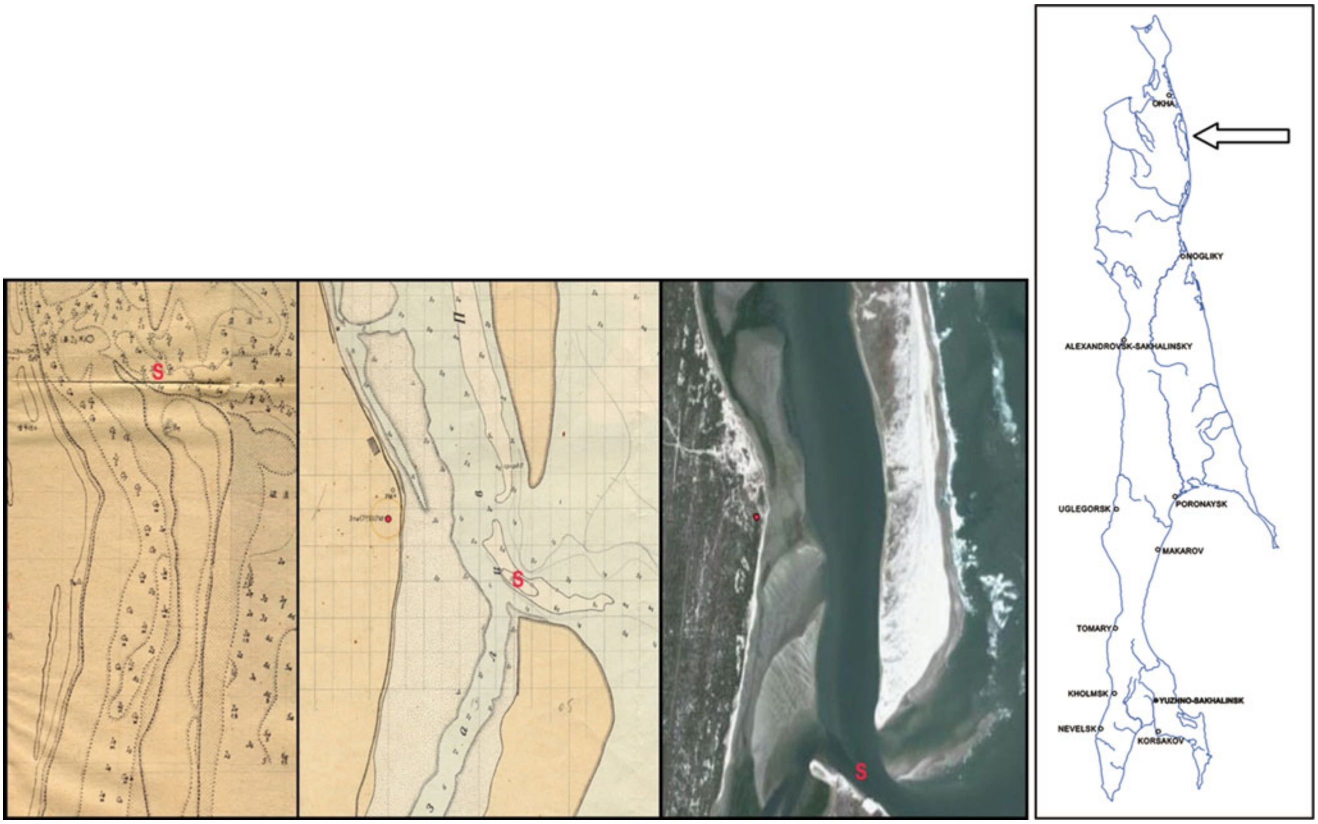


Fig. 3.10 Shift of the Piltoon Strait to the south, determined by navigational maps, dated 1920 and 1972, and (space image) 2006 (S – the greatest depths in fairway)

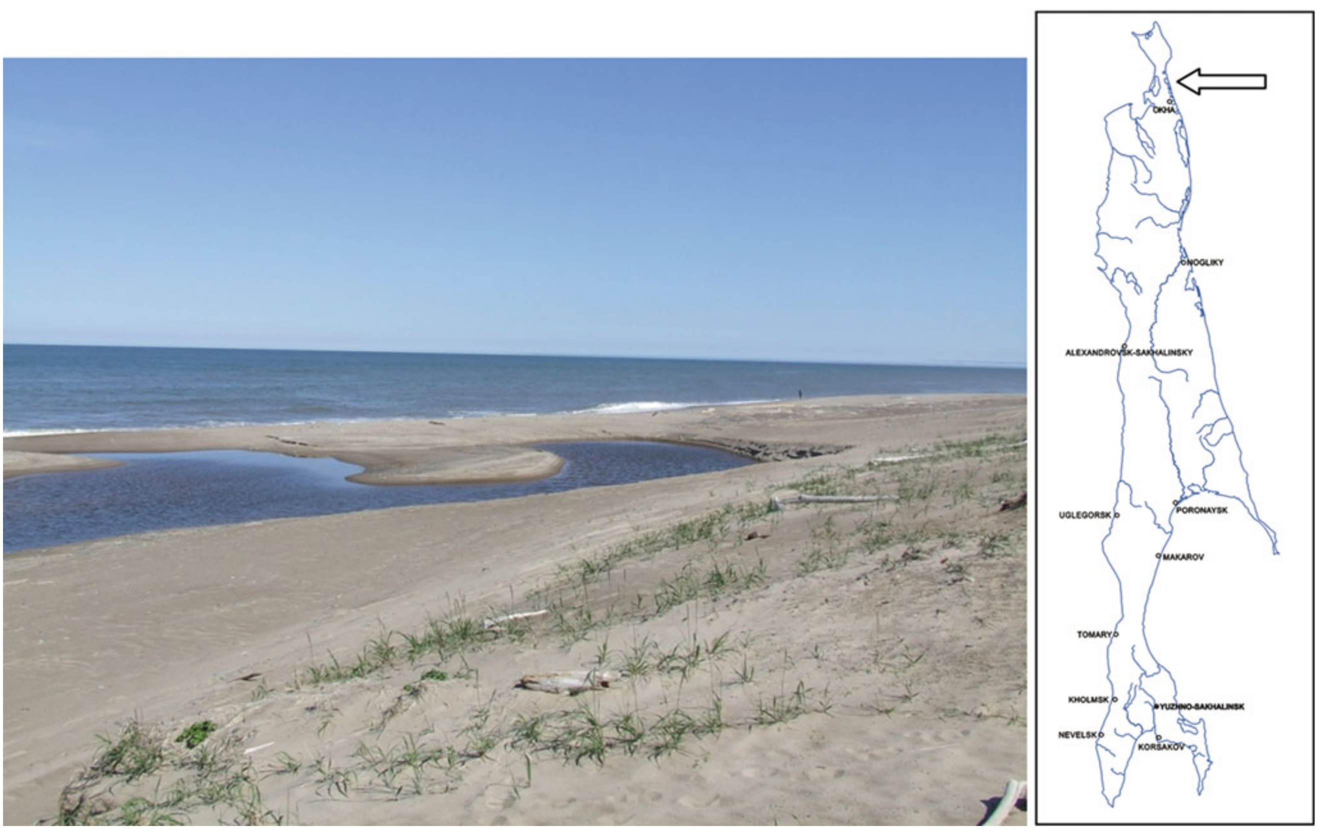


Fig. 3.11 Seasonal type strait, washed out during storms

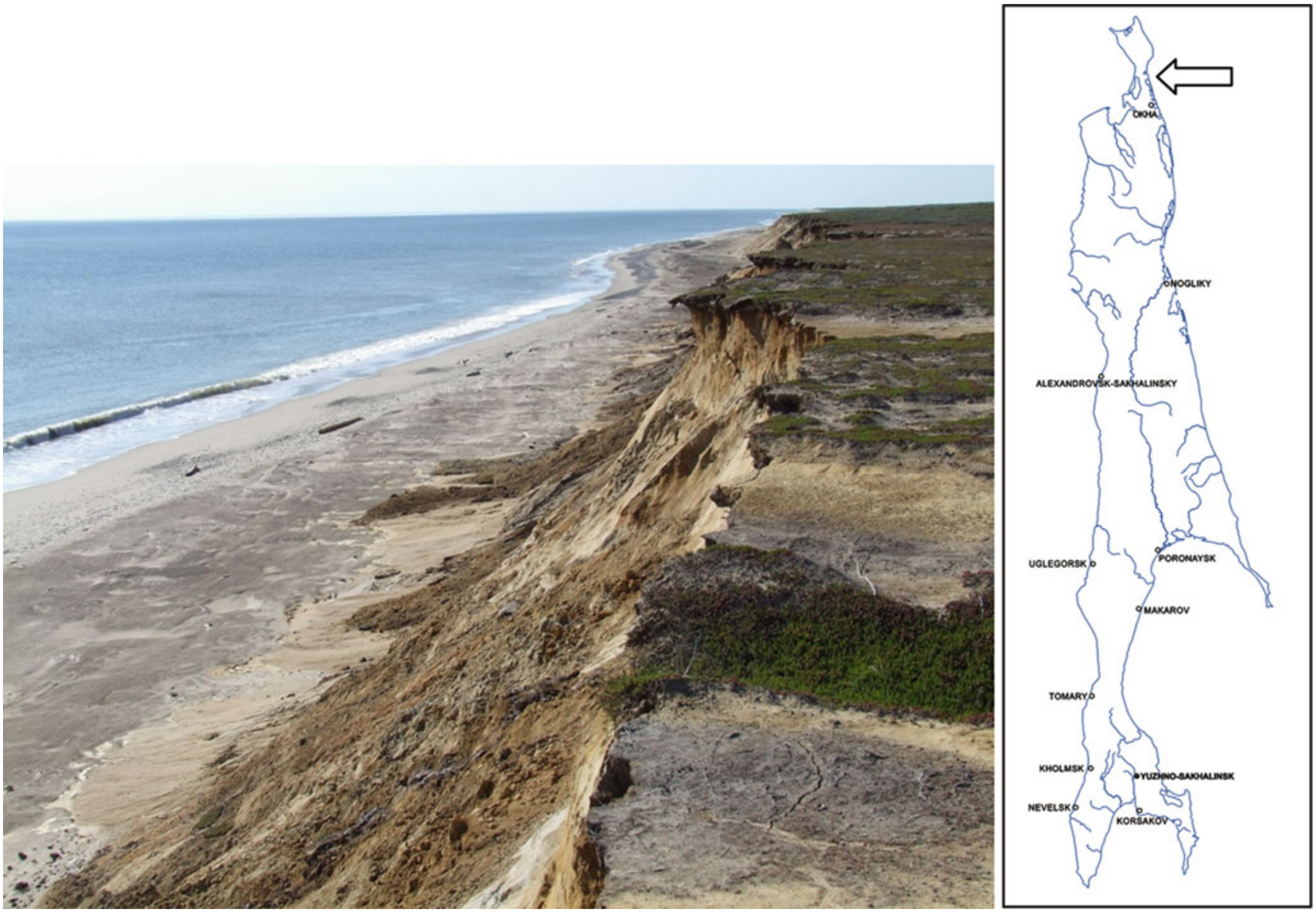


Fig. 3.12 Active cliff with the wide display of talus and landslide

Changes in the chemical composition of waters, regardless of the contamination source, lead to irreversible structural changes in the seabed biocenosis. Meanwhile, lagoons possess the highest biological productivity and are the most favorable water areas for farming in comparison with straits, open bays and gulfs.

Lagoons, as natural monuments, can be included within larger environmental structures, for example, national parks. A national park is planned in the south of Sakhalin (Fig. 3.16).

The Sakhalin lagoons are also used for creating refuge harbors and marinas, as well as the production of therapeutic muds. Usually, these facilities are localized in specific areas and do not involve the entire lagoon; however, environmental and geomorphological monitoring would have to be conducted in all cases.

3.3.2 Nabil Lagoon

The Nabil Lagoon is stretched along the shore. It is separated from the Sea of Okhotsk by a wide sandy bank with coastal shafts and eolian relief forms (dunes, blowing boilers). Its length is 16 km; its width, 6.6 km. The coastal line length is 61.5 km. The total square is 181 km^2.

The lagoon is connected to the sea by a strait – a channel with a depth of 10–12 m of submeridional spread. The lagoon is shallow (1–3 m); its depth increases only at the northern part, where a group of small accumulative islands is located (Zalesenniy, Chayka, etc.). These islands are the continuation of the narrow Gilyatskaya spit, stretching for 2 km. The islands' surface rises above the sea level by 2.6–3.9 m. The shores are low-lying and swampy. Around the islands, the drainage exposes itself during low tide with a width up to 200 m, which is formed by viscous, sandy silts (Brovko et al. 2002) (Fig. 3.17).

The internal shores of the lagoon are indented. The southern coast has the most complex shape, where a number of rivers, the Nabil, Vazi, Orkunyi, etc., flow into it through numerous sleeves forming a wide delta. The turbidity of the rivers is 10–50 g/m^3 on average and reaches its maximum values during spring floods.

The eastern and western coasts are relatively straight. At the eastern coast, between Aslanbekova spit and the peninsula of the same name, there is a long, narrow gulf, Old

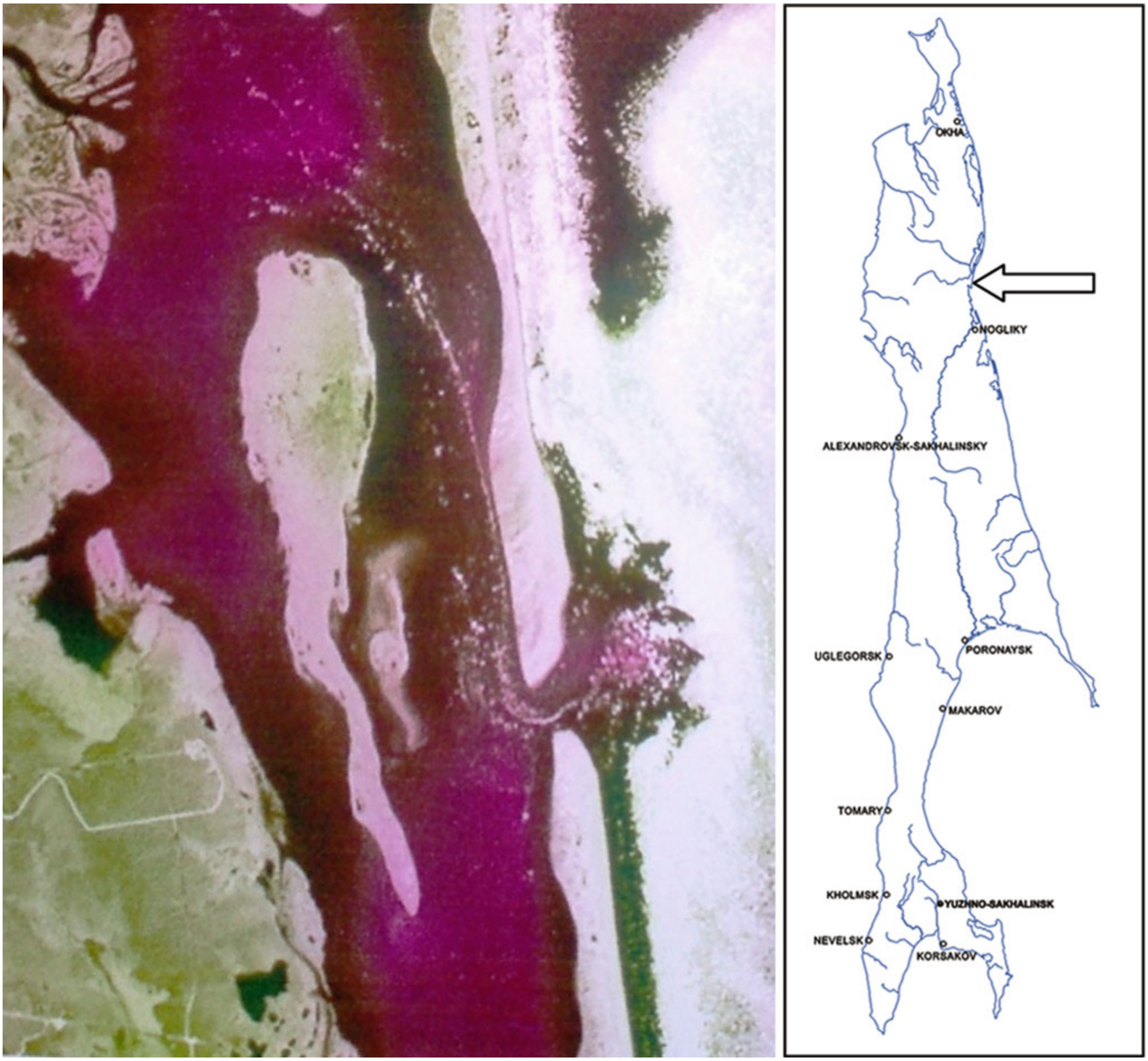


Fig. 3.13 Dagi Lagoon and the strait, which connects it to the Sea of Okhotsk (Space image 2002)

Nabil. The gulf entrance is limited by two small spits, growing towards each other.

The bottom sediment formation in the lagoon is tightly connected to the activity of the three main factors – river (alluvion being carried out), sea (material coming in with tidal flows) and biogenic. The complex interaction of these factors determines sedimentary material differentiation along the lagoon water area and the formation of bottom sedimentation, influenced by the hydrodynamic regime and bottom relief. There are several granulometric types of Nabil Lagoon sediment; some of the most developed are large-middle sized, fine-grained sands and aleurites.

Large-middle sized sands are widely spread throughout the northern part of the lagoon and inside the lagoon strait. They are characterized by a wide spectrum of separate fractions with an approximately equal content of fractions. The fraction of 0.5–0.25 mm prevails, forming up to 76.5 % of the sediments, with an average value of 39.5 %. Sand grading varies along a great range (So = 1.26–6.16) and depends on the hydrodynamic conditions of the water area.

Fine-grained sands (38.4–79.7 % the size of the small-grained sand) are found in the area of the channel ending at the tidal drain-off places. In the central part of the lagoon, there is 50–70 % of the fine-grained sand. To the north, the content of this fraction decreases to 30–50 %, in the southern

Fig. 3.14 Dagi Lagoon, two straits and the new island (Space image 2007)

part, to 10 % and less. The sands are homogeneous in material structure and are well sorted (So = 1.30–2.83).

Aleurites are spread around the entire lagoon. In the southern part, their concentration reaches 70 %. Aleurite sediment formation is connected with the solid drainage of large rivers – the Nabil, Vazi and Orkunyi – which is perfectly demonstrated by the character of the median diameter lines. Rivers flow mainly along the quaternary sea and alluvial sediments, and carry out the dissolved, weighted and drawn material.

The average turbidity of the river waters does not exceed 50 g/m^3; the waters are slightly mineralized (50–60 mg/l), weak-acid (pH~6), and rich in organic substances (oxidability7.2–9 mg O/l). The material carried out by the rivers is accumulated in the southern part of the lagoon, forming a homogeneous layer of small aleurite silts at the area of 80 km^2; moreover, on the southwestern coast, there is a maximum content of fractions less than 0.01 mm (50 %) and the thinnest sediments are represented. This information confirms the fact that, on the northeastern coast of Sakhalin Island, a considerable part of the thin fragmental sedimentary material, brought in by rivers, remains in the lagoons. The lagoon-mouth conditions of non-wave accumulation are formed here (Fig. 3.18a) (Brovko 1990).

Carbonate content in the bottom sediments is insignificant (1.22 % on average), which allows for classifying them as carbonate-free. The average carbonate content decreases from large-middle sized sands (2.30 %) to fine-grained sands (0.30 %). Distribution of carbonates by granulometric types of sediment perfectly corresponds to the distribution of components by surface area. The carbonate content varies between zero and 15.41 %. The main background is made up of content up to 0.50 %, with two outstanding spots of maximum carbonate amount. The biggest is located near the eastern coast of the lagoon; the other is found near the islands in the north. These sediments contain a lot of shell remains. There are many bivalve mollusks burrowing into the ground at the drain-off places in the near-strait part of the lagoon. Pieces of their shells are drawn by the tidal currents towards the eastern coast of the lagoon.

The content of organic carbon, mainly brought in by river flows, varies between 0.34 and 2.88 % in the surface sediments of the lagoon. The majority of the higher percentage content (2.26–2.88 %) is found in the southwest part of the lagoon. Small spots of higher percentage are also located near the islands, which are now outlined by sandy-silt drain-off places with multiple forms of Zostera accumulation and traces of burrowing organisms (Kafanov et al. 2003).

The average content of organic carbon (Corg) triples from fine-grained sands (0.66 %) to aleurite silts (2.20 %). At the same time, there is an increase in the average content in large-middle sands to 1.34 %. Such distribution is typical of small basins, where organic substances are not destroyed while transiting, and their maximal concentration corresponds to the area of fine sediment distribution.

The content of amorphous silica, mostly generated from diatom and radiolarian shells, varies in the lagoon sediments between 0.88 and 8.40 %. Distribution of amorphous silica by granulometric types is similar to the distribution of organic carbon. The content of amorphous silica decreases from large-grain sands (3.90 %) to fine-grain sands (2.30 %), and then increases to aleurite silts (3.70 %).

In the distribution of phosphorus by granulometric types of sediment, there is a decrease in its content from large-middle grain (0.048 %) to fine-grain sands (0.035 %) and aleurite silts (0.082 %). The main background of the element content is 0.01–0.05 %.

Iron, manganese and titanium are carried out to the sea as part of the suspended matter; its distribution around the basin is determined by the hydrological regime.

An average content of iron decreases from large-middle grain sands (2.25 %) to fine-grain sands (1.35 %) and then increases to aleurite silts (2.32 %). The content of iron in the surface sediments ranges from 0.39 to 3.43 %.

Fig. 3.15 Sand extraction at the Keutu Lagoon

The distribution of manganese around the lagoon is mostly even (0.02–0.05 %). An increase in the content of the element in the southern part of the lagoon shows that there is migration in the form of hydroxides in addition to the migration in the suspended form. After entering the lagoon environment, manganese hydroxides, like iron hydroxides, coagulate and the finest suspended material is captured by thick growths of seaweed, of the Zostera type. The content of manganese grows from large-grain sediments to fine-grained sediments.

The titanium content by granulometric types of sediment increases from large-middle grain sands (0.107 %) to aleurite silts (0.336 %). Distribution of the element along the surface layer of lagoon bottom sediments is connected with the solid flow. The maximal content of titanium (0.180–0.376 %) is found in the aleurites of the southern lagoon.

Distribution of chemical elements in the Nabil Lagoon is typical of a small water body in the humid zone. Their distribution by granulometric types of bottom sediments results in four groups defined by specific principles and dependence on the hydrological regime. Phosphorus, manganese, organic carbon and amorphous silica constitute the first group, defined by the distinct maximum in the fine-grain fraction with a sufficiently high content in large-middle grain sands. The second group consists of iron, which has no distinct trends. The third group includes titanium; its content increases from large-grain sediments to fine-grain ones; and the fourth group consists of carbonates, whose maximal content is found in large-grain sands.

3.3.3 Busse Lagoon

Busse Lagoon is situated in the south of the Muravyevskaya Lowland; it was formed in the middle-late Holocene when the bar separated a shallow-water bay. The Arakul stream channel connects the Lowland with the desalted lakes of Vavai and Chibisan. The area of the lagoon is 43 km^3; its average depth is 4.8 m (Brovko 2002).

The offshore bar, which separates the lagoon from the sea, has a series of 3–4 m-high beach bars, mostly consisting of gray medium sands, which lie on gravel-pebble deposits. Similarly to other bars of Sakhalin, it was formed in the middle and late Holocene during which it was repeatedly restructured. The age of the wood found in the beach bar southward towards the Suslov Strait was identified as being 1678 ± 85 years old (FEFU, p. 137).

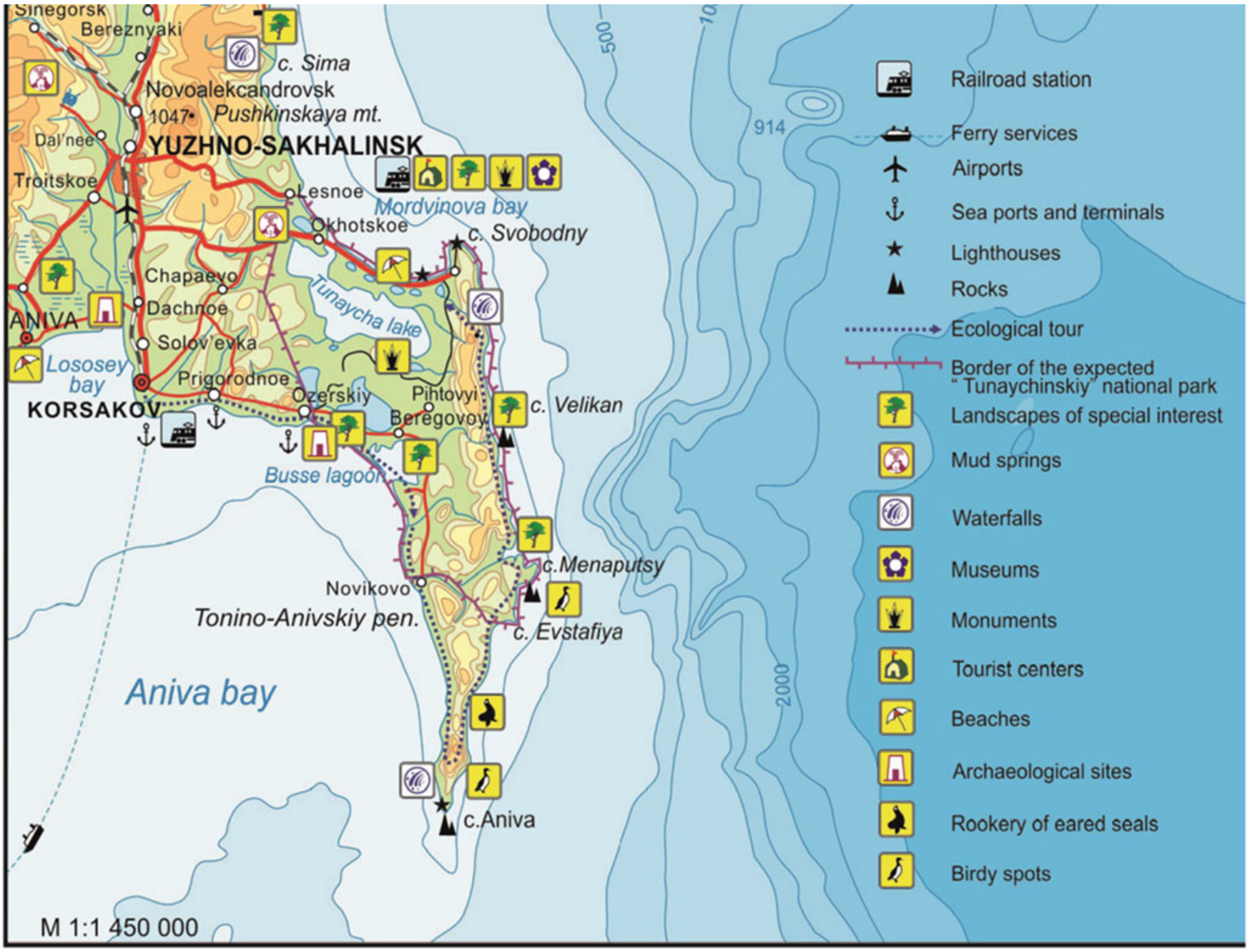


Fig. 3.16 Border (*red line*) of the expected "Tunaychinskiy" national park (*Yellow* and *white squares* – are natural monuments and attractive tourist objects)

The bottom configuration includes accumulative sea-bottom plains, an accumulative tidal plain, and crater slopes (Fig. 3.19). The accumulative bottom plain has a low-sloped undercut profile and an oval-shaped crater lying at a depth of 4–6 m. The depth of Holocene sediments exposed in the course of geological examination is over 10 m (The coastal lagoons of Sakhalin Island 2002). The plain surface has local surface degradations of 0.5–1.0 m deep and 200–400 m in diameter.

The accumulative tidal plain (unwatering, marshlands) occupies a 0.5–2.0 km.-land corridor along the western coast of the lagoon. It has a smooth surface with traces of ice impact, and is slightly titled relative to the lagoon. The plain is almost completely, and in many places completely, covered by grassweed (Zostera marina).

Abrasive-accumulative slopes rise 3–4 m above the crater bottom. Their width ranges from 300 m near the northern shore, where the primary rocks are exposed, to 1.2–1.5 km near the eastern shore. The offshore part of the slope is 200–300 m wide and up to 3 m deep; farther along, it flattens out and gradually turns into the bottom. Here, the sediments are more coarse-grained than in other sections of the slopes.

A branched system of erosive ravines created by tidal currents stretches from the Suslov Strait to the lagoon. The width of the ravines varies between 50 and 250 m; the depth of erosion is 2–5 m. The depths are bigger in the narrow water of the strait (Fig. 3.20).

The bottom sediments of the lagoon are formed from several sources of sediment material. Tidal currents from the Bay of Aniva bring fine-grained sand and carry out more coarse-grained sand. With decreasing influence of the sea factor, the sediment size is reducing to a very fine sand. In erosive ravines, the sediments consist of sand and gravel with shell detritus and live bivalve mollusks.

Inflow of alluvial material into the lagoon is not consistent. For most of the year, the stream sediments consist of fine sand; solid content does not exceed 20–50 mg/l. During cyclones with heavy rains, this content increases by 20 times.

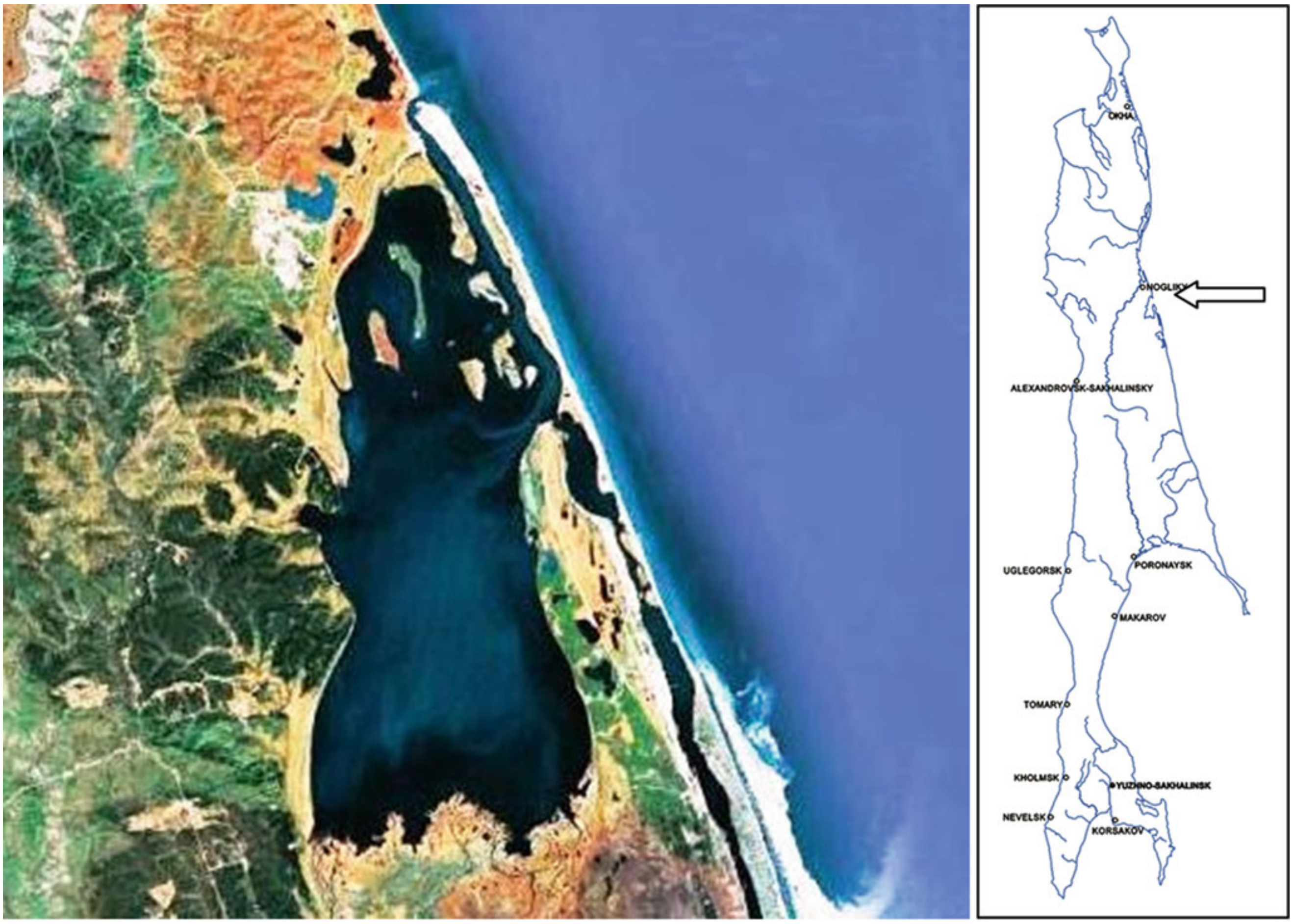


Fig. 3.17 Nabil Lagoon (Space image)

The amount of stream sediments goes up dramatically as well. Solid content enters the general circulation and spreads around the lagoon.

The biogenic material includes shell detritus, which concentrates in the central lagoon and in the areas of Zostera and Ahnfeltia (C_{opr} >5 %) growth. Increased content of detritus is registered in the southern and southeastern part of the lagoon. The detritus of bivalve mollusks is found among coarse sediments; small gastropods are found in aleuritic alluvia.

Distribution of bottom sediments, especially of sand-alluvia, is very consistent. Sands are more typical of the beaches, the upper section of the underwater slope, tidal channels and unwaterings. Coarse-grained sands (0.5–1.0 mm) are found only on the beach of the strait; this type of sand is never found in the lagoon. Average-grained sands (0.25–0.5 mm) are typical of the northern part of the lagoon and strait. In all cases, the average-grained sand is well graded. Fine-grained sands (0.125–0.25 mm) are very common; they border the lagoon shores with average-grained sands and gravel-pebble deposits and are most often found around the strait. These sands are instrumental in unwatering and mark the zone of maximum impact of tidal current in the lagoon. In shallow water areas, fine-grained sands are formed when waves prevail: the sands are well graded.

Fine-grained sands (0.063–0.125 mm) form a narrow land strip closer to the central lagoon. They are less graded and primarily found in the southern part of the lagoon.

Aleurites lie in the deepest parts of the lagoon and occupy about 40 % of the bottom surface.

Distribution of the lagoon bottom sediments by granulometric types reflects the hydrodynamic situation and is obviously connected with the bottom configuration while influencing the distribution of chemical elements.

The elements can be classified into two groups by their distribution in the lagoon and by granulometric types. Each group has its own dependencies related to hydrological regimes and sources (Zadkova et al. 1975; Brovko et al. 2002).

The first group includes the components the percentage of which is increased in the fine-grained sediments. They make two further groups. The first group includes: amorphous silica, manganese, titanium, phosphorus, copper, and organic carbon. The content of these elements increases from coarse-

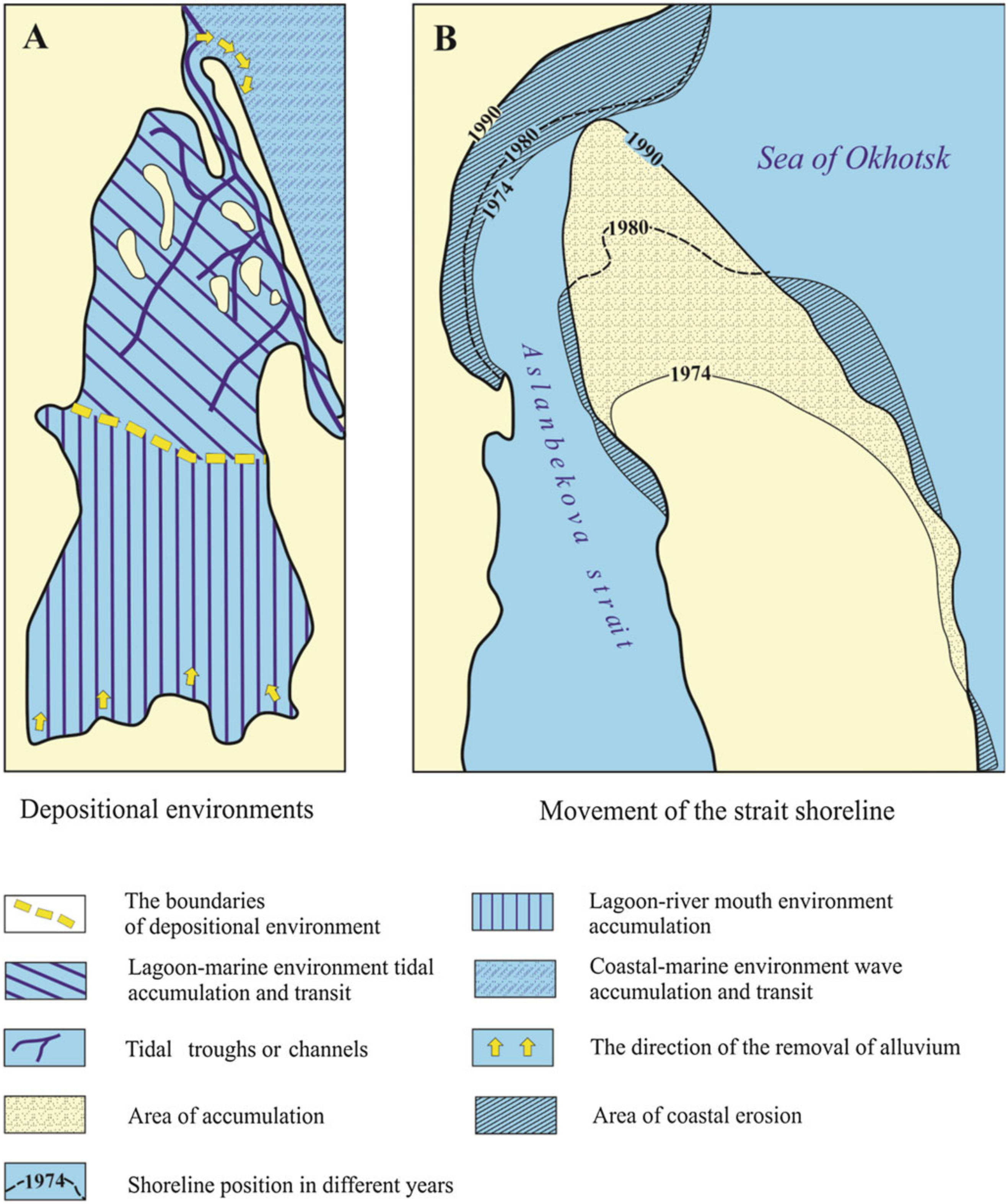


Fig. 3.18 Sedimentation at the Nabil lagoon. Distribution of chemical elements around the lagoon area is determined by the hydrodynamic regime that influences the mechanical differentiation of the sedimentary material entering the Nabil Lagoon (**a**). The influence of the tidal flows in the strait is high, with their velocity reaching 2 m/s. The strait has a tendency to shift northward (**b**)

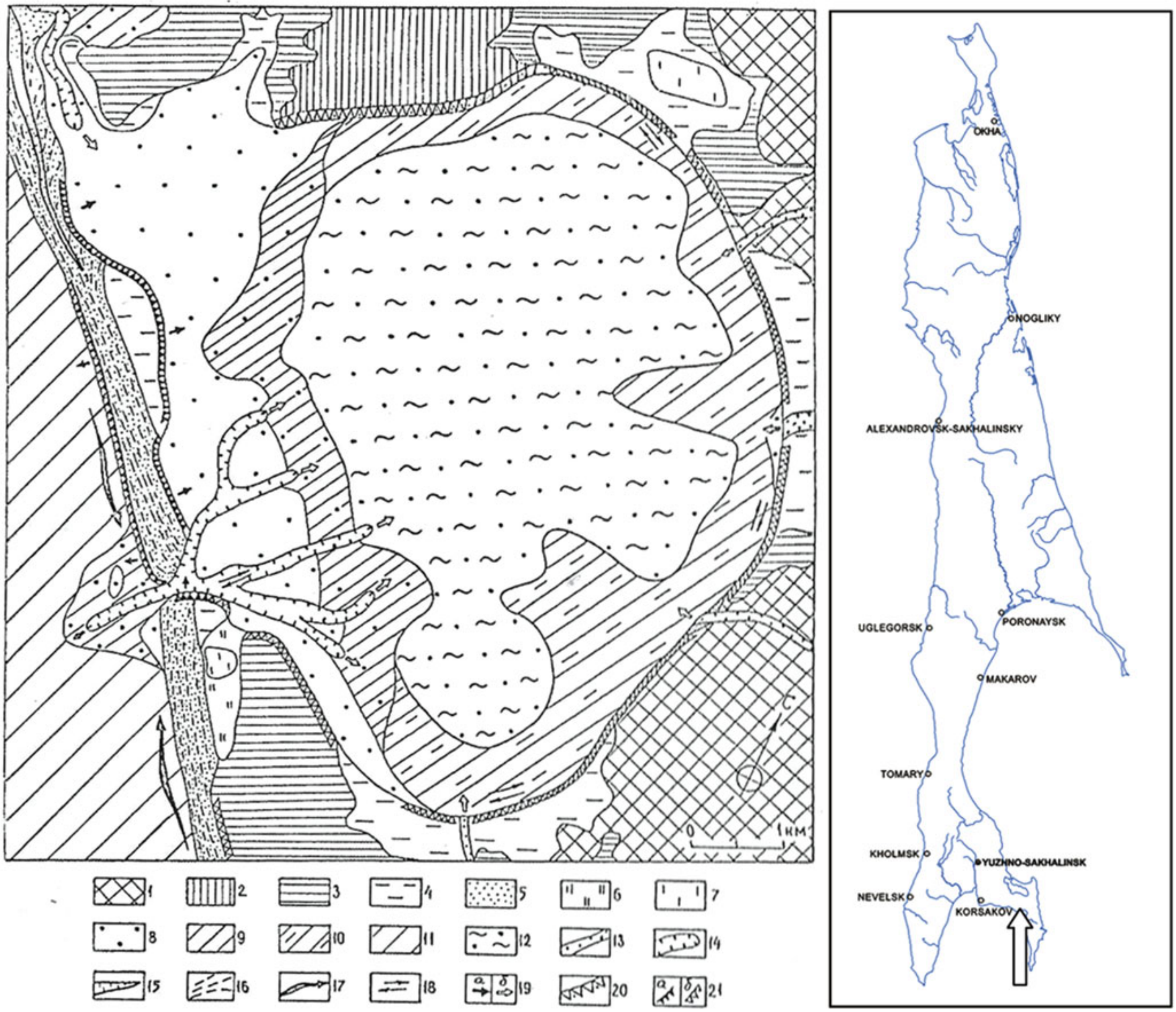


Fig. 3.19 Geomorphological scheme of the Busse Lagoon. *1* Low mountains with erosional dismemberment, *2* hills and ridges, *3* upper Pleistocene sea terrace with a height of 6–15 m, *4* mid-Holocene terrace with a height of 3–5 m, *5* coastal accumulating forms, *6* low lagoon terrace, *7* bottoms of residual reservoirs, *8* marches, *9* accumulating slope, *10* abrasion-accumulating slope of lagoon, *11* accumulating slope of Aniva Bay, *12* accumulating plain of the lagoon's bottom, *13* floodplain, *14* erosional hollows of the tidal delta, *15* dead erosional hollows, *16* coastal shafts, *17* sediment movement direction, *18* sediment migration, *19* material receipt: *a* during coasts abrasion, *b* from rivers and erosional hollows, *20* dead cliff in bedrocks, *21* cliff in loose rocks: *a* active, *b* dead

grained sediments to aleuritic alluvia. The second group includes iron, nickel, and chrome. The quantity of these components decreases from coarse-grained sands to fine-grained sands; then it grows again, reaching the maximum in aleuritic alluvia. The second group also includes the elements, the content of which is increased in the sands and coarse aleurites: zinc, cadmium, and carbonates.

First Group Organic carbon, amorphous silica, phosphorus, and carbonates can typically be called biogenic, since they pass through the zone of river water and seawater, mixing without sedimentation. In the sedimentation of components, the major role belongs to their immediate biological extraction from water, sediments in the form of shell material or the products of their decomposition.

Average content of organic carbon increases from coarse-grained sands (2.21 %) to aleuritic alluvia (7.17 %) by 3.2 times. The content of organic carbon in the surface layer of the Busse Lagoon sediments varies between 0.34 % and 12.01 %. The content of C_{opr} in the southern Lagoon is especially high; this is the largest fishing area of Ahnfeltia (the biomass of Ahnfeltia can be up to 4 kg/m^3).

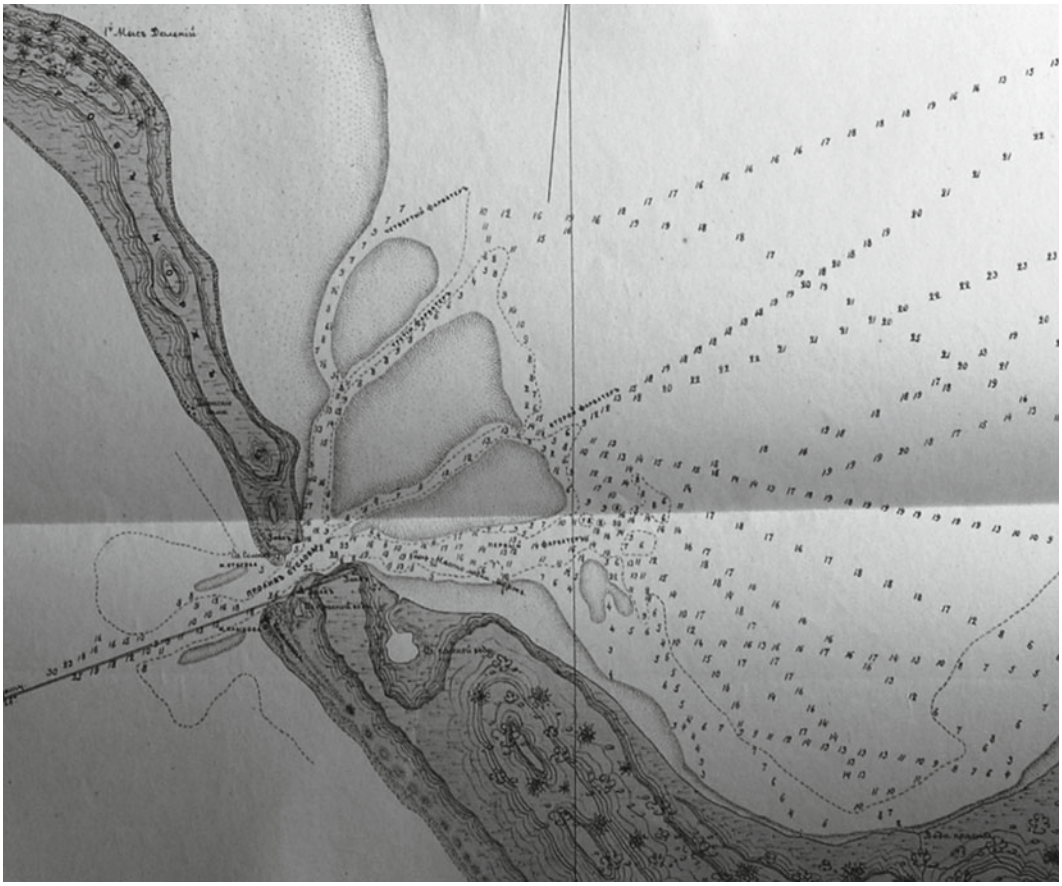


Fig. 3.20 Tidal delta with erosional hollows on an 1866 map

Amorphous silica is mostly produced by plankton (diatomic seaweed), which extracts it from water for building skeletons; in this form, the extracted material finds its way into the sediments. Distribution of amorphous silica is close to the distribution of organic carbon. Its content increases from coarse-grained sands (1.34 %) to aleuritic alluvia (2.86 %).

The lagoon waters are not rich in biogenic elements, especially phosphates, which is explained by the biota's high consumption. Phosphorus enters the bottom sediments after die-offs of diatoms and plants, as well as with river run-offs; the highest content of general phosphorus in the lagoon bottom sediments was registered near river mouths. The phosphorus content in the Busse bottom sediments increases from coarse-grained sediments (0.037 %) to fine-grained sediments (0.093 %). Accumulation of phosphorus in fine-grained sediments of the central lagoon, which is also quite deep, is attributed to the accumulation of the element by plankton and its partial burial later.

The majority of manganese enters the Busse Lagoon in suspended form: its average content in the suspended solids of the river is 0.164 mg/l. The element distribution in bottom sediments follows the major principles of mechanic differentiation.

Changes in the titanium content by granulometric types of sediment are insignificant (0.023–0.028 %). Maximum quantities of the element prevail in the fine deposits of the central lagoon. Minimal quantities are registered in the southern part of the lagoon near the shore.

Copper is found in the lagoon's river run-offs in a dissolved state (48 % of the total runoffs) and in a suspended state. Relatively high concentration of dissolved copper seems to be determined by the low quantity of organic matter in the river's suspended solid materials, which allows the element to stay in the ionic state.

Dissolved copper, which enters the water body, is accumulated by Ahnfeltia and plankton; later (after sedimentation of plankton and Ahnfeltia decomposition), some copper will penetrate into the bottom sediments. The average content of the element increases from coarse-grained sediments ($1.0 \bullet 10^{-4}$ %) to aleuritic alluvia ($1.6 \bullet 10^{-4}$ %) very insignificantly.

The elements of the second subgroup prevail in fine-grained sediments; however, the quantity of all elements of this group is minimal in fine-grained sands, which is connected with the forms of migration in river waters.

The majority of iron enters the lagoon through river runoffs (60.6 % as suspended matter and 39.4 % in a dissolved state). The solid phase is divided into the sand-aleuritic and pelitic phases. The iron content in the surface layer of sediments varies between 0.86 and 5.65 %, with the average being 3.67 %.

The average content of plumber in granulometric sediments decreases from coarse-grained sands ($1{,}7 \bullet 10^{-2}$ %) to fine-grained sands ($1{,}3 \bullet 10^{-2}$ %) and almost doubles to aleuritic alluvia ($2{,}4 \bullet 10^{-2}$ %). Plumber distribution is similar to the distribution of iron in bottom sediments.

Second Group Zinc enters the lagoon in a suspended state with river runoffs. Average contents of the elements decrease from coarse-grained sediments ($2{,}5 \bullet 10^{-2}$ %) to fine-grained sands ($1{,}16 \bullet 10^{-2}$ %) almost by half.

Carbonates distribution by granulometric types of sediment is very inconsistent. The average content of the component decreases from coarse-grained sands (1.57 %) to fine-grained sands (0.79 %), increases to aleurites up to 2.33 % and drops in aleuritic alluvia. Maximum values (up to 7.0 %) are registered in the eastern and southeastern parts of the lagoon with large gatherings of bivalve mollusks, Primorye scallops being one type.

3.3.4 Tunaycha Lagoon

The Tunaycha Lagoon is the biggest and deepest water body of Sakhalin; it is situated in the northern part of the Muravyevskaya lowland. It stretches parallel to the shoreline of the Mordvinova Gulf, connected to it by the narrow and shallow Strait of Krasnoarmeyskiy. The lagoon has the shape of an irregular oval of 10 × 30 km in size, extended northwestward.

There are two morphologically different parts of the lagoon: the western (Malaya Tunaycha) and the eastern (Bolshaya Tunaycha). The western part is much smaller and shallower: its depth does not exceed 15–20 m. The maximal depth of the eastern part is 39 m; it was discovered in 1990 500 m south of the Menshikov Cape.

The seabed of Krasnoarmeyskiy Strait, which connects the Tunaycha with the sea, has a complex structure. The width of the Strait reaches 700 m along the Boyle Peninsula.

A distinctive temperature stratification of the water is a peculiar feature of the Tunaycha Lagoon. The biggest temperature amplitude is registered in summer: the maximal temperature is 20.9 °C on the surface while the minimal temperature is 10.3 °C at the bottom.

Annual fluctuations of the water level do not exceed 50 cm. The water level rises (by 10–30 cm) after floods in the rivers that collect water, which happens most often in the fall.

Average salinity of the surface waters in 1990 was 3.7‰ in spring, 4.5‰ in summer, and 4.1‰ in the fall.

Daily salinity fluctuations are only registered in the Krasnoarmeyskiy Strait: the maximal 32.4‰ and minimal 6.1‰ salinities correspond to the time of high and low tides.

In the past, water exchange between the Tunaycha Lagoon and the Sea of Okhotsk was extensive, which is proven by the higher salinity of the water in the lagoon basin. A certain dynamic in the interaction between the lagoon and the sea was registered in the Krasnoarmeyskiy Strait only after construction of a smaller, man-made canal in 1990 (Fig. 3.21).

Among the main sources of sediments entering the lagoon, there is river solid discharge, coastal erosion, biogenic processes, and, to a lesser degree, volcanic matter, which erupted out of volcanoes on Hokkaido and the Kurils. The river solid discharge prevails, since coastal erosion is insignificant and the major volcanic eruptions that supply eruptive materials to the lakes rarely occur more often than once or twice every few hundred years. Biogenic processes are the second major contributor of sediments: they include mollusk shells, diatom sections and vegetable detritus formed by the die-away of multiple aquatic plants. They increase the content of organic matter in silt sediments.

The whole spectrum of sediments, ranging from coarse-grain sand to pelite (Fig. 3.22), can be found on the bottom of the Tunaycha.

Sands are often found in the lagoon, especially in the eastern part of Bolshaya Tunaycha; they are better graded than all other sediments. In addition to the area shown on the map, the sand is mostly spread along the upper part of the submersed coastal slope (between the encroachment line and the sea vegetation belt) and sections of beaches in bay and gulf heads. Sand covers the bottom to depths of 10–15 m in the areas exposed to waves.

Very fine-grain sands almost completely outline the silt sediments. Like fine-grain sands, they spread depending on the bottom slope and reach their maximum width on the smooth slopes in the eastern part of the lagoon.

In comparison with other types of sediment, pelitic and aleurite-pelitic silts lying 13–15 m deep in Malaya Tunaycha and 20–39 m deep in Bolshaya Tunaycha occupy the greatest areas. Usually, these are greenish and dark gray (approaching black) silts of sloppy consistency with a distinct smell of hydrogen sulfide.

Distribution of chemical elements in the bottom sediments of Tunaycha has its specific features (Table 3.1).

The majority of these elements have maximal values in fine sediments. They are as follows: organic carbon, magnesium, phosphorus, aluminum, ferrous iron, sodium, manganese, titanium, zinc, copper, nickel, lead, and cobalt. Distribution of silicon has an inverse relation. The silt sediments of the lake are depleted in many chemical elements: the content of aluminum, ferrous iron, titanium, manganese, magnesium and calcium is below bulk earth values.

The coastal part of the lagoon (except for the surf zone), which is a few hundred meters wide, is covered by a thick

Fig. 3.21 Estuarine part of the Krasnoarmeyskaya channel with the flume

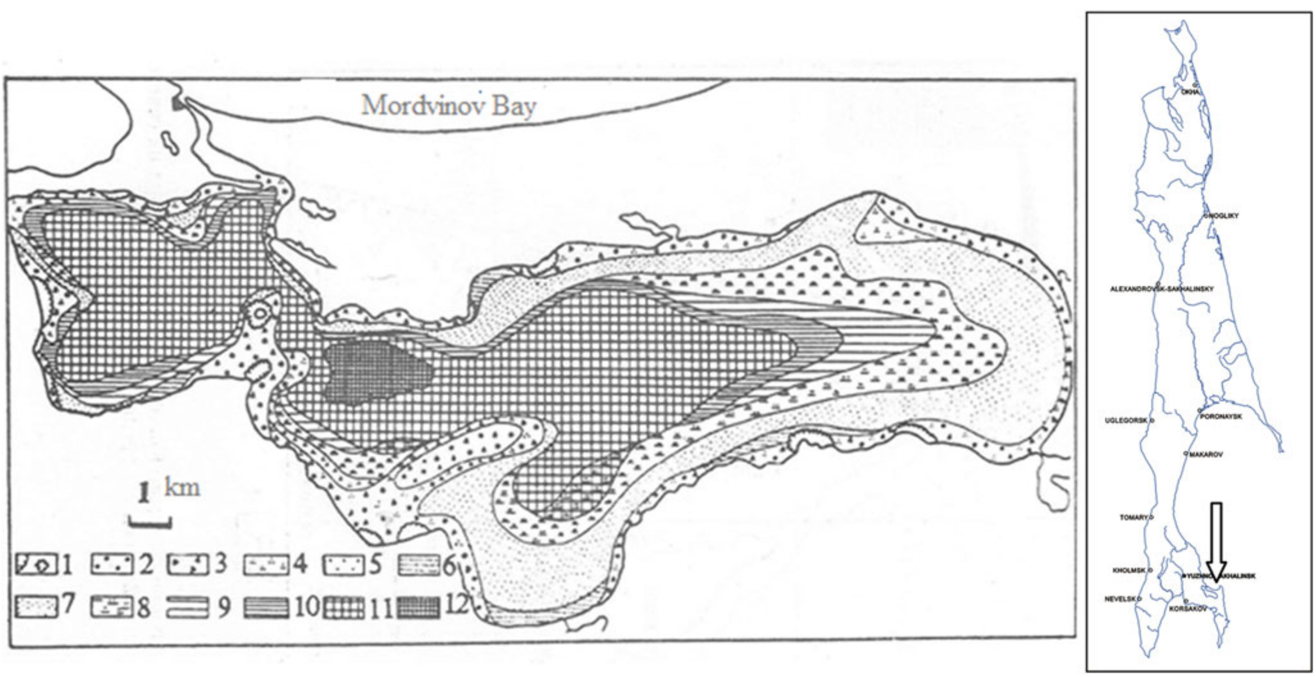


Fig. 3.22 Bottom sediments of the Tunaycha Lagoon. Bottom sediments types: *1* bedrock outputs, *2* pebble, *3* gravel. Sands: *4* undifferentiated, *5* hard-grained, *6* medium-grained, *7* close-grained, *8* fine-grained. Aleurites: *9* large, *10* small. Pelites: *11* large, *12* small

Table 3.1 Chemical composition of the Tunaycha Lagoon bottom deposits, in % (average values) The average rate of pelite sediment deposition is about 0.4 mm/year in Tunaycha

Type of sediment	Number of samples	Si	Fe	Al	Ti	Mn	Ca	Mg	P	Na	K	$C_{opr.}$
Fine grain sand	19	36.2	2.54	4.49	0.30	0.02	0.52	0.80	0.04	1.16	1.54	1.32
Aleurite	9	31.5	3.54	5.11	0.32	0.02	0.65	1.05	0.07	1.26	1.74	2.78
Pelite	24	27.5	4.24	5.41	0.34	0.03	0.60	1.19	0.08	1.62	1.72	4.07

vegetation of macrophyte seaweed, growing at depths ranging from 0.5 to 5–8 m (Labai et al. 2014). The fauna in the vegetation includes communities of amphipods, isopods, and gastropods. The zooplankton of the lagoon mostly consists of copepods: their maximal number in July reaches a few tens of thousands per 1 m^3.

Tunaycha is inhabited by 29 species of fish, including valuable commercial species such as cherry salmon, humpback salmon, and chum salmon, as well as Sakhalin taimen, red-eye, and crucian carp.

3.4 Deltaic Estuarine System of the Amur River

Estuaries, situated in the zone of interaction between land and sea, are partially enclosed water bodies, mainly in the mouths of tidal rivers. Their hydrological regime is unique due to many factors, including river run-offs, tides, and sea waves, as well as the runoff, wind-induced and reversing tidal currents, and water density stratification, etc. (Mikhailov 1998). Together with lagoons, estuaries are geosystems of high biological productivity. Estuaries provide for various economic activities – from port construction to fisheries and tourism. Therefore, aspects of economic and geopolitical cooperation between countries are becoming increasingly relevant in major river basins.

The Amur River falls into the Sea of Okhotsk, forming a huge 140 km-long estuary (the Amur Liman) (Chelomnin 2009). The Amur Liman is separated from the Sea of Okhotsk by Sakhalin Island and is connected to it via long, narrow straits (passes). Study of the Liman and the search for a solution to its environmental problems became the target of joint work of researchers from Russia and China – the countries where the greater part of the Amur River basin is situated.

3.4.1 Overview

The Amur River mouth is a complex unique natural system: a river with large run-offs, flowing into a shallow liman with composite bottom topography; the liman belongs to two tidal seas: the Sea of Okhotsk (anomalistic diurnal tides) and the Sea of Japan (anomalistic semi-diurnal tides).

The Amur River mouth is of the estuarial kind, with no subaerial delta. The Amur River is still forming its delta (arms and passes of the Amur Liman), which is still submerged, i.e., the Amur delta is still in its initial stage of development. The Nikolayevsk-on-Amur gate, situated 48 km. away from the estuarial gate, is the summit of a submarine delta. The Sakhalin pass is a sea border of the submarine delta in the East.

The Amur Liman is a shallow-water basin (average depth is 5 m) connecting the Sea of Okhotsk and the Sea of Japan. The major part of the liman consists of estuarine flats and banks crossed by narrow ship passes between 5 and 20 m deep. The northern exit from the liman into the Sea of Okhotsk (Baidukov Island – Rybnovsk) is relatively wide (36–40 km, and the Liman is only 48 km wide), while the southern exit (Lazarev Peninsular – Pogibi Peninsular) has a minimum width of 7.5 km.

The total area of the Amur Liman is 4205 km^2; the water volume is 16.4 km^3.

The monsoon climate is the most important feature of the geographical location of the Amur mouth on the border between the mainland and the ocean. In summer, south winds prevail, causing piled-up water level increases on the southern border; the majority of the Amur water mass shifts to the north towards the Sea of Okhotsk. In cold seasons, when summer monsoons change into winter monsoons, the water masses pile up on the northern border of the liman and Amur's run-offs turn in the direction of the Sea of Japan.

The hydrological regime of the Amur River mouth is mostly influenced by the climatic conditions defined by its geographical locations, atmospheric circulation patterns, thermal impacts and landscape topography.

Average yearly temperatures range between −0.1 and −4.8 °C, the lowest generally being around −31 °C, but dropping some days to as low as −44 °C. The average temperature in warm seasons across the years has been 15.5 °C.

Wind is the most important element, defining such hydrological phenomena as wind-induced and reversing water level fluctuations and waves. In warm seasons, south winds prevail, with the most frequent speeds being 5–10 m/s (over 90 %). The frequency of strong winds (10–13 m/s) does not exceed 4 %. Maximum speeds do not exceed 25 m/s. Seasonal changes from summer to winter result in the alteration of baric fields. Major air flows change direction to the north just as frequently.

The precipitation regime is influenced by monsoon circulation, cyclonic activity and landscape. The yearly amount of precipitation increases in the direction towards the sea – from 450 mm at the top of the mouth to 580 mm along the coast. In winter (December–February), the precipitation amount is 10–16 % of the yearly amount; in spring and the first half of summer, it comprises 26–30 % of the yearly total. The majority of precipitation falls in the second half of summer and early fall.

The soils and vegetation are not very diverse. Forests cover over 80 % of the territory. Along the coastal line, there are vast mountains covered in dark coniferous forests of taiga with mountain taiga podzolic and sour non-podzolic soils. The Amur flood basin is rich in forests of great size.

The Amur River mouth has a composite topography and geological structure. The right banks of the Amur are mountainous terrains; the left bank is a flood basin lowland.

The hydrological regime is closely connected with the geological structure and geomorphological features. The territory is abundant in quaternary deposits in a layer of relatively low power (100–200 m in dimples (впадина), and only a few meters on mountain slopes). They are mostly continental, sea and volcanic formations. The outskirts of the mountain systems and the depressions are rich in alluvial pebbles, sands, conglomerates and sandstones.

The Middle Quaternary deposits consist of alluvial loam, clay and terrace gravels 20–40 m high.

The Upper Quaternary deposits consist of alluvial sand, gravel, loam, sandy loam, and clay. These deposits form complexes of terraces 6–20 m high.

Modern deposits consist of alluvial, lake, sea, organogenic and dilluvial deposits. They are located in river valleys and mouths; they form beaches, sandbars and beach barriers. The cliff-covered coastline consists of very abrasion-resistant mountain materials (granite and basalt).

Relatively low development of abrasive processes affects the quantity of sediments in the coastal zone.

At the beginning of the estuary, the river waters are concentrated in one streambed, and the Amur is divided by the vast shallow area and the Island of Oremiph into two streambeds: the Northern one, which turns northeast into the Nevelskoy pass, and the Southern pass (Fig. 3.23).

In the east of the liman, the Sakhalin pass is situated along the coast of Sakhalin. The Nevelskoy pass is 3.5–22 m deep. It carries the majority of water masses and sediments of the Amur towards the Sea of Okhotsk in summer. The Southern pass has variable depths (from 3 to 11 m) and is

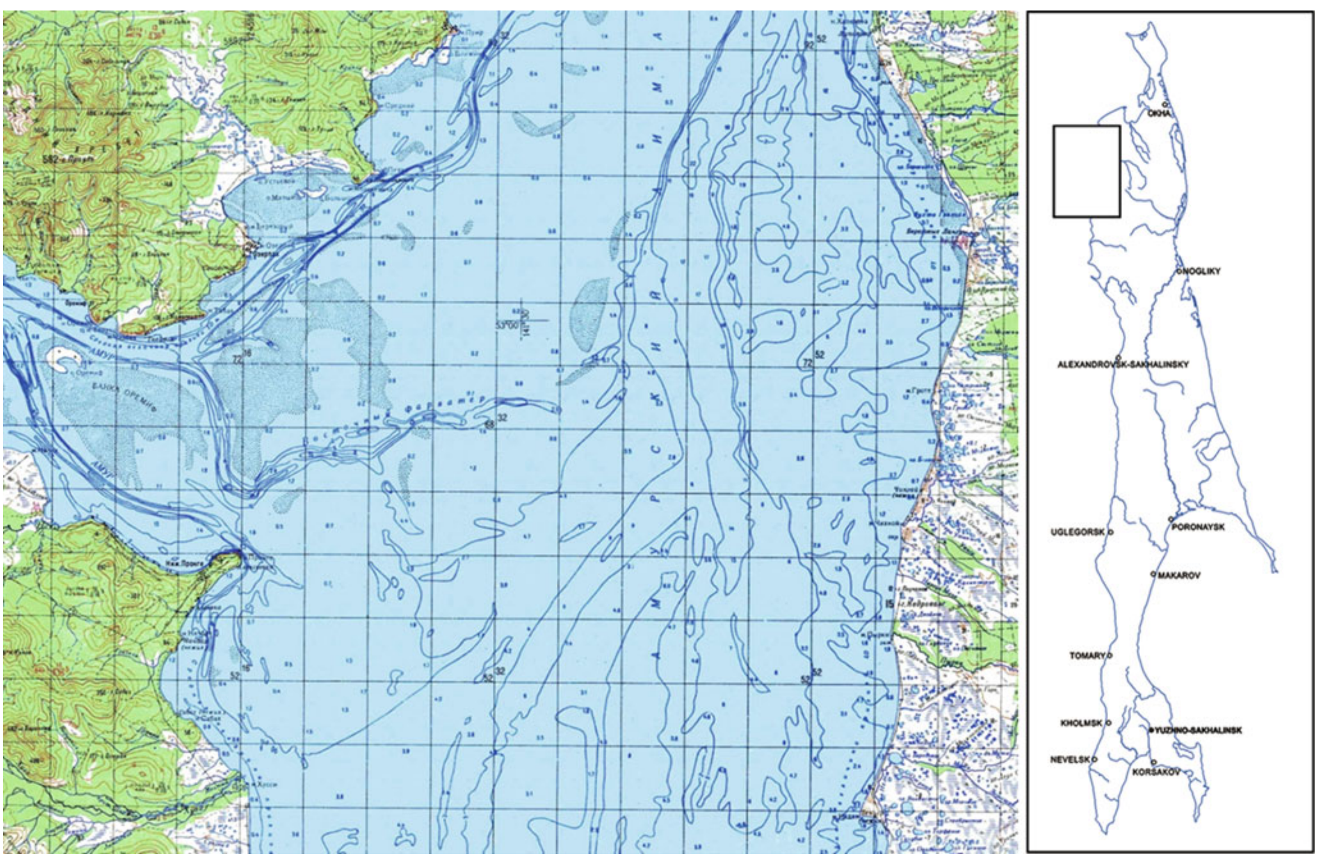


Fig. 3.23 Mouth of the Amur River and central part of the Amur firth with fairways

used for navigation from the Sea of Japan into the Amur during high tide.

The depth of the Sakhalin pass in its southern part is over 20 m.

3.4.2 Hydrological Conditions

Run-Off of Water and Sediments

Water run-off is one of the area's most important factors, forming the hydrological regime of the Amur mouth. The water run-off has been observed since 1963 in the top section of the mouth area, near the Bogorodskoye settlement, 238 km away from the coast. This observation period has been correlated with a multi-year run-off in Komsomolsk-on-Amur observed since 1933.

In Bogorodskoye, the average multi-year run-off of the Amur from 1934 to 2012 was 343 km^3/year (10,900 m^3/s); the lowest yearly water run-off was 6240 (2008) – 15,200 m^3/s (1956).

The run-off from the Amur varies dramatically by seasons: the majority of run-off (87–90 % of its volume) falls within the warm season; other months account for 10–13 %. Maximal run-off of water usually occurs in September and constitutes up to 40,000 m^3/s; the minimal goes down to 600 m^3/s during the lowest point of the winter run-off. The low of the summer run-off is almost nonexistent (Rostov and Zhabin 1991).

In 1975–1982, the Amur River run-off was influenced by human economic activity – construction of the Zeya and the Bureya Hydroelectric Power Stations. During that period, the run-off decreased dramatically in all its phases, mainly as the result of non-recoverable losses in reservoir filling. Estimation of the anthropogenic changes of the run-off has shown that, during the admittedly natural period (1934–1974), the economic activity in the river basin was so insignificant that it could not affect the run-off in the Amur River mouth (Ponomareva et al. 1982).

During the period of Zeya reservoir filling – its total volume is 68.4 km^3 (1975–1982) – the average water run-off in warm seasons went down by 9.8 %, and by 8.1 % in cold seasons.

During the period of run-off regulated by the Zeya reservoir (1983–2002), the summer run-off went down insignificantly (5.7 %, as opposed to the norm); however, the winter run-off went up a lot (23.3 %).

In April 2003, filling of the Bureya reservoir began and the run-off trend has remained unchanged since: winter run-off continues to grow, though less intensively (7 %), and summer run-off drops substantially (15.5 %). Water run-off is the main factor for evaluating sediment run-off under the influence of water management activity.

Non-stop observation of sediment run-off was conducted between 1965 and 1985 at the mouth top (the Bogorodskoye settlement). The observation data shows that the average sediment run-off over the whole period comprised 19.5 million tons (620 kg/s); during the natural period (until 1974), it was 23 million tons (736 kg/s). Anthropogenic reduction in the water run-off resulted in a dramatic decrease in the run-off of sediments. During the period of disrupted run-off (1975–1982), the annual sediment run-off went down by 22 % (515 kg/s) in comparison with the natural period; during the regulated run-off, starting from 1983, the annual sediment run-off went up to 550 kg/s (17.3 million tons). The volume of the annual sediment run-off changed from 290 (1976) to 1000 kg/s (1981).

Average yearly water turbidity in the estuarine gate is 65 g/m^3. In summer, the water turbidity in the liman depends on the current velocity influenced by tides and storm winds. Occasional observations during strong storms show that turbidity along the surface horizons of the Amur Liman increases to 600–800 g/m^3; at the bottom, it reaches 1600 g/m^3 (Hydrology 1989).

Water Levels

The level regime of the Amur Deltaic Estuarine system fluctuates, influenced by the changes in river water content and sea level. The most continuous non-stop observations (since 1900) have been conducted in Nikolayevsk-on-Amur, considered to be the top of the Amur underwater delta. Water level fluctuations are significant along the entire Amur estuarine delta system. The average yearly fluctuation range at the estuarine top (Bogorodskoye) is 2.32 m; at the top of the underwater delta (Nikolayevsk-on-Amur), 0.70 m, and in the gate (Pronge), 0.21 m.

Annual changes in the river gate level involve spring floods, summer and fall floods and the low winter run-off. There are two maximum periods: summer and fall floods and spring floods. This correlation remains until you reach the top of the underwater delta, where both maximums become equal; the spring maximum prevails at the exit of the Amur going into the liman. In summer, the prevailing south winds result in a piled-up water level increase along the southern border of the liman, while the water level along the northern border (Baidukov) decreases. In the fall, due to changes in wind patterns (north wind increases), the surface level of the liman becomes even for a short time, and then the water level difference reverses.

Tide-related water level fluctuations are another specific feature of the water level regime in the deltoid estuarine system of Amur. Interaction between the diurnal tidal waves of the Sea of Okhotsk and semidiurnal tidal waves of the Sea of Japan occurs around the entire Amur Liman. Tidal water fluctuations along the sea borders of the Amur estuarine seashore reach 2.0–2.2 m. The biggest penetration range of tidal waves reaches 300 km at the Amur River mouth during the low run-off in the warm season. During the flood period, the range of tidal waves up the river goes down to 200 km.

Estuarine Seashore Water Dynamics

Analysis of water balance elements in the Amur Liman has shown that the intensity of water exchange between the Sea of Okhotsk and the Sea of Japan through the Amur Liman is not great, due to its shallowness (Ponomareva and Povalishnikov 2002). The net flow of sea water in the warm season travels from the Sea of Japan into the Sea of Okhotsk and constitutes an average of 72 km^3, i.e., its volume is a quarter of the fresh-water run-off coming from the Amur into the liman during the same period. In the cold seasons, 16.8 km^3 of seawater flow from the Sea of Okhotsk into the Sea of Japan.

Streambed Deposits and Streambed Processes

The Amur brings solid 0.001–0.4 mm sediments into the Amur Liman. The particles of less than 0.05 mm prevail on the surface and down to the mid-depths; at the bottom, their size exceeds 0.1 mm. These particles are mostly suspended; they determine the turbidity of the river water, which varies by season. In winter, the typical turbidity between Nikolayevsk-on-Amur and the estuarine gate ranges from 5 to 50 g/m^3 on the surface and increases threefold along the near-bottom horizons. In summer, it goes up to 20–100 g/m^3 on the surface, and increases by three to four times near the bottom (Hydrology 1989).

Observations at the estuarine section of the Amur show that the stream sediments mostly consist of large particles of sand between 0.005 and 2.0 mm. Average weighted size of the particles is 0.75 mm. When the flow speed falls below the critical level, the stream sediments of certain sizes stop moving. At the top of the Deltoid estuarine system (Nikolayevsk-on-Amur), the critical non-erosive velocities calculated by Latyhsnkov's formula vary between 0.32 m/s for 0.05 mm sediments and 1.09 m/s for 2.00 mm sediments. The flow speeds in Nikolayevsk-on-Amur during tides go down to 0.58–0.60 m/s; therefore, the sediments over 0.3 mm stop moving. Only during low tides are all sediments up to 1.0 mm carried to the estuarine seashore. Here, the river water flow velocity goes down to 0.4 m/s and reduces the transporting ability of the flow, which causes the sediment to settle on the bottom. These sediments turn into bottom deposits and form the bar near the estuarine gate.

The Southern pass is formed by two adjoining bars. The Eastern pass has only one bar near the Sakhalin pass where the tidal wave front is parallel to the route of the pass and affects it in a similar manner along the entire length.

The location of the liman passes changes dramatically. They can only be analyzed via the navigation maps of 1909 and 1968: during this period, the northern bars of the Nevelskoy and Sakhalin passes changed significantly. Both bars are slowly shifting towards the north, while the passes are shifting towards the east. According to I.A. Solovyev (1994), the Nevelskoy pass near the bar shifted towards the east by 3.9–4.7 km.; the Sakhalin pass, by 2.2 km. The Southern pass turns out to be the most stable, but only until the latitude of the Dzhaore Peninsula; in the south, it shifted towards the west by 1.5 km. This tendency has continued in recent years: the depths along the entire liman are decreasing. In order to improve the situation, the navigation passes are being deepened and straightened along the liman bars.

Ice-blocks have a major effect on the streambed deformations of the Amur mouth; ice blocks the water cross sections and change the direction and velocity of the flow (Kononov et al. 1975; Solovyev 1994). According to A.I. Solovyev, the gravel-pebble and coastal bars in the lower Amur, as well as the gravel-pebble varieties in the alluvial deposits of different parts of the liman, show that many of them appeared under the influence of ice (Fig. 3.24).

3.4.3 Geomorphology and History of Delta Formation

From a geomorphological aspect, the valley of Lower Amur is in the zone of Mesozoic and Cenozoic depressions, characterized by developed lake-alluvial, alluvial and lake plains (Nikolskaya 1972). Below the settlement of Bogorodskoye (at the top of the estuarine area of Amur), the Amur River cuts through the branches of the Chayatyn range. In this narrow section, the width of the valley does not exceed 3–4 km. Then, the river flows through the Amur-Amgun lowland, which is abundant in lakes and swamps. The last narrow section (6–8 rm.) of the Amur valley comes before the estuary, where the river again flows between the rocky banks. Finally, the valley becomes wider, reaching 18 km. in the estuarine part of the Amur.

The slopes of the Lower Amur valley have terraces of different levels. Thus, between Khabarovsk and Bogorodskoye, river terraces reach 150–200 m; in the area of the Amur pass through the Chayatyn mountain range, there are no high terraces of this kind; here, they are only 15–20 m high, and there is a 20–30-m terrace occupied by urban buildings in Nikolayevsk-on-Amur.

According to seismic analysis, the layer of sediment underlying the Amur Liman bottom near the mainland is about 500–600 m; near the shore of Sakhalin, especially in front of the Amur estuary, it grows to 4500–5000 m. In the

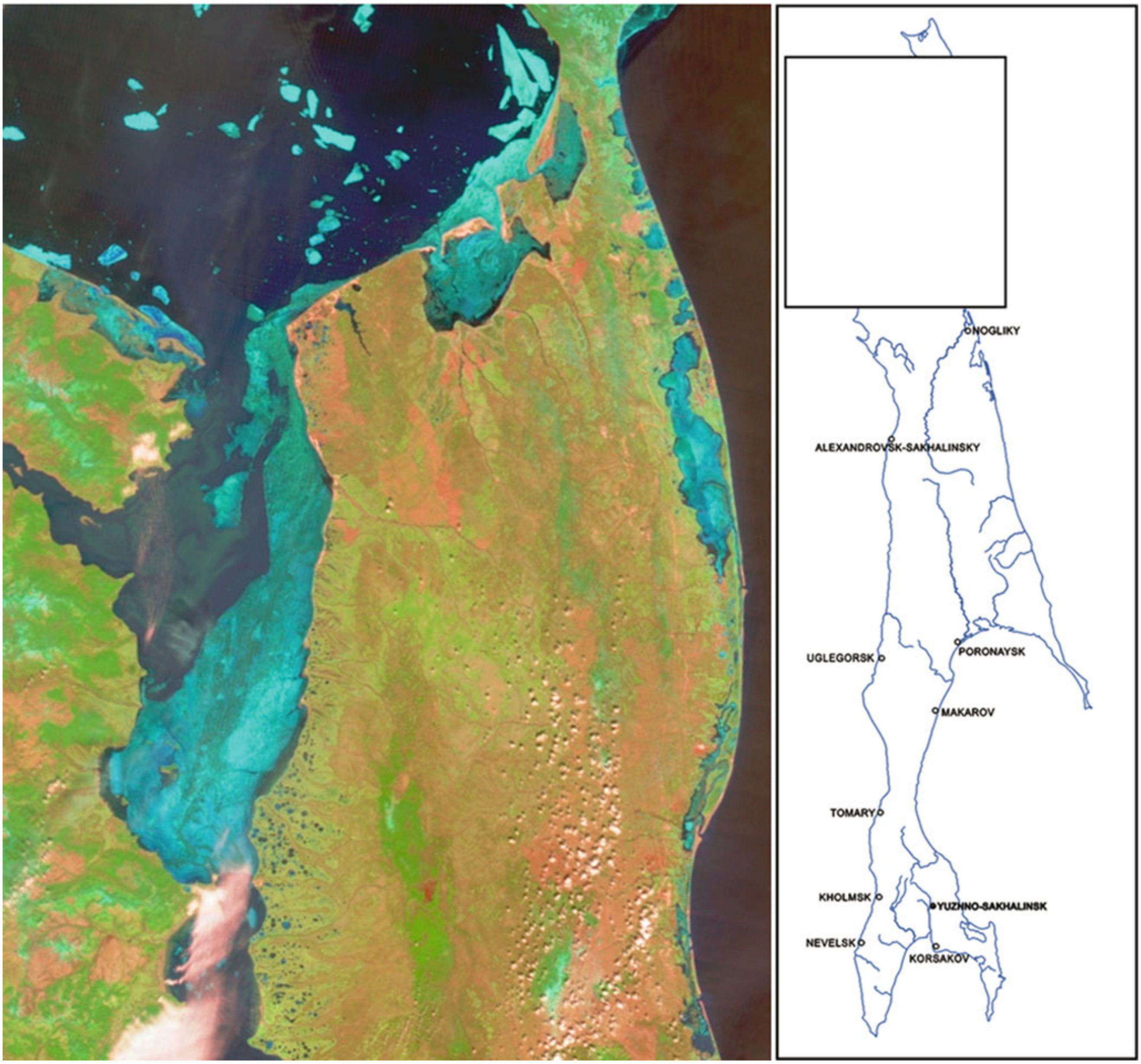


Fig. 3.24 Ice mode of the Amur Liman. Ice melting in May (Space image)

northern and southern parts of the liman, it goes down to 2700 m; near the Pogibi Peninsula, down to 1500 m. The whole of Northern Sakhalin is an ancient Amur River delta. O. A. Melnikov marks its paleo-streambed on the paleographical scheme of the Cretaceous period (Matyushkov et al. 2014). There are Quaternary deposits along the Sakhalin coast of the liman; they consist of inequigranular sands with small gravel.

The Amur Liman is not only the flooded delta of the Amur; it is also a straight between the Sea of Japan and the Sea of Okhotsk. The modern composition of its bottom is defined by interaction between reversing tidal and run-off currents, translocation of solid sediments and the breaking of ice during the fall and spring. Complex processes of modern landscape formation and sediment accumulation in the Amur estuarine have been described in recent research works (Yakunin et al. 2000; Chelomnin 2009; Shulkin et al. 2014).

3.4.4 Economic Activity

About 50 % of the total volume of freshwater run-off from Far Eastern rivers is carried into the sea through the Amur River mouth; it has a great influence on the hydrological regime of the coastal zone. Additionally, the mouth is a channel for outflowing biogenic substances and warmth, which are important for the biological resources of the Sea of Okhotsk and the Sea of Japan. The environmental role of the estuary is extremely important (Ponomareva 1981).

The Amur Liman plays a very significant role in the economy: it hosts fisheries, forestry, agriculture, and mining, as well as sea, river and air transport and pipelines. Their condition and developmental prospects are closely connected with the natural conditions. The role of ecological tourism is growing as well, especially due to the establishment of the Shantar Islands national park in the western part of the Sea of Okhotsk in 2013.

Nikolayevsk-on-Amur is situated in the Amur estuary. The city was founded in 1850 by a Russian admiral, G.I. Nevelskoy, as a military and administrative settlement – the Nikolayevskiy Post (after the Emperor Nikolai I). Thanks to its geographical location, this settlement soon became economically and politically significant on the Pacific coast (Brovko and Ponomarev 2013).

The OJCS Nikolayevsk-on-Amur Sea Port is located here; its cargo turnover includes the cargos bound for city enterprises and settlements situated along the Sea of Okhotsk. The port handles general cargos, timber, minerals and construction materials, coal, and containers. The port operates solely during the navigation period, which only lasts for 6 months, from June until November.

The major economic activity involves production and processing of fish, primarily humpback and chum salmon. The fish is processed at the local facilities and shipped to other regions in a frozen and salted state.

The CJSC Mnogovershinnoye gold mining company is situated 55 km away from Nikolayevsk-on-Amur.

Across the Strait of Nevelskoy, there are pipelines transporting the oil and gas from Sakhalin to the refineries and thermal power plants of Komsomolsk-on-Amur, Khabarovsk, and Vladivostok. A seaport called De Castri was built to the south of the strait. The territory of the port houses the OJSC Dallesprom and Exxon Neftegas Limited, an operator of the Sakhalin-1 project.

There are projects connecting Sakhalin with the mainland near the Nevelskoy Strait. Two variants are being scrutinized: a bridge or a tunnel. Implementation of this project can help make more efficient use of the economic potential of Sakhalin.

3.5 Conclusion

In the Northeast Asia Seas, lagoons and estuaries are most common on Sakhalin Island, where they occupy a full fifth of the coastline. There are also many lagoons on the coast of the Strait of Anadyr. Fjord-lagoons are found on the Chukotka Peninsula, the Koryak coast and the eastern coast of Kamchatka. Ria coasts with lagoons are found in the western part of the Sea of Japan and the Sea of Okhotsk.

The major Amur Liman, separating northern Sakhalin from the mainland, stands out for its hydrologic regime, which is formed by the Amur River outflow and tidal currents. A complex ice regime affects the shore dynamics and the transfer of sediments.

The lagoons and estuaries are mostly small and shallow. Their surface area rarely exceeds 500 km^2; the depths usually vary between 1 and 5 m. Only the fjord-lagoons and the Tunaicha Lagoon are over 20 m deep. The bottom topography is usually leveled; silts and aleurites are common. The bottom topography is most rugged in the Amur Liman; its seabed consists of sand and multiple channels (trenches) formed by tidal currents.

The lagoons and estuaries are situated within the poorly developed and low-populated coasts. The distance between coastal settlements can reach a hundred kilometers. The most densely populated areas and major cities are situated in the Peter the Great Bay, where the number of lagoons is insignificant. The lagoon coast of Southern and Northern Sakhalin is more developed.

The major economic activities include oil and gas exploration (Northern Sakhalin), harvesting and processing of fish and marine products (the Anadyr Liman, the Amur Liman, Peter the Great Bay, Aniva Bay, etc.). Mariculture farms have been established in the Busse Lagoon. Lagoons, estuaries, and limans play a great role in transportation infrastructures: the ports of Anadyr, Nikolayevsk-on-Amur, Moskalvo, Shakhtersk, Okhotsk, Nabil, and others.

Deposits of therapeutic muds are found on the lagoon shores; sand is mined in open fields; gold placer deposits and deposits of titanium-magnetite have been discovered. In general, the shores with lagoons and estuaries are prospective for further economic development and exploration.

References

Aibulatov NA (2001) Geoecology of the shelf and shores of the Russian seas. Noosphera, Moscow (in Russian)

Archikov EI (1986) Problems of the theoretical and applied geomorphology the coast of the Far Eastern seas. Publishing House of the Far East University Press, Vladivostok (in Russian)

Arkhipkin VS, Pishchalnik VM (1999) Seasonal variation of water circulation in the Okhotsk sea shelf of Sakhalin island. Sci Collect 2:84–95. Vladivostok: Dalnauka (in Russian)

Brovko PF (1979) Coastal erosion in Sakhalin Island. In: Morphostructure and paleogeography of the Far East, Vladivostok, pp 131–135 (in Russian)

Brovko PF (1990) Development of coastal lagoons. Publishing House of the Far East University Press, Vladivostok (in Russian)

Brovko PF (ed) (2002) Atlas of the coastal zone of Sakhalin island. Far Eastern National University, Primorsky Aerogeodetic Enterprise, Vladivostok (in Russian)

Brovko PF (2010) Geomorphological research and mapping the shores of the sea of Okhotsk. In: Navigation and naval science. Yuzhno-Sakhalinsk, pp 247–257 (in Russian)

Brovko PF, Mikishin YA (1999) Modern trends in the development of the North-Eastern coasts of Sakhalin. In: Scientific collection. Dalnauka, Vladivostok, pp 193–203 (in Russian)

Brovko PF, Ponomarev SA (2013) Nevelskoy GI: Amur expedition and settlement of the frontier problem in Eastern Russia. Vestnik DVO RAN 6:227–236. Vladivostok: Central Scientific Library of FEB RAS (in Russian)

Brovko PF, Manuylov VA, Petrenko VS (1988a) Geoecology lagoon complex of southern Primorye. Geogr Nat Resour 2:68–72. Springer Publisher House (in Russian)

Brovko PF, Tokarchuk TN, Cherepanova MV (1988b) Sedimentation in the Semlyachek lagoon (East Kamchatka). In: The biocenoses of the Far Eastern seas. DVO AN SSSR, Vladivostok, pp 170–188 (in Russian)

Brovko PF, Mikishin YA, Rybakov VF (2002) The coastal lagoons of Sakhalin Island. Publishing House of the Far East University Press, Vladivostok (in Russian)

Buzlaev VA (1993) New data on the speed of coastal erosion of Sakhalin. In: Geographical studies of the shelf of Far Eastern seas. Publishing House of the Far East University Press, Vladivostok, pp 78–86 (in Russian)

Chelomnin VP (ed) (2009) Condition of sea ecosystems influenced by Amur River runoffs. Dalnauka, Vladivostok (in Russian)

Gorin SL (2007) Hydrological and environmental conditions in the estuaries of the rivers of Kamchatka during the summer period. In: Vestnik MGU. Series 5. Geography, vol 5. MSU, Moscow, pp :38–40

Gorin SL (2014) Morphodynamical the mouth of the Kamchatka river in XVIII–XX centuries and its influence on the hydrological regime of the estuarine waters. In: Research of water biological resources of Kamchatka and North-Western Pacific Ocean, vol 32. KamchatNIRO, Petropavlovsk-Kamchatsky, pp 6–26

Hydrology of sea estuaries of rivers in the Russian Far East 1989. In: Proceedings DVNIGMI vol 38. Dalnauka, Vladivostok (in Russian)

Ionin AS (1959) Shores of the Bering Sea. RAS USSR, Moscow (in Russian)

Ionin AS, Kaplin PA, Leontiev OK, Medvedev VS, Nikiforov LG, Pavlidis YA, Scherbakov FA (1971) In: Kaplin PA (ed) Development of the landform and modern sediments in the coastal zone of the USSR Far Eastern seas. Nauka, Moscow (in Russian)

Ivashinnikov YK (2010) Physical geography and natural resources of the Russian Far East. FEFU, Vladivostok (in Russian)

Kafanov AI, Labai VS, Pecheneva NV (2003) Biota and communities of macrobenthos lagoons of northeastern Sakhalin. SakhNIRO, Yuzhno-Sakhalinsk (in Russian)

Kantakov GA (2002) Modern research currents in fishing areas of Sakhalin-Kuril region. In: Proceedings of SakhNIRO, vol 4. SakhNIRO, Yuzhno-Sakhalinsk, pp 4–21 (in Russian)

Kononov YI, Morin VA, Petric NS (1975) Role of ice in forming the stream sediments in Nevelskoy Strait. In: Voprosy Geographii Tikhogo Okeana I Pritikhookeanskikh Raionov. FENU, Vladivostok, pp 39–45 (in Russian)

Korotkiy AM, Khudyakov GI (1990) Exogenous geomorphological systems of seashores. Nauka, Moscow (in Russian)

Kovalev PD, Shevchenko GV, Kovalev DP (2001) The study of dangerous sea phenomena in the port of Korsakov. In: Dynamic processes on the shelf of Sakhalin and the Kuril Islands. Yuzhno-Sakhalinsk, pp 138–145 (in Russian)

Kulakov AP (1980) Morphotectonics and paleography of the continental coasts of the Sea of Okhotsk and the Sea of Japan in the Anthropogene. Nauka, Moscow (in Russian)

Labai VS, Atamanova IA, Zavarzin DS (2014) Bodies of water of Sakhalin Island from the lagoons to the lakes. Sakhalin Regional Ethnographer Museum, Yuzhno-Sakhalinsk

Matyushkov GV, Solovyev AV, Melnikov OA (2014) Geological past of Sakhalin. Sakhalin Museum of Regional Studies, Yuzhno-Sakhalinsk

Medvedev VS (1961) The shore of the Sea of Japan. In: Main features of geology and hydrology of the Sea of Japan. RAS USSR, Moscow, pp 35–101 (in Russian)

Mikhailov VN (1998) Hydrology of river estuaries. MSU, Moscow (in Russian)

Mikishin YA (1998) Forecast of development of the lagoon coast of Sakhalin island in the sea-level rise. In: Geographical studies of sea coasts. Publisher DVGU, Vladivostok, pp 66–75 (in Russian)

Nikolskaya VV (1972) Morphosculpture of Amur river basin. Nauka, Moscow (in Russian)

Petrenko VS (2009) Morphology and dynamics of the coast of Primorye. In: Proceedings of the society for Amur region studies, vol XXXIX. OIAK, Vladivostok, pp 196–201 (in Russian)

Pishchalnik VM, Bobkov AO (2000) Oceanographic Atlas of the offshore zone of Sakhalin island, vol 1. Sakhalin State University, Yuzhno-Sakhalinsk (in Russian)

Ponomareva TG (1981) Research of influence of human economic activity on the hydrological regime of the Amur River estuary. In: Proceedings DVNIGMI, vol 94. Dalnauka, Vladivostok, pp 95–100 (in Russian)

Ponomareva TG, Povalishnikova ES (2002) Water balance of Amur River estuary. Vestnik MGU 5, Geography vol 4. MSU, Moscow, pp 45–49 (in Russian)

Ponomareva TG, Ryabchikova TN, Kozlovskiy VB (1982) Distribution of Amur runoffs around the estuary. In: Proceedings DVNIGMI. Dalnauka, Vladivostok, pp 57–59 (in Russian)

Rostov ID, Zhabin IA (1991) Hydrological features of Amur estuarine area. Meteorol Gidrol 7:94–99. Moscow: SRC Planeta. (in Russian)

Shulkin VM, Zhabin IA, Abrosimova AA (2014) Influence of Amur runoffs on biochemical cycle of iron in the Sea of Okhotsk. Okeanologiya 54(1):44–51. Moscow: IAPC Nauka/Interperiodica. (in Russian)

Solovyev IA (1994) Amur-Liman evolution of the riverbed and waterways. FEB RAS, Vladivostok (in Russian)

Tambovsky VS, Putov VF, Shevchenko GV, Tikhonchuk EA (2001) Morphometry and dynamics of the ice waters of the northeastern Sakhalin shelf. In: Nature protection, monitoring and construction of the Sakhalin shelf. Yuzhno-Sakhalinsk, pp 123–42 (in Russian)

Yakunin LP, Dudarev OV, Botsula AI, Anikeev VV, Kolesov GM (2000) Modern sedimentation in Amur estuary. Tikhookeanskaya Geologiya 19(3):30–43. Vladivosok: Dalnauka (in Russian)

Zadkova II, Malyushko LD, Sorochan VF (1975) Geochemistry Busse lagoon on Sakhalin. Nauka, Novosibirsk (in Russian)

Zenkevich VP, Ionin AS, Kaplin PA, Medvedev VS (1967) Shores of the Pacific Ocean. Nauka, Moscow (in Russian)

Lagoons of the Black Sea

4

Vyacheslav Krylenko and Marina Krylenko

Abstract

The length of the Russian Caucasus coast of the Black Sea is approximately 400 km. The prevalence of abrasion coasts and the deficiency of sediments and accumulative forms are characteristic of the Russian Black Sea. This coast has only two significant lagoon localities: the Black Sea Kuban limans (Kiziltashsky group) and the Imeretinskaya lowland, along with some small lagoons. The Kiziltashsky group is included in the lagoon system of the Kuban River delta and separated from the Black Sea by the Anapa bay-bar. The history of the formation of the geosystems of this lagoon group and the Anapa bay-bar are closely interrelated. In middle of the XXth century, the runoff of the Kuban waters into the Kiziltashsky lagoon group completely stopped, and since the natural restoration of the Kuban River, run-off to the lagoons is nearly impossible, the further development of the lagoon ecosystem depending completely on the state of the accumulative body of the Anapa bay-bar. The Imeretinskaya lagoons are located between the Mzymta and Psou Rivers. After 2008, during construction for the Sochi Olympic Games of 2014, all the lagoons were irreversibly changed and their existence as natural water reservoirs was almost negated. The modern hydrographic network of the Imeretinskaya Lowland is represented by a system of melioration irrigation-drainage channels and semi-artificial ponds. Unique basins in the zone of the land and sea border, formed as a result of landslide processes, are located at the coast of the Russian Black Sea as well. Black Sea lagoons are used as areas for recreation and fish farming. Thus, there are lagoons of different types on the coast, the structure and intensity of the natural processes determining their stability varying considerably. Nevertheless, there are a number of natural threats to the stability of the lagoon coasts, and they are common for lagoons of different type and size. At present, out of the consequences of the sea level rise, changes in the surface run-off volume and degradation of accumulative features resulting from the inflow of sediments are the most apparent.

Keywords

Liman • Lagoon • Black sea • Bay-bar • Anthropogenic impact

4.1 Introduction

The Black Sea is an inland sea of the Atlantic Ocean basin. The area of the sea is 422,000 km^2. The maximum depth is 2210 m, and the mean depth is 1240 m (Dobrovolsky and Zalogin 1982). The coasts of the Black Sea are almost free of indentation, and what there is can mostly be found along its

V. Krylenko (✉) • M. Krylenko
P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (IO RAS), 1-g, Prostornaya, Gelendzhik 353467, Russia
e-mail: krylenko.slava@gmail.com; krylenko@mail.ru

R. Kosyan (ed.), *The Diversity of Russian Estuaries and Lagoons Exposed to Human Influence*, Estuaries of the World, DOI 10.1007/978-3-319-43392-9_4

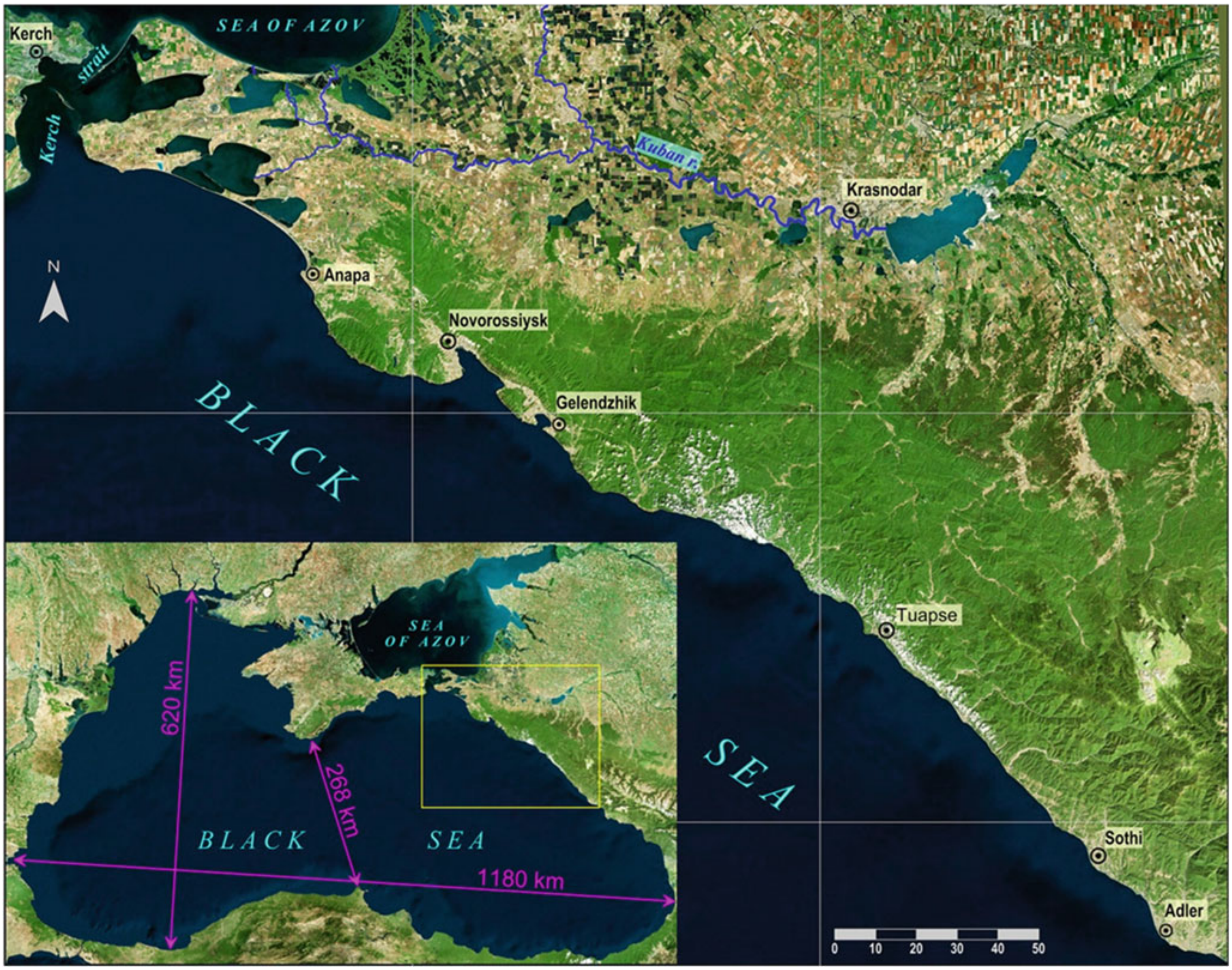


Fig. 4.1 A scheme of the Black Sea coast in the Krasnodar region (Modified from Kosyan 2013)

northern part. The total length of the coastline is 3400 km. The length of the Russian Caucasus coast of the Black Sea, from Cape Panagia to the Psou River, is approximately 400 km (Fig. 4.1).

The northwestern part of the Russian Black Sea coast is located in the northernmost part of the dry subtropical zone, and in the region south of Tuapse, the coast is in the semi-humid subtropical region. The Black Sea is a tideless sea; the variations in the sea level are determined by variations in the water balance components (Catalogue 1990). The seasonal sea level variations on the eastern coast are caused by fluctuations in river run-off and storm activity. The highest sea level elevations are observed in June and the lowest are in the period from October to November. The peak-to-peak fluctuations do not exceed 1 m along the entire coast.

The winds from the southern, southwestern, and western directions have the greatest influence on the formation of the storm waves (Report GOIN 1996). The stormy waves from the western, southwestern, and southern directions dominate. The waves from these directions can be as high as 6.0 m and up. The maximum wave height recorded in field observations exceeded 12.3 m (Divinsky et al. 2003). The wavelengths of such height reached 120–200 m.

Only two large regions of accumulative shore exist on the Caucasus coast of the Black Sea (Zenkovich 1954; Kosyan et al. 2013): the Imeretinskaya Lowland in the southeast and the Anapa bay-bar in the northwest (Fig. 4.1). The shore south of Anapa is represented by cliffs (in some places, they are as high as 80 m), alternating with ledges (the Abrau Peninsula, Cape Idocopas, and Cape Kodosh) and bays, the largest of which are Tsemess and Gelendzhik. The shores are abrasive in the region between Tuapse and Adler. A large number of coastal protection constructions have been built here.

4.2 Lagoons of the Imeretinskaya Lowland

The Imeretinskaya Lowland, located south of the town of Sochi, is a local name for the delta ledge formed by the discharge of solid particles by the mountainous Mzymta and Psou Rivers. The sediments transported there by the rivers have almost completely covered a narrow shelf (5–6 km). The marine edge of the delta approaches the shelf break (Krylenko et al. 2011a). The formation of the delta ledge was accompanied by a permanent variation in the configuration of the bars in the estuaries (Fig. 4.2), which is related to the fluctuations in the volumes of the solid discharge, the dominating directions of the waves, and fluctuations in the sea level (Balabanov 2009). These factors facilitated the appearance of a few comparatively small lagoons, which changed their coastlines when the sea level changed.

In the geomorphological sense, the Imeretinskaya Lowland is a large fragment of the Holocene alluvial marine terrace. The northwestern flank of the terrace at the right bank of the Mzymta River adjoins the cliffs of the Large Caucasus spurs; at the left bank of the Psou River, its southeastern flank adjoins the cliffs of the Gagra Ridge south of the town of Gantiadi. The total length of the terrace is 23–24 km and the width between the two rivers is up to 2.0–2.5 km but not greater than 0.2 km at its flanks (this is essentially the river valley) (Balabanov 2009; Balabanov et al. 2011). Similarly to the other Holocene terraces of the Caucasus coast, the Imeretinskaya Lowland is a lowland marine coastal plane with marshes in the rear part whose coastal zone abrades with a variable degree of intensity.

The modern surface of the Holocene terraces on the Black Sea coast began to form 5.5 to 6.0 th. year. BP, when the sea level reached its present-day marks. During this time, thick wide bars (bay-bars) were formed at the seaside of the mouths of such large rivers as the Mzymta, Psou, Bzyb, Gumista, Kodori and others downstream from the main flow of sediments out of their estuaries. In the rear sides of these bars, open lagoon basins separate from the sea along the coastline. The degree of their connection to the open sea gradually decreased as the surface of the terrace became greater. The open lagoons became closed. Large marsh lowlands in the rear parts of the Imeretinskaya Lowland, Pitsunda, Gudauta, Sukhumi, and Kodor peninsulas and in other regions of the Caucasus coast are now the remaining relicts of these lagoons (Balabanov et al. 2011).

The Imeretinskaya Lowland is located between the Mzymta and Psou Rivers. It is the central fragment of the Holocene (Black Sea) alluvial marine terrace formed by the run-off of the Kudepsta, Mzymta, and Psou Rivers. A large ancient lagoon depression remains in the central part of the Holocene terrace within the boundaries formed by the Mzymta and Psou rivers. The modern surface of the region between the Mzymta and Psou Rivers has different ages. Detailed geomorphological analysis has allowed us to distinguish three generations of shore ridge. An ancient lagoon depression is located beyond the oldest of them (the Gemetine). At its rear part, it is covered by a thick, extended alluvial-deluvial-proalluvial cover, a continuous wide (up to 0.6–0.8 km) band that stretches along the southern slope of the low ridge of hills. Large swamps and marshes remain in the central depressed part of the lagoon with absolute marks 0.5–0.7 m below the sea level. The location of the lagoon between two large rivers of the Black Sea coast specifically influenced the character of its formation and development (Balabanov et al. 2011; Krylenko et al. 2011a, b).

The marine and lagoon Holocene sediments in the region between the Mzymta and Psou Rivers and the alluvial sediments of these rivers form a complex facial-genetic layer up to 90 m thick. Clays dominate in its composition; however, sandy loam and sand grounds are frequently found near the shores of the lagoon. Facies of flowage and isolated lagoon

Fig. 4.2 A bar in the mouth of the Mzymta River, Black Sea coast (Photo by V. Petrov in August 1990)

basins are distinguished here based on their spatial location and several material indicators (mainly the presence of fauna and granulometric composition). The existence of several buried peat layers is characteristic of the lagoon sediments. They alternate with lagoon clays and reflect the regressive stages of the Imeretinskaya paleo-lagoon development (Balabanov et al. 2011). Thus, a clear dependence on the degree of isolation (or flowage) of the Imeretinskaya Lagoon from the open sea and its level evolution exists.

Thus, by the end of the twentieth century, the Imeretinskaya Lowland was a relatively flat, wide (0.8–2.0 km) coastal plane extended over 8 km along the Black Sea coast, elevated above sea level by 1–5 m. A group of Lebyazhie (Swan's) ponds was located in the western part of the Imeretinskaya Lowlands, the remains of an ancient lagoon separated by shore ridges from the sea. A notable anthropogenic load on this system appeared in the 1960s, which was represented by the regulation of the River Mzymta run-off and intense removal of pebble material from the river bed and adjacent beaches, and also in the construction of the coastal dykes near the shore that block the alongshore currents in the direction of the Imeretinskaya Lowland. A network of melioration channels was constructed on the lowland surface, which made it possible to use a significant part of its territory for agriculture (Fig. 4.3). Nevertheless, the remaining waterlogged regions and lagoons remained a reserve for the local flora and fauna (Mishchenko 2006; Wetlands of Russia 2015). A group of the Lebyazhie ponds was a location in which the region's natural biocenoses were found. They were characteristic of the virgin forest swamps of the Imeretinskaya Lowland. In addition, a large number of migrating birds stop here to rest. A total of 187 bird species have been recorded here. After 2008, during the construction for the Sochi Olympic Games of 2014, all the lagoons were irreversibly changed and their existence as natural water reservoirs was almost negated (Figs. 4.3 and 4.4).

The modern hydrographic network within the Imeretinskaya Lowland is represented by a system of melioration irrigation-drainage channels and small artificial ponds. At present, a group of Lebyazhie ponds is located in the central part of the Imeretinskaya Lowland; most of them are artificial. The following basins are located here:

The area of Lake Lebyazhie (Fig. 4.4) is approximately 4.5 ha. The artificial basin was formed after ground excavation from a swamp that existed beyond the Nymphaeum transgression ridge. The maximum depth of Lake Lebyazhie is 6.5 m, assuming that the level mark is equal to 0.59 m. The form of the lake is semi-elliptical. Under natural conditions, in the absence of any drainage system, the surface flow from marsh territory of the Imeretinskaya Lowland passes this waterlogged basin and a channel connecting it to the sea. A wide marsh territory currently exists around this basin. The lake and the surrounding waterlogged territory are characterized by a wide floral diversity of aquatic marsh vegetation.

The area of the Small Lebyazhie Ponds is approximately 1ha. This is a group of three ponds with rich aquatic-marsh vegetation.

A pond of the "Southern cultures" state farm, whose area is approximately 0.29 ha, is also located here.

Several ponds with a total area of approximately 2.2 ha are located in the eastern part of the Imeretinskaya Lowland in close vicinity to the Psou River estuary.

In general, the majority of the ponds naturally blend with the environment micro-terrain (Fig. 4.5). Generally, the coastal marks are below 1.0 m; therefore, these ponds are confined to the natural depressions between the ridges. The maximum water levels were recorded in the ponds in the spring, reaching marks of 0.95 m in the eastern part of the lowland. The water level in the ponds is shown in the topographic maps of the last decade as being in a range of 0.3–0.5 m, which exceeds sea level by 0.5–0.8 m (minus 0.26 m).

We already mentioned above that the modern hydrographic network of the Imeretinskaya Lowland is based on a vast network of irrigation channels. Before irrigation, the lowland region of the Imeretinskaya Lowland was an impassible swamp, covered with cane and forest, and was a source of malaria. The irrigation began at the end of the nineteenth century. From 1896 to 1902, the Russian Ministry of Agriculture for the first time conducted works over an area of 600 ha. As a result, the Main channel was made approximately 5 km long, and was connected to 13 branching channels. The drainage waters flowed into the Mzymta River. As a result of these works, a significant portion of the Imeretinsky swamps was drained. In the subsequent decades, the network of channels was gradually widened.

At present, the regime of underground and surface waters within the boundaries of the Imeretinskaya Lowland is regulated by a complex system of mountain and drainage channels, with water discharge forced to the sea by means of a pump station. The mountain and main channels for water release are gently sloping, a fact related to the peculiarities of the lowland terrain. They are quickly filled with silt and covered with marsh vegetation uner the conditions of a subtropical climate (Fig. 4.6). Since 1953, the water flow in the drainage channels has been directed to the pump station. The station operates in a continuous mode and provides forced discharge of drainage waters to the sea. The water transport through the pump station fluctuated in wide limits. According to the data gathered during the period from 1988 to 2007,

Fig. 4.3 The Imeretinskaya Lowland – location of the 2014 Olympiad – in 2002 (*top*) and in 2014 (*bottom*)

and the remaining data from the earlier period, it fluctuates from 10,200 to 256,840 m^3/day (November 30, 1989), as a result of the amount of shower flooding and the flow of the underground waters to the drainage system. The mean daily water transport of the pump station in 1988–2007 was 35,164 m^3/day.

Fig. 4.4 Lake Lebyazhie on the Imeretinskaya Lowland is a residual of the lagoons that remained after the Olympic construction (The photo was taken in the summer of 2014)

Fig. 4.5 Regulator pond № 2a (The photo was taken in the summer of 2014)

Fig. 4.6 Nagorny Channel-3, Imeretinskaya Lowland. The channels are quickly filled with silt and covered with marsh vegetation under the conditions of a subtropical climate

4.3 The Black Sea Lagoons of the Kuban River Delta

The Anapa bay-bar is an accumulative sand body approximately 47 km long located to the northwest of the town of Anapa. The bay-bar is a narrow band extending from the southern end of the Taman Peninsula in the north to Cape Anapsky in the south (Fig. 4.7). It separates a system of lagoons from the Black Sea, which were previously sea bays: Lake Solyenoye and Bugazsky (Kiziltashsky) Liman, Vityazevsky Liman, and Anapskiye Plavni (Kosyan and Krylenko 2014). The Bugazsky (Kiziltashsky) and Vityazevsky Limans are related to the delta region of the Kuban River, whose sources are on the slopes of Elbrus, the highest Caucasus mountain.

Formation of the Anapa bay-bar started 5–8000 years ago when the last glacial period ended. The level of the Black Sea at that time was 80–90 m below its present level (Izmailov 2005; Mikhaylov at al. 2010; Kosyan et al. 2012a, b, c, d). The mouth of the Kuban River then was located west of the modern line of the bay-bar. Part of the alluvial sediments of the Kuban deposited during that period remained as underwater sand fields at depths of 30–50 m. When the glacial period ended, the sea level ascended to the present marks. When the sea level increased, part of the alluvial material was transported, together with the coastline. Thus, the alluvial material of the ancient Kuban accumulated when it was debouching into the Black Sea and later participated in the formation of the lithodynamic system of the Anapa bay-bar during the initial period of its formation.

When the Black Sea level reached its modern marks after the Holocene transgression (5–7000 years BP), the alluvium of the Kuban River was not transported to the basin of the Black Sea, but instead accumulated in the basins of the bays (future lagoons) (Fig. 4.8). From this moment, the formation of the Anapa bay-bar occurred from the abrasion material transported from paleo-cape Zhelezhy Rog and remains of the Blagoveshchensky bedrock. The products of shore destruction were entrained into the alongshore flow of sediments and transported to the southeast, forming spits with the basement at the southern tips of capes gradually closing the entrances to Bugazsky (Kiziltashsky) and Vityazevsky Bays (Izmailov 2005). After the northern and southern parts merged, a unique lithodynamic system of the Anapa bay-bar was formed, in which the dominating direction of sediments was from north to south (Krylenko et al. 2011a, b; Kosyan et al. 2012a, b, c, d; Kosyan and Krylenko 2014). A system of lagoons was formed simultaneously with the Anapa bay-bar.

The Kiziltashsky group is included in the Taman lagoon system of the Kuban River delta. As long as 150 years ago, these lagoons were united into a single water basin, through which the Kuban River debouched into the Black Sea (Fig. 4.9). As the alluvial sediments accumulated in the estuary of the river (approximately in 1881), the southeastern part of the lagoon separated and formed the Vityazevsky Liman (Mikhaylov et al. 2010). The Kiziltashsky group includes the Kiziltashsky, Bugazsky, Tsokur, and Vityazevsky Limans. Since the latter has no direct water exchange with the other lagoons, it is sometimes considered to be a separate basin.

The outflow of the Kuban River to the Black Sea basin rapidly decreased from the middle of the nineteenth century, which was related to the technogenic impact (direction of the river runoff to the Azov Sea basin). The permanent Bugazsky channel, through which the fresh water excess flows to the sea, was eventually completely blocked in 1918 by sand sediments from the sea side. The direct exchange between the Kiziltashsky Liman and the sea completely stopped. By the 1940s, the runoff of the Kuban waters into the Kiziltashsky Liman had ended completely. The limans began to become shallow very rapidly, and at the beginning of the 1950s, they became dry, with strongly salty grounds covered by halophyte vegetation. Small puddles existed only in the places adjacent to the sea. They were formed as the result of water filtration through the sand bay-bar. In 1955, a channel was made between the sea and the Bugazsky Liman, which was regulated by a water lock (Mikhaylov et al. 2010). Artificial replenishment of the Kiziltashsky Liman occurs through this channel. Since natural restoration of the Kuban River flow to the lagoons is hardly possible, further development of the lagoon ecosystem depends completely on the state of the accumulative body of the Anapa Bay-bar, which actually controls the water exchange between the lagoons and the Black Sea.

Thus, the history of the formation of the geosystems of the Anapa bay-bar, Kiziltashsky lagoon group, Lake

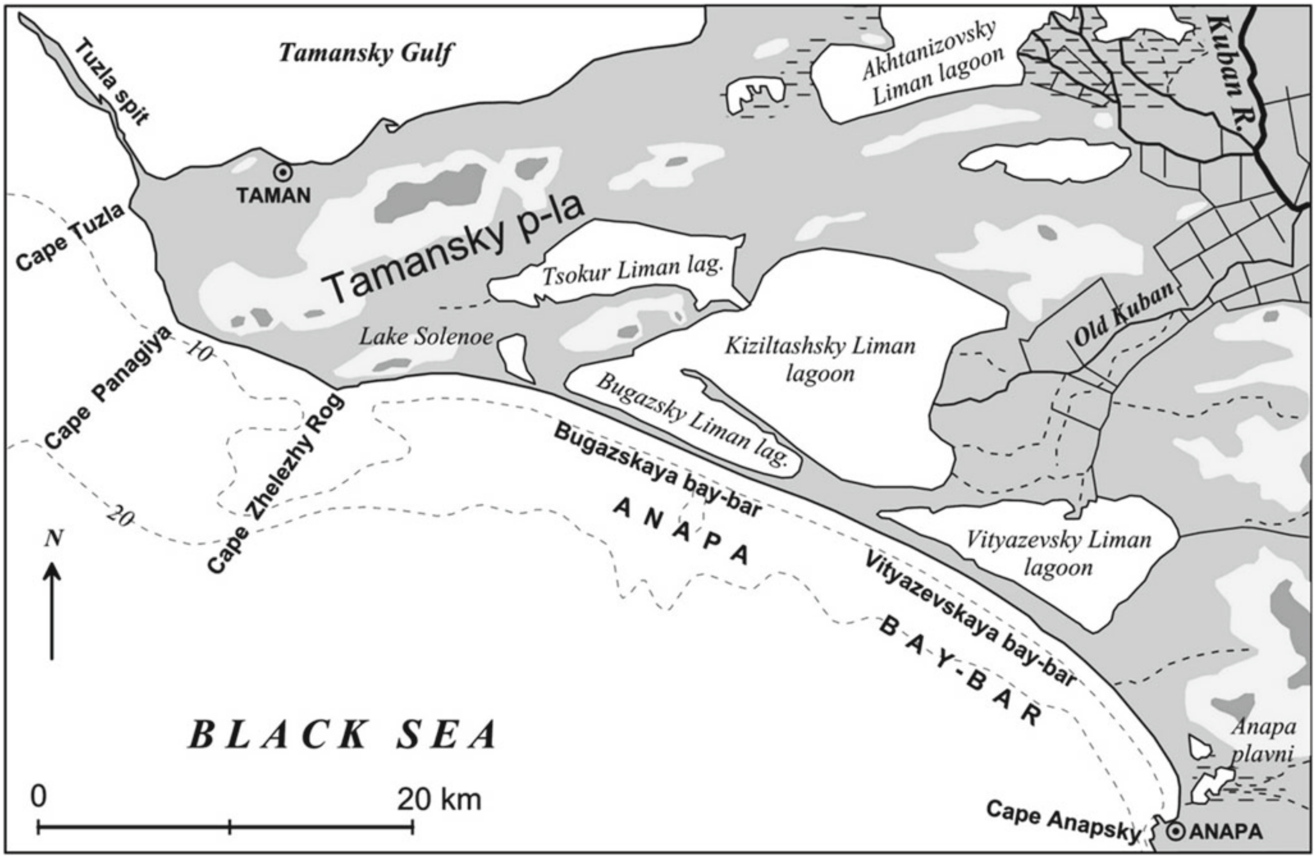


Fig. 4.7 Location of the Anapa bay-bar. This part of the Black Sea coast has featured the largest relief changes and water regime over the last few millenia (Modified from Kosyan 2013)

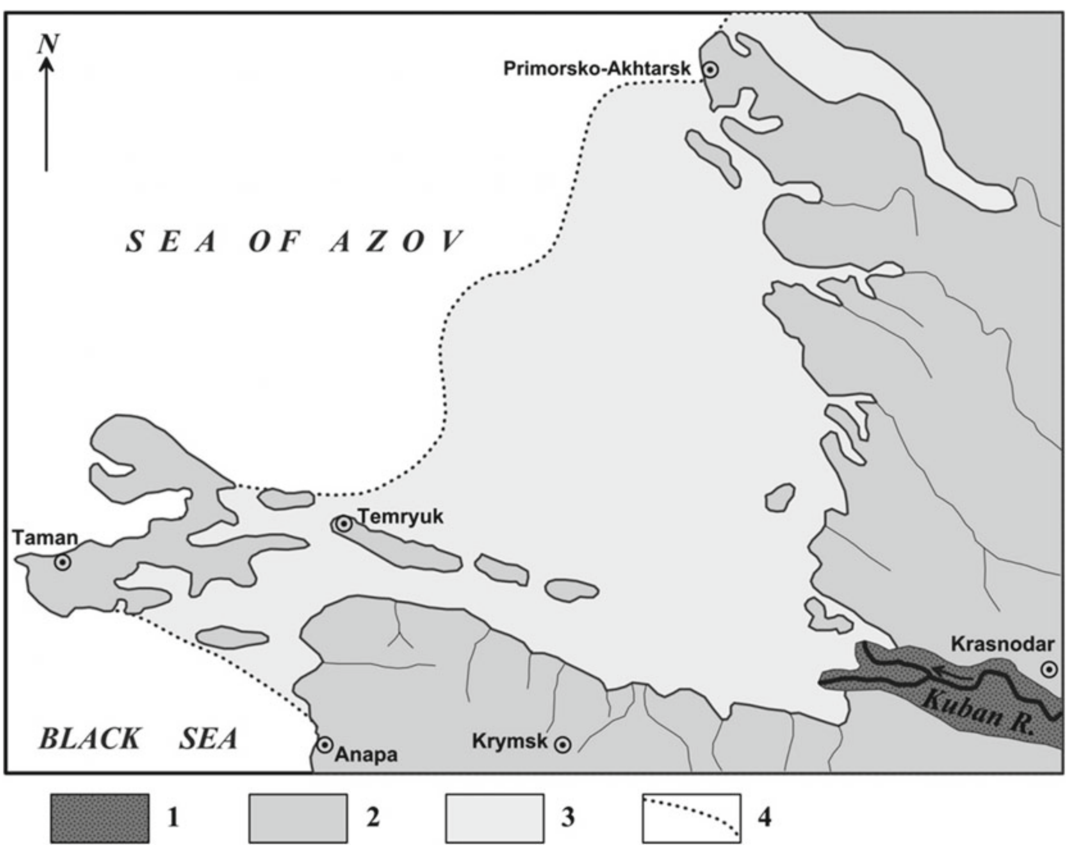


Fig. 4.8 A scheme of the land and water reservoirs in the lower course of the Kuban River during the Kalamitian transgression (6–7000 years ago). (*1*) flood lands of the Kuban River; (*2*) ancient territories beyond the flood lands; (*3*) marine bays and straits; (*4*) modern coastline of the Azov and Black Seas (Modified from Mikhaylov et al. 2010)

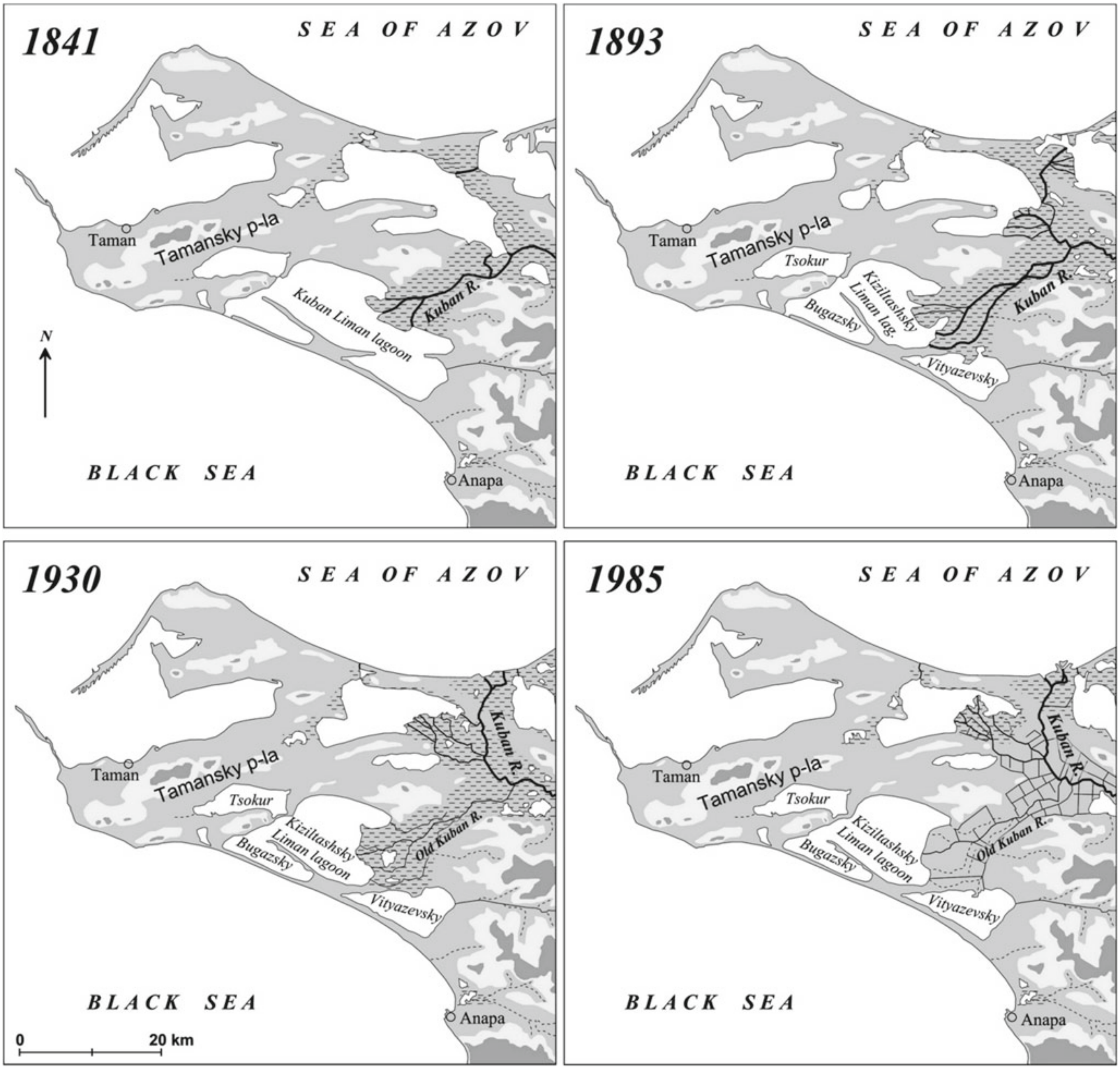


Fig. 4.9 A scheme of the development of the southwestern part of the Kuban delta (Mikhaylov et al. 2010). From ancient times, the water regime's greatest changes in the estuarine region of the river Kuban were the result of economic activity

Solenoye, and Anapa Plavni are closely interrelated. At present, we observe a decrease in the width of the Anapa bay-bar (mainly due to natural causes). In the next few decades, compete destruction of the accumulative body above the water is possible in the narrowest parts of the bay-bar, which will lead to the direct exchange between the lagoon and the sea (Kosyan et al. 2012a, b, c, d; Krylenko et al. 2015). The water level and water salinity will stabilize, provided that the water exchange with the sea becomes permanent. Seasonal migrations of fish (including food fish) will occur naturally.

Anapa plavni ("flooded lands") occupy an area of approximately 1000 ha; they are almost completely covered with reeds and sedge. The depth of the basin is up to 1.2 m. The water supply to Anapa plavni is provided by the discharge of the Kumatyr and Koshloma Rivers and also the underground waters of the Black Sea. The water excess flows to the Black Sea as the Anapka River. The northwestern part of Anapa plavni (Lake Chemburskoye), separated by the automobile road dam, is covered with water only in the autumn-winter period, due to atmospheric precipitation waters. During this period, the water layer does not exceed 30–50 cm.

Fig. 4.10 The coast of the Vityazevsky Liman near the town of Vityazevo (*top*) and the town of Blagoveshchensky (*bottom*). The shallow depth and flat bottom contribute to significant changes in the water surface area because of fluctuations in the lagoon level

The Vityazevsky Liman is located at a distance of 12 km north of Anapa. It is separated from the sea by the Vityazevsky bay-bar (Figs. 4.10 and 4.11), 0.5–1.0 km wide, which is a part of the Anapa bay-bar. The Vityazevsky Liman is separated from the Kiziltashsky group by the accumulative sediments of the Kuban River and the remains of the Blagoveshchensky bedrock (Kosyan and Krylenko 2014). The water supply occurs due to atmospheric precipitation and surface discharge, as well as through the waters of the Black Sea, which are filtered by the bay-bar and overwashed during storms. Additional artificial water supply to the lagoon occurs by means of the irrigation system of the Old Kuban River (Dzhiga River) in the region of the town of Suvorov-Cherkessky.

The Kiziltashsky group located to the north is separated from the Black Sea by the Bugazsky bay-bar (the northern part of the Anapa bay-bar), whose width is 60–300 m (Fig. 4.12). The Kiziltashsky group is represented by three lagoons: the Kiziltashsky Liman (its area is 15,700 ha), the Bugasky Liman (4050 ha), and the Tsokur Liman (4670 ha). All the lagoons are shallow basins of the lagoon type. The depths vary from 0.3 to 2.5 m. A direct permanent water exchange exists only between the Kiziltashsky Liman and the Bugazsky Liman (Fig. 4.12). The water exchange between the Kiziltashsky Liman and the Tsokur Liman is small due to the low water level. There is no natural water exchange between these lagoons and the Black Sea.

The hydrological regime of the Kiziltashsky group is distinguished by high dynamics. Up to the end of the nineteenth century, the water from the Kuban River was flowing to the Kiziltashsky Liman (the Bugazsky Branch). The water excess was flowing to the sea through the Bugazsky Channel, which is 150–650 m wide, depending on the hydrological situation. In the 1940s, the transport of the Kuban water to the Kiziltashsky Liman ceased. In January 1955, a channel of the Kiziltashsky mullet fishing farm was made between the sea and the Bugazsky Liman, which was regulated by a water lock (Mikhaylov et al. 2010). The artificial Bugazsky Channel (sea water supply) and the Main Channel (fresh water supply from the Kuban River) control water exchange in the lagoon. Simultaneously, the operation of these channels provides a seasonal supply of fish to the lagoon and the release of the mullet family of fish to the Black Sea for winter (www.azcherrybvod.ru). In the summertime, the water level in the lagoon may decrease to 0.1–0.2 m below sea level, while in the wintertime, it can exceed sea level by the same value (Izmailov 2005). As a result of the non-uniform water supply with fresh and sea waters, salinity fluctuates strongly over time and over their territories. Salinity in the Bugazsky Liman fluctuates within 39.5–50.0‰, while in the Kiziltashsky Liman, it ranges within 29.0–58.0‰. The maximum salinity (82‰) was recorded in the western part of the Tsokur Liman (in August), while the minimum salinity (18‰) was found in the mouth of the main channel and the Gostagaike River (Wetlands 2015).

Fig. 4.11 Shelly spit (*top*) and shelly ridge (*bottom*) at the shore of the Vityazevsky Liman. Shelly detritus contributes to the stabilization of the lagoon coasts

In the northwest, the Anapa bay-bar separates Lake Solyenoye, whose maximum depth is 20–30 cm, from the sea (Fig. 4.13). By the end of summer, the lake has completely dried and is covered with a thick layer of salt due to evaporation. The lake is filled with water in the autumn-winter period by the surface water flow, atmospheric precipitation, and seawater that overflows the bay-bar during storms.

The ecosystems of the lagoons formed by the Anapa bay-bar provide for the existence of various animal communities. There are places for the compact nesting of rare hydrophilic birds. The region is important for the reproduction of colonial aquatic birds, including rare and endangered species. The Kiziltashsky Liman is the location of mass nesting of gulls, cormorants, shorebirds, and shelducks. Twenty one bird species nest here. This can be related to the natural stations of waiting for natatorial and aquatic birds during cold weather migration periods. An approximate number of migrants reach 0.5 mln specimens (Mishchenko 2006). In the winter period, the sea regions are used by migrating birds for rest and also for shelter in the period of autumn hunting. The total number of wintering natatorial birds is approximately 200,000 individual birds belonging to 12–18 species.

4.3.1 The Economic Importance of Fishing to the Black Sea Lagoons of the Kuban River Delta

Sixty five fish species lived in the Kiziltashsky lagoons before their salinification. Now, their number has decreased to 45 species (Svetovidov 1964). The following species

Fig. 4.12 Bugazsky bay-bar (*top*). A view to the southeast. The Bugazsky Liman is on the left, the Black Sea is on the right. The Golen'kaya Spit (*bottom*) separates the Bugazsky Liman and the Kiziltashsky Liman. The close position of water bodies with contrasting wind-wave regimes promotes the development of extreme sports (windsurfing, kiting) in the region

Fig. 4.13 Bay-bar of Lake Solyenoye. A view to the southeast

dominate here: Black Sea sprat, mullets (the golden grey mullet *Liza aurata* (Risso) (only in the summertime) and the so-iuy mullet *Liza haematocheilus* that acclimatized here), nine-spine and three-spine sticklebacks, Black Sea pipefish, and gobies (steer bullhead, Caucasus goby, goby-tsutsik, round-goby, goby-shirman, and grass goby). In addition, large numbers of *Atherina boyeri* (Risso), flounder *Platichthys flesus* (L.), and Baltic prawn *Palaemon adspersus* (Rathke) are found here. Black Sea mussels, spider crabs, stone crabs, and mysidas are in abundance among the invertebrates.

In 1955, a separate mullet fishing farm with a total square of 24.4 thousand ha was formed in the Kiziltashsky lagoon group (the Bugazsky , Kiziltashsky , and Tsokur Limans). In autumn, large, sexually mature grey mullet and young fish were caught here. In 1978, the economic type of the farm changed: the Kiziltashsky lagoon group started to be used for fattening reproductive basins to replenish the stock of Caucasus grey mullet. Fattening of the Azov-Black Sea grey mullet (the golden grey mullet *Liza aurata* (Risso), the flathead grey mullet *Mugil cephalus* (L.), and the leaping mullet *Liza saliens* (Risso)) in the lagoon group is a biological necessity for these species. Intense growth of mullets, increase in fatness, and fat accumulation occurs only when they are fed on fouling and detritus, which are abundant in the lagoon group. The Kiziltashsky fattening reproduction farm is the only farm in the south of Russia for the fattening and reproduction of the Azov-Black Sea mullet. Young fish and fish of greater age, which appeared in the lagoon after passing the artificial channel to the sea, fatten in the lagoon group. In summer, the reproductive mullets travel to the sea for spawning. The grown specimens of the Azov-Black Sea mullets return to the sea for winter.

In 1987–1989, a new breed stock was formed on the basis of the Far East so-iuy mullet *Mugil soiuy* (Basilewsky) that passed acclimatization in the Azov-Black Sea basin. Biological technology was developed and measures were accomplished to reproduce the so-iuy mullet and release the grown young fish into the natural basins. Therefore, a self-reproducing population of so-iuy mullet was created in the Azov-Black Sea basin. In 1989, a sharp increase in the abundance of this species was recorded, which caused it not only to spread throughout the entire Azov and Black Seas, but also to propagate into the Mediterranean Sea. In summer, a total of 300–400,000 reproductive specimens of the Azov-Black Sea mullet and so-iuy mullet enter the Kiziltashsky lagoon group. In winter, the young so-iuy mullet fish and fish of greater age migrate to the channel that starts at the Kuban River and debouches into the Kiziltashsky Liman, while a portion of the so-iuy mullet remain in the Kiziltashsky Liman.

In the 1970–1980s, during the planned economy for the Kiziltashsky lagoon group, the annual size of big-scale sand smelt (atherina) catches ranged from 100 to 200 tons. Due to economic changes in the country, catches of low value fish species were occasionally utilized primarilyu for agricultural needs, in particular, for pork production. However, in the period from 1998 to 2003, up to 60 tons of atherina were caught in the Kiziltashsky lagoon group. The introduction of quotas for catches of low value fish in general and quotas for atherina catches in miserable amounts up to 48 tons (in 2006) for the entire Azov-Black Sea region formed problems for the catching of this species in the Kiziltashsky lagoon group and the formation of favorable conditions for the fattening of valuable mullet fish species.

At present, no commercial fishery activity is taking place in the Kiziltashsky lagoon group. The spawning-fattening farm is involved only in the reproduction and protection of mullet fish. This is the only region in which the artificial reproduction of mullets is carried out in Russia.

4.3.2 The Modern and Future Economic Use of the Black Sea Lagoons of the Kuban River Delta

Vineyards and gardens are located on the western and northern shores of the lagoons. The accumulative isthmus between the Kiziltashsky and Vityazevsky Limans is used for cultivating irrigated plants. Eight fattening and milk farms are located around the lagoons. Cattle breeding pastures are located around the lagoons and haying is organized there (Mishchenko 2006).

One of the elements of the planned development of the town of Vityazevo is the formation of several artificial islands in the basin of the Vityazevsky Liman (Kosyan and Krylenko 2014). Recreation zones and related constructions are planned for the new territories (Fig. 4.14).

Shallow water is one of the peculiarities of the Kiziltashsky lagoon group. The depth over the majority of the basin does not exceed 1.5–2 m. Water exchange between segments of the lagoon group is low. The concentration of organic matter in the lagoon group is high, and the water becomes quite heated in the summertime. These facts cause intense water blooming and the accumulation of large amounts of died-off algae in the summit parts of the lagoon group and at their shallow beaches. Toxic substances are formed during the vital activity of certain micro-algae and their degradation that are hazardous to both the aquatic fauna and humans. The disgusting stink of decaying algae in summer decreases the recreational potential of the town of Vityazevo. The creation of artificial islands and the separation of the stagnant part of the Vityazevsky Liman will clearly lead to intensification of these negative processes. The newly formed territories and the objects located on these lands will lose their investment attraction.

Fig. 4.14 Different projects for creating artificial territories in the Vityazevsky liman basin

4.4 Sudzhuk Lagoon

The Sudzhuk Lagoon (Lake Sudzhuk) (Fig. 4.15) is located in the eastern part of Tsemess Bay (city of Novorossiysk). The lagoon is a regional natural sanctuary (established in 1983).

In the east, the lagoon is separated from Tsemess Bay by a bay-bar, which is formed out of pebbles, silt, and sand. The width of the bay-bar is 25–70 m. In the south, it is separated from the sea by a pebble spit 10–15 m wide. The area of the lagoon is approximately 30 ha. The lagoon is connected to the sea by a small channel in its southwestern part near the continental shore.

The mean depth of the flat bottom is 0.85 m and the maximum depth does not exceed 1.5 m. The lagoon bottom in its northern and central parts is formed of silt and silt-sand grounds. Shell rock and pebble materials appear in the southern part. A pebble band extends along the coastline at the bottom.

The water is supplied to the lagoon predominantly by atmospheric precipitation over the area of the basin and runoff from the catchment zone. To a lesser degree, water flows to the lagoon through the discharge of small creeks in the territory of Pionerskaya Roshcha (small wood grove) and underground waters from nearby ponds. The lagoon periodically connects with the sea through a channel, which can be formed either as a result of the spit breaking during storms or may be restored by the neighboring fishing organization.

The hydrochemical regime in the lagoon is unstable. The main indicators (temperature, salinity, dissolved oxygen, nutrients, etc.) are subject to seasonal and interannual fluctuations. In some years, the lagoon waters become fresher, and in the others, the salinity approaches that of seawater. Sometimes, storms close the channel, and the lagoon becomes a closed lake, which leads to eutrophication under the conditions.

In the cold time of the year, the lagoon becomes a shelter for swans and other natatorial birds (Fig. 4.16). The lagoon has important economic value for the fattening of young fish: sprat, European anchovy, big-scale sand smelt (atherina), golden grey mullet, flathead grey mullet, goatfish, etc. A total of 22 zooplankton species, 40 benthos invertebrate species, 15 mollusk species, and 14 concroid species can be found there. Aquatic vegetation is represented by ruppia and red lophosyphonia algae, typical representatives of the vegetation in lagoons.

4.5 Small Lagoons

The land and sea border along the coast of the Black Sea is also host to certain unique basins, formed as a result of landslide processes: the Lake Sladkiy Liman and Lake Abrau.

The *Lake Sladky Liman* is located on the Abrau Peninsula a couple dozen or so meters from the sea shore, in the approximate middle of the coastal arc of the peninsula coastline. The lake occupies a basin beyond the landslide body, which was formed as a result of the seismic gravity displacement of a large mass of rocks from the slopes of Orel Mountain (548.5 m). The area of the lake is 19,400 m^2, its length reaches 220 m, the maximum width is 108 m, and the depth is 5.5 m. This lake is a natural sanctuary.

Lake Abrau is located 18 km west of the city of Novorossiysk. It is located at an altitude of 84 m above sea level, its area is 180 ha, and the depth is 10.5 m. The western and eastern shores of the lake are steep, with a smooth line at the shore. The northern shore is gently sloping. The lake is shallowest here. The bottom of the coastal portion is formed of broken crushed stone, while the deep parts are covered with gray silt and the shallow bays with dark silt. Lake Abrau is located in a closed depression. The lake is fresh, its water supplied by the small Abrau River, atmospheric precipitation, and underground sources. The lake has no sink. Its

Fig. 4.15 The Sudzhuk Lagoon from space. The lagoon ecosystem is influenced by anthropogenic pollution (Modified from Kosyan 2013)

Fig. 4.16 Swans wintering in the Sudzhuk Lagoon

water is filtered through limestone rocks to the sea shore. The transparency of the water does not exceed 1 m.

4.6 Conclusion

Within the Russian sector of the Black Sea, the number of lagoons is not large but those that are there are interesting natural objects. There are lagoons of different type along the coast, so the structure and intensity of natural processes determining their stability vary considerably. Nevertheless, there are a number of natural threats to the stability of lagoon coasts, and they are common for lagoons of different type and size. At present, the consequences of sea level rise (Kaplin et al. 1997; Kaplin and Selivanov 1999), changes in the surface run-off volume (including solid run-off) (Khmaladze 1978; Balabanov et al. 2011), degradation of accumulative features resulting from the inflow of sediments (Peshkov 2000, 2003; Kosyan and Krylenko 2014) are the most apparent.

Variations in the inflow of sea and fresh water volumes are of considerable importance for the lagoon ecosystems of the Kuban Delta. As shown in Sect. 4.2, after a sharp decrease in fresh water inflow into the Black Sea lagoons of the Kuban Delta, these bodies became critically endangered (Bogucharskov and Chebanov 1990; Izmailov 2005; Mikhaylov et al. 2010). The water volume sharply reduced, a considerable rise in salinity was observed, and both biodiversity and bioproductivity decreased (Pashkov 2001). It fell to an artificial recharge of the lagoons with sea and fresh water to save their ecosystems.

The Black Sea lagoon ecosystems in the Kuban Delta are directly related to the stability of the Anapa bay-bar. At present, there are several segments within the Anapa bay-bar where its width decreases by more than 1 m per year on the average (Krylenko et al. 2015). The northern part of the Anapa bar-bay, which is at least 70 m in width, is in the most dangerous position. In contrast to the classical scheme of bay-bar evolution, where sea coast recession is balanced with lagoon coast accretion, the lagoon coast does not accrete in this segment. This is indicative of the lack of material for replenishing beaches; meanwhile, the intensity of the longshore sediment flux is rather high. As anthropogenic interference in the process under consideration is minimal, natural factors are mainly responsible for the deterioration of the Anapa bay-bar.

The research into the Anapa bay-bar geosystem conducted by a number of different scientists has shown that there are several factors contributing to the degradation of the accumulative body of the Anapa bay-bar:

1. The appearance and large-scale evolution in the Black Sea of invading species of Rapana led to the almost complete disappearance of many kinds of bivalve (Saenko 2006; Kosyan 2012). As a result, the amount of shells delivered to the bay-bar, which plays a significant role in its lithodynamic balance, decreased sharply.

2. Changes in the direction of predominant winds and waves, which have been observed over the last half century, also considerably change the parameters of longshore sediment flux and sand eolian motion (Vykhovanets 2003; Prokopov 2007; Titov et al. 2010; Krivosheya and Moskalenko 2012).
3. Decline of the active cliff length or a decrease in abrasion rate reduced delivery of beach-forming sediments (abrasion products) to the lithodynamic system (Aibulatov 1990).
4. Storm activity grew, and the amount and intensity of wind-driven effects increased.
5. An increase in the variation amplitude of the sea level and a general tendency for it to rise have been observed (ESIMO 2007).

Thus, there exists a probability that the above-water portion of the Anapa bay-bar could be eroded at certain segments. At first, the scours will only appear in periods of severe storms, but permanent channels connecting the Black Sea with the lagoons could arise later. Strangely enough, the connection of the lagoons to the sea will be favorable for their ecosystems (Kosyan and Krylenko 2014). The water level and salinity in the lagoons will become stabilized with permanent water exchange. Seasonal fish migrations, which are artificially provided at present (as shown in Sect. 4.2), will take place naturally.

The situation differs for the lagoons in the Imeretinskaya lowland. These lagoons, formed as the result of accretion of the Mzymta and Psou estuaries, featured great biodiversity (Wetlands of Russia 2015). A certain balance between the accumulation and erosion processes was observed here before the start of economic development. There were no natural threats to the stability of the accumulative coast and lagoons. The gradual sea level rise, as well as the longshore flux of sediments or their loss on the underwater slope, was compensated for by the large volume of solid river run-off. The technogenic decrease of deposits entering from the rivers and forming the beaches led to the gradual recession of the coast along a number of segments. In addition to that, failed attempts at coast protection led to an intensification of the shelf submarine canyons (Saf'yanov et al. 2007). As a result, deposit deficiency on the underwater slope increased. Nevertheless, due to the large volume of the accumulative body of the Imeretinskaya lowland, a recession of that kind could not lead to its erosion. Overall, in that moment, the ecosystems of the Imeretinskaya lagoons were out of danger.

The building of Olympic constructions, in particular, the port in the Mzymta River estuary, completely stopped sediment transport from that river. Catastrophic coast erosion began at the coastal segment adjacent to the port. In addition to that, the building of sport constructions and infrastructure led to a complete change in hydrological and hydrogeological connections within the entire estuary. Some of the lagoons were completely filled up, most of them left without alimentation from freshwater sources. The relic near water fauna was eliminated; bird habitats and migratory paths were destroyed. At present, the Imeretinskaya lowland lagoons' existence as natural ecosystems has actually ceased to be.

All of the small lagoons in the region are exposed to strong anthropogenic impact, because they are located near settlements and recreational objects. As a rule, the impact becomes apparent in the changing of the lagoons' freshwater alimentation and the destruction of their water exchange with the sea. In addition to that, severe technogenic pollution of the lagoons has been observed, leading to the degradation of their ecosystems.

The processes determining the evolution and stability of lagoons and adjacent accumulative bodies along the Black Sea coast of Russia seem to be extremely complicated. Further research into the lagoons and accumulative forms is necessary, including investigation of the influence of global climatic changes. It is evident that the Black Sea lagoons and accumulative bodies need protection against negative natural and anthropogenic impact.

References

Aibulatov NA (1990) Dynamics of solid material in the shelf zone. Nauka, Moscow (in Russian)

Balabanov IP (2009) Paleogeographical background to formation of modern natural conditions of the Caucasus littoral Holocene terraces and their long-term development forecast. Dalnauka, Moscow (in Russian)

Balabanov IP, Nikiforov SP, Pashkovskiy IS (2011) Imeritinskaya lowland. Natural geological conditions, problems of development. Izadatelskii Dom Nedra Publishing Co, Moscow (in Russian)

Bogucharskov VT, Chebanov MS (1990) Anthropogenic remaking of nature reservoirs of the Kuban river delta. In: Ekologo-geographical problems of the North Caucasus and Nizhny Don. RSU, Rostov-on-Don (in Russian)

Catalogue (1990) Catalogue of observations above the Black sea and Sea of Azov level. SO GOIN, Sevastopol (in Russian)

Divinsky B, Kosyan R, Podymov I, Pushkarev O (2003) Extreme waves in northeast part of the Black Sea in February. Oceanology 43(6):948–950. Moscow: IAPK Nauka/Interperiodica (in Russian)

Dobrovolsky AD, Zalogin BS (1982) Seas of the USSR. Publishing house of the Moscow University, Moscow (in Russian)

ESIMO (2007) Climate of the Russian Seas and the key regions of the world ocean. In: Digital atlas. Join informational system on the World Ocean. Obninsk. http://www.esimo.ru/atlas/Black/2_water-level_station_98062_3.html. Accessed 15 Mar 2015 (in Russian)

Izmailov YA (2005) Evolutionary geography of the Black Sea and Sea of Azov coasts. Book 1: Anapa Bay-bar. Sochi (in Russian)

Kaplin PA, Selivanov AO (1999) Variation of the sea level of the Russia seas and coas development. GEOS, Moscow (in Russian)

Kaplin PA, Leontiev IO, Selivanov AO (1997) Features of the coastal zone reorganization the in terms of sea level raising. In: Kaplin PA, Selivanov AO (eds) Development of the Russia coasts and their changes under possible sea level raising of the World ocean. MSU, Moscow, pp 28–88 (in Russian)

Khmaladze GN (1978) Sediment subtraction by Black Sea coast rivers. Gidrometeoizdat, Leningrad (in Russian)

Kosyan RD (ed) (2013) Scientific support for the balanced business planning on the unique coastal landscapes and proposals for its use by the example of the Azov-Black sea coasts. Research report. SB SIO, Gelendzhik (in Russian)

Kosyan RD, Krylenko VV (2014) Modern status of marine accumulative shores of Krasnodar Krai and their use. Nauchnyi Mir, Moscow (in Russian)

Kosyan AR, Kucheruk NV, Flint MV (2012a) Role of the shell clams in the sediment balance of Anapa by-bar. Oceanology 52(1). Moscow: IAPK Nauka/Interperiodica

Kosyan RD, Kuklev SB, Krylenko VV (2012b) Fragile equilibrium of the Anapa Bay Bar. Priroda 2:19–28. Moscow: RAS (in Russian)

Kosyan RD, Krylenko VV, Krylenko MV (2012c) Features of modern morphological structure of the Anapa bay-bar southern part. Geomorphology 4:73–80. Moscow: Nauka (in Russian)

Kosyan RD, Goryachkin YN, Krylenko VV, Dolotov VV, Krylenko MV, Godin EA (2012d) Crimea and Caucasus accumulative coasts dynamics estimation using satellite pictures. Turk J Fish Aquat Sci 12:385–390. Trabzon: CFRI

Kosyan RD, Krylenko MV, Chubarenko BB, Ryabchuk DV (2013) Russian coasts of European seas. In: Pranzini E, Williams A (eds) Coastal erosion and protection in Europe. Earthscan, London, pp 9–30

Krivosheya VG, Moskalenko LV (2012) Effect of the wind regime and thermal condition variability on the structure and dynamics of water in the Black Sea north- eastern part. Oceanology 52(4):484–497. Moscow: IAPK Nauka/Interperiodica

Krylenko VV, Isupova MV, Krylenko MV, Dzaganiya EV (2011a) Geoecological peculiarities of the Mzymta River estuary and coastal area of Imeretinskaya lowland affected by natural and anthropogenic factors. Eng Ecol 5(101):3–15. Moscow: CJSC Engineering Ecology (in Russian)

Krylenko VV, Kos'yan RD, Kochergin AD (2011b) Regularities of the formation of the granulometric composition of the bottom and beach deposits of the Anapa Bay-Bar. Oceanology 51(1):1061–1071. Moscow: IAPK Nauka/Interperiodica

Krylenko, Marina, Krylenko, Viacheslav, Kosyan Ruben (2015) Accumulative coast dynamics estimation by satellite camera records. In: Hadjimitsis DG, Themistocleous K, Michaelides S, et al. (eds) Proceedings of the SPIE 9535, Third International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2015), 95351K June 19, 2015; doi:10.1117/12.2192495. http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=2347406. Accessed 21 June 2015

Mikhaylov VN, Magritsky DV, Ivanov AA (eds) (2010) Hydrology of the delta and offshore zone of the Kuban river. GEOS, Moscow (in Russian)

Mishchenko AL (ed) (2006) Wetlands of the Northern Caucasus. Wetlands of Russia, vol 6. Wetlands International, Moscow (in Russian)

Pashkov AN (2001) Ichthyofauna of the Black Sea coastal shelf in polyhalite conditions. Moscow (in Russian).

Peshkov VM (2000) Sea shores. Kuban textbook, Krasnodar (in Russian)

Peshkov VM (2003) The sea coastal zone. Lakont, Krasnodar (in Russian)

Prokopov OI (2007) Long-term variability of thermal atmospheric conditions in borders of the actual winter and summer seasons (north-east part of the Black Sea, 1935–2004). Bull South Sci Cent 3(3):41–50. Rostov-on-Don: Publishing house SSC RAS (in Russian)

Saenko EM (2006) The results of monitoring of Rapana in the north-eastern part of the Black Sea. In: Problems of the sustainable functioning of aquatic and terrestrial ecosystems. Proceedings of the international scientific conference. Rostov-on-Don, pp 362–364 (in Russian)

Saf'yanov GA, Menshikov VL, Peshkov VM (2007) Submarine canyons – their dynamics and interaction with the ocean coastal zone. Edart-print, Krasnodar (in Russian)

Scientific-Technical Report GOIN (1996) Hydrometeorological conditions of the Sea of Azov and Black Sea coasts of Krasnodar region. GOIN, Moscow (in Russian)

Svetovidov AN (1964) Fishes of the Black Sea. Nauka, Leningrad (in Russian)

Titov VB, Kuzevanova NI, Chasovnikova LA (2010) The complex interaction of hydrometeorological processes on the Black Sea north- eastern shelf. Meteorol Hydrol 35:132–146. Moscow: FGBU SRC Planeta (in Russian)

Vykhovanets GV (2003) Eolation on the sea coast. Astroprint, Odessa (in Russian)

Wetlands of Russia (2015) Official website. www.wetlands.oopt.info. Accessed 21 June 2015 (in Russian)

Zenkovich VP (1954) Morphology and dynamics of the Black Sea coasts within the borders of the Soviet Union, V III, Part III. Regional; Section II. Central part. SIO RAS, Moscow (in Russian)

Lagoons of the Smallest Russian Sea

5

Marina Krylenko, Ruben Kosyan, and Vyacheslav Krylenko

Abstract

The Sea of Azov is one of the smallest on the planet. Its surface area is 39.1 thousand km^2 and the average depth is about 7.4 m. The total length of the seashores along the Russian part of the Sea of Azov is about 500 km. The majority of the population of the Krasnodar region lives in the coastal zone of the Sea of Azov. This area includes important federal and international communications, ports, industrial and civil establishments. A comprehensive study of contemporary seaside processes has allowed for identifying four main types of coastal development: abrasion (representing two types), accumulation and stable. In general, the following natural processes defining the state and dynamics of the region's coasts can be highlighted: abrasion processes, sea level fluctuations, changes in wind-wave regime parameters, and fluctuation in the volume of biogenic materials.

Lagoons, like other water bodies of land-to-sea interface, have long attracted the attention of scholars and experts because of their abundance in the littoral area of the Sea of Azov, their natural uniqueness and their high resource potential. Historically, the majority of the land-to-sea interface water bodies of the Sea of Azov are called "limans". There are three main lagoon groups: the Azov-Kuban limans, the East-Azov limans, the lagoons of the Kerch Strait and many small lagoon reservoirs. As a rule, these are brackish-water reservoirs separated from the Sea of Azov by accumulative forms. Until the middle of the nineteenth century, the evolution of the Azov lagoons was determined by natural factors, as the population of the coastal area was very small and the agriculture was undeveloped. Now, the role of man's impact is significant. Water bodies are used for irrigation and as areas for recreation, hunting, fishing and fish farming. It has also proved to have significant value for fisheries. In recent decades, a significant reduction in river run-off, used for irrigation farming, resulted in the salinization of lagoons, causing the degradation of species of flora and fauna and a general reduction in the ecosystems' productivity, especially the fish capacity of the water basin. The Azov lagoons occupy an important place in the reproduction of the local semi-aquatic and water birds, as well as for the migratory routes of the many birds that run through this territory. The Azov lagoons are unique coastal systems. A large part of the Azov lagoons is included on the Ramsar Convention list of wetlands of international importance.

Keywords

Lagoon • Sea of Azov • Liman • Hydrological regime • Specially protected areas

M. Krylenko (✉) • R. Kosyan • V. Krylenko
P.P. Shirshov Institute of Oceanology Russian Academy of Sciences (IO RAS), 1-g, Prostornaya, Gelendzhik 353467, Russia
e-mail: krylenko@mail.ru; rkosyan@hotmail.com; krylenko.slava@gmail.com

R. Kosyan (ed.), *The Diversity of Russian Estuaries and Lagoons Exposed to Human Influence*, Estuaries of the World, DOI 10.1007/978-3-319-43392-9_5

5.1 Introduction

The Sea of Azov is located between the 47°17′ and 45°16′N parallels and the 33°36′ and 39°21′ E longitudes. It is a type of inland sea and is surrounded by land from almost all sides (Fig. 5.1). In the south, the narrow and shallow Kerch Strait connects it to the Black Sea. The boundary between the seas passes by the southern entrance to the Kerch Strait along the Cape Takil – Cape Panagia line. There are no big islands in the Sea of Azov.

The Sea of Azov is one of the smallest on the planet, with a surface area of 39.1 thousand km^2, a water volume of 290 km^3, a maximum depth of 14 m, and an average depth of about 7.4 m. The maximum length of the sea from the Arabat Spit to the delta of the Don is 360 km, whereas the maximum width from north to south is 180 km (Dobrovolsky and Zalogin 1982).

By the nature of its sedimentation, the Sea of Azov can be divided into an area of intense deposit accumulation, a zone of matter transit and area of poor accumulation, as well as a zone of steady erosion. The area of intense accumulation is located in the eastern and south-eastern parts of the Gulf of Taganrog, where the suspended matter flowing in from the Don River is deposited, and in the central part of the Sea of Azov, characterized by an intense immersion in the Quaternary Holocene age. The steady erosion zone covers the coastal strip of the sea down to a depth of 6–7 m, on average. In the northern and western parts, it is confined to the eastern shores of the accumulative forms and the Arabat Spit, and in the eastern part, to the Yeisk Peninsula, and Akhtar and Beysug Limans. The main sources of terrigenous material forming sediments in the Sea of Azov are the products of coastal abrasion of the sea and river alluvium. Thus, for example, as a result of an active ongoing seashore abrasion, 16–17 million tons of terrigenous material get into the sea annually. River alluvium comes in with the Don and Kuban River flows, as well as with the flows of the northern seashore rivers. The volume of annual solid matter transported by rivers constitutes around 19 million tons.

The water catchment area of the Sea of Azov is 630 thousand km^2. The role of river run-off in the overall balance of the Sea of Azov waters is very significant. Two major rivers flow into the Sea of Azov in Russiam territory – the Don and Kuban Rivers, as well as about 20 small ones (the Mius, Protoka, Yeya, Beysug, Chelbas and Kirpili Rivers) (Investigation 2005).

Fig. 5.1 Sea of Azov

The Sea of Azov is tide-free. Annual variations and long-term fluctuations in the water level of the Sea of Azov are caused by changes in the total sea water volume due to changes in the ratio between the water balance components: river run-off, the amount of precipitation, evaporation and water exchange through the Kerch Strait with the Black Sea. The main contribution to the incoming portion of the water balance is made by the river run-off (41 %) and the water inflow from the Black Sea (41 %), whereas the water flow into the Black Sea through the Kerch Strait (60 %) and evaporation (39 %) contribute to the outgoing portion (Scientific-Technical Report 1996).

The Sea of Azov has well-marked, non-recurring surging effect level fluctuations that occur most frequently in autumn and winter and less frequently in spring. The most significant negative and positive surges can be observed in the Taganrog Bay and the western part of the sea. The period of time during which the high level of the surge remains above dangerous marks is, in most cases, no more than 12 h.

The wave climate of the Sea of Azov is determined by a small area of the sea, shallow depths and serious embayment. Winds of the east quarters dominate in winter seasons on the east coast, whereas a western disturbance of air mass is typical of warm seasons. The strongest storms in the eastern part of the sea are associated with westward winds. Winds of N, NW, W, SW and NW directions have the highest repetitivity; the maximum wind speed in winter reaches 28–34 m/s.

The small size of the Sea of Azov and its shallowness severely limits the build-up of wind waves. Wind waves develop quickly, but after 4–6 h of growth, wave parameters cease. The largest waves in the central part of the sea reach a height of 3–3.5 m (rarely up to 4 m). The wave period does not exceed 4–5 s, with their length of 50 m. Waves are quite steep (ESIMO 2012).

Despite relatively weak wave impact, most of the shores of the Azov Sea are eroded. The special feature of the current dynamics of the seashore is the predominance of abrasion and the accumulation of local character. The high speed of shore retreat with a respectively low wave effect is facilitated by: active landslides; surge level fluctuations; the geological structure of the seashore (loess-like loam and clay); and human activity.

A comprehensive study of contemporary seaside processes has allowed for identifying four main types of coastal development: abrasion (abrasion-landslide), abrasion-slip-off, accumulation and stable. In general, the following natural processes that define the state and dynamics of the regional coasts can be highlighted:

- abrasion processes;
- sea level fluctuations (related to the surges or long-term natural processes);
- changes in wind-wave regime parameters;
- fluctuation in volumes of biogenic materials (shells), related to the restructuring of the biological communities of the sea.

The total length of the abrasion seashores of the eastern part of the Sea of Azov is about 300 km. Abrasion coastal cliffs of 20–45 m high are made of loess-like loam and clays, almost entirely carried over by the erosion to the depths and not contributing to the material that forms beaches. Shores have a scalloped structure, while capes are formed by the most compact varieties of loam (Fig. 5.2). Average abrasion rate is 1.0–3.6 m/year, maximum – up to 6.0 m/year. The abrasion shores range from the village of Ilyich to that of Peresyp, from the town of Primorsko-Akhtarsk to the root of the Yasensk Spit, from the root of the Kamyshevatskaya Spit to Dolzhanskaya station and on to Yeyisk, and then from near the village of Shabelskoye to the north of the root of the Glafirovskaya Spit.

The abrasion-landslide type of the coast is typical of the Cape Kamenny-Temryuk town area. Shallow landslides can be found in the Schabelsk and Yeyisk areas (Peshkov 2003). Figure 5.3 illustrates the slip-off coast near the village of Priazovsky. The landslide zones stretching a dozen kilometers cover the coastline with a width of 300–1000 m. Even grass-covered slopes, composed of easily-washed loam, are exposed to landsliding. The average abrasion rate is 0.5–0.6 m/year. The beaches are narrow; their width is increased opposite ravines, which are composed of sand and shells.

The accumulative coasts are associated with Achuevsk, Yasensk and other spits, bay-bars of limans and river delta areas. Beaches of a width from 5 to 40 m are made of quartz sand, shell material and detritus mixed with pebbles and gravel. Currently, the accumulative forms are prone to erosion. Destruction of the northeastern coast of the Dolgaya Spit (Fig. 5.4) has been especially extensive in the past decade (up to 8 m/year).

The length of the stable shores where abrasion and accumulation processes are not clearly expressed is about 130 km. These are common in the limans and on the sections blocked by spits. The shore is low-lying, often covered with canes and cloaked by coasts.

The alongshore streams and sediment migration play a very important role in the modern dynamics of the seashore area of the Sea of Azov. The main sources that feed it are a solid flow of rivers, erosion products and material of biogenic origin (shells and their fragments). In the eastern part of the littoral area of the Sea of Azov, alongshore sediment transition is most inherent in the southeastern part of the sea.

Lagoons, like other water bodies of land-to-sea interface, have long attracted the attention of scholars and experts because of their abundance in the littoral area of the Sea of

Fig. 5.2 Abrasion-landslide coast (Dolzhanskaya village)

Fig. 5.3 Slip-off coast (Cape Kamenny)

Azov, their natural uniqueness and their high resource potential. Historically, the majority of the land-to-sea interface water bodies of the Sea of Azov are called limans (Yastreb et al. 2007). All natural water bodies in the delta of the Kuban River are traditionally called limans, regardless of their location in the delta, origin, nutritional nature of the water, connection to the sea or regime specifics. The origin and regime of different limans in the Kuban River Delta can vary profoundly. N. Danilevsky (Mikhaylov et al. 2010) suggested that only those water bodies that are located in the

Fig. 5.4 Erodible northeastern shore of the Dolgaya spit

maritime zone of the delta are connected to the Azov Sea through the straits-delta arms and have a regime, determined by both water nutrition from delta streams (arms and shallow channels) and water exchange with the seas, can be regarded as "real" limans. On the other hand, Danilevsky also proposed designating the water bodies located inside the delta away from the sea and being fed only by the delta streams, and are therefore desalinated, as delta lakes.

For a more strict classification, a modern interpretation of such notions as "liman", "lagoon" and "delta lake" should be used and applied.

A liman is an elongated bay with low-level shores. It is formed when the lowland rivers' estuaries or littoral lowland areas are flooded by the sea. Limans can be open towards the sea (lips) or closed, separated from the sea by a spit or a bay-bar. The Ecological Encyclopedia (Danilov-Danilyan 1999) also classifies "liman" as a flooded part of a river's estuary or as one type of estuary. Littoral area water bodies of other types, such as lagoons and delta lakes, are often incorrectly referred to as limans. A lagoon is a shallow part of the sea, separated from it by a bar (bay-bar, spit) and linked to it with a narrow strait (Danilov-Danilyan 1999; Mikhaylov et al. 2010).

Their further description contains the established geographical names of the Priazov lagoons, as traditionally recognized on maps, in literature and in water management plans.

5.2 Azov-Kuban Limans

The Priazov estuary of the Kuban River includes a vast delta and the estuarine offshore zone, exposed to the influence of the river run-off littoral area of the Sea of Azov. It is a unique geographical site, with rich agro-climatic, water, land and biological resources and an advantageous geographical position. The estuary of the Kuban River begins at the place of the separation of the river into two branches – the Protoka and the Kuban (Fig. 5.5). Since 2006, the delta apex has been the Tihovsk waterworks, which artificially distributes the Kuban River water run-off between the Kuban branch, the Protoka branch and the trunk channel of the Petrovsk-Anastasievsk irrigation system. The modern estuaries of the Kuban River represent the non-tidal, delta type, and include the low-branch delta of the lagoon and an open steep-bottom estuarine offshore zone. The Azov maritime delta stretches from the northern part of the town of Primorsko-Akhtarsk to Peresyp village; it has two large protrusions (near Cape Achuevsky and the Achuevskaya Spit) and two small ones (near the estuary of the Kuban branch and the Protoka branch), as well as numerous breaks along the coastline, related to the delta branches' estuaries and marine delta arms. It is 139 km long.

The Azov-Kuban Limans are the most extensive group out of hundreds of natural deltaic water bodies, located within the area of the current Kuban River Delta. The limans'

Fig. 5.5 Limans of the Kuban River delta: *1* Akhtarsky, *2* Kirpilsky, *3* Prigibskaya, *4* Zapadnaya, *5* Mechetnaya, *6* Sladkovskaya, *7* Gorkovskaya, *8* Zhesterskaya, *9* Kulikovskaya, *10* Kurchanskaya, *11* Akhtanizovsky, *12* Kiziltashskaya, *13* Vityazevsky

configurations are very diverse. They are connected with each other and with the Sea of Azov through delta arms and shallow channels; they mostly have low-lying flat shores covered by hydrophilic vegetation, mainly cane, reed, sedge and macereed species. Limans are usually shallow. Their average depth ranges from 0.5 to 2.5 m.

The natural deltaic water bodies in the Kuban River Delta are represented by lagoons, "real" limans and regular deltaic lakes. It's much easier to classify freshwater bodies located in the delta of the Kuban River far from the sea. These are typical delta lakes, which include ponds, "located in deltas of larger lowland rivers" (Danilov-Danilyan 1999). A lot of water bodies existing earlier in the Kuban Delta turned into flood plains (plavni) or completely dried up (or were drained) as a result of sultage and overgrowing (Mikhaylov et al. 2010). How can the Kuban River limans actually be classified as water bodies? Genetically, the majority of the ponds in the Kuban River Delta are the remnants of large lagoons located in the huge, ancient Kuban Bay, separated from the sea by coastal bars and spits. To date, these lagoons are almost entirely filled with river and sea sediments and, in maritime parts of the delta, are transformed into numerous small residual water bodies, some connected to the sea (they can be regarded as lagoons) and some unrelated to the sea (turned into freshwater deltaic lakes). The Kurchansky Liman may be related to the real Kuban Limans, a flooded stretch of a once high-water stream flow of the Kirpilsky (Malyi) Delta and Liman, and a continuation of the Kirpili River valley. The maritime water bodies, which can be regarded as lagoons, are currently as follows (out of the relatively large bodies): the Akhtarsky (separated from the sea by the northern end of the Achuevskaya Spit and connected to the sea by a wide delta arm), the Shiroky (salty), the Bojkievsky (connected to the sea by Godzhievsky delta arm), the Kruglo-Solyony, the Durnoy, the Sladky (connected to the sea by the Sladkovsky Delta arm), the Gorky (connected to the sea by the Gorky Delta arm), the Konovalovsky, the Bolshoi Bashtovoi and the Gniloi (connected to the sea by the Zozulievsky Delta arm), the Kulikovsky (connected to the sea by the Kulikovsky Delta arm), and the Akhtanizovsky (connected to the sea by the Peresypsky Delta arm).

The hydrological regime of the Azov-Kuban Limans currently depends mainly on the climate of the delta, the water content of the Kuban River, the water regime of the Sea of Azov and ongoing melioration measures. The water balance of deltaic water bodies is determined by river water flow, return water flow from rice systems, precipitation onto the water table and the flooded areas, inflow of marine waters into limans and outflow from limans into the sea, groundwater flow rate, evaporation, vegetation transpiration, and volume changes due to interannual level fluctuations. The water level in the limans is subject to fluctuations, which depend on the inflow of inland and sea waters. Fluctuations in average monthly levels usually do not exceed 0.8 m. Strong negative and positive surge winds cause short-term fluctuations in water level, which, in large limans, usually do not exceed 0.4 m, but in limans connected to the Sea of Azov through wide delta arms, may reach greater values. The mineralization and chemical composition of the limans' water are significantly different, vary throughout the year and depend directly on the hydrological regime. Among the Azov-Kuban Limans are freshwater, briny and salty water bodies. The salinity of any onoe of them or of the whole system depends mainly on the sea, inflow of river or reservoir waters, precipitation, evaporation from water surfaces and water vegetation transpiration. The limans' shallowness causes a quick temperature change in their waters with air temperature changes: in July, the water may warm up to 35 °C.

All water bodies of the Kuban River Delta are traditionally divided into three large blocks: northern (located to the north of the Protoka branch), central (located between the Protoka and Kuban branches) and southern (located south of Kuban River and the Petrushin branch). Within the limits of these three blocks of deltaic water bodies (Fig. 5.5), the following liman systems are delineated: Akhtarsko-Grivenskaya, Chernoerkovsko-Sladkovskaya, Zhesterskaya, Kulikovsko-Kurchanskaya, Akhtanizovskaya and Kiziltashskaya (Black Sea basin) (Table 5.1). The largest limans are the following: the Akhtanizovsky (67.5 km^2), the Kurchansky (53.6 km^2), the Vostochny (50 km^2), the Kirpilsky (72 km^2), and the Akhtarsky (65 km^2) (Mikhaylov et al. 2010).

5.2.1 Akhtarsky Liman

The Akhtarsky Liman is part of the namesake group of the Akhtarsko-Grivenskaya system of the Kuban Limans (Fig. 5.6). The Akhtarsky Liman's square area is 45.2 km^2,

Table 5.1 Blocks, systems and groups of limans of the Kuban River Delta (Mikhaylov et al. 2010)

Blocks (surface area, km^2)	Systems (surface area, km^2)	Groups
Northern (358)	Akhtarsko-Grivenskaya (358)	1. Akhtarsky
		2. Kirpilsky
		3. Prigibskaya
		4. Zapadnaya
Central (411.1)	Chernoerkovsko-Sladkovskaya (98.4)	5. Mechetnaya
		6. Sladkovskaya
		7. Gorkovskaya
	Zhesterskaya (82.4)	8. Zhesterskaya
	Kulikovsko-Kurchanskaya (132.5)	9. Kulikovskaya
		10. Kurchanskaya
Southern (264.7)	Akhtanizovskaya (97.8)	11. Akhtanizovsky
	Kiziltashskaya (264.7)	12. Kiziltashskaya
		13. Vityazevsky

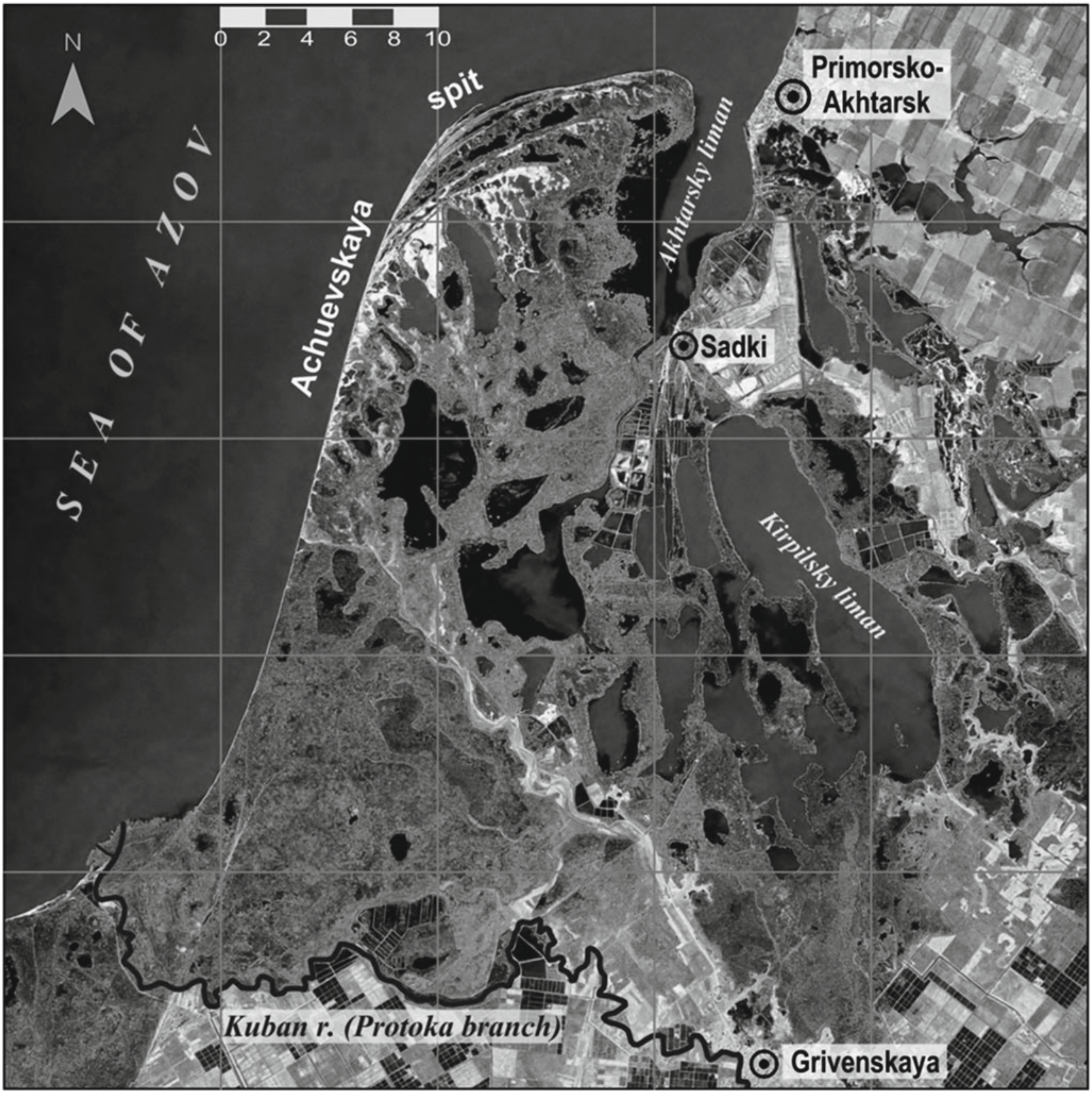


Fig. 5.6 The Akhtarsko-Grivenskaya system of limans

with a maximum depth of 1 m. The bottom is fairly smooth and silty. The Akhtarsky Liman is connected to the sea by the delta arm, 2.5 km wide and 1.5–2.1 m deep. It was formed several centuries ago as a result of partial abjunction (by the Achuevskaya Spit) of the mouth of the Protoka branch from the Sea of Azov.

The shores of the liman are composed of the river and marine sediments. For a considerable stretch, they are lowlands, changing over into flooded areas, except for the eastern seashores, to which dry lowlands adjoin. The low sandy beaches of the Akhtarsky Liman are almost completely overgrown with reeds (Fig. 5.7). The shore is stable, but is prone to positive surges. A 3-m high cliff of bed-rock forms the liman's shores near Primorsko-Akhtarsk.

Five inter-liman channels, called delta arms, flow into the liman from the Akhtarsko-Grivenskaya system: the Chapaevskoye, Sadkovskoye, Bezymyannoye, Krutobereshnoye, and Grekovo. In all these delta arms, the streams can be directed either way, but they are mostly directed towards the Akhtarsky Liman. Currents of the oppo-

Fig. 5.7 The shore of the Akhtarsky Liman near Sadki village

site direction (from the Akhtarsky Liman), however, are brief and occur when winds blow from the sea. When the north quarter winds blow, the sea water gets into the liman, raising its level and salinizing it. The waters of the Akhtarsko-Grivensky Limans freshen the Akhtarsky Liman by getting there through the above-mentioned delta arms. Therefore, zones with levels of salinity ranging from 1‰ near the delta arms to one comparable with the salinity of the sea where the two bodies interface can be located within its limits simultaneously (Mishchenko 2006).

The Achuevskaya Spit, adjacent to the liman at its distal end, is about 31 km long (Fig. 5.8). The orientation and morphology of the seashore not only indicates the impact of alongshore sediment transition, but also the big role played by northwest swells, which determines the material transfer to the Akhtarsky Liman. The width of the beaches on the seashore of the spit varies from 5 to 15 m, on the slopes, from 0.01 to 0.02. Shells and detritus prevail in the sediments (70–90 %) and fine-grained quartz sand (10–30 %). The underwater slope is flat, at 0.0001.

5.2.2 The Kurchansky Liman

The Kurchansky Liman is a member of the Kulikov group of the central block of the Kuban Limans (Fig. 5.9). The liman's length is more than 20 km; its area is 55 km^2. The average depth is 1.2 m. The liman is fed by the Kuban River waters from the Kurchansky channel. Water discharge is regulated by the gateway. The liman is directly linked to the Sea of Azov through the Solovyev Delta arm. The overall water mineralization here is from 2.94 to 8.70 g/l.

The shores of the liman are mainly flood-type. The Verbyanaya Spit is the bay-bar of the Kurchansky Liman and it stretches from the southwest to the northeast for 9.5 km. It has a width of 25–50 m. The spit is dominated by low-lying silty, sand and silt shores, with minor land and underwater slopes.

Within the past few decades, the Verbyanaya Spit has suffered from a lack of sediments, resulting in a restructuring of the underwater slope. Since the 1970s and 1980s, significant rates of shore erosion and shoreline retreat have been regis-

Fig. 5.8 The Achuevskaya spit

tered near the Verbyanaya Spit. As a result, over the past 30–40 years, the width of the Verbyanaya Spit has decreased from 100–150 to 15–60 m, or even less. A coastal protection dike has been built on the Verbyanaya Spit, through which a motor road runs, connecting fishing camps, recreation facilities and an oil drilling platform. Over the period of existence and operation of the 8.6 km long and 0.77 m high wave suppression dike, starting in 2007, the most significant erosion was registered approximately 0.5 km to the west of the Kulikov Delta arm (13 m) and on the western flank of the spit (29 m). The beach width reduces noticeably where the surface of the underwater slope allows waves, weakly exposed to deformation, to approach the edge line. On the southwestern (to the east of the Solovyev Delta arm) and northeastern flanks of the spit, local accumulation of sediments is registered, expressed in relative underwater slope surface elevation up to 0.4–1.0 m (Pogorelov and Antonenko 2010).

5.2.3 The Akhtanizovsky Liman

The Akhtanizovsky Liman is a large freshwater liman on the southeastern shore of the Sea of Azov (Fig. 5.10). Its length is about 100 km, its width, about 20 km; the maximum depth is 1.6 m. Until the beginning of the nineteenth century, the liman looked like a landlocked body of salt water, connected only to the Sea of Azov. In 1819, the locals connected this liman to the Kuban River. Since that time, the sixth part of the river run-off has been flowing into the Akhtanizovsky Liman through the Kazachy Erik River, a branch of the Kuban River (Peshkov 2003).

The liman is separated from the Sea of Azov by a strip of land, the lowland part of which is called the Peresyp (bay-bar). The accumulative bay-bar of the Akhtanizovsky Liman (Fig. 5.11) has an elevation above sea level of 0.5–0.7 m. The shore area as a whole is relatively stable, with a shell-and-sand beach width of 20–25 m. During strong storms with positive surges, the terrace cusp and beaches undergo erosion with an average speed of 0.5 m per year, in separate periods up to 1–1.5 m. At its narrow part, the Peresyp is cut by the Peresypsky Delta arm (Fig. 5.12), which was formed in the early twentieth century. The delta arm gradually narrows and becomes shallow. The reduction in river water inflow into the Akhtanizovsky Liman from the Kazachy Erik River led to periodic natural closures of the Peresypsky Delta arm (Kosyan and Krylenko 2007).

The surface of the coastland is formed by deltaic and alluvial sediments underlaid by Neogene and Paleogene marine sediments. From the south, the liman is limited by the Starotitarovskaya upland, indented by numerous gullies and ravines. To the west, the Borisoglebskaya Hill rises and the Cossack village of Akhtanizovskaya directly overlooks the

Fig. 5.9 Central block of limans

shoreline. The northern coast is high as well. A strip of reeds of different width separates the water table from the solid coast.

All of the Azov-Kuban Liman-lagoons and flooded areas have been created as a result of the separation of parts of the ancient gulf from the sea by coastal bars, then through further filling in by alluvial and liman sediments, as well as the annual flooding of river waters and infiltration of sea water into the delta (during major positive surges). The history of their existence and evolution dates back several thousand years.

The first written mention of the Kuban Limans and flooded areas goes back to the end of the second and the beginning of the first century BC. But only since the seventeenth century has information on limans and flooded areas in the Kuban River Delta become more detailed and reliable (Mikhaylov et al. 2010).

For a long time, the evolution of limans and flooded areas was determined by natural factors, since the population of the delta at the time was very small and the agriculture was undeveloped. When these lands joined Russia and the Black Sea, Cossacks migrated there to live, and when the number of people and human settlements started to grow, the question arose as to whether to dry-out the flooded parts of the delta. However, it was not until the mid-nineteenth century that this issue was first tackled. Until that time, the area of

Fig. 5.10 The Akhtanizovsky liman

Fig. 5.11 The Akhtanizovsky liman bay-bar

Fig. 5.12 The Akhtanizovsky liman delta arm

certain limans, particularly those fed by river water, continued to decline naturally, whereas the square area of swamps, contrastingly, continued to increase.

The first significant anthropogenic changes in the size and natural regime of the limans and flooded areas were initially connected with artificial changes in flow direction in the Kuban branch and the filling in by positive river surges of a considerable part of the Akhtanizovsky and Kurchansky Limans' water areas. Following that, an impact was felt as the result of the closure of multiple shallow channel sources, feeding the limans with river water, and their subsequent backfilling and plowing, as well as improvement of principle river delta branches.

Changes in size of the areas of the limans and flooded areas became visible as early as the 1860–1880s. For example, between 1865 and 1885, many swamplands from Petrovskaya station to the Kurchansky Liman completely dried-out and the Akhtarsk Limans, receiving insufficient amounts of river water, had dramatically reduced their own river water contents by the mid 1860s. In the years that followed (until the 1920–1930s), the Dolgy, Gluboky, Zapadny, Mechetny, Gorky and Sladky limans' areas were noticeably reduced because of silting and overgrowing, whereas the limans between the Kurchansky and Kulikovsky Limans decreased or partially disappeared; the Lebyazhy liman completely dried out (Mikhaylov et al. 2010).

In the middle and second half of the twentieth century, the onset of humankind on limans and flooded areas in the Kuban River Delta only increased. On the one hand, a majority of bogs and a number of limans have been drained in the course of agricultural development. The areas of limans have also been reduced owing to natural decay (due to the regulation of the Kuban River flow and improvements in the delta branches' riverbeds). That said, a much bigger role in the limans' silting and in negative impact on the relief was now being played, not by river deposits, but by disappearing aquatic vegetation. On the other hand, to increase the fish capacity of limans, a complex of measures was taken in regard to the flooding and desalination of a great number of limans. Interaction of these opposing processes led to significant changes in the number and area of limans by the end of the twentieth century.

It is difficult to measure the acreage of the Kuban River Limans due to variations in their levels: thus, for example, a 20 cm change in the water level changes the acreage by 26 %. In addition, the measured area of the limans also depends on the time the measurements are taken (aerial photo survey). Images taken in summer register a much smaller area of open water surface on the limans due to water bodies being overgrown with emergent plants. The total number of natural and artificial water bodies within the boundaries of the modern Kuban River Delta is 665, with a total acreage of about 1060 km^2. Of them, 265 water bodies have a water table of more than 0.1 km^2, and 400, less than 0.1 km^2. The open water surface constitutes 900 km^2.

Various water plants with floating leaves prevail on the open waters of the freshwater Kuban Limans (water-lilies, duckweed, eelgrass, floating moss, and frogbit, as well as a rare, disappearing plant, an insect-eater called Aldrovanda) and submerged plants (naiad, water milfoil, morass-weed and pondgrass). Morass-weed and milfoil very often form such a powerful weed bed in the deltaic lakes that almost all other types of plants are completely displaced.

In the shallow waters (up to 1.5 m deep) of limans, the reed grows abundantly. Water chestnut or caltrop grow in some limans. Relatively recently (since 1948–1950), thanks to the efforts of S. Troitsky and A. Shekhov, the Hindu lotus has appeared (Belyuchenko 2010) in several delta limans.

Fig. 5.13 Lotus *Nelumbo nucifera*

Now, this exotic plant can be found in the Akhtanizovsky and Sredny Limans, as well as in the Sadkovsky Delta arm (Fig. 5.13).

During the salinization of limans, the number of species of plants and their density (coverage) is reduced, changing their species composition. Here, we may find naiads, zannichellia, and sea grass (eelgrass, halophyte, stonewort, pondgrass and water milfoil). Reeds in such reservoirs grow at depths as low as 0.6–0.8 m. In rare instances, sea clubroot can be found at depths of 1 m.

Between 70 and 95 species of fish inhabit the limans (Mishchenko 2006), as well as crayfish and amphibians. The following fish species live here permanently or only during the period of spawning or nursing: pike-perch, Azov roach, carp, bream and silver bream, pike, catfish, crucian carp, perch, roach, rudd, asp and others. This great diversity of species is typical for the limans of the Akhtarsko-Grivensky and Chernoerkovsko-Sladkovsky groups. In connection with the development of the pond and liman-lake fish farming, the carp, perch and introduced species (buffalo, silver carp, grass carp) are widely spread here nowadays. The following migratory fish come to the Kuban River Delta from the sea: great sturgeon, starred sturgeon, Azov shad, Black Sea roach, etc. Zooplankton and benthos are abundantly represented in the Kuban River Delta (about 400 species, including rotifers, copepods, cladocerae and shellfishes, worms, etc.), as well as phytoplankton (Mikhaylov et al. 2010). Up to two million bird species fly in and stay in the liman and flooded area of the Kuban River Delta for the winter.

A large portion of the Azov-Kuban Limans is included in the Ramsar Convention list of wetlands of international importance, as the "Group of limans between the Kuban branch and the Protoka branch" and the "Akhtarsko-Grivenskaya System of Limans" (Fig. 5.14). The federal Priazovsky zoological nature reserve of 37.8 thousand ha has been functioning here since 1958. Since 1994, the "Sadki" strict nature reserve with an acreage of 92,000 ha has as well. Two areas of habitat for the Hindu lotus (in the Primorsko-Akhtarsky district) have been declared to be state nature sanctuaries of local significance.

5.3 The Beisugsky Liman and Lake Khanskoye

The Beisugsky Liman and Lake Khanskoye are located in the eastern part of the littoral area of the Sea of Azov, 15 km northeast of the town of Primorsko-Akhtarsk in the territory of Krasnodar. Lake Khanskoye lies in the southern part of the Yeisk peninsula, and the Beisugsky Liman is adjacent to it from the south side (Fig. 5.15).

The Beisugsky Liman is the largest in the East Priazovye desalinated lagoon, with a length of 30 km and a width in its middle part of 12 km. The average depth is 1.7 m, the area of the water table is 272 km^2, and the volume of water is approximately 400 million m^3 (Belyuchenko 2010). The coastline of the Beisugsky Liman is relatively poorly indented.

Lake Khanskoye, by contrast, is the most salted lagoon of the Azov Sea. The lake was previously the bay of the Sea of Azov and was connected to the Beisugsky Liman (Fig. 5.15). The lake is oval, oriented along the NW-SE axis; its length is

Fig. 5.14 Wetlands of the Kuban River Delta (Gineev 2002)

19 km, its maximum width is 7.0 km, the medium width is 4.4 km, and the acreage is 93.26 km^2. The catchment area is approximately 300 km^2. The volume of water at an average depth of 0.7 m constitutes 65.3 mln m^3 (Mishchenko 2006).

The Yasenskaya Spit separates the Beisugsky Liman from the Sea of Azov. The spit's length is 18 km; it is oriented in the northeastern direction, with its highest level being 1.4 m (Fig. 5.16). The width of its beaches along its narrowest part does not exceed 5 m. In the middle of the spit, the beaches' width increases up to 15–20 m, within the distal zone, 50 m (Kosyan and Krylenko 2007). The spit is built mainly of biogenic material. This biogenic material comes from the

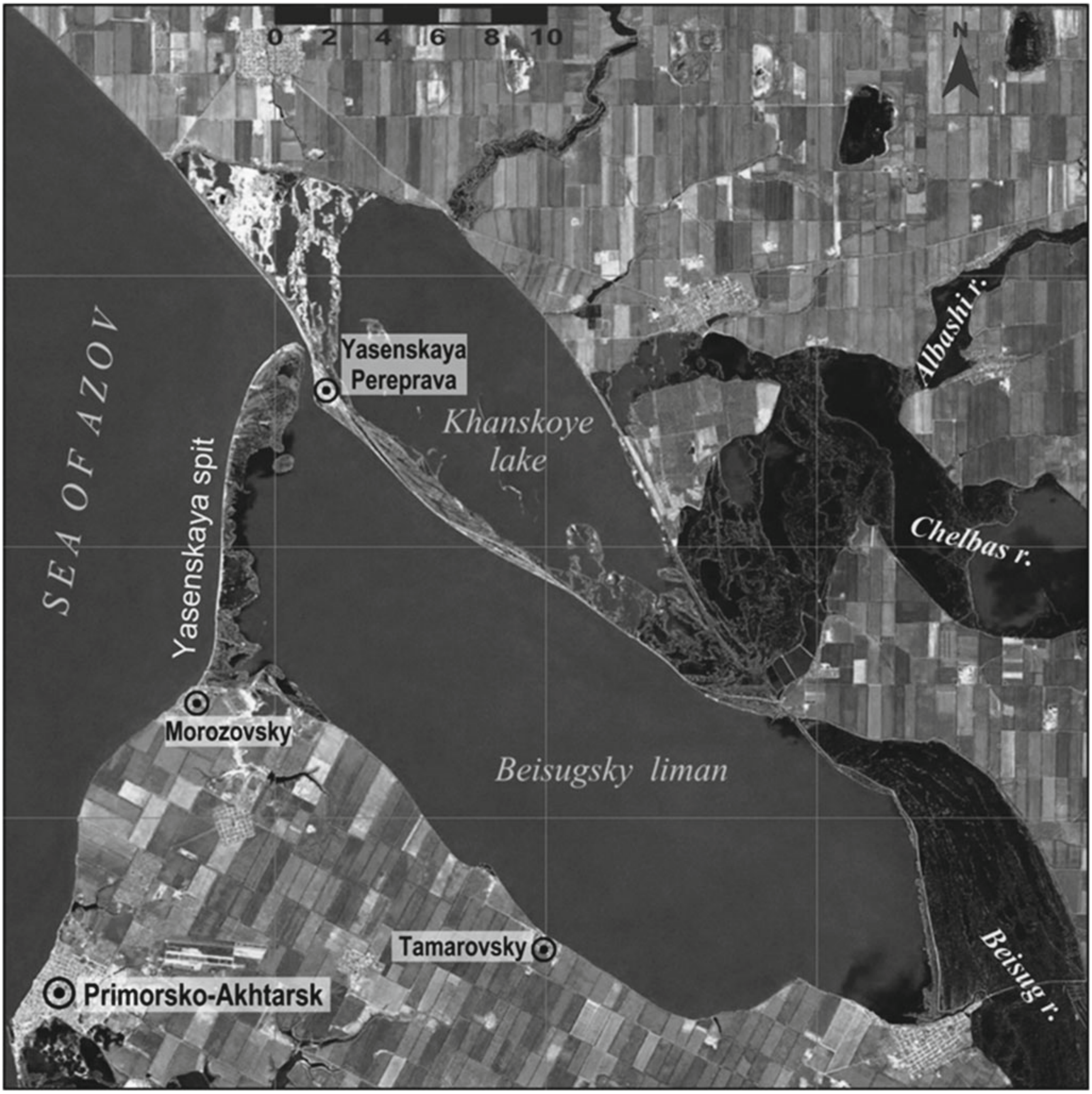


Fig. 5.15 The Beisugsky Liman and Lake Khanskoye

bottom. During the nineteenth century, the spit grew at a rate of up to 40 m a year. After 1960, the growth slowed down and the marine edge started to erode (Peshkov 2003). Comparison of aerial photography and topographic survey materials shows that, from 1948 to 2005, the total area of the erosion of the spit's marine portion along 10 km constituted 2.4 million km^2; the volume, about 2.5 million m^3. That said, the maximum value of the retreat of the shore horizon in the root section of the spit over the indicated period was 410 m, in the middle part, 215 m, and in the distal, 83 m. The spit has been eroding at an exceptionally great speed since 1994 (up to 12–15 m per year). Measures taken to use crushed stone from the village of Morozovsky to fill the bridge over the delta arm (about 500 m) have slowed down this process slightly, but only on the fortified site. Downstream of the wave stream of the spit, erosion continues at the same rate (Vostrikov 2006). From the liman side, the spit shores are low-lying and overgrown with reeds (Fig. 5.17).

The low-lying shore of the bay-bar is between the Beisugsky Liman and Lake Khanskoye. The bay-bar of

Fig. 5.16 The Yasenskaya spit from the seaside

Fig. 5.17 The coast of the Beisugsky Liman from the side of the Yasenskaya spit

Lake Khanskoye is 25 km long and 1–2 km wide. It was formed when the Beisugsky Liman had an unimpeded connection with the sea. The bay-bar of Lake Khanskoye has been built up like other delta bars and is a more ancient formation than the Yasenskaya spit. The body of the bay-bar consists of 80–90 % shell detritus piled with a slight admixture of sand, gravel and pebbles from the erodible coast rocks. The width of the beaches near the village of Yasenskaya Pereprava exceeds 30 m (Kosyan and Krylenko 2007) (Fig. 5.18).

The southeastern shore of the Beisugsky Liman is relatively stable, with coasts overgrown with reeds (Fig. 5.19). The northeastern and eastern coasts of Lake Khanskoye and the Beisugsky Liman are low-lying, and small channels join the water bodies with a system of small lakes. Islands are spread throughout Lake Khanskoye.

The southwestern shore of the Beisugsky Liman – is made of clay and loess loam and represents a steep slope of the Kuban valley. The coast near the village of Tamarovsky is a grass-covered plateau 2–2.5 m high. A dead cliff of the

Fig. 5.18 The bay-bar of Lake Khanskoye

Fig. 5.19 Typical view of the shore of the southeastern part of the Beisugsky liman

Fig. 5.20 Coastal protection in the village of Tamarovsky

same height is near the rim. The beach is shelly, with a width from 1 up to 10 m. In the center of the village the coast is strengthened by inclined concrete plates (Fig. 5.20). A steep, landslide-abrasive coast starts 1–1.5 km northwest of the village. The height of the almost vertical, loess soil cliffs reaches 15 m (Fig. 5.21). The coast has an expressed, scalloped structure. There are practically no beaches (Kosyan and Krylenko 2007).

The eastern coast of Lake Khanskoye is low-lying, piled up with sand sediments from the Chelbas River (Fig. 5.22). The northern coast is cliffy and steep (Kosyan and Krylenko 2007).

Two rivers flow into the Beisugsky Liman: the Beisug and Chelbas Rivers – bringing in, approximately, 230 million m^2 of fresh water annually. There are 208 ponds on the Beisug River and its tributaries, and the Beisugskoye fish farm resides in its delta. In recent years, the waters of this river have rarely reached the liman. There are 120 ponds on the Chelbas River, which itself is one of rivers dying out in the area. It doesn't reach the liman forming overflow land. The Yasen River flows into Lake Khanskoye, as does the Albashi River, through a buffer system of small lakes. The coasts of the Yasen River near Lake Khanskoye are swamped. The river flow is poor. The water level in the Beisugsky Liman and Lake Khanskoye is influenced by changes in the water balance of the Sea of Azov. The bulk of the water that flows from the Sea of Azov into the Beisugsky liman comes through the Yasenskoye and Bugazskoe Delta arms. Positive surges of water from the lagoon can be observed within deltaic areas. Water level oscillation amplitude reaches 3 m. Lake Khanskoye, during surges, is filled by the waters of the Beisugsky Liman and the Sea of Azov.

Lake Khanskoye is desalinated during the period that the surge winds start (winter, spring), and conversely, it is salinated during summer, when, as a result of evaporation, the lagoon area is reduced and the water gets 12 times saltier than the waters of the Sea of Azov. Ions of sodium, chlorine and sulphate prevail. The steppe rivers' waters do not contribute to the lake's desalination process.

Transparency of waters in the water bodies being studied depends on wave processes and overgrowing. In shallow waters (of a depth up to 1.5 m), transparency is 100 %. In the Beisugsky Liman, near the Yasenskoye Delta arm, the depths increase up to 2.0–2.5 m, reaching 4–5 m at its central part.

Fig. 5.21 Abrasion-landslide southwestern coast of the Beisugsky liman

Transparency falls down to 70 %. The oxygen contents change depending on the season and the depth grows from 4.8 to 7.2 ml/l. Mass fish mortality occurs in Lake Khanskoye due to a lack of oxygen. Average concentrations of plant nutrients vary within the following limits: phosphorus, 73.4 37.8 mg/m^3; nitrogen, 620–690, silicic acid, 700–800 mg/m^3.

The surface vegetation of the liman grows quite poorly. There are only rare thickets of reed, cane and sedges near the Yasenskaya spit and at the mouths of the Beisug and Chelbas Rivers. Eel-grass grows throughout the entire territory of the liman. The biomass of zooplankton in the southeastern part of the Beisugsky Liman is 1.3–1.9 g/m^3, with a population of 137.6–140.2 thousand copies/m^3. Zooplankton is represented by two types of Rotifers, three species of Konopeds and three species of Cladocera. The most productive in termsof zoo- and phytoplankton is the group of barrier or intermediate reservoirs. The natural aquatic fauna there is quite rich, comprising up to 30 fish species (Belyuchenko 2010): roach, Azov roach, bleak, pike, silver bream, perch pike, carp, rudd, perch, crucian carp, and bream. The perch pike, Azov roach, sprat and carp are of commercial value.

Water bodies occupy one of the central places in the reproduction of semi-aquatic and water birds. The open water surface attracts many inhabitants during the nesting, moulting and wintering periods. Of particular value are the numerous islands and spits of Lake Khanskoye. The migratory routes of many birds run through this territory. Massive spring and autumn bird migrations fall in February–March and August–December. The total number of migrants in separate years reaches 0.5–0.7 million. There are 41 species of nesting semi-aquatic and water birds registered. Much of the local populations of waterfowl stay for the winter.

Fig. 5.22 The eastern coast of Lake Khanskoye

Lake Khanskoye and the Beisugsky Liman have not undergone significant anthropogenic transformation. Water bodies are used as areas for recreation, hunting and sport fishing. At the mouth of the Beisug River, a fish farm has been created, covering an area of 9.3 thousand hectares, where catadromous and diadromous fish reproduction is ongoing; the "Beisugsk Fish Farm" is the main enterprise on the Sea of Azov growing young species of Azov roach and perch pike.

The flow of most rivers is regulated along their entire length, water being taken for irrigation and other purposes. Therefore, the salinity in the salination zone of the Beisugsky Liman increases all the time, whereas the surface area has been decreasing with the growing salinity of Lake Khanskoye. There is a danger of a Yasenskaya spit breakthrough, especially during a strong positive surge, which would entail the beginning of the disintegration of the entire accumulative form into separate islands and the salinification of the Beisugsky Liman by the salt waters of the Sea of Azov (Vostrikov 2006).

The "Beisugsky Liman and Lake Khanskoye" wetland is included on the perspective list of the Ramsar Convention on Wetlands of International Importance.

5.4 The Yeisk Liman

The Yeisk Liman is the second largest lagoon-type water body on the Azov Sea coast in the Krasnodar region. The Yeisk Liman is located near the town of Yeisk, and has the form of an ellipse, stretching from east to west; its length is 24 km, its maximum width is 12 km, and the area of the water table is 240 km^2 (Mishchenko 2006). By its geomorphological demarcation, the Yeisk Liman is related to the platform zone of the Kuban valley. At a depth of 1–4 km, this water reservoir has a solid foundation of Paleozoic, pre-Cambrian, Mesozoic, Paleogene and Neogene rocks. The latter are covered by a powerful layer of Quaternary deposits of ancient alluvial and fluvioglacial loams and clays. In the historical period, the Yeisk Liman was completely separated from the Taganrog Gulf by the Yeiskaya and Glafirovskaya spits. During a heavy storm in March 1914, a strait the width of which is now 2.5–3.0 km, was created between the spits. At the northern edge of the spit, Yeisk Island appeared. At present, the liman is separated from the Sea of Azov's Gulf of Taganrog by the Eiskaya spit in the southwest and by the Glafirovskaya spit in the northwest, as well as by two islands and shoals (Fig. 5.23).

The liman is shallow, with dominating depths of 0.5–1.5 m; only closer to the sea do they grow up to 3–3.5 m. The bottom of the liman is flat and covered with a layer of silt (Belyuchenko 2010).

Fluctuations in water levels in the liman are due to changes in the water balance of the Sea of Azov, the highest amplitude of its fluctuations reaching 69 cm. At the same time, the Don River flow affects the annual level changes in the Gulf of Taganrog. Therefore, the water level in the Yeisk Liman rises in May, while the minimum level values are in October–December. The prevailing eastward and westward winds cause negative and positive surges of water. The magnitude of negative surges is bigger than that of positive surges in the Yeisk Liman, with amplitude of water level fluctuations reaching up to 3 m. Quite recently, the liman was fed by the waters of the Yeya River. Due to anthropogenic transfor-

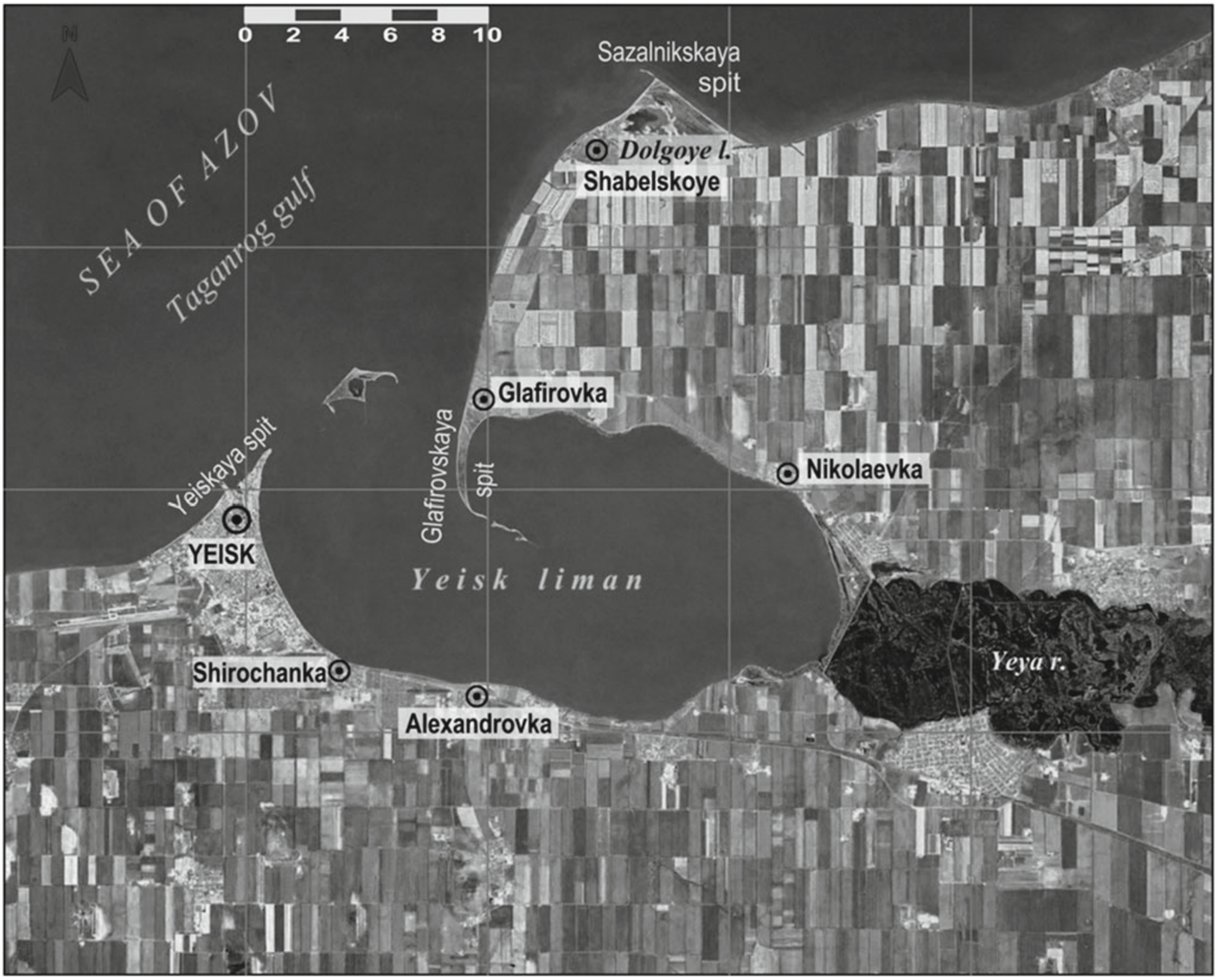


Fig. 5.23 The layout of the Yeisk liman

mations, the river flow into the liman has actually stopped. From its source to the mouth, the river is blocked by 437 dams. Water surface area is 70 ha. In this regard, the Yeya River waters, though forming bogs in the lower reaches, only reach the liman during floods.

The Yeiskaya spit has quartz sand, shell material and detritus mixed with pebbles and gravel. The spit surface is built up. The width of the beaches in the distal part of the liman is 13–15 m; from the Gulf of Taganrog, the width constitutes 20–30 m. Strengthening of the Yeiskaya spit from the side of the Taganrog Gulf is executed between the port and its distal end at a length of 1.8 km (Kosyan and Krylenko 2007). The coast within the limits of the Yeiskaya spit is accumulative. There are no expressed wave-cut escarpments whatsoever in this area. The sandy and shell detritus body of the spit has a gentle slope, rising above sea level. The surface slopes are measured by first degrees. The distal part of the spit is reinforced by the boulder-pebble fill (Fig. 5.24). The same fill constitutes a considerable length of the outshore (western side) of the spit. Currently, the project named "Construction of the isthmus between the Yeiskaya spit and the island of Yeiskaya spit" is being reviewed.

The Glafirovskaya spit has a length of about 7 km. Its distal end is turned towards the Yeisk Liman. The beach is formed out of middle-size shells with a width of 12–20 m (Figs. 5.25 and 5.26). Ancient bars stretching along the west coast lay on the surface of the spit. It should be noted that the western edge of the Glafirovskaya spit recedes at the same speed as the adjacent section of the abrasion shore, whereas the distal end is growing (Kosyan and Krylenko 2007).

The islands separating the Yeisk Liman have a flat terrain, their height does not exceed 1.5 m, and their lengths are 4.5 and 6.8 km, respectively. They are made of shell deposits, silt and sand. The islands were formed over the recent centuries through a process of accumulation and deposition, as well as a slow, progressive shallowing of the gulf.

Fig. 5.24 Distal part of the Yeiskaya spit

Fig. 5.25 The Glafirovskaya spit

Fig. 5.26 The Glafirovskaya spit root

The southern and northern shores of the liman, being the border of the Kuban valley, are steep, with a trend of erosion during strong storms. The western and eastern shores are flat and made of shell deposits, as well as sand and silt carried by the Yeya River. The sea cliffs of the Yeisk Liman are loess loam and related to the abrasion-landslide type, with a height from 5 to 19 m. Cliffs are cut by ravines and gullets. The width of the beaches is 4–6 m, with 0.10–0.26 slopes. The shore on the Yeisk protrusion is abrasion-landslide, intensively exposed to ablation, weathering and erosion. The bench of the Scythian clays is exposed almost everywhere. Landslides and rockslides progress on the shore cusps of small height, with landslides and soil slips at higher levels (above 18 m).

The erosion of coasts has been registered on the southern shore of the liman, where the Yeisk-Krasnodar railroad runs. Near the village of Shirochanka, the shore is distinctly abrasive, with a clear-cut shore cusp of up to 10 m high and in some places even higher. The steep slope (20–30°) is fully or partially grass-covered and forested. Only in the lower part of it can exposed steep sections of up to 1.5–2 m high be seen in separate areas, but they are localized. Under the slope, there is a beach up to 8–10 m wide adjacent to it, going flatly under the liman's edge.

Westward of the Shirochanka village, the shore is a slope of up to 7–8 m high, with an incomplete profile leaning against its base. The beach's width is 1.5–2 m and the surface slope is 4–5°. The beach surface has been upgraded with rubby and boulder material. The slope is 25–35° steep. Its upper part is the slope leading to the railroad track shoulder, here and there fixed with the geo-web with boulder-pebble filler. The lower 2–3 m is a natural slope, the lower part of which is reinforced by the shore protection structures in the form of a retainer wall up to 1.5 m (5.5 km) high and a berm of crushed stone (3.0 km) (Fig. 5.27). The wrecks of some partially destroyed shore protection installations lay on the surface of the beach. There is no beach line whatsoever for a considerable length of the area, the rest of it having a width of 1–5 m. Nonetheless, there are no obvious morphological signs of an active beach retreat in this area nowadays. Such shore protection installations have provided stability for the shoreline for 40 years already. The coast slope is currently 80 % covered with grass, whereas, in the neighboring unprotected section, the edge of the abrasive cusp has retreated by 20 m (Kosyan and Krylenko 2007).

Further on to the west, for quite a long length, the shore is relatively homogeneous. Only fluctuations in the width of the beach can be registered, which, in some areas, disappears altogether. In such areas, destruction of the retainer walls is especially noticeable. As we approach the root of the Yeisk spit, the height of the coastal cliffs is decreasing, whereas the width of beaches and the apparent thickness of accumulative

Fig. 5.27 The storm wall and the rockfill blanket erected to protect the railway track at Shirochanka village

bodies are growing. At a height of no more than 2.5–3 m, the steepness of the slope does not exceed 10–15° and there are no traces of its current degradation. The beach adjacent to it has a width of 10–15, and in some places even more meters, and is formed mainly by anisomerous sand with a high content of shelly detritus.

An artificial shingle beach 1 km long has been built on the southern shore of the Gulf of Yeisk near the village of Alexandrovka (Fig. 5.28). The shores were reinforced in the early 1990s to stabilize the shoreline and create a recreational beach. The beach is stable; it has a width of 15 m and protects the shore against abrasion (Kosyan and Krylenko 2007).

In the eastern and northeastern parts of the liman, the shores are relatively stable. Loamy cliffs are separated from the edge by a reedbed (Fig. 5.29).

Transparency of the liman waters depends on the wave phenomena, and at middle depths of 0.6–1.5 m, constitutes about 100 %. In the western part of the liman, with depths increasing up to 3–3.5 m, transparency is reduced to 80 %.

It is mainly marine sodium chloride water that makes it to the Yeisk Liman, with an average mineralization of 11–12 g/kg, and, to a lesser extent, river water during flooding, hydrocarbonate-calcium water of medium mineralization of 0.42 g/kg. The water's salt content decreases in summer and increases in winter, up to 5–8 ‰. The mean concentrations of nutrients are as follows: phosphorus, 71.4 mg/m^3; nitrogen, 900–990; silicic acid, 710–750 mg/m^3. In periods of high floods, the Yeya River waters pour into the liman and have a high mineralization degree (3000–8000 mg/dm^3) (Mishchenko 2006).

The Yeisk Liman is of significant value for fisheries. The main commercial species are: Azov roach, pike-perch, young fish of sturgeon and stellate sturgeon. Commercial fishing (32 tons/year) is ongoing within the water area of the reservoir. It is also the place that the young sturgeon grow. In recent decades, a significant reduction in the volume of the Yeya River water entry, used for irrigation farming, has resulted in the salinization of the Yeisk Liman, causing a degradation of flora and fauna species and a general reduction in the ecosystem's productivity, especially the fish capacity of the water basin.

Fig. 5.28 An artificial shingle beach near the village of Aleksandrovka

Fig. 5.29 The typical view of the shore in the northeastern part of the Yeisk Liman near the village of Nikolaevka

5.5 The Lagoons of the Kerch Strait

The shoreline of the Kerch Strait that connects the Black and Azov seas is extremely curved, with deep bays and sharp capes. Its geological structure, tectonic processes, and fluctuations in sea level have resulted in the destruction of the sea shore over a considerable length, but also contributed to the formation of large accumulative pieces of land – the Chushka and Tuzla spits. The creation of accumulative lands has cut the shoreline in even stronger fashion, separating shallow bays – the Dinskoi and the Taman – from the Kerch Strait (Fig. 5.30). Dinskoi Bay is relatively small and covers an area of approximately 2000 ha. Its northern and southern shores have a height of 10–12 m; the eastern one is low-lying and sandy. From the west, the bay is limited by the Chushka spit; in the south, it is adjacent to Taman Bay. Taman Bay has depths of 3–5 m. From the Kerch Strait, it is separated by the Chushka and Tuzla spits. The shores are formed of soft rock, which, for a long time, has been destroyed by the sea. All along the Dinsko-Taman shoreline, the bottom is silty and only at the exit point of Taman Bay does it turn into sand and shell.

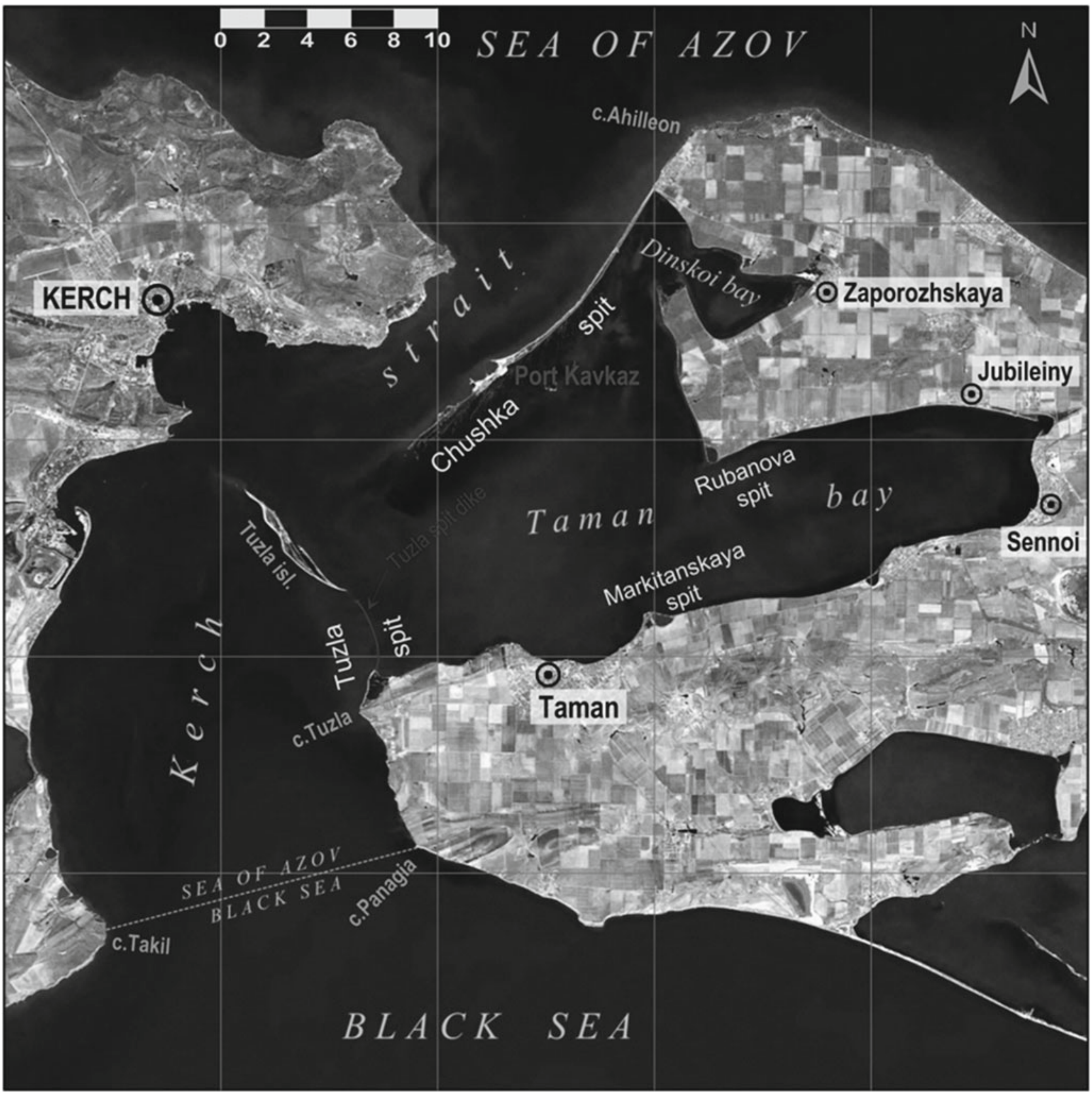


Fig. 5.30 Satellite survey plan of the Kerch Strait

The intricate stream regime of the Kerch Strait, a degraded water exchange with the sea, formed unique lagoon ecosystems, substantially different from those of the Azov and Black Seas. The availability of a wide range of environmental conditions in a small territory contributed to the formation of unique aquatic and terrestrial biotic communities. Although these bays are still connected to the sea, their hydrologic, geochemical and biological features suggest that they can be regarded as lagoons.

The temperature regime of the lagoon waters is determined by the water exchange with the Sea of Azov and the Black Sea. Temperature fluctuations within Taman Bay exceed 15°. In summer, the water temperature near the shore often reaches 28°.

The salinity in Taman Bay is influenced by the fresher waters of the Sea of Azov and the saltier waters of the Black Sea. The salinity of the Black Sea surface waters is 17.8‰. The average salinity of the Sea of Azov is 12.37‰. The evaporation rate over Taman Bay's lagoon is 998 mm/year. Since there are no major surface stream flows running into the bay, the freshwater balance in the bay is negative and constitutes 558 mm/year. Given that the acreage of the bay is about 336 km^2, the freshwater deficit amounts to 0.187 km^3. The water deficit is compensated for by the inflow of salt water (originally coming from the Black Sea) from the Kerch Strait.

There are two major accumulative forms on the eastern shore of the Kerch Strait – the Chushka spit in the north of the strait and the Tuzla spit in the south. The Chushka spit's sediment nutrition comes from the Sea of Azov, the Tuzla spit's nutrition comes from the Black Sea (Nevessky 1967). A gradual erosion of these accumulative forms has been observed over the last century. A reconstruction of the palaeogeographical conditions of the shore in question suggests that the end of growth or abrasion of accumulative littoral forms in the region is the natural trend of their present developmental stage.

At its southwestern part, Taman Bay is separated from the Kerch Strait basin by a major accumulative form, the Tuzla spit. This spit is formed of quartz sand, pebbles (coming from the cliff being destroyed) and shells. In the southern part of Taman Bay, the sediment stream flows in a southwest direction. The sediment stream from the Taman Bay lagoon is weak, because there are no nutritional sources: the share of the beach-forming material as a result of the abrasion of the cliffs is not significant, and wave energy is not enough to move the sand from the bottom. So, the alongshore sediment stream, which feeds the Tuzla spit from Taman Bay, is not enough for the spit's nutrition.

The nutrition of the Tuzla spit by sediments currently comes mostly from the south. The shore here is a smooth arc, limited on the west flank by Cape Tuzla, and in the east, by Cape Panagia. The Tuzla spit's nutrition from the Black Sea is currently degraded and is mainly the result of biogenic material.

With the growth of the bench width, the number of incoming sediments has gradually reduced as the bedrock coast abrasion process has slowed down. Sediment deficit was accompanied by increasing ablation and a narrowing of the near-root part of the spit. Analysis of old maps reveals that the above water part of the Tuzla spit has periodically split into separate parts. During the heavy southern storm of 1925, the spit was cut at the Taman shore, the ablation was progressing, and eventually, its distal part would be turned into an island separated from Cape Tuzla by a wide strait. At its near-root part, the spit split into separate shoals, inundable during the level rise. In 2003, the spit was reinforced by a stone dike (Fig. 5.31). The Tuzla spit was restored by rockfill material, mainly of bryozoan limestone. The total length of the restored spit's body is 3.8 km, the width of its underwater part is 44–48 m, and above-water, 20–28 m. The elevation of the spit body over the water's edge is 3.0–3.5. Comprehensive studies conducted in 2004–2005 showed that accumulative bodies in the form of spits and beaches with a width up to 15–25 m were forming around the spit. Underwater and above-water accumulative forms are composed of sand, shells and marly rusty pebbles. In addition, the material needed to rebuild stone dykes of varying size, from boulder to gravel, is present in the swash zone sediments. Effects of the spit on hydrodynamic conditions are manifested in the increase of alongshore currents from the Black Sea side and of currents between the island of Tuzla and the spit; and, contrastingly, in the formation of the still zone from the side of Taman Bay, particularly in the near-root part of the spit. The spit with the dyke is now the western border of Taman Bay. Restoration of the spit has significantly reduced the water exchange between Taman Bay and the Kerch Strait and has aggravated the differences between their ecosystems.

From Cape Tuzla to the village of Sennoi (southern shore of Taman Bay), shores of abrasion-landslide and abrasion-slip-off types alternate. Geomorphology-wise, the shore is an abrasion-denudation zone, complicated by landslide-slip-off processes and erosive channels of temporary water streams, as shown in Fig. 5.32. Quaternary sediments prevail in the shore structure, represented mostly by dense Neogene clays. Over much of the sea cliff (the average height is 12–15 m, sometimes reaching 23–27 m), it has an almost vertical profile with an expressed wave-cut niche; width of the beaches, for the most part, does not exceed 3–5 m. The main reason for abrasion is the trimming of the cliff base by storm waves, especially during positive surges, slope erosion and rainwash. The sea cliff retreat rate is estimated at 0.3–1.0 m a year.

To protect the shore and the objects on it, coastal protection of a 5-km long section was carried out in 2011–2013.

Fig. 5.31 Tuzla spit dike

Along with this coastal protection, construction and landscaping of the embankment took place, as well as a beach upgrading (Fig. 5.33).

On the northern shore of Taman and Dinskoi Bays, and at the root of the Chushka spit, the predominant type of shore is the abrasion shore. The shores are soft rocks, of a height up to 10 m (Fig. 5.34), with topographic lows in the eastern part, where the shore is low and silty and sandy. Taman and Dinskoi Bays are vast, but due to their shallowness, they almost never produce high waves. The bottom is mostly muddy and flat, with a wide strip of tideland along the shore, where the bottom gets exposed over a large area during negative surges (Fig. 5.35). Along the base of the bedrock coast, reed bushes may occur. Bedrock ablation takes place only during positive surges of a storm.

At the bottleneck of Taman Bay, two small spits – Rubanova (to the north) and Markitanskaya (Fig. 5.36) – lie on the opposite shores. These spits are the remains of a baybar (well-expressed, even now, in the underwater terrain), blocking Taman Bay.

In general, the Dinskoi Bay shores feature slow abrasion (up to 0.3 m/year). The shore height varies from 1.5 to 6.0 m. The western shore (the root of the Chushka spit) is subject to moderate erosion. The northern part of the bay near the village of Zaporozhskaya can be marked out separately. The abrasion-accumulative shore here is in a stable condition due to the moderate impact of waves.

The ridge separating Dinskoi and Taman Bays is being eroded by waves only slightly. Dinskoi Bay shores retreat at moderate rates of 0.3–1 m/year. Abrasion here is intensified by negative\positive surge level fluctuations. The shoreline from the root of the ridge to the Rubanov spit is characterized by a change of the abrasion areas into abrasion-accumulative stable areas.

The shoreline of Taman Bay from the Rubanov spit to the village of Jubileiny is being exposed to slow abrasion of up to 0.3 m/year. The bay between the villages of Jubileiny and Sennoi is abrasion-accumulative. The shoreline from the village of Sennoi to Cape Tuzla features alternating low and moderate abrasion of 0.3–1 m/year. Only on the Markitanskaya spit has accumulation been observed that is due to changes in the alongshore currents from the Markitanskaya to the Rubanov spit.

The eastern shore of the Chushka spit is almost entirely composed of multiple small islands and peninsulas, completely covered with semi-aquatic vegetation (Fig. 5.37). In fact, all these forms are dead distal wings of the spit, formed in different phases of its growth. This beach of the spit is generally stable. No traces of modern erosion or accumulation have been observed here.

The root part of the Chushka spit began to be strengthened in 1947. In all, 140 dike dams have been constructed along a total of 11 km of shoreline. At present, most of them have deformations, but they hold back a sandy beach 10 m wide (Fig. 5.38). The lithodynamics of the spit changed after

Fig. 5.32 Southern shore of Taman Bay: *top* – view towards Cape Tuzla; *bottom* – view towards Taman village (Photo by V. Peshkov)

the construction, in 1954–1955, of protective structures in Port Kavkaz. Construction of a chain of dunes and a protection breakwater pier in the harbor led to the accumulation of sediments in the central part of the spit. To the south of Port Kavkaz, the shore, completely devoid of a supply of sediments, underwent erosion. Beach material was washed out to the south and deposited on the distal part of the spit.

Almost all littoral landscapes feature low-lying terrain. Individual elevations (with a maximum height of 164 m above sea level) are active or extinct mud volcanoes. The surface of the coastland is formed out of deltaic and alluvial sediments underlaid by Neogene and Paleogene marine sediments.

Psammophilous, halophilous and hydrophilous vegetation communities can be found on the shores of the bays (Fig. 5.39). In some littoral areas, typical wetland vegetation, such as common reed grass, mace reed and sedge grass, can be found (Mishchenko 2006). The entire water area of the

Fig. 5.33 Coastal protection of a Taman Bay shore section near Taman village, *top* – before the work start; *bottom* – during the work (Photo by V. Peshkov)

Kerch Strait lagoons serves as the main route of mass flights, wintering and molting of waterfowl. The Kerch Strait is located on an intensive migration route of birds, running along the shores of the Azov and Black Seas. Up to one million birds stop here en route. The role of this area as a breeding ground for birds is very significant; this is the place for the reproduction of the wading bird species listed in the Red Books of the Russian Federation and of the Krasnodar

Fig. 5.34 Northern shore of Taman Bay (Photo by V. Krylenko)

Fig. 5.35 Dinskoi Bay shore with a wide strip of tideland (Photo by V. Krylenko)

Territory (Mishchenko 2006). The area is one of the centers of waterfowl wintering, the value of which only increases in particularly cold winters, when the limans of the Eastern Azov freeze.

The role of the area as a habitat for marine mammals should be noted separately. Taman and Dinskoi Bays are home to bottlenose dolphins, the subspecies listed in the Red Books of the Russian Federation and of the Krasnodar Territory.

A protected natural area – the Taman-Zaporozhye strict nature reserve – covers the water area and shorelines of Dinskoi and Taman Bays. It was organized in 1968 for the protection of waterfowl. Economic activities within its boundaries are minimized. Taman and Dinskoi Bays are included on the "Shadow List" of wetlands of international importance (wetlands entered into the Perspective List of the Ramsar Convention). The territory and water area of the nature reserve along the railway, harbor and oil tank farm of Port Kavkaz on the Chushka Spit are characterized by a strained geo-ecological condition.

Over the last decade, geopolitical events began to impact the development of the Kerch Strait lagoons. Construction of a dam to restore the Tuzla Spit after it had been shattered by the sea was the result of geopolitical events of 2003–2004.

Fig. 5.36 Accumulative forms with specific vegetation on the northern shore of Taman Bay (Photo by V. Krylenko)

Fig. 5.37 East shore of the Chushka spit (from Dinskoi and Taman Bays) (Photo by V. Krylenko)

Nowadays, the reconstructed part of the Tuzla Spit (Figs. 5.40 and 5.41) is stable even when exposed to strong storms (Vostrikov 2006). Restoring the root part of the Tuzla Spit has greatly reduced the impacts of the Black Sea on the ecosystem of Taman Bay (Peshkov 2004).

Geopolitical events of the past couple of years have also necessitated the construction by Russia of a combined (road and rail) bridge across the Kerch Strait. Its construction is expected to be set firmly in place using the largest accumulation forms of the strait, either from the Chushka Spit or along the axis of the artificially restored Tuzla Spit, which is likely to have an impact on the ecosystems of the Kerch Strait lagoons.

One of the protection measures might be to give the Kerch Strait (including not only all the water areas of Taman and Dinskoi Bays, but the adjacent areas of the seashore as well) the status of the Ramsar parks. Within the protected natural area, a differential protection mode should be introduced,

Fig. 5.38 The dike dam protects the beach from erosion on the western shore of the Chushka spit (Photo by V. Krylenko)

Fig. 5.39 Vegetation of the littoral accumulative forms of Dinskoi Bay (Photo by V. Krylenko)

duly accounting for natural, historical-cultural, economic and other specific relations of certain of its areas. Delineated functional areas, with due consideration of natural and socio-economic factors, should contribute to the effective protection of the unique natural complex, while retaining the ability to use the favorable geographical position of the region commercially.

5.6 Small Lagoons of the Sea of Azov

In addition to the aforementioned big lagoons on the Azov Sea shore, there are many small lagoon reservoirs: Lake Golubitskoye, Lake Markitanskoe, Solyonyi Liman, Lake Tuzla, Lake Dolgoye, and others.

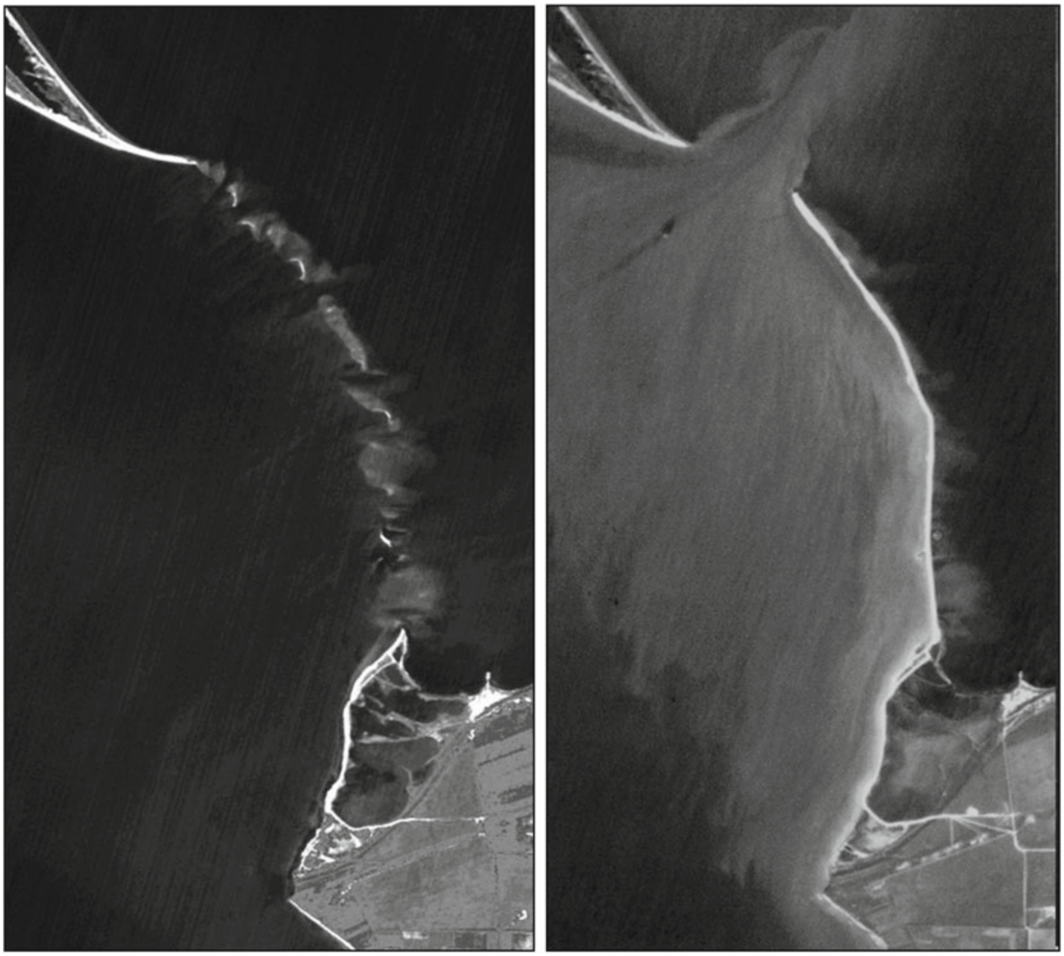


Fig. 5.40 Tuzla spit before and after filling the dike in 2003

Fig. 5.41 Status of the wing dike and the beach at the tip of the Tuzla Spit in 2007 (Photo by M. Krylenko)

Lake Golubitskoye is located in the northwest part of the village of Golubitskaya in the Temryuk District (Fig. 5.42). This is a small saltwater lagoon with a length of about 600 m and a depth of up to 2 m. It is separated from the sea by a sandy shell bay-bar 200 m wide and 1.5–3 m high (Kosyan and Krylenko 2007). With strong sea winds, occurring several times a year, storm waves roll over the bay-bar, adding sea water to the lagoon and, at the same time, bombarding it with sand and shells, thus preparing the die-off. The main value of Lake Golubitskoye is its therapeutic mud, a layer of

Fig. 5.42 Lake Golubitskoye (Photo by V. Krylenko)

which covers almost the entire bottom, with a thickness of 0.25–0.5 m. The mud offers a high content of hydrogen sulphide, high plasticity and uniformity and, as a rule, low contamination. The mud solution contains bromine and iodine, which increases its medicinal properties. Commercial reserves of dirt are about 25,000 tons. The status of a natural monument was assigned and approved for "Lake Golubitskoye" in 1978.

Lake Dolgoye (Sazalnikskoye) is located on the eastern portion of the Gulf of Taganrog, 25 km northeast of the town of Yeisk. This is a shallow saline lagoon, located in the body of the Sazalnikskaya Spit. The lagoon is connected to the Sea of Azov by a periodically functioning channel. Its low-lying shore is predominantly marine shells and silt. Aquatic vegetation has generously developed along the coasts. The water depth in the majority of the water areas does not exceed 30 cm.

5.7 Conclusion

As shown above, the Russian lagoons of the coast of the Sea of Azov are represented by three large groups: the Azov-Kuban Limans, the lagoons of the East coast, and the lagoons of the Kerch Strait, along with many small lagoon ponds. The total number of lagoons is about 250. The largest lagoons are the Beysugsky (272 km^2) and the Yeisk (240 km^2) Limans. Most of the Azov lagoons are shallow water reservoirs, whose shores are covered by wetland and steppe vegetation (Mishchenko 2006). The water of the Azov lagoons is usually brackish.

The location of the lagoons on the border of the land-sea is the cause of their high sensitivity to external impact (natural and anthropogenic) and, as a result, is also the cause of their high dynamics. Process variability in this ecotone zone is predetermined by the peculiarities of its geological structure, and its hydrological, hydrodynamic, hydrochemical and hydrobiological factors. Each factor is characterized by large fluctuations in space and time (Matishov et al. 2014). In general, researches within the Sea of Azov lagoon systems have been realized in the studies of the geography and biota of the Krasnodar region. In addition, in recent years, the special average-winter count of waterfowl populations has been realized within the framework of the project "Wetlands International" for the Central Asian Migrant Path, funded by the Ministry of Agriculture, Nature and Food of the Netherlands (Mishchenko 2006).

Most of the Eastern Azov lagoons are unique natural objects and are part of specially protected natural territories of the Krasnodar region. They have various protected levels, from international to local. The Taman Peninsula, with the Akhtanizovskaya liman system, has been marked as a specific natural area of the Northwest Caucasus by geographers (Kanonnikov 1977) and biologists (Mnatsekanov et al. 1990). It is the most southwestern of the typical variant of the eastern wetland complexes of the Sea of Azov. Near Azov, the lagoon waters are habitats and reserves for rare or commercially essential species of plants and animals.

These waters have favorable conditions for nesting and migrant resting for waterfowl, pelecaniformes, gulls and other birds. Lagoons are important places for the spawning and feeding of young fish. But real protection for these areas is absent, the boundaries have not been accurately defined, and a mode of limitation of economic intake has not been approved. For example, a wetland of international importance, the "Delta Kuban" (Ramsar Convention), has the status of a protected natural area since 1994, but this wetland area has not been zoned. The rules of economic activity and water and land use are not fixed. The wetland protective zone is not defined (Kosyan 2013). Despite the fact that the Azov lagoons are unique coastal systems, many of the lagoons and the surrounding lagoon areas are used for fishery, agricultural and industrial purposes. This leads to a permanent increase in the anthropogenic pressure on the ecosystems

(Artyuhin 1989; Belyuchenko 2010; Peshkov 2003; Kosyan 2013).

The potent realization of the building of hydro-technical port constructions (especially in the lagoons of the Kerch Strait) impacts the lithodynamic conditions of the adjacent shore sectors. It can lead to transformation or erosion of accumulative forms, separating the lagoons from the sea (Kosyan and Krylenko 2014). The agriculture affects on the lagoon are mainly manifested indirectly, through the pollution of the sea and river waters (Gineev 2002; Lucoyanov 2013; Kosyan 2013). Certain sectors (rice agriculture, irrigated agriculture, fish farming) impact the hydrological regime of the Kuban River Delta and the estuaries of other rivers, reducing the amount of fresh water flowing into the lagoons. As a result, a decrease in lagoon depth, a lowering of the water exchange with the sea, and eutrophication have all been observed. In some limans, zones of a sulfated water class uncharacteristic for this region have formed (Lucoyanov 2013). These agricultural sectors can cause substantial damage to the lagoons' ecosystems, because the vitality of freshwater and marine aquatic organisms and waterfowl depends on the hydro-chemical regime of the lagoons.

In recent years, industrial and transportation development in the region associated with the extraction, processing and transport of mineral products, mainly hydrocarbons, has become more and more intense. Permanent pollution of lagoons by hydrocarbons has expanded, and the risk of an ecocatastrophe as a result of operating trouble has increased. It is unlikely, in the coming years, that the economic structure of the coastal regions shall see any significant change. The above factors will remain the greatest man-made danger for the lagoon ecosystems of the Sea of Azov (Lucoyanov 2013; Kosyan and Krylenko 2014).

The multifunctional character of the economic marine activities on the coasts of the Sea of Azov requires legislative regulation of the economic development of the lagoons and surrounding area, determination of permissible anthropogenic load norms and intensification of control of compliance (Bondarenko 2003; Dvortsova 2010). The necessity of a radical revision of previous approaches to the protection of near-coastal areas has been noticed in a number of policy-making organ resolutions, in particular, in the decision of the Government of the Russian Federation of 02.01.1992, № 02 "About immediate measures to protect the Black Sea and the Sea of Azov coasts from abrasion and to improve the ecological state of the coastal resort areas". Unfortunately, at the present time, the rate of development of the coastal water bodies is far ahead of the creation of a legislative base. Mismanagement of natural resources can lead to full degradation of the natural lagoon ecosystems of the Sea of Azov.

To preserve the unique ecosystems of the Eastern Azov lagoons, it is necessary to minimize economic activities within existing protected areas; additionally, the use of economic and technical solutions and environmental protection measures must meet modern protection requirements. The federal law, "About the coastal zone of the seas", including the provisions on the special status of the delta-lagoon coasts, and accountability for the complexity of the natural mechanisms of such systems, are necessary for the success of integrated coastal management (Kosyan 2013; Kosyan and Krylenko 2014).

References

Artyuhin YV (1989) Some features of human evolution of southern seas coastal zone. Southern seas of USSR. Geographical problems of research and development. Nauka, Leningrad, pp 103–110 (in Russian)

Belyuchenko IS (2010) Ecology of Krasnodar region (Regional ecology), Manual. FGOU VPO Kuban GAU, Krasnodar (in Russian)

Bondarenko VS (2003) Regional environmental management in coastal regions. Oikumena, Smolensk (in Russian)

Danilov-Danilyan VI (ed) (1999) Ecological encyclopedic dictionary. Noosphera, Moscow (in Russian)

Dobrovolsky AD, Zalogin BS (1982) Seas of the USSR. Publishing House of the Moscow University, Moscow (in Russian)

Dvortsova EN (2010) Coastal areas: international experience of economic development and management. Russ Foreign-Econ Bull 7:13–18. Moscow: RFTA (in Russian)

ESIMO (2012) Uniform state system of information on a situation in the World Ocean. Dynamic electronic handbook. State Oceanographic Institute. Accessed 18 Mar. www.esimo.oceanography.ru

Gineev AM (2002) Inventory of users of natural resources in Kuban Ramsar reservations. Topical issues of ecology and conservation of ecosystems of the southern regions of Russia and neighboring territories. Materials XV inter-republican scientific-practical conference. Kuban State University, Krasnodar, pp 260–274 (in Russian)

Investigation of the dynamic processes of the Sea of Azov coastal zone and their influence on coast erosion (2005) Report on research work. SB SIO RAS, Gelendzhik (in Russian)

Kanonnikov AM (1977) The nature of the Kuban and the Black Sea regions. Publisher Russian Geographical Society, Krasnodar (in Russian)

Kosyan RD (ed) (2013) Scientific support for the balanced business planning on the unique coastal landscapes and proposals for its use by the example of the Azov-Black sea coasts. Research report. SB SIO, Gelendzhik (in Russian)

Kosyan RD, Krylenko MV (2007) Complex characteristics of a current state of the Sea of Azov coast. In: Ecosystem researches of the Azov, Black and Caspian seas and their coasts 5(9):50–68. KSC Russian Academy of Sciences, Apatity, pp 50–68. V. IX (in Russian)

Kosyan RD, Krylenko VV (2014) Modern status of marine accumulative shores of Krasnodar region and their use. Nauchnyi Mir, Moscow (in Russian)

Lucoyanov VA (ed) (2013) About the state of natural resources and environmental protection of the Krasnodar region in 2012, Report of the Ministry of Natural Resources of Krasnodar Region. The Administration of Krasnodar Region, Krasnodar (in Russian)

Matishov GG, Kolomiychuk VP, Polshina TN (2014) Floral zoning of coastal zones of the Sea of Azov. Bull Southern Res Cent 10(1):55–59. Rostov-on-Don: Publisher SSC (in Russian)

Mikhaylov VN, Magritsky DV, Ivanov AA (eds) (2010) Hydrology of the delta and offshore zone of the Kuban river. GEOS, Moscow (in Russian)

Mishchenko AL (ed) (2006) Wetlands of the Northern Caucasus. Wetlands of Russia, vol 6. Wetlands International, Moscow (in Russian)

Mnatsekanov RA, Tilba PA, Emtyl MH, Solovyov SA, Ivanenko AM (1990) Data about the bird fauna of the Eastern Azov and adjacent territories. In: Proceedings of the XV inter-republican scientific-practical conference: Topical issues of ecology and conservation of ecosystems of the southern regions of Russia and neighboring territories, vol 1. Kuban State University, Krasnodar, pp 155–164 (in Russian)

Nevessky EN (1967) Sedimentation processes in a coastal zone of the sea. Moscow Science, Moscow (in Russian)

Peshkov VM (2003) Coastal zone of the sea. Lakont, Krasnodar (in Russian)

Peshkov VM (2004) About restoration of the Tuzla spit. In: Proceedings of the XXI international conference on "Coastal zone of the sea". Publisher KubSU, Krasnodar, pp 190–194 (in Russian)

Pogorelov AB, Antonenko MV (2010) The monitoring of the coastal zone of the seas of Azov by satellite images (district Verbyanoy braids). Sci Kuban 4:29–34. Krasnodar: Video-Press-News (in Russian)

Scientific-Technical Report GOIN (1996) Hydrometeorological conditions of the Sea of Azov and Black Sea coasts of Krasnodar region. GOIN, Moscow (in Russian)

Vostrikov AV (2006) Modern methods and technologies of protection of the accumulative coast of the Sea of Azov (on the example of the Yasenskaya Spit). International and domestic technologies of development of natural mineral resources and global energy. In: Proceedings of the Vth international scientific and practical conference. Publisher Astrakhan State University, Astrakhan, pp 196–200 (in Russian)

Yastreb VP, Ivanov VA, Khmara TV (2007) To a question of classification of reservoirs of a land and the sea interface of the Azov and Black seas coast. Hydrophysical institute of NAS, Sevastopol, pp 326–348 (in Russian)

Transboundary Lagoons of the Baltic Sea

6

Boris Chubarenko, Dmitriy Domnin, Svetlana Navrotskaya, Zhanna Stont, Vladimir Chechko, Valentina Bobykina, Vasiliy Pilipchuk, Konstantin Karmanov, Anastasea Domnina, Tatiana Bukanova, Victoria Topchaya, and Alexander Kileso

Abstract

The Curonian and Vistula Lagoons should be considered to be a part of one natural hydraulic system, as they are connected via two branches of the Prgolya River (the Pregolya River proper and the Deyma branch). The catchment upstream of the point of bifurcation of the Pregolya River into these two branches belongs to both lagoons and comprises 14 % and 57 % of the entire catchments of the Curonian and Vistula Lagoons, respectively. Approximately 36–40 % and 60–64 % of the run-off of the Pregolya River discharges into the Curonian and Vistula Lagoons, respectively.

While the Curonian Lagoon has maintained the same environmental conditions over the ages, the Vistula Lagoon experienced considerable anthropogenic modification at the end of the nineteenth century, evolving from a freshwater running coastal lake to an estuarine lagoon with predominant marine influence.

Nowadays, changes in the physical characteristics of both lagoons are mostly expressed in water level and temperature rise. Details of the annual hydraulic cycle and the spatial patterns of salinity, temperature and bottom sediment variability are discussed for the Vistula Lagoon.

Both lagoons are transboundary, belonging to countries with different water management systems (Russia is a non-EU country, Lithuania and Poland are EU countries). Both lagoons are most intensively used for fishing, but the Vistula Lagoon has many other significant purposes as well, especially navigation. As a consequence, there exist numerous potential conflicts between environmental and anthropogenic use, as well as other types of use, of the lagoon area.

Keywords

Coastal lagoon • Baltic Sea • Vistula Lagoon • Curonian Lagoon • Pregolya River • Hydrology • Sediments • Usage • Climate changes • Maritime spatial planning • ICZM

6.1 Introduction

The waters of certain main and medium rivers of the southern and eastern parts of the Baltic Sea catchment do not enter into the Baltic Sea directly, but rather pass through flat, semi-enclosed coastal water bodies, which serve as natural filters for the seaward terrestrial flow of sediments, nutrients and chemical pollutants (Chubarenko et al. 2005b). These are,

B. Chubarenko (✉) • D. Domnin • S. Navrotskaya • Z. Stont
V. Chechko • V. Bobykina • V. Pilipchuk • K. Karmanov
A. Domnina • T. Bukanova • V. Topchaya • A. Kileso
Atlantic Branch of the P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (AB IO RAS), Kaliningrad, Russia
e-mail: chuboris@mail.ru; dimanisha@rambler.ru; navsvet@gmail.com; ocean_stont@mail.ru; che-chko@mail.ru; bobyval@mail.ru; vasex90@mail.ru; mr.pocketoff@rambler.ru; annasta_sea@mail.ru; tatiana.bukanova@gmail.com; piwis@mail.ru; aleksandr.kileso@gmail.com

R. Kosyan (ed.), *The Diversity of Russian Estuaries and Lagoons Exposed to Human Influence*, Estuaries of the World, DOI 10.1007/978-3-319-43392-9_6

Fig. 6.1 Locations of lagoons on the Baltic Sea shore, from West to East along the southern shore (marked by *rectangular frames*): Darss-Zingst Bodden Chain - *1,* Szczetin Lagoon - *2,* Puck Lagoon - *3,* Vistula Lagoon - *4,* Curonian Lagoon - *5,* Neva Bay - *6* (the artificially-made estuarine lagoon in the very northeast of the Gulf of Finland)

from South to North[1] (Fig. 6.1): the Darss-Zingst Bodden Chain (Germany), the Szczetin Lagoon or the Odra Estuary (Germany-Poland), the Puck Lagoon (Poland), the Vistula Lagoon (Poland-Russia), and the Curonian Lagoon (Lithuania-Russia), as well as one recent, artificially-constructed lagoon, Neva Bay (Russia). All of them could be considered estuarine lagoons, where fresh waters mix with the saline waters of the recipient coastal areas of the Baltic Sea. These lagoons (except Neva Bay) occur along the sandy shores of the Baltic Sea: the southern shore and the eastern shore up to the Gulf of Riga.

The range of spatial scale for the main Baltic lagoons is 20–100 km (Table 6.1), while, for example, the similar scale for the Sakhalin lagoons (Far East of Russia) is 10–40 km. The natural depths of the Baltic lagoons are rather limited, with average depths ranging from 2 to 3.8 m, the maximum depth being 5.8 m in the Curonian Lagoon. The water volume, water area and length of the coastal line are in the ranges of 0.34–4.2 km^3, 75–1584 km^2 and 42–560 km, respectively. All the lagoons have regularly maintained navigable canals, with depths of 4–14 m and lengths up to 50–70 km. As tides in the Baltic Sea are negligible, the wind surge is the main forcing factor determining water level variations in the lagoons, with a character range of 1 m in amplitude.

[1]All geographical names mentioned in this chapter are given in order from South to North or from West to East. The names of rivers, in case they have different ones in different national areas, are given in order from upstream to downstream. The country names will be given in alphabetic order.

Table 6.1 Main morphometric characteristics of the Baltic lagoons

	Darss-Zingst Bodden Chain	Szczecin Lagoon	Puck Lagoon	Vistula Lagoon	Curonian Lagoon	Neva Bay
Volume of water body (km^3)	0.397	2.58	0.26	2.3	6.2	1.2
Average area of the lagoon surface (km^2)	197	687	75	838	1584	329
Length of inner shore line (km)	120	560	42	270	324	100
Length of the longitudinal axis (km)	55	75	15	91	95	21
Average lagoon depth (m)	2	3.8	3.5	2.7	3.8	3.5
Maximum natural depth (excluding artificially-dredged, navigable canals) (m)	4	8.5	8	5.2	5.8	7
Maximal depth in artificially-dredged canals (permanently increasing due to intensification of navigation) (m)	4.5	10.5	4.5	10	14	12
Parameter of shoreline development (ratio of the length of lagoon shoreline to a length of the circle having the same area as the lagoon) (dimensionless)	2.41	6.03	1.37	2.63	2.30	1.56

(Data collected by B. Chubarenko from sources, cited in the reference list to this chapter)

The catchment areas of the Baltic lagoons are in the range of 1580–281,000 km^2. The biggest catchments are in Neva Bay, and the Curonian and Szczetin lagoons, which receive drainage from the Neva, Neman and Oder Rivers, respectively. The ration of water area to catchment area is in the range of 0.001–0.125 for all the Baltic lagoons mentioned above. The temperature and salinity regimes are characterized by brightly expressed seasonal variations; all lagoons freeze during winter time.

Thia chapter will focus on the Vistula and Curonian Lagoons, which partly belong to the Russian Federation. Both of these lagoons are transboundary (Chubarenko and Alexeev 2005; Chubarenko 2008). The Vistula Lagoon is shared by Poland and Russia, the Curonian Lagoon, by Lithuania and Russia.

Overviews of the general environmental characteristics of the Curonian and Vistula Lagoons (Fig. 6.2a) were published earlier in (Gasiunaite et al. 2008a, b; Chubarenko and Margonski 2008; Chubarenko 2008). The materials below represent some further extension of the environmental and economic descriptions of these natural coastal water systems.

Responsibility for the text in this section is distributed as following among co-authors: Chubarenko B.V. (Sects. 6.1, 6.2, 6.3, 6.4, 6.5, 6.6, 6.11, 6.12, and 6.13), Domnin D.A. (Sects. 6.2 and 6.10), Navrotskaya S. (Sect. 6.4), Stont Z. (Sects. 6.4 and 6.5), Chechko V. (Sect. 6.7), Bobykina V. (Sect. 6.8), Pilipchuk V. (Sects. 6.3 and 6.6), Karmanov K. (Sects. 6.3 and 6.6), Domnina A. (Sects. 6.9, 6.11, and 6.12), Bukanova T. (Sect. 6.5), Topchaya V. (Sect. 6.7), Kileso A. (Sects. 6.3 and 6.13). The authors thank their colleagues from the Polish and Russian national hydrometeorological agencies for their hard routine work on the collection of data, which was used in the overview, as well as the FP7 project LAGOONS for partial support of preparation of materials included in this overview.

6.2 Drainage Basin of the Vistula Lagoon-Pregolya River-Curonian Lagoon System

The proper catchment of the Curonian Lagoon is 98.2 thousands km^2 (Gasiunaite et al. 2008a, b). It is formed by the Neman River, and fully belongs to Lithuania and Belorus, with one small exception – the part (up to of 900 km^2) constituting the drainage basin of the Sheshupe River, the second biggest southern tributary of the Neman River, which crosses the Kaliningrad Oblast of the Russian Federation.

The Vistula Lagoon (Fig. 6.2b) watershed (23.9 thousands km^2) covers parts of the Kaliningrad Oblast of Russia (to the north) and the Warmian-Masurian and Pomeranian Voivodeships of Poland (to the south). The Pregolya River is the main river discharging into the lagoon; its catchment area is 13.7 thousands km^2. The lower part (49 %) of the Pregolya River catchment is located in the Kaliningrad Oblast of

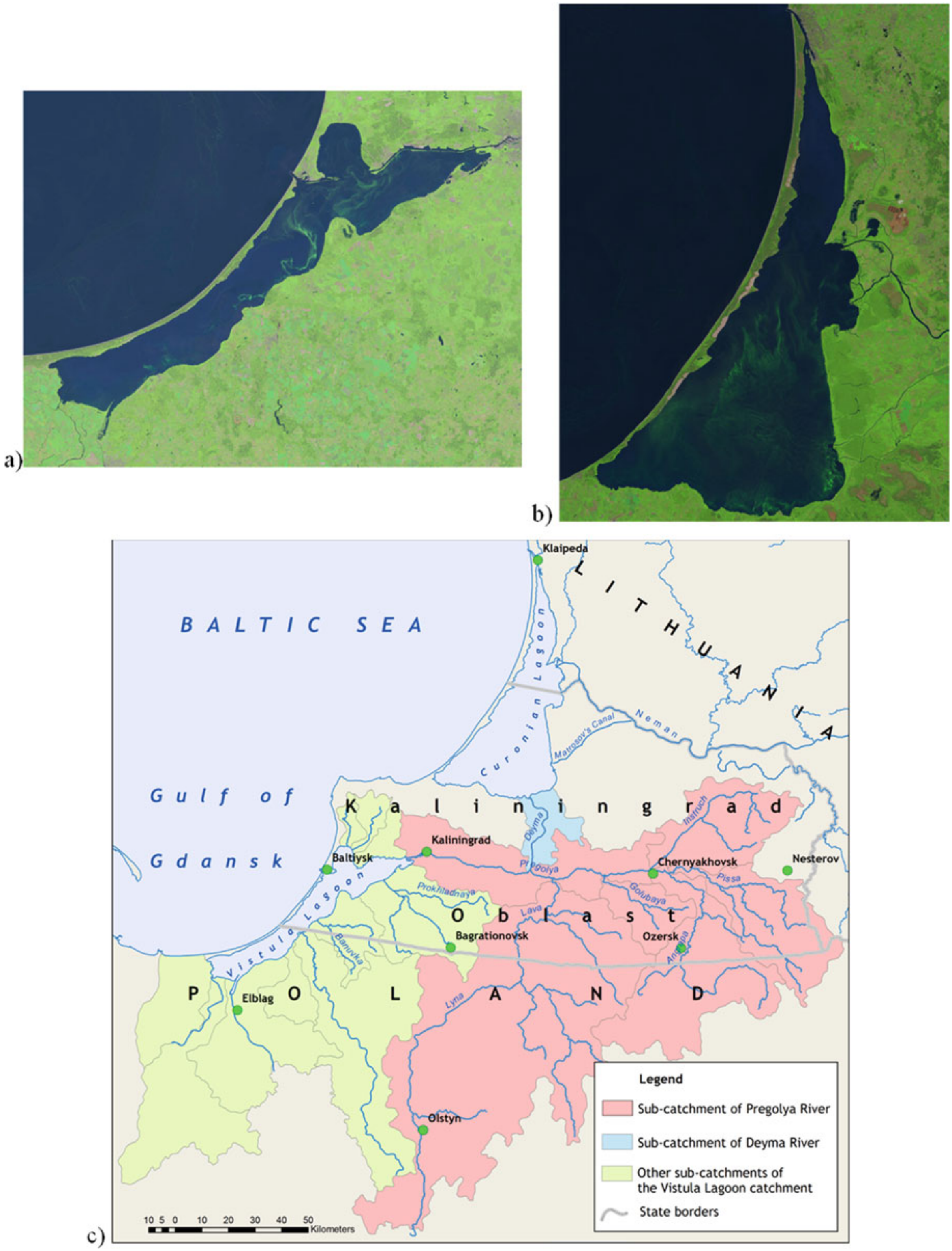


Fig. 6.2 Vistula and Curonian Lagoons: fingerprints of algae bloom are well visible for both lagoons on the Landsat 8 satellite images (**a**, **b**) on 03.07.2015 (USGS 2015); **c** the Vistula Lagoon catchment is connected with the Curonian Lagoon via the Deyma branch. The map was compiled by D. Domnin using the GIS tool on the basis of data about river catchments

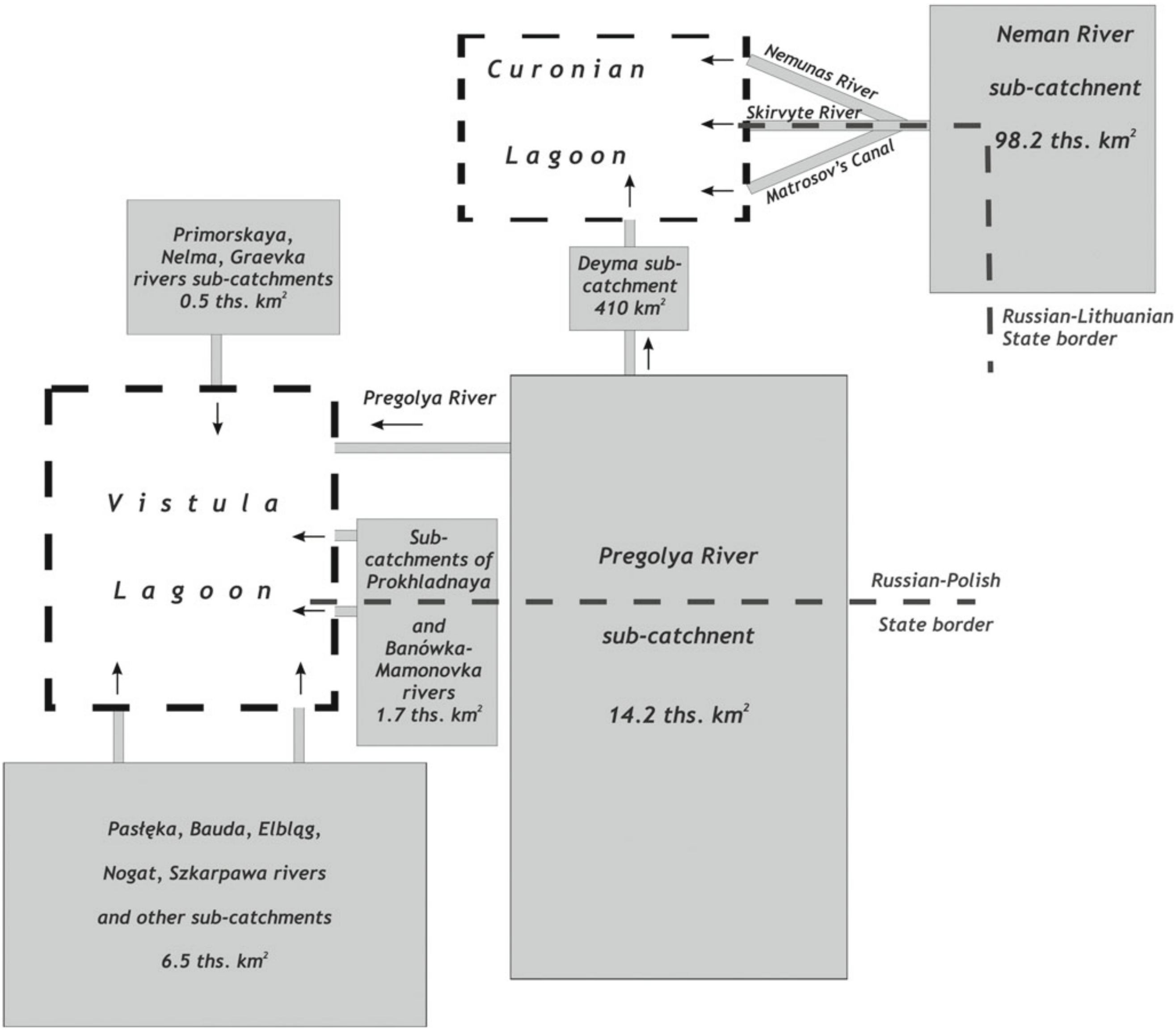


Fig. 6.3 Principal structure of the "Vistula Lagoon – Pregolya River catchment – Curonian Lagoon" system (The scheme was developed by D. Domnin)

Russia and the upper part (51 %), in Poland (Chubarenko and Margonski 2008).

The specific feature of that main part of the Vistula Lagoon catchment, namely the Pregolya River catchment, is that it is partly shared with the Curonian Lagoon (Fig. 6.3). This fact has not been deeply discussed in previous research publications.

Analysis of the watershed structure of the Vistula Lagoon in a transboundary context is given in the Fig. 6.4 (Chubarenko 2008), in which parts of the catchment are shown in relation to the national territories of Lithuania, Poland and Russia.

Constant water exchange between the Vistula Lagoon and the Baltic Sea is realized via the single Baltiysk Strait. 20.5 km^3 of water per year flow from the lagoon to the sea, and 17 km^3 of water per year enter into the lagoon. A difference of 3.5 km^3 of water per year is a river component of the Vistula Lagoon water balance (Silich 1971). Evaporation and precipitation balance each other (both are about 0.6 km^3 per year).

All the main tributaries of the Pregolya River (the Łyna-Lava, Węgorapa-Angrapa, and Pissa Rivers) begin in Poland within the uplands, at an altitude of 150–300 m above sea level. A small part of the catchment (about 90 km^2) is located in Lithuania around Lake Vištytis. Other main rivers discharging waters directly into the Vistula Lagoon are the Szkarpawa River (catchment area of 0.8 thousands km^2), the Nogat River (4 thousands km^2), the Bauda River (0.56 thousands km^2), and the Pasłęka River (2.4 thousands km^2), all of which come from the Polish side; and the Prokhladnaya River (1.1 thousands km^2), the Banówka-Mamonovka River

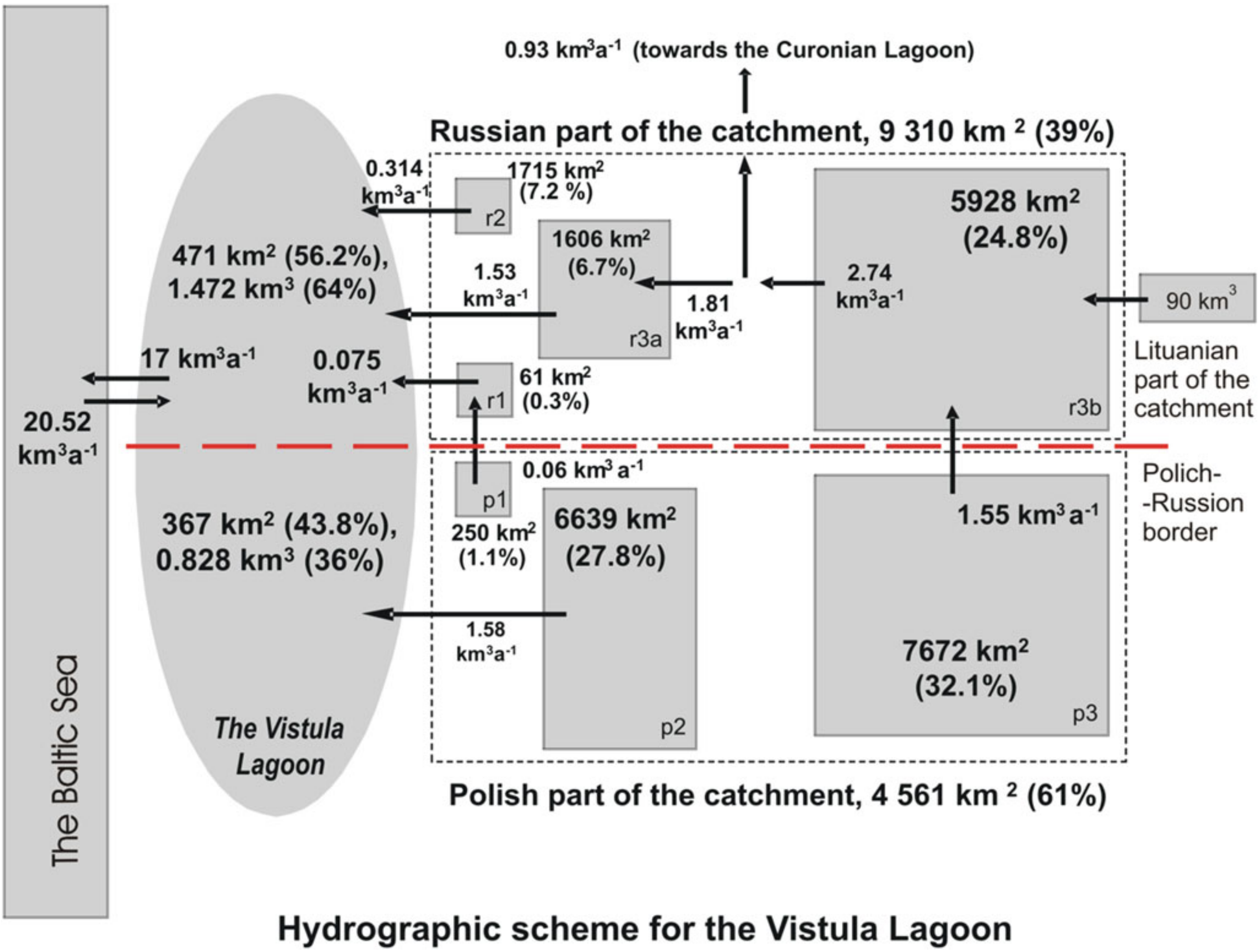


Fig. 6.4 Principal hydrographic scheme of the Vistula Lagoon catchment (Chubarenko 2008). The areas and mean annual discharges (in km^3/year) are indicated for the sub-catchments, as well as the water area and volume for the Vistula Lagoon. The state border divides the Polish (southern) and Russian (northern) parts of the Vistula Lagoon and its catchment. Each national sub-catchment consists of pure national ones, e.g., p2 (the Pasłęka, Bauda. Elbląg, Nogat, Szkarpawa Rivers, etc.) and r2 (the Primorskaya, Nelma, Graevka Rivers, etc.) or transboundary catchments, e.g., p1-r1 (the Prokhladnaya and Banówka-Mamonovka Rivers) and p3-r3b (the Pregolya River and its transboundary tributaries). The Vistula Lagoon consists of two national parts and has one inlet, on the Russian side, connecting the lagoon with the Baltic Sea

(0.3 thousands km^2), the Nelma River (0.2 thousands km^2), and the Primorskaya River (0.1 thousands km^2), all of which discharge from the Russian side.

The Pregolya River proper brings about 1.53 km^3 of water per year to the Vistula Lagoon (it is 44 % of the full discharge coming from the lagoon drainage basin), while all the other rivers contribute 1.96 km^3 of water per year to the lagoon (56 %) (Silich 1971).

The mean discharge of the Pregolya River before the bifurcation of the river stream into two branches is 86 m^3/s (or 2.7 km^3/year) (Fig. 6.5). The measured discharges of other rivers entering the Vistula Lagoon are as follows: the Primorskaya River, 0.9 m^3/s, the Nelma River, 1.7 m^3/s, the Banówka-Mamonovka River, 4.3 m^3/s, the Pasłęka River, 14 m^3/s. The Prokhladnaya River, despite its significance in terms of discharge, was never covered by monitoring measurements, so only numerical modeling may help in estimation of its run-off.

The main stream of the Pregolya River divides into two branches at the City of Gvardeysk (56 km upstream the mouth). The Pregolya River proper brings 60–64 % of water to the Vistula Lagoon, and the second stream, the Deyma branch (it is also known as the Deyma Arm or Deyma River), draws about 36–40 % of the water volume to the Curonian Lagoon (Markova 1999). Under the extreme conditions of western winds, the upstream intrusion of water from the Vistula Lagoon may reach the City of Gvardeysk and enters the Curonian Lagoon via the Deyma branch. Therefore, it is actually two lagoons (the Vistula and the Curonian) and the Pregolya River that form a combined natural hydraulic system, in which the proportions of discharge of fresh water to both lagoons are regulated by conditions of the water level (dependent on winds) in each of them.

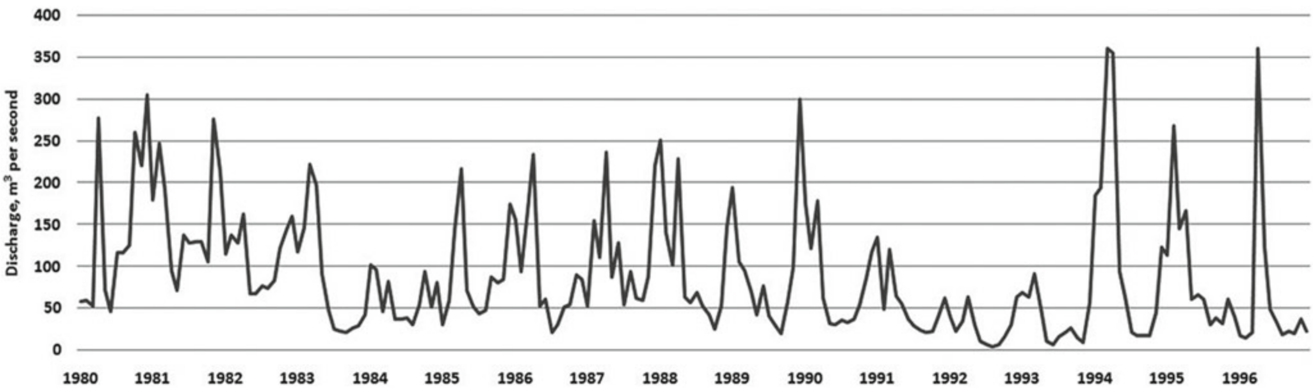


Fig. 6.5 Monthly average discharge (according to data of the Russian Hydrometeorological Service) of the Pregolya River for the period of 1980–1996, measured at the hydrological section in the City of Gvardeysk, which is located just before the bifurcation of the river stream into two branches – towards the Viatula and Curonian Lagoons

6.3 Environmental Conditions of the Curonian and Vistula Lagoons

6.3.1 The Curonian Lagoon

Gasiunaite et al. (2008a, b), the largest lagoon in Europe, is shared by Lithuania (Klaipeda County, northern part of the lagoon) and the Russian Federation (Kaliningrad Oblast, southern part of the lagoon). The Curonian Lagoon is a highly euthrophied, nearly total freshwater coastal water body, connected to the South-Eastern Baltic by a single inlet – the Klaipeda Strait (400 m width). The lagoon's water circulation is determined by the wind and the discharge of the Neman River, and seawater intrusions are frequent and irregular, and penetrate only into the deepest area, the Klaipeda Strait, the total area of which is used as a deep water harbour (Port of Klaipeda 2015). The main bottom sediments in the lagoon are sand and silt. The northern part of the lagoon acts as a transitory area for river sediment transport, while the central and southern parts are mostly heterogeneous in respect to bottom geomorphology and sediment type. Muddy bottoms occur in local depressions in the deeper, western part of the lagoon.

The lagoon area is 1584 km^2 and mean depth is approx. 3.8 m; the Klaipeda Port area, which covers the Klaipeda Strait, has been artificially deepened down to 14 m depth.

The Curonian Lagoon (Fig. 6.2) has a triangle shape of about 100 km length (from south to north) and up to 40 km width along the southern shore. Water currents in the central and southern parts of the lagoon are mainly determined by the wind, which creates different circulation sub-systems: a dominant gyre with an anticlockwise direction (during winds from the west) and one that is clockwise (during winds from the southeast), as well as some additional small gyres. In the case of southwest winds, the circulation pattern is characterized by a two-gyre system (Razinkovas et al. 2005).

The hydrological regime of the lagoon is generally determined by river discharge (23 km^3/year) and marine water inflow (about 5 km^3/year). The maximum amount of river discharge (40 % of the annual amount) occurs during the spring months. Intrusions of Baltic Sea water, with salinity of 6.5–7 psu and durations of half-to-six days, usually happen in autumn. Seasonal variations in water temperature range from 0 °C under ice during the winter up to 25–29 °C in summer. Temperature stratification of the water column is weak, and ice coverage is present for a period of 2–3 months. High temperature is a trigger of anoxia, which takes place in summer, usually at night, and is most probable in the southern part of the lagoon (Gasiunaite et al. 2008b).

Winter and early spring are characterised by highest concentrations of nutrients. Phosphate concentrations drop rapidly in April and regenerate quickly in early summer, and nitrogen concentration could decrease down to nearly zero in May, while ammonium concentrations have no pronounced seasonal pattern (Gasiunaite et al. 2008b).

6.3.2 The Vistula Lagoon

Chubarenko and Margonski (2008), Chubarenko (2008) is located on the southern shore of the Baltic Sea (Fig. 6.6). It is oriented along the Baltic shore and has an elongated shape ca. 91 km in length. The width of the lagoon varies between 2 and 11 km. The average volume and water surface area of the lagoon are 2.3 km^3 and 838 km^2, respectively. The average lagoon depth equals 2.7 m, and the maximum depth, excluding the artificially-dredged navigable channel, is 5.2 m. The state border between Russia (Kaliningrad Oblast) and Poland divides the lagoon into two parts, which occupy 64 % and 36 % of the water volume and 56 % and 44 % of the lagoon area, respectively. The length of the lagoon's coastal

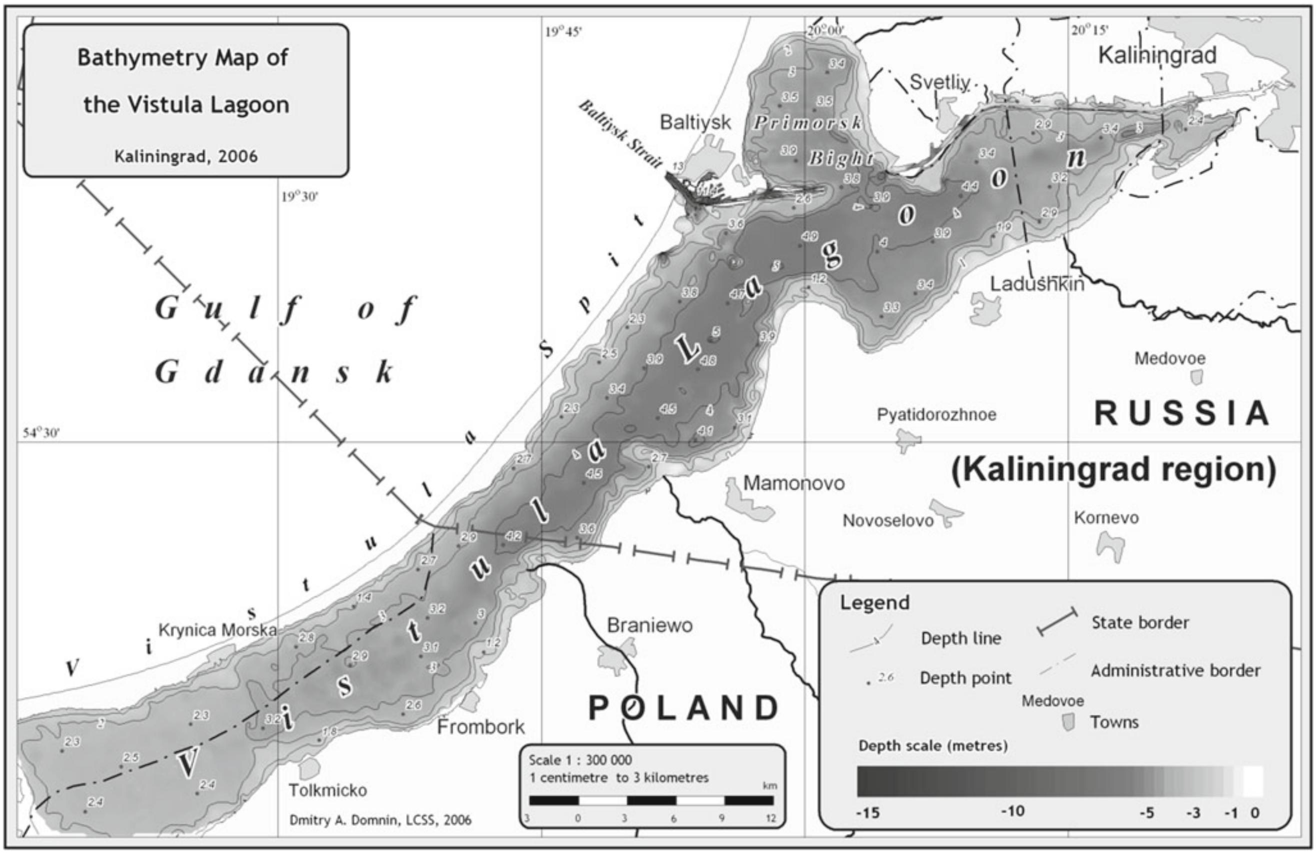


Fig. 6.6 Bathymetry of the Vistula Lagoon (Made by D. Domnin using data available from navigational charts of different scales)

line is about 270 km (111 km belonging to Poland, and 159 km belonging to Russia) (Lasarenko and Maevskiy 1971).

The Baltiysk Strait (referred to in some papers as the Baltic Strait), with a width of 400 m, is the single lagoon inlet connecting the Russian part of the lagoon with the Baltic Sea. Its depth varies between 10 and 12 m on average along the fairway, and the limited minimal vertical inlet cross-section has an area of ca. 4200 m^2. The navigable channel built in 1901 (nowadays, officially referred to as the Kaliningrad Seaway Canal) connects the Baltiysk Strait and the Pregolya River mouth, passing along the northern coast of the lagoon. The depth of the canal varies between 9 and 12 m along the 35 km length. The canal is separated from the lagoon proper by a set of artificial islands with narrow passes between them (the width is ca. 20–50 m, and the depth is ca. 1–3 m). The canal only has an open segment (ca. 3.5 km long) where it crosses the Primorsk Bight (Fig. 6.6), which is a semi-enclosed bight located in the northern part of the lagoon. The navigational canal is actually a hydro-technical construction where permanent maintenance dredging occurs, and various small harbours and peers are still being developed now. Such a specific configuration of a cannel-lagoon system as exists in the Vistula Lagoon needs a specific combined approach to modelling (Chubarenko and Chubarenko 2003).

The Vistula Lagoon was historically formed as a part of delta of the Vistula River, the total average run-off of which is more than 30 km^3/year nowadays (Andrulewicz and Witek 2002). In former times, the Vistula River discharged ca. 8–9 km^3/year into the Vistula Lagoon through the Nogat branch. The closing of the Nogat branch by lock at Biala Gora in 1915, in fact, turned the natural evolution of the Vistula Lagoon from that of a freshwater running coastal lake to that of an estuarine lagoon (Chubarenko and Chubarenko 2001).

Seasonal salinity changes in the Vistula Lagoon are caused by variations in the balance between marine and river drain influences. The minimum salinity in the lagoon (0.5–4.5 psu) occurs in the late spring, after the maximum of the spring river run-off (usually in March and April). Then, from May until August, salinity increases to 3.5–6.5 psu, the river run-off is very low and the marine influence prevails. In autumn, smooth desalinization starts, and finally, in winter, the ratio between the fresh and salt water inflows is stabilized during ice coverage and the lagoon comes to equilibrium between the salting and refreshing processes. During beginning of winter, the most significant amount of salt enters the water column from the developed ice, mixing it thoroughly, and it may cause an increase in lagoon water salinity of

Table 6.2 Hydrological characteristics and water balance components for the Curonian and Vistula Lagoons

Hydrological characteristics and water balance components	Curonian Lagoon	Vistula Lagoon
Area of the basin (km^2)	100,458	23,870
Water surface area (km^2)	1584	838
Salinity range (psu)	(<0.5)–7.5	(<0.5)–6.5
River discharge to the lagoon (km^3/year)	20.75	3.68
Underground water discharge to the lagoon (km^3/year)	0.02	0.07
Precipitation to the lagoon (km^3/year)	1.28	0.5
Inflow of marine water through the lagoon inlet (km^3/year)	5.07	17
Evaporation from the lagoon area (km^3/year)	0.92	0.65
Outflow to the sea through the lagoon inlet (km^3/year)	26.18	20.6

(Dailidiene and Davuliene 2008; Chubarenko and Margonski 2008)

10–25 % (Chubarenko et al. 2005b). Further the strong stratification is re-established under the ice cover.

Both the **Curonian and Vistula lagoons** belong to the geomorphic class of choked lagoons and the morphologic-hydrological class of non-tidal estuarine lagoons (Davies 1972; Kjerfve 1986; Phleger 1969). They fall into different types according to hydrological-hydrodynamic typology (Chubarenko et al. 2004): the Curonian Lagoon is an example of a freshwater lagoon under the predominant influence of their catchment area, while the Vistula Lagoon, with water of relatively low salinity, is under the predominant influence of the Baltic Sea.

Both lagoons accumulate significant river input and experience irregular but intensive marine water intrusions. Therefore, they exhibit the main hydrological features of an estuary – a mixing of marine and fresh waters (Table 6.2). For the Curonian Lagoon, this is true only for the northern part. The Russian, southern part of the lagoon is nearly completely fresh. The Vistula Lagoon is significantly influenced by intrusions of marine waters. The lagoon inlet and main river (the Pregolya River) are in the northern part of the lagoon, and one may consider the estuarine characteristics to exist mostly in the northern, Russian part of the Vistula Lagoon. The southern part is more conservative in regard to seasonal salinity variations, but still there is a permanent salinity gradient from the remote southwestern part of the lagoon to its center.

According to the index in the stratification-circulation diagram (Martin and McCutcheon 1999), the Vistula Lagoon corresponds to an estuary of type 2, which is partly well-mixed and has flow reversal at depths. The estuary number E_d (Martin and McCutcheon 1999) ranges within 5–10, therefore the Vistula Lagoon may be referred to as the water basin of intermediate type that refers to a variation between the well-mixed and partly-mixed coastal waters. Due to classification (Fischer et al. 1979), an Estuarine Richardson Number for the Vistula Lagoon (the value is a little less than 0.08) shows that its waters are well-mixed, and the vertical variations of its characteristics are negligible. But our data prove that the same Estuarine Richardson Number, estimated not for the total lagoon, but for some of it parts (such as entrance area or certain points of steep gradient in the bottom topography), shows the significance of stratification, and therefore the importance of baroclinic effects on the water dynamics.

The principal differences in the morphometric structure of the two lagoons regardless of their spatial sizes shows that distributions of the lagoon area versus the depth are significantly different (Chubarenko et al. 2002). The Vistula Lagoon is shallower in comparison with the Curonian Lagoon in terms of the portion of the lagoon area representing lesser depth.

Average values of concentrations of suspended particulate matter in the Vistula Lagoon vary between 25 and 66 mg/l (Chubarenko et al. 1998b), whereas they vary between 10 and 85 mg/l in the Curonian Lagoon (Repechka et al. 1980; Pustelnikovas 1998). According to estimations by V. Chechko, both the content of sand in the upper layer of 10 cm of the lagoons sediment and the content of coarse material in the suspended sediments are higher in the Curonian Lagoon in comparison with the Vistula Lagoon. For both lagoons, the content of sand in the sediment averages 54 % and 30 %, respectively. Suspended sediments contain 81 % and 76 % of particles with a size larger than 0.01 mm in the Curonian and the Vistula Lagoons, respectively.

The recurrence of wind with a speed greater than 10 m/s is high at the Vistula Lagoon for total annual wind grades on average, e.g., the recurrence of winds 10–20 m/s are 20.8 % and 10.9 %, and that of winds greater than 20 m/s are 0.15 % and 0.09 % (in the period from the 1950s to the 1980s) for the Vistula and Curonian Lagoons, respectively. This means that the Vistula Lagoon is under more active wind influence than the Curonian Lagoon.

Both lagoons exhibit the significant influence of wind waves. A comparison of potential conditions for wind-wave-generated impact on bottom sediments for the Vistula and Curonian Lagoons was fulfilled by analysis of numerically-simulated annual wind-wave dynamics (Chubarenko et al. 2002). The potential wind-wave impact was parameterized through the "one quarter wave length" criterion (Sly 1978; Floderus 1988) to reveal the case in which wave impact becomes significant in the resuspension of sediments at a given point, i.e., the depth at this point should be less than one quarter of the significant wave length. To quantify this criterion, the fact that the wave potential penetration depth equals one quarter of the significant wave length was introduced in the paper and compared with the actual depth at each point of the numerical grid. Using wind statistics, both impact recurrence and intensity (how often the penetration depth is higher than the actual depth and how much higher it is) was studied.

Results showed the unexpected feature that potential wave impact on bottom sediments is comparatively higher in the deeper Curonian Lagoon than in the Vistula Lagoon, which is shallower. Three factors control wind wave impact on bottom sediments in the Curonian and Vistula Lagoons: wind conditions (A) and such morphometric characteristics (B) as bathymetry structure (B_1) and lagoon shape (B_2). Their combination defines the specific wave fetch distribution over the course of a year, which potentially produces more favorable conditions for resuspension in the deeper Curonian Lagoon than in the shallower Vistula Lagoon. It was further supposed that the deeper water areas located in the southern part of the Curonian Lagoon are maintained by wind wave action, which prevents final deposition of suspended material transported by the Neman River.

The hydrological monitoring in the Russian part of the Vistula Lagoon has been conducted by the Laboratory for Coastal Systems Study of the Atlantic Branch of the P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences (AB IO RAS), starting in 1994. It was designed according to baseline monitoring methodology (Chubarenko 2007b). The monitoring schedule includes regular cruises (once per 1–2 months, during the period without ice), along with the fixed station net (Fig. 6.7). The maximal number (112 samples) of salinity and temperature measurements in the upper and bottom layers were made at the station V01, the minimal (30 samples), at the station V08.

Salinity distribution in the Russian part of the Vistula Lagoon is not homogenous, but rather varies from station to station (Fig. 6.8), by depth (see Sect. 6.5) and in time (Fig. 6.9). The maximum salinity is observed near the lagoon inlet, while salinity drops towards the remote ends of the lagoon. Near the Pregolya River mouth, the minimal salinity at the surface is 0.3 PSU, while the maximal salinity at the bottom is 4.9 PSU, average salinities equalling 2.7 and 2.9 PSU at the surface and bottom, respectively. Near the Polish

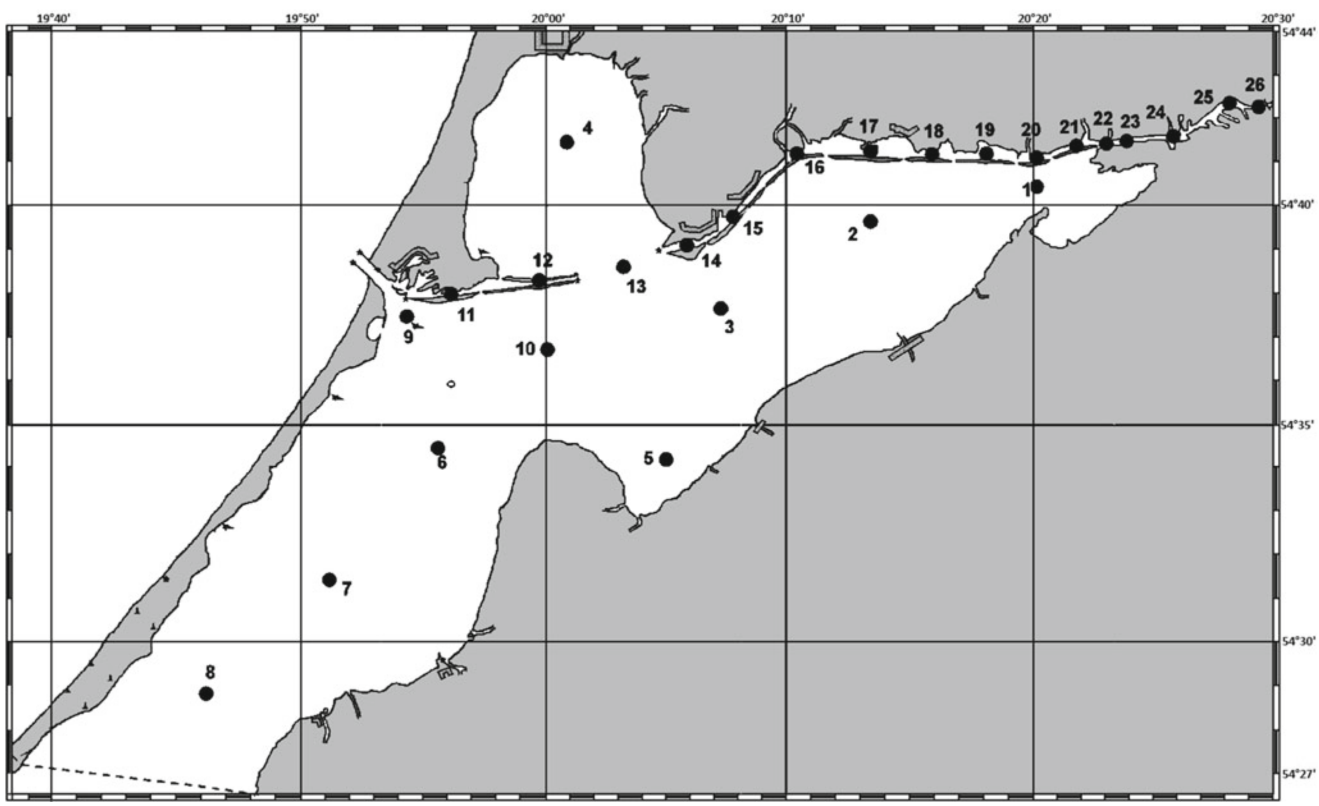


Fig. 6.7 Scheme of stations of the hydrological monitoring program of AB IO RAS in the Russian part of the Vistula Lagoon. All stations shown on the map are referred to in diagrams below as V01, …, V10 (within the lagoon area) and 11, …, 26 (in the area of the Kaliningrad Seaway Canal and downstream of the Pregolya River)

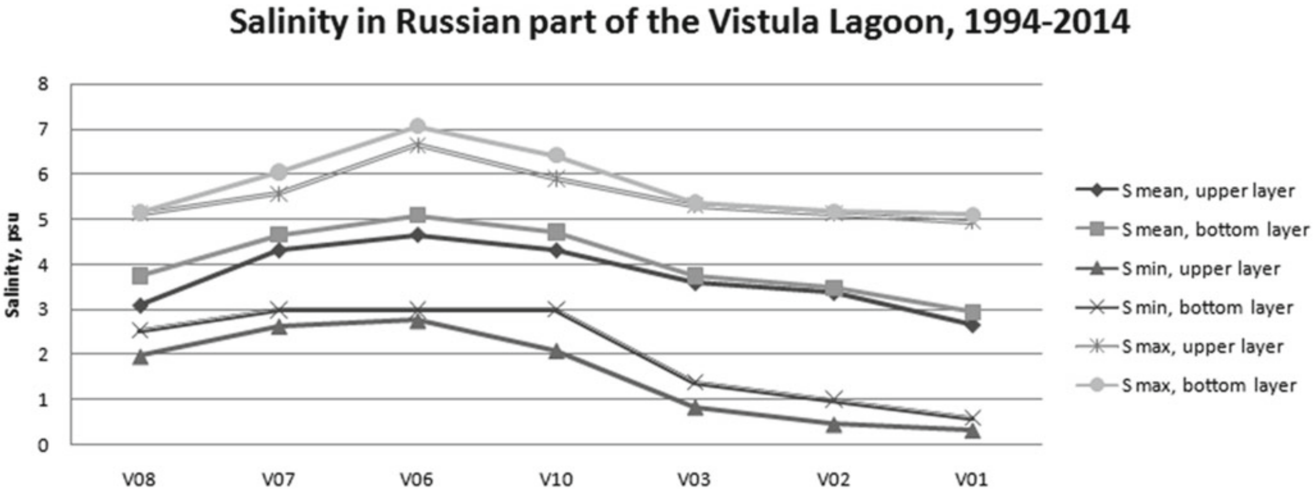


Fig. 6.8 Ensemble mean, maximal and minimal salinity measured at the *upper* and *bottom* layers at the monitoring stations in the Russian part of the Vistula Lagoon during the period of 1994–2014

a) b)

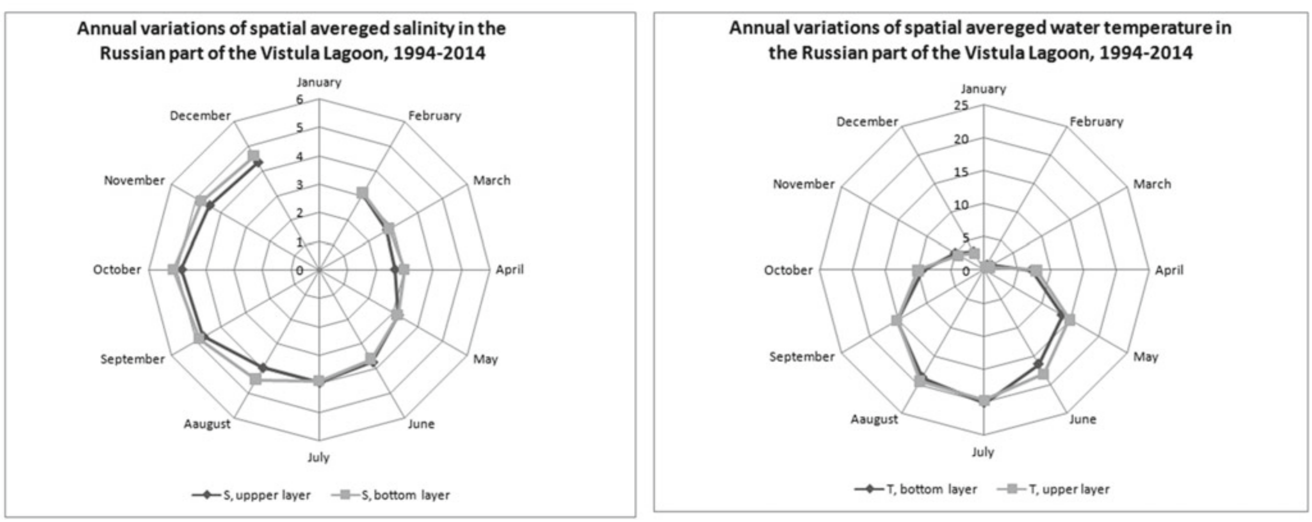


Fig. 6.9 Seasonal variations of monthly values of spatially averaged salinity (**a**) and temperature (**b**) for the ensemble of measurements at the monitoring stations in the Russian part of the Vistula Lagoon during the period of 1994–2014

border (station V08), variations in the salinity are much smaller: average salinities at the surface and bottom are 3.1 PSU and 3.7 PSU, respectively, while minimal salinity is 2.0 psu (upper layer), and maximal is 5.1 psu (upper and bottom layers). The absolute maximal salinity (7.1 psu) was measured at the bottom at station V06 on October 28, 2005, while the minimal (0.3 psu) was measured at the surface layer at station V01 on April 14 of the same year.

The maximal deviation of salinity in the upper and bottom layers was observed at station V10, where it comprises 0.9 psu between minimal values, and 0.5 psu between maximal ones. The waters are stratified in their salinity, but the stratification is not strong: the difference in salinity between the upper and bottom layers is in the range of 15–22 % (17 % on average) of the depth-averaged salinity value.

Seasonal variations in spatially-averaged salinity for the Russian part of the Vistula Lagoon (Fig. 6.9a) shows that the salinity in the bottom layer is higher on average than that in the upper layer for all months of the year. In February–March, May–July waters are well-mixed vertically. The difference between the upper and bottom salinity is 0.2–0.3 psu for the late summer and autumn periods.

The annual dynamics of water temperature (from −0.2 up to 25–26 °C) in the Vistula Lagoon (Fig. 6.9b) are stipulated by solar heating. The horizontal differences in surface temperature between the remote ends of the lagoon are ca. 0.5–0.8 °C.

Active wind mixing results in a mostly homogenous temperature structure in the Vistula Lagoon (Chubarenko et al. 1998a). The maximum temperature is usually observed at the end of July or the beginning of August, and it usually happens 1 and 2 weeks later than the maximum air temperature and the maximum solar irradiation occur, respectively. Ice coverage of the lagoon is not stable. In the coldest years of the 1970s, the permanent ice stayed in the lagoon from December to March, while in warmest years, this period was very short, staying 1–1.5 months (Lasarenko and Maevskiy 1971). Nowadays, the climate has become warmer and years without any ice-cover are not unusual (e.g., winter 2015). Space distinctions and vertical variations in temperature are very insignificant in comparison with the temporal variations (for example, daily temperature variations during summer are ca. 1–1.5 °C on average, with a maximum of 3–4 °C (Lasarenko and Maevskiy 1971)). The high vertical gradients are observed only in the vicinity of the lagoon entrance during the Baltic water inflow, when vertical temperature difference could be up to 5 °C.

Temperature is also not homogenous in the horizontal and vertical directions (Fig. 6.10). Minimal temperature at the upper layer at some stations drops below 0 °C, while at the bottom layers, it always greater than 0 °C. The extreme temperature is usually observed at the V01 monitoring station: the maximal one was 24.7 °C (15.06.1995), the minimal −0.2 °C (21.02.2013).

Differences in temperature between the upper and bottom layers are from 0.2 °C (at station V03) to 2 °C (at station V08), with an ensemble average of 1.3 °C.

Seasonal variations in spatially-averaged temperature for the upper and bottom layers (Fig. 6.9b) shows that, for the period from April to October, the upper layer temperature exceeds that of the bottom layer, but not by more than 1.6 °C. Inverse stratification, when the bottom layer temperature is greater than that of the upper layer, exists in the period from November-February, due to the denser saline bottom waters that come from the Baltic Sea, which is warmer than the lagoon waters, by a difference not exceeded by 0.5 °C.

Annual variations in salinity and temperature are characterized by the one minimum and the one maximum; these maxima are not simultaneous, the salinity maximum setting 1–2 months later than the temperature maximum occurs (Chubarenko et al. 2004). Therefore, annual variation of the TS-index (Fig. 6.11) looks like a clockwise orientated loop.

The time scale of the wind-induced water level rise is equals to the time of long gravity wave propagation. For the Vistula Lagoon, the level rise at its end begins 2–4 h after the wind starts, with the maximum rate of the level rise being established in 5–6 h and the maximum water level being set in 6–12 h during permanent wind blowing (Lazarenko and Maevskiy 1971). As concerns the physical mechanisms, the maximum level rise on the shore of the Vistula Lagoon is caused by the multiple

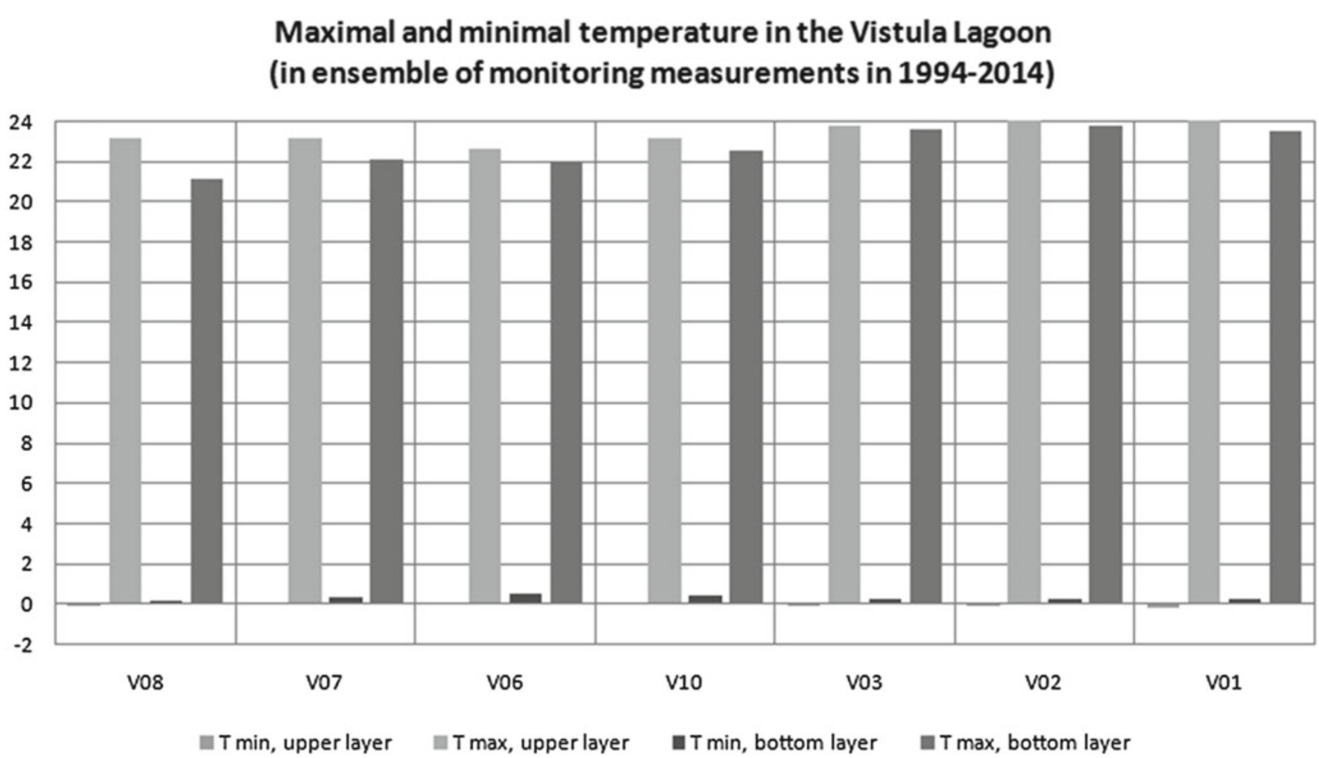


Fig. 6.10 Maximal and minimal water temperature at the monitoring stations in the Russian part of the Vistula Lagoon for the period of 1994–2014

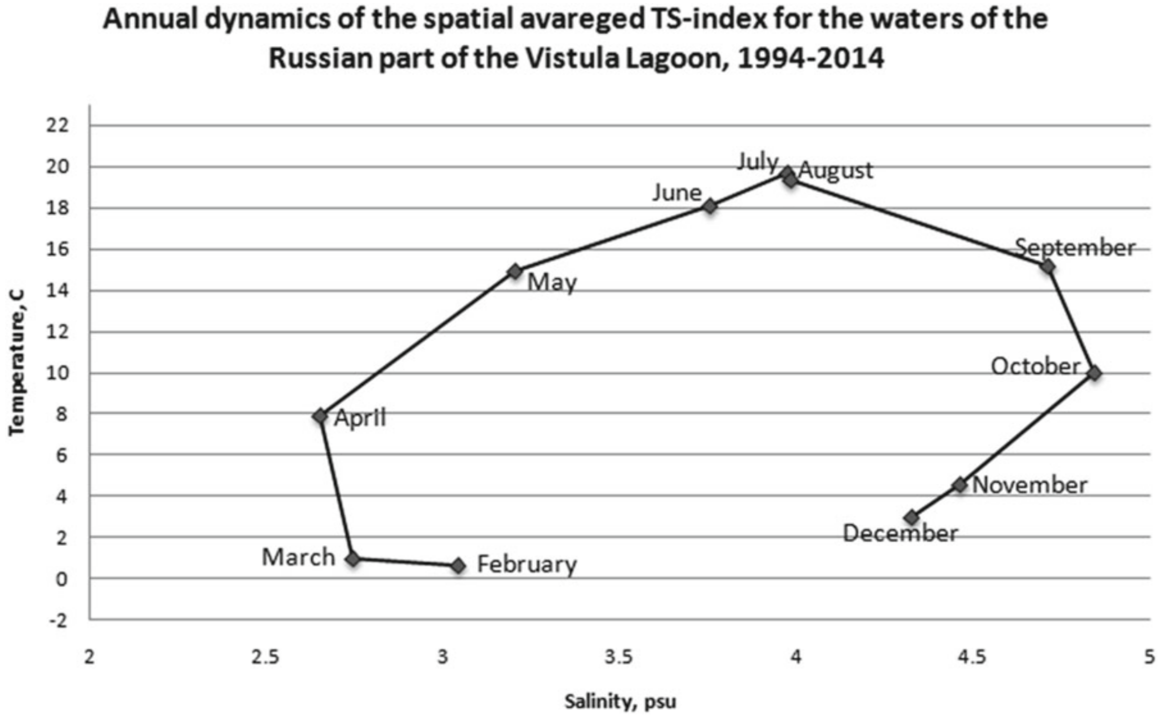


Fig. 6.11 Seasonal variation of spatially averaged TS-index for the Vistula Lagoon. The salinity drop in winter usually happens during the period of intensive autumn rains and ice-coverage

effect of both the level rise in the adjacent Baltic Sea area and the local wind induced set-up. Both of these factors, when they happen, usually contribute to a level rise at remote corners of the Vistula Lagoon in a proportion up to 1:3, respectively. As a result of the lengthwise winds, the water level in the lagoon rises continuously from one end to the other. Due to the fact that the lagoon inlet is (a) located in the central part of the lagoon, (b) has low hydraulic resistance, and (c) the lagoon itself has alongated shape, the level variations along the lagoon could be considered to be the arithmetic sum of the constant level rise at the inlet and the wind-induced level set-up varied along the lagoon. The extreme values of water level rise at the remote corners of the lagoon are ca. 1.3–1.7 m, where 0.9–1.1 m is the contribution of the wind-induced local level set-up. The difference in water levels at both remote ends during a stormy period usually equals 0.5–0.7 m, but could even exceed 1.5–1.7 m (Lazarenko and Maevskiy 1971).

The lagoon bottom deposits consist of the three main types of sediment: medium and fine grained sands (fractions of 0.1–1.0 mm prevail on 30 % of the bottom area), coarse aleurite (0.05–0.1 mm, 22 %), and fine aleurite mud (0.01–0.05 mm, 45 %). The remaining 3 % is represented by aleuropelitic mud (0.005–0.01 mm), shells and pebble-gravel deposits. The muddy sediments cover the deeper parts of the lagoon (more than 2–2.5 m in depth), while sandy sediments are mostly found along the hydrodynamically-active, shallow coastal zone at depths of 1.5–2 m. The greatest amount of coarse sands can be found in the vicinity (1–1.5 km) of the lagoon inlet, where it forms the inner (or reversed) bar inside the lagoon area (the water depth at the bar is 1.5–2 m) (Chechko and Blazchishin 2002). The average lagoon concentration of suspended sediments varies within 4–230 mg l^{-1}, with an average value of 30 mg l^{-1} that is ten times bigger than that found in the Baltic Sea. At any moment, the spatial distribution of the suspended sediments is being controlled by the bathymetric structure, and the maximal concentrations can be observed in the shallow coastal zones. The biotic component comprises 54 % of the total amount of annual average concentration of the suspended matter. Seasonal variations are evident: an abiotic component prevails in windy autumn periods, when it comprises more than 60 % of the total amount (Chechko 2002, 2004; Chubarenko et al. 1998b).

6.4 Local Climate and Water Level Characteristics for the Vistula and Curonian Lagoons

The climate in the southeastern part of the Baltic Sea, where the Curonian and Vistula Lagoons are located (Fig. 6.12), is transitional, going from the marine to the moderately continental, and is characterized by small amounts of annual air temperature variation (~20 °C), high humidity (~80 %), and active precipitation (the annual sum is up to 800 mm).

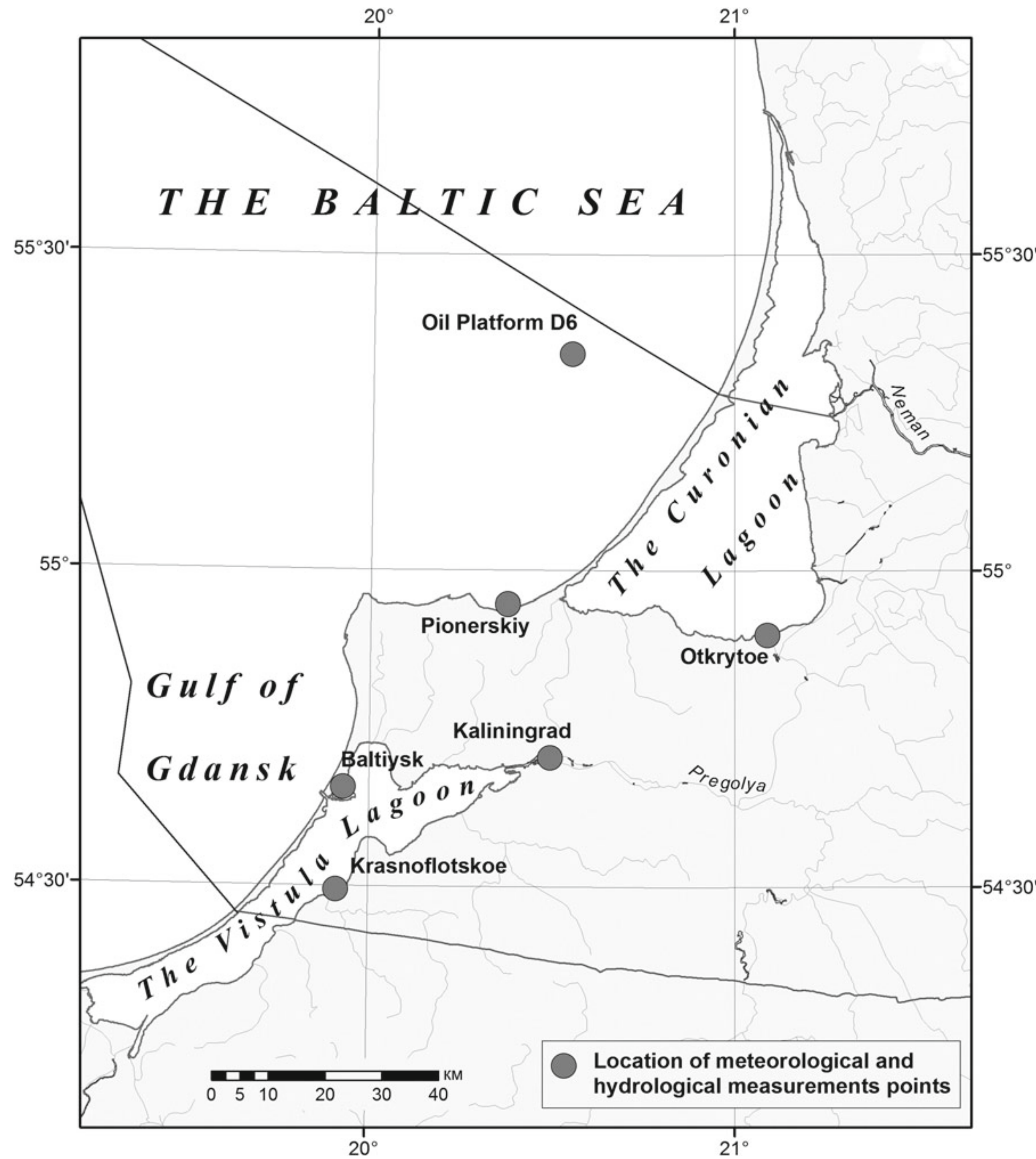


Fig. 6.12 Locations of stations for hydrological measurements of the Russian Hydrometeorological Service in the southeastern Baltic: Baltiysk, Kaliningrad, Krasnoflotskoe (in the Vistula Lagoon), Otkrytoe (in the Curonian Lagoon), and Poinerskiy (open shore of the Baltic Sea). Measurements at point D-6 (an oil platform) are fulfilled by the Luckoil Company. *Lines* show the state borders of the Russian area (Kaliningrad Oblast)

The radiation balance is positive from April to October. Its mean-annual value fluctuates in a range from 1500 to 1630 MJoul/m^2 a year. The annual value of the sum of solar radiation varies from 3400 to 3450 MJoul/m^2 (Barinova 2002).

Western and southwestern winds prevail in the area, their speed increasing during cold periods. Winds from the southwestern quarter prevail in particular, the wind strengthening the more westerly its direction (Fig. 6.13).

The largest number of days a month with cloudy weather occurs in December, at a count of 20; the lowest (7–10) occurs in June. Fog occurs in every season; in the heating period, it is marine fog; in autumn and winter, the fogs are due to evaporation. The largest number of days manifesting fog occurs from December to March; the lowest, from June to September; their repeatability may go up 20–25 % in particular months. The quantity of precipitation is around 700

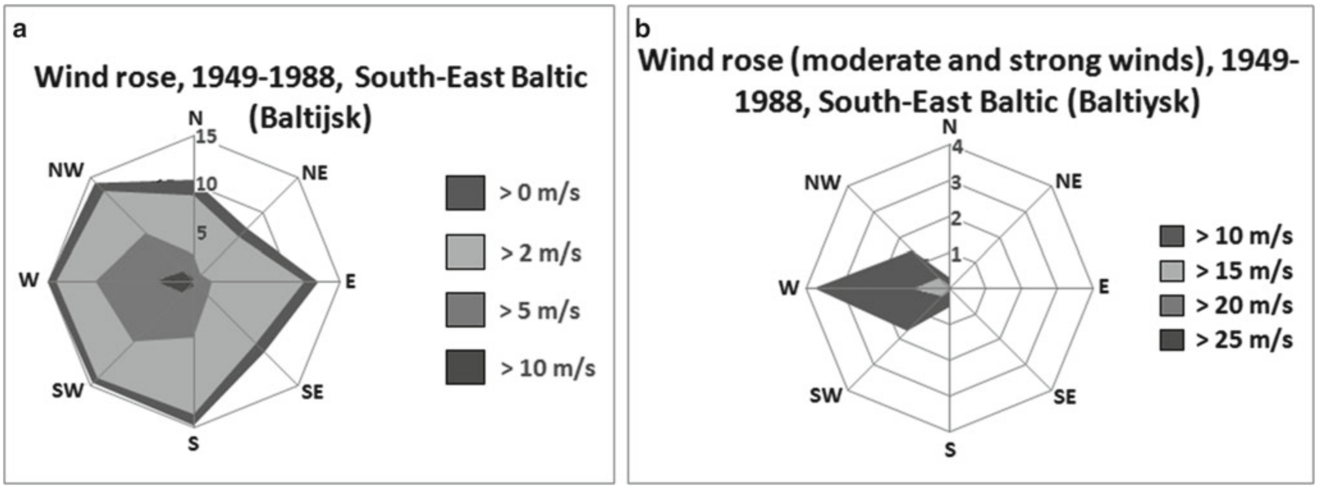


Fig. 6.13 Repeatability (%) of wind directions for all winds, data for Baltiysk (1947–1988) in a form of nested 'wind roses' per wind speed grades: (**a**) winds more than 0, 2, 5 and 10 m/s, (**b**) winds more than 10, 15, 20 and 25 m/s (Data from the Russian Hydrometeorological Service)

mm/year, with the maximum occurring from July to August and the minimum from January to March (Handbook on Climate of the USSR 1969).

The winter air temperature fluctuates near 0 °C; in summer, 16–20 °C (Barinova 2002). A specific feature of the climate near the coast is the long frost-free period. Its duration is around 200 days. The freeze-up of the lagoon has not been observed in any particular year at all.

A change in the climate of the southeastern Baltic was estimated in (Chubarenko et al. 2012) (Table 6.3), based on data from contact measurements obtained at the Kaliningrad weather station of the Russian Hydrometeorological Service at Devau Airport (Climate data Kaliningrad Airport 2015).

Average air temperature has increased by 1 °C over the last 30 years (1981–2010); this is the largest temperature rise in the last 90 years. The greatest rise in precipitation took place in the middle of the twentieth century (1951–1980); later, it gradually started to decrease and was eventually reduced to only three times larger during the period from 1981 to 2010 in comparison with the regulatory period. The atmospheric pressure has the lowest level of fluctuations: it has increased by 0.1 hPa since 1971 (Chubarenko et al. 2012).

The wind speed module started to decrease in 1961. The most significant changes occurred in the period from 1971 to 2000, when the rate of wind decrease was 0.08 ms^{-1}/year, the absolute decrease in wind speed being 2.3 ms^{-1}/ period. After 2000, average wind speed started to growth, and the next 30-year period (1981–2010) was characterized by a positive trend (0.04 ms^{-1}/year), with the total positive change in wind speed rise being 1.2 ms^{-1}/ period (Chubarenko et al. 2012).

Observations made by the Russian Hydrometeorological Service clearly show a constant increase in the average annual water level in the Russian sector of the Vistula Lagoon, with a rate of 1.7 mm/year (Baltiysk, 1840–2006), and 1.9 mm/year (Kaliningrad, 1901–2006) (Navrotskaya and Chubarenko 2012a). A speeding up of the level increase was noticed in the second half of the twentieth century up to 2.2–4.5 mm/year, especially after 1975 (Tables 6.4 and 6.5). The highest rate of average annual level increase was observed after 1993, closer to 10 mm/year. These changes followed a long-term level increase in the Global Ocean, with a rate of 1.7–1.8 mm/year in the previous century speeding up to 3.1 mm/year by the end of that century and the beginning of the present one (Bates et al. 2008; Malinin et al. 2010).

The positive linear trend (Table 6.5) of the average annual water level from 1959 to 2006 (3.6–3.7 mm/year) is a reflection of an increase in minimal levels (3.9–5.0 mm/year), which, in its turn, is connected to general tendencies of level growth due to climate changes. The maximal water levels mostly reflect tendencies in wind regimes (rate of increase is 0.4–3.2 mm/year). A water level change in the lagoon responds to the global climate warming and to regional changes in climate-forming factors, which provide wind and rainfall regimes in the watershed.

The mean annual sea level in Kaliningrad is 3–5 cm higher than that in Baltiysk, and the water level in Krasnoflotskoye is 1–2 cm higher than that in Baltiysk (Fig. 6.14, Table 6.5) in the period from 1959 to 2006. This "pseudo slope" of the water surface in the lagoon from the northeast coast (Kaliningrad and Krasnoflotskoye) in the direction of the Baltiysk Strait is the result of the most frequent active western winds (wind-induced water level set-up occurs in the mouth of the Pregolya River, Kaliningrad) (Navrotskaya and Chubarenko 2011).

Year to year variations in average annual water levels are in good correlation (correlation coefficient is 0.96) with the

Table 6.3 Average meteorological parameters, their linear trends and increase (According to the trends) based on a data obtained from the Kaliningrad weather station (UMKK 26702) from 1921 to 2010. Yearly variations in all characteristics are so high that ***R2*** (which indicates how precisely the trend line represents a function) is usually very small

Average annual atmospheric temperature*, *Ta*, °*C				
Years	***Yearly average***	***Change for the period °C/period***	***Trend °C/year***	***R2***
1921–1950	7.2 ± 1.00	0.42	0.014	0.02
1931–1960	7.2 ± 1.00	−0.45	−0.015	0.02
1941–1970	6.9 ± 0.88	−0.21	−0.007	0.01
1951–1980	7.0 ± 0.80	0.09	0.003	0.00
1961–1990	7.2 ± 0.98	0.84	0.028	0.07
1971–2000	7.5 ± 0.98	0.93	0.031	0.08
1981–2010	7.9 ± 0.93	1.02	0.034	0.11
Total annual precipitation*, *Pr*, *mm				
Years	***Yearly average***	***Change for the period*, *mm/ period***	***Trend*, *mm/year***	***R2***
1921–1950	743 ± 101	−45	−1.5	0.02
1931–1960	723 ± 96	21	0.7	0.00
1941–1970	731 ± 131	102	3.4	0.05
1951–1980	754 ± 142	159	5.3	0.11
1961–1990	786 ± 149	141	4.7	0.07
1971–2000	817 ± 146	105	3.5	0.04
1981–2010	841 ± 143	48	1.6	0.01
Average annual atmospheric pressure*, *hPa				
Years	***Yearly average***	***Change for the period*, *hPa/period***	***Trend*, *hPa/year***	***R2***
1961–1990	1014.5	−0.6	−0.02	0.00
1971–2000	1014.4	0.03	0.001	0.00
1981–2010	1014.5	0.00	0.00	0.00
Average annual wind				
Years	***Average*, *m/s***	***Change for the period*, *ms1/ period***	***Trend*, *ms⁻1/year***	***R2***
1961–1990	3.3 ± 0.9	−0.7	−0.02	0.00
1971–2000	3.2 ± 0.7	−2.3	−0.08	0.81
1981–2010	2.8 ± 0.5	1.2	0.04	0.39

Table 6.4 Rate of sea level rise for the World Ocean, and locations around the Vistula and Curonian Lagoons (Navrotskaya and Chubarenko 2012b)

Lagoon	Measurement point	Trend of level rise, mm/year			
		1901–2000	1961–2003	1980–2005	1993–2003
World Ocean		1.7–1.8	1.8	1.8	3.1
Vistula Lagoon	Baltiysk	1.8	3.2	3.9	11.7
	Kaliningrad	1.7	3.1	2.7	9.6
	Krasnoflotskoye	–	3.5	2.2	3.5
Curonian Lagoon	Otkrytoe	–	1.2	−2.8	−3.5

stations located on the Vistula Lagoon, but extreme annual values are not reached simultaneously: coefficient correlations are 0.74–0.84 for the minimal annual level and 0.44–0.75 for the maximal level (Navrotskaya and Chubarenko 2012a). That means that the lagoon reacts as a single unit in regard to general tendencies of interannual variations, but is significantly inhomogeneous in regard to the realization of extreme conditions.

Climate change in the southeastern Baltic is a reality (Dailidiene et al. 2011; Navrotskaya and Chubarenko 2013). The precipitation has increased, especially in the summer time. An air temperature increase (averages and extreme values) further proven that global warming has become an obvious over recent years. Water level is increasing as well, as it is in other lagoons of the Baltic Sea (Dailidiene et al. 2011).

Table 6.5 Linear trends and increases due to a trend for annual average, maximal and minimal sea levels, as well as for a difference between maximum and minimum levels (amplitude) at the points of the Vistula Lagoon (Kaliningrad, Krasnoflotskoye, Baltiysk) and Curonian Lagoon (Otkrytoe) for the period from 1959–2006 (Navrotskaya and Chubarenko 2012a)

Measurement point	Mean annual level, cm	Mean annual level		Maximum level		Minimum level		Annual amplitude	
		Trend, mm/year	Increase, cm/period	Trend, mm/year	Increase, cm/period	Trend, mm/year	Increase, cm/period	Trend, mm/year	Increase, cm/period
Kaliningrad	1	3.7	17.4	3.2	15.0	4.3	20.2	–1.8	–8.5
Krasnoflotskoye	–2	3.6	16.9	0.4	1.9	3.9	18.3	–3.5	–16.4
Baltiysk	–4	3.6	16.9	2.2	10.3	5.0	23.5	–2.7	–12.7
Otkrytoe	11	2.0	9.4	0.8	3.8	2.3	10.8	–1.4	–6.6

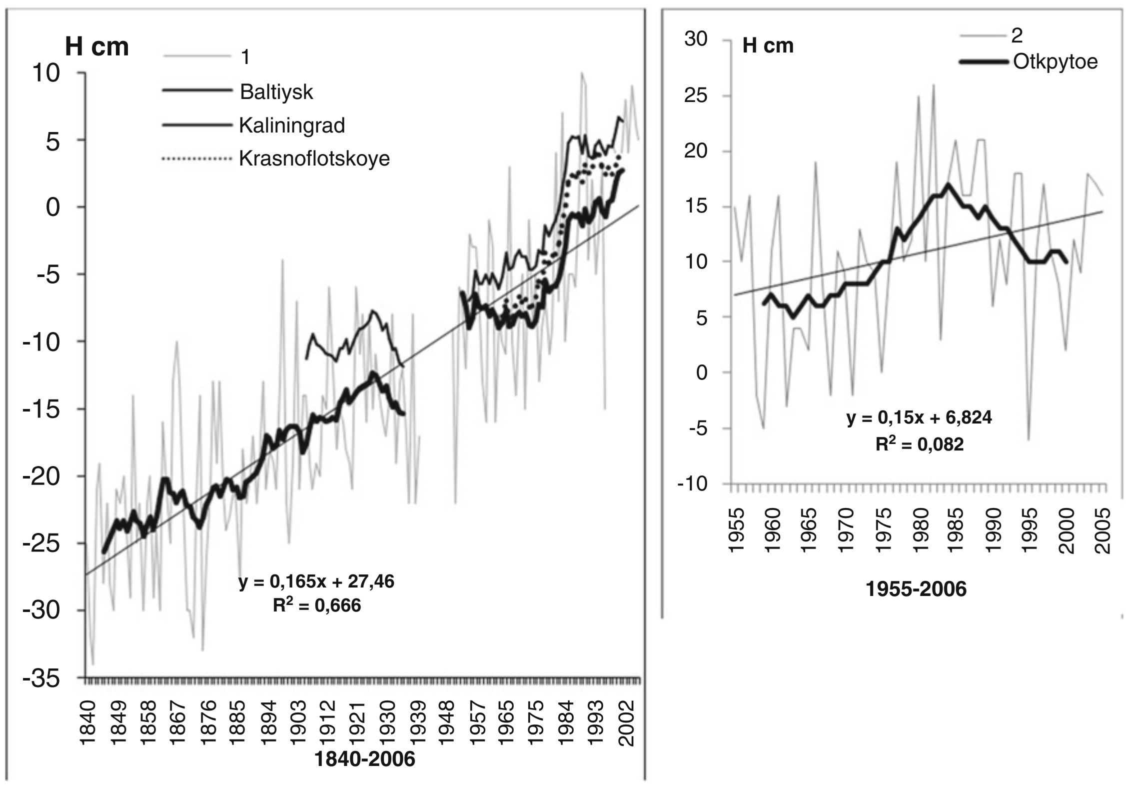


Fig. 6.14 Variations in average annual sea level (smoothed by 5-year running average) at the points of the (**a**) Vistula Lagoon (Baltiysk, from 1840; Kaliningrad, from 1901; Krasnoflotskoye, from 1959) and (**b**) Curonian Lagoon (Otkrytoe, from 1955). The initial yearly data are presented by *thin lines* (*1* for Baltiysk, and *2* for Otkrytoe) for illustration of year-to-year variations. The *trend line* for Baltiysk (of 1.65 mm/year) and the one for Otkrytoe (of 1.5 mm/year) are shown in (**a**, **b**), respectively (Navrotskaya and Chubarenko 2012b)

6.5 Trends in Water Surface Temperature in the Vistula and Curonian Lagoons

The thermal regime of Baltic Sea waters has changed over the last hundred years (BACC- 2008; Meier 2006; Siegel et al. 2006; Stigebrandt and Gustafsson 2003). Identified trends in sea surface temperature (SST) are consistent with regional climate changes and are expected to continue into the future. Scientists predict further warming of the climate over the Baltic Sea, but indicate a regional diversity in this respect (Meier 2006; Siegel et al. 2006). Local hydrometeorological conditions are the major factor in regime shift for the areas of the Curonian and Vistula Lagoons (Chubarenko and Chubarenko 2002).

The southern part of the Baltic Sea is characterized by a general long-term change in the annual mean SST. An SST increase of 0.3 °C has been observed in the southeastern Baltic over the last decade (Siegel et al. 2006).

SST in-situ measurements for the period from 1997 to 2007, carried out by the Atlantic Branch of the P.P.Shirshov Institute of Oceanology in the area of Kosa Village (Baltijsk City), located on the Vistula Spit close to the Baltic Strait, present a positive trend in the annual mean SST, with an increase of 0.17 °C per period of measurements (Stont et al. 2010).

Satellite data from the ocean color scanner MODIS (on Aqua and Terra satellites) with a spatial resolution of 1 × 1 km have been widely used for climatological investigations. SST derived from MODIS data of the period from 2003 to 2012 was used for analysis of thermal regime changes in the Vistula and Curonian Lagoons and for identifying potential trends.

6.5.1 The Vistula Lagoon

The satellite data for this transect (Fig. 6.15a) show that SST both decreased and increased (Table 6.6) in the decade from 2003 to 2012. A decrease in SST occurred at the point located in the northeastern part of the lagoon near the Pregolya River mouth. The maximum increase was found at the point close to the lagoon inlet. The average positive trend of SST in the lagoon (0.07 °C/period) is weaker than the trend observed in the southeastern part of the Baltic Sea (0.2–0.3 °C/period) in the same MODIS data (Bulycheva et al. 2015).

The delay in SST development in the lagoon relative to the SST increase in the open part of the sea is caused by lower heat content in the shallow lagoon and lower thermal inertia. Hence, shallow, rapidly-warming lagoon areas emit a greater amount of moisture into the atmosphere. Apparently, high values of evaporation from the water surface indicate stability in the thermal regime of the lagoon.

During the investigation period (2003–2012), the average increase in SST in the Vistula Lagoon was 0.01 °C per year (Table 6.6). The maximum increase occurs in warm periods: 1.0 ± 0.2 °C/period in spring and 1.5 ± 0.3 °C/period in summer (Table 6.7). Winter time is characterized by a slightly negative trend – (0 °C or −0.7 ± 0.4 °C/period). The maximum negative trend occurs in autumn (−1.1 ± 0.8 °C/period). The negative trend in the winter and autumn periods is almost two times lower than the positive trends in the spring and summer months.

Thus, the investigation period is characterized by a positive trend in the annual mean SST of the Vistula Lagoon, with an increase of 0.07 °C over 10 years. Summer and spring dominate this positive trend. The winter and autumn periods show a negative trend. Evidently, the SST's positive trend will keep rising in the future, generally due to an

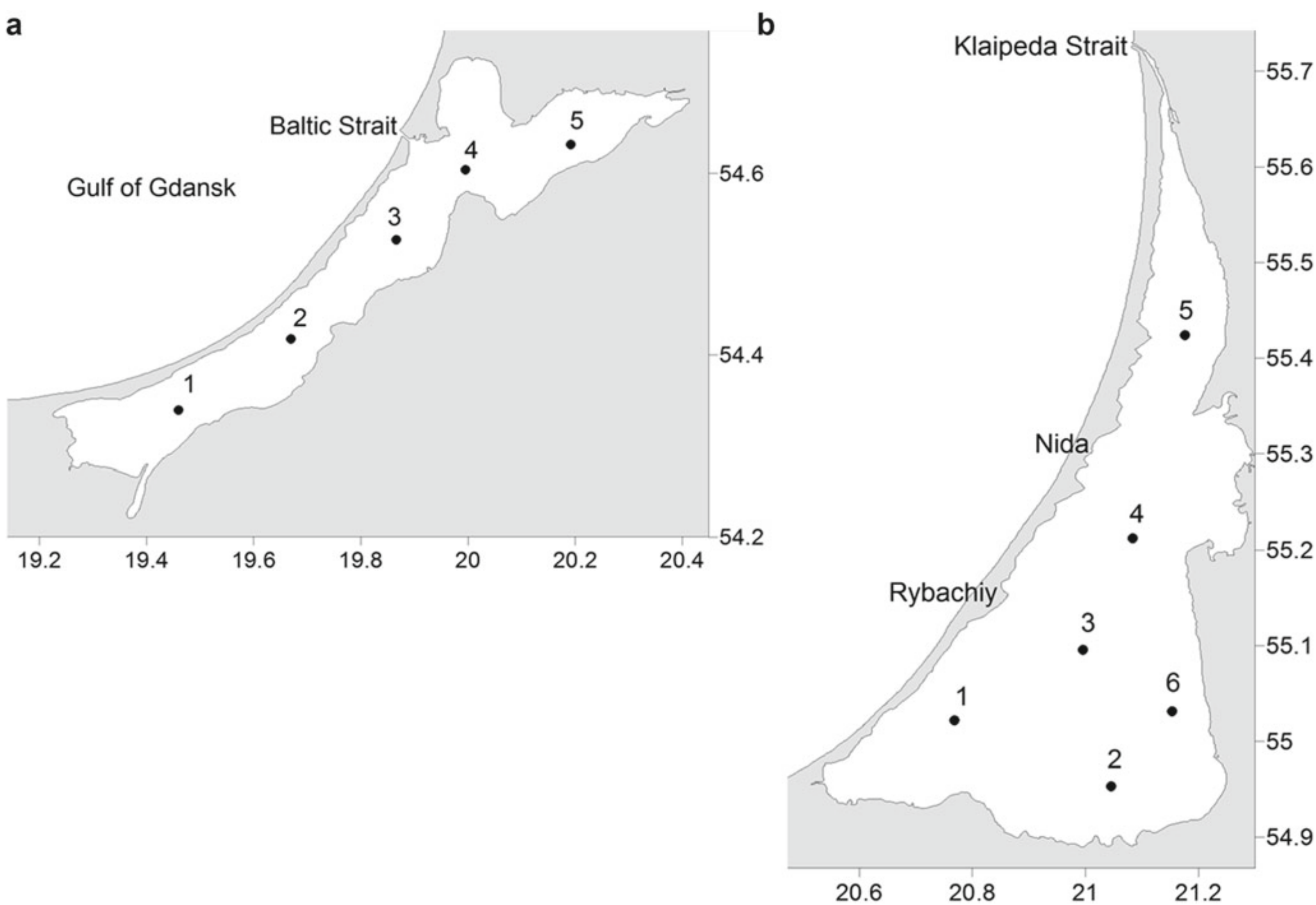


Fig. 6.15 Locations of points of satellite monitoring in the Vistula (**a**) and Curonian (**b**) Lagoons (The frame presents geographical coordinates in a format of degrees)

Table 6.6 Average surface temperature (SST), their linear trends and increases (According to the trends) in the Vistula Lagoon (MODIS data from 2003 to 2012)

Measurement point	Average ± σ	Trend		Increase, °C/period	t-student/N[a]
		°C/day	°C/year		
P. 1	13.8 ± 6.5	0.00050	0.02	0.22	0.231/551
P. 2	13.6 ± 6.5	−0.00003	−0.01	−0.07	0.082/555
P. 3	13.3 ± 6.7	0.00001	0.004	0.04	0.048/565
P. 4	13.5 ± 6.7	0.00068	0.025	0.25	0.257/569
P. 5	3.5 ± 6.8	−0.00003	−0.010	−0.11	0.104/554
Average	13.5	0.00023	0.01	0.07	

[a]*N* number of measurements

Table 6.7 Average surface temperature (SST), their linear trends and increases (According to the trends) per seasons in the Vistula Lagoon (MODIS data from 2003 to 2012)

Measurement point	Increase, °C/period			
	Winter	Spring	Summer	Autumn
P. 1	−0.5	0.6	1.7	−1.5
P. 2	−0.5	1.2	1.0	−2.2
P. 3	−1.3	1.0	1.4	−1.1
P. 4	−0.7	1.2	1.7	0.0
P. 5	−0.5	1.0	1.7	−0.6
Average	−0.7	1.0	1.5	−1.1

increase in the maximum temperatures of water and air, and a consequent warming of the surface water layer in the summer period, and a decline in warming rates in the cold period.

6.5.2 The Curonian Lagoon

According to the assessment (Dailidiene et al. 2011), the warming trend of the mean SST in the Curonian Lagoon near the Nida was about 1.4 °C for the period from 1961 to 2008, and the annual warming rate was 0.03 °C/year.

According to the results of (Jurgelėnaitė et al. 2012) for the period from 1991 to 2010, the increase of the SST and air temperature (in the warm period) for the rivers entering the Curonian Lagoon is 0.04 and 0.06 °C, respectively. Thus, air temperature is one of the most significant factors affecting SST. SST trends in the Curonian Lagoon identified by MODIS data and discussed below include the cold period, which could be a reason for the generally lower rate of surface warming.

SST in-situ measurements carried out by the Atlantic Branch of the P.P. Shirshov Institute of Oceanology near Rybachiy Village, located at the Curonian Spit, show a positive trend in the annual mean SST, with a slight increase of 0.07 °C for the period from 1997 to 2007 (Stont et al. 2010).

Satellite data from the ocean color scanner MODIS (on Aqua and Terra satellites) with a spatial resolution of 1 × 1 km was used to derive SST in the Curonian Lagoon for the period from 2003 to 2012. The area of investigation (Fig. 6.15b) includes 6 points in the central part of the lagoon. Regular satellite data about SST enabled analysis of thermal regime changes in the Curonian Lagoon, identification of decadal and seasonal SST trends, and a detailed comparison between the warming trends in the Vistula and Curonian Lagoons. A positive linear trend of SST, with an increase ranging 0.03 ± 0.04 °C per year, was observed in the Curonian Lagoon for the period from 2003 to 2012 (Table 6.8).

The satellite data show that SST has increased by 0.27 °C over the decade from 2003 to 2012. All points show positive SST trends, however, the maximum increase in SST (0.93 °C/period) occurs at the very northern point located in the northern part of the lagoon close to the Klaipeda Strait, where there is a good water exchange with the open sea. The points 2, 4 and 6 are influenced by the run-off from the Neman and Deima Rivers. Thus, air temperature is one of the most significant factors affecting SST. SST trends in the Curonian Lagoon include the cold period, which could be a reason for the lower rate of surface warming.

The increase in SST in the Curonian Lagoon is three times weaker than the positive SST trend observed in the southeastern part of the Baltic Sea (0.7 ± 0.3 °C for the period from 2003 to 2012 (Bulycheva et al. 2014)).

During 2003–2012, the maximum increase in SST occured in warm periods: 1.3 ± 0.3 °C/decade in spring and 1.1 ± 0.4 °C/decade in summer (Table 6.9). Cold periods are characterized by negative trends: (−0.8 ± 0.3) °C/decade in winter and (−1.1 ± 0.3) °C/decade in autumn. The seasonal SST trends observed in the Curonian Lagoon are similar to the seasonal SST development in the Vistula Lagoon.

Table 6.8 Average surface temperature (SST), their linear trends and increases (According to the trends) in the Curonian Lagoon (MODIS data from 2003 to 2012)

Measurement point	Average ± σ	Trend		Increase, °C/period	t-student/N[a]
		°C/day	°C/year		
P. 1	13.1 ± 6.8	0.00003	0.01	0.11	0.099/564
P. 2	12.9 ± 6.8	0.00004	0.01	0.14	0.140/552
P. 3	13.1 ± 6.8	0	0	0	0.011/552
P. 4	13.1 ± 6.8	0.00003	0.01	0.11	0.106/547
P. 5	12.7 ± 6.9	0.00025	0.09	0.93	0.982/542
P. 6	13.1 ± 6.9	0.00009	0.03	0.32	0.332/535
Average	13.0		0.03	0.27	

[a]*N* number of measurements

Table 6.9 Average surface temperature (SST), their linear trends and increases (According to the trends) by seasons in the Curonian Lagoon (MODIS data from 2003 to 2012)

Measurement point	Increase, °C/period			
	Winter	Spring	Summer	Autumn
P. 1	−1.1	1.1	1.2	−1.2
P. 2	−0.9	1.4	1.1	−1.3
P. 3	−1.0	1.2	0.7	−1.2
P. 4	−0.4	0.8	1.3	−0.7
P. 5	−0.7	1.3	1.8	−0.8
P. 6	−0.6	1.8	0.7	−1.5
Average	−0.8	1.3	1.1	−1.1

6.5.3 Final Remarks

The investigation period was characterized by a positive trend in the annual mean SST of the Curonian and Vistula Lagoons, with an average increase of 0.27 and 0.07 °C for the decade, respectively. A similar seasonal tendency was revealed for both lagoons: positive trends were recorded in summer and spring, negative trends in the winter and autumn periods.

Nevertheless, the annual increase in SST in the Curonian Lagoon is four times more rapid than in the Vistula Lagoon. SST is rising much more slowly in the Curonian and Vistula Lagoons than in the open parts of the southeastern Baltic Sea (by ratios of 3 and 10, respectively). These positive trends dominate in a warm period.

6.6 Spatial and Seasonal Variations of Salinity in the Vistula Lagoon, Including the Navigable Canal

Salinity in the Russian part of the Curonian Lagoon is practically zero, as freshwater input dominates. The lagoon could be considered to be a running, shallow freshwater lake. Salinity intrusions happen only at the very northern part of the lagoon, in the Klaipeda Strait (Gasiunaite et al. 2008a, b).

In contrast, the Vistula Lagoon is a marine-dominated, coastal water body (Chubarenko and Margonski 2008) and is an arena for the permanent mixing of fresh and saline water. The hydrological regime of the Vistula Lagoon has changed dramatically since the beginning of the nineteenth century. Before 1916, only the Nogat River (southern part of the Lagoon) brought up to 2200 m^3/s of water to the Vistula Lagoon during the spring freshet. The sediment flux was up to 0.3–0.4 millions of m^3. The Nogat River Delta increased by 15 ha per year. Marine water intrusions were very infrequent and not intensive. In 1916, the discharge of the Nogat River was regulated, and today, it equals only 25 m^3/s on average. The lagoon became marine water-dominated after that event, and salinity has gradually increased up to today's values (Lazarenko and Maevskiy 1971).

Seasonal salinity changes are caused by variations in the balance between marine influence and river drain. Monitoring investigations at the station's net (Fig. 6.16) has allowed for the estimation of the main patterns of vertical distribution of salinity in the Vistula Lagoon and the Kaliningrad Seaway Canal.

The minimum salinity in the lagoon (0.5–4.5 psu) occurs in the late spring after the majority of the river run-off occurs (March and April) (Fig. 6.16a). Then, from May until August, salinity increases to 1.5–5.5 psu, the river run-off is very low and the marine influence prevails, especially in the deepest layers of the part adjacent to the inlet (Fig. 6.16b). In autumn, smooth desalinization starts (Fig. 6.16c), and finally, in winter, the ratio between the fresh and salt water in-fluxes stabilizes during ice coverage and the lagoon comes to equilibrium between the salting and refreshing processes (Fig. 6.16d) (Chubarenko et al. 2004).

The Kaliningrad Seaway Canal and the deep lower segment of the Pregolya River (from its mouth towards the centre of the city of Kaliningrad) form an estuary-type part of the river mouth, where a permanent mixing of both saline lagoonal waters (as well as incoming marine waters) and fresh river waters occurs. The mixing zone seasonally migrates along a 10–20 km distance both upstream and downstream, as well as becoming longer or shorter. In winter and very early spring, the mixing zone shrinks up to 3–5 km in length along the river and becomes localized in Kaliningrad harbour (Fig. 6.17a). At this time, characteristic values of the vertical and horizontal gradients are ca. 0.3–0.35 psu per m and per km, respectively. A spring increase in the Pregolya River run-off spreads the gradient up to 10–25 km in length along the canal and pushes the mixing zone towards the lagoon inlet (Fig. 6.17b). The centre of the zone is 10–20 km from the river mouth, and the horizontal and vertical gradients are ca. 0.05–0.15 psu per m and per km. At the beginning of summer (Fig. 6.17c), the river run-off significantly decreases, and any water level rise near the inlet immediately induces a salt water near-bottom intrusion upstream of the canal and its mixing in the total water column due to regular shipping along the canal. As a result, a salt-wedge with maximum salinity of 4.5–5 psu reaches the Pregolya River mouth

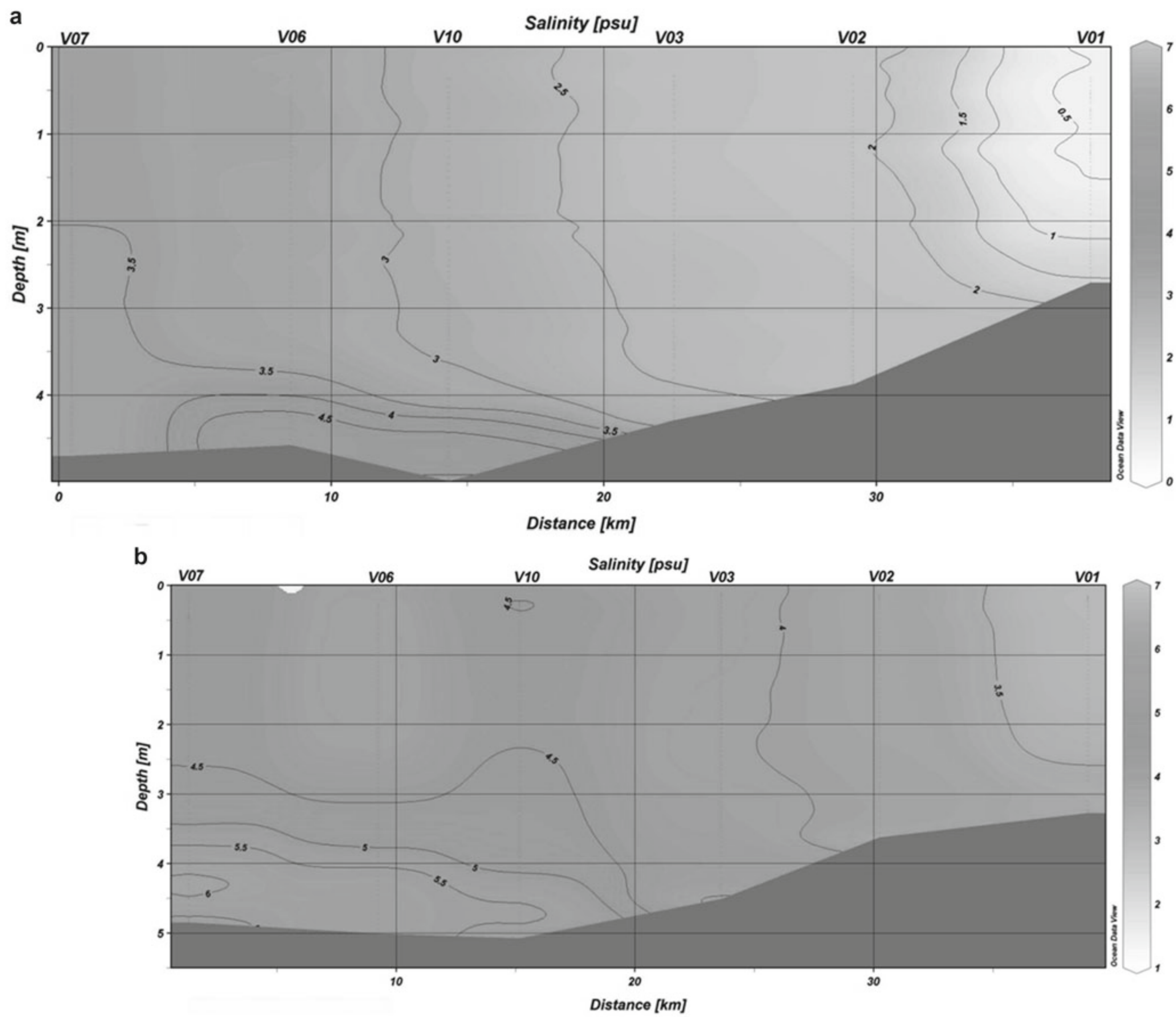


Fig. 6.16 Vertical structure of salinity distribution along the main axis of the Vistula Lagoon: (**a**) spring, 11.04.11; (**b**) end of summer, 05.09.2013, (**c**) late autumn, 22.11.2012, (**d**) middle of winter, ice-covered period 06.02.2013

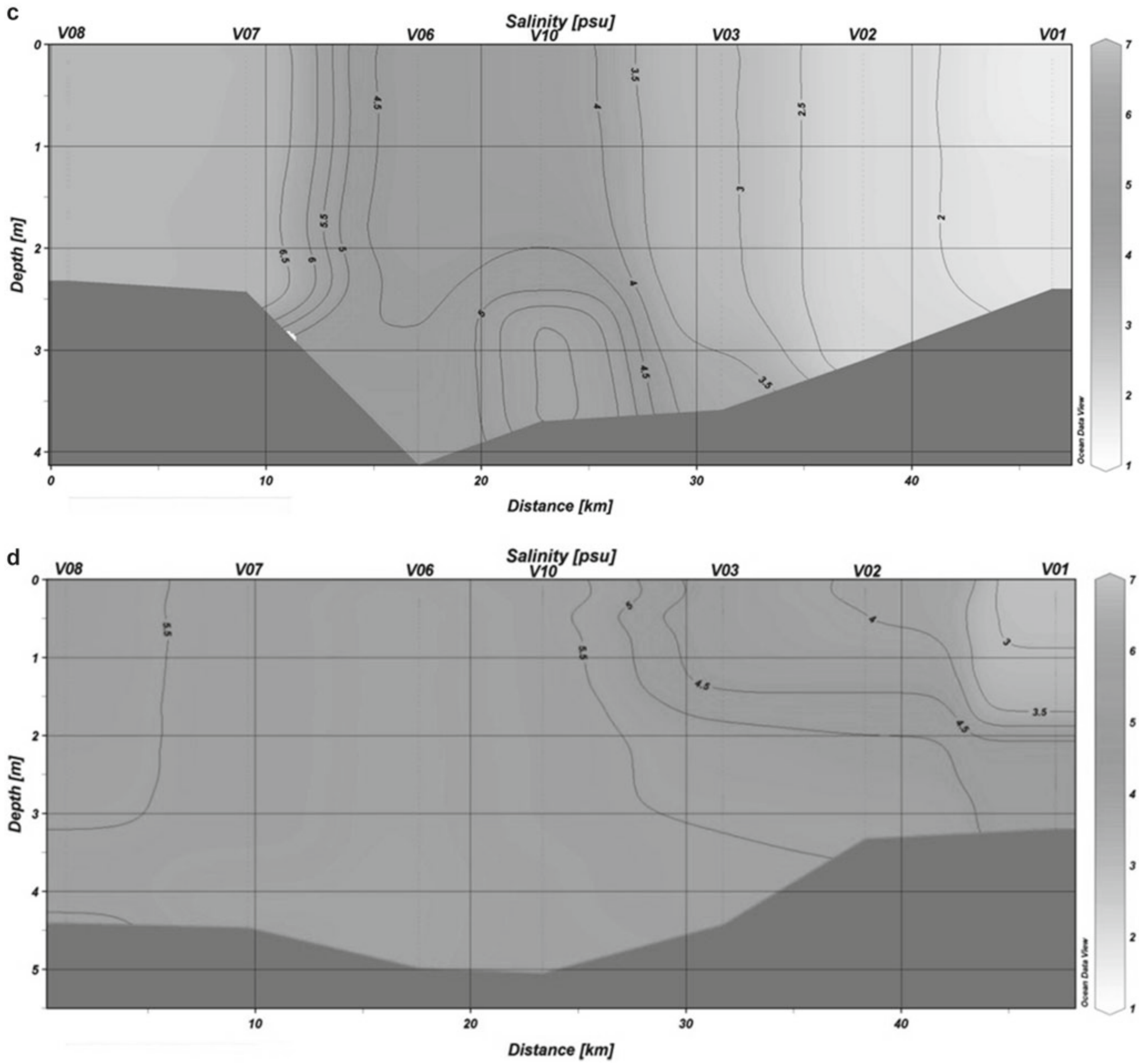


Fig 16.6 (continued)

by autumn (Fig. 6.17d), but the upper water layer remains predominantly fresh. Vertical gradients increase up to 0.5 psu per m. Autumn winds and the active mixing of both waters in the lagoon, and between the lagoon and the canal, destroy vertical gradients in the canal, and the mixing zone is ultimately kept in the harbour area (Chubarenko 2008).

6.7 Bottom Sediments in the Vistula Lagoon

A comparison (Chechko 2008) of the bottom sediment scheme (Fig. 6.18) developed in (Chechko and Blazhchishin 2002) with the one published 35 years earlier (Wypych and Nieczaj 1975) allows us to conclude that the majority of changes were found in redistribution areas, covered by clayey silt, i.e., the finest sediments. This type of sediment dominates in the southwestern part of the lagoon for both periods of time, however, its area had been considerably reduced, from 29 % to 20 %.

The bottom area adjacent to the lagoon inlet (Baltiysk Strait) is characterized by serious changes in the distribution of bottom sediments. In accordance with the scheme (Wypych and Nieczaj 1975), silt covered nearly the entire bottom of the central part of the lagoon (except for the narrow coastal band). At present, it has become much narrower near the inlet and has almost completely been replaced by coarse sediments – sandy silt and sand. At the same time, silt

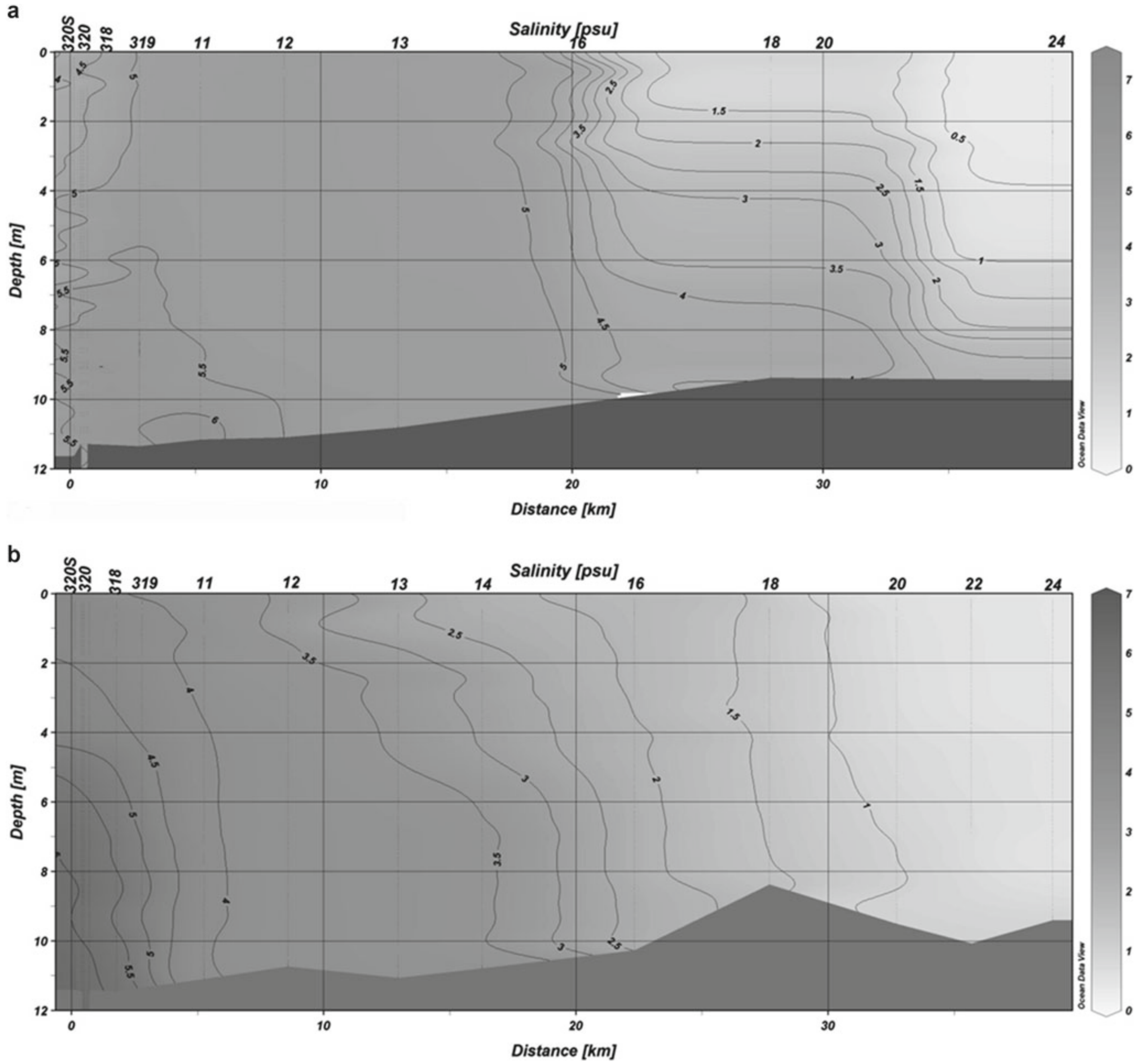


Fig. 6.17 Vertical structure of salinity distribution along the Kaliningrad Seaway Canal: (**a**) winter situation, 17.01.12; (**b**) spring situation, 12.03.2012; (**c**) summer situation 29.06.2012; (**d**) autumn situation, 31.10.2012. Depths at points are not equal for different dates of measurement, due both to variations in the time of water level and small spatial variations in the location of measurements across the canal

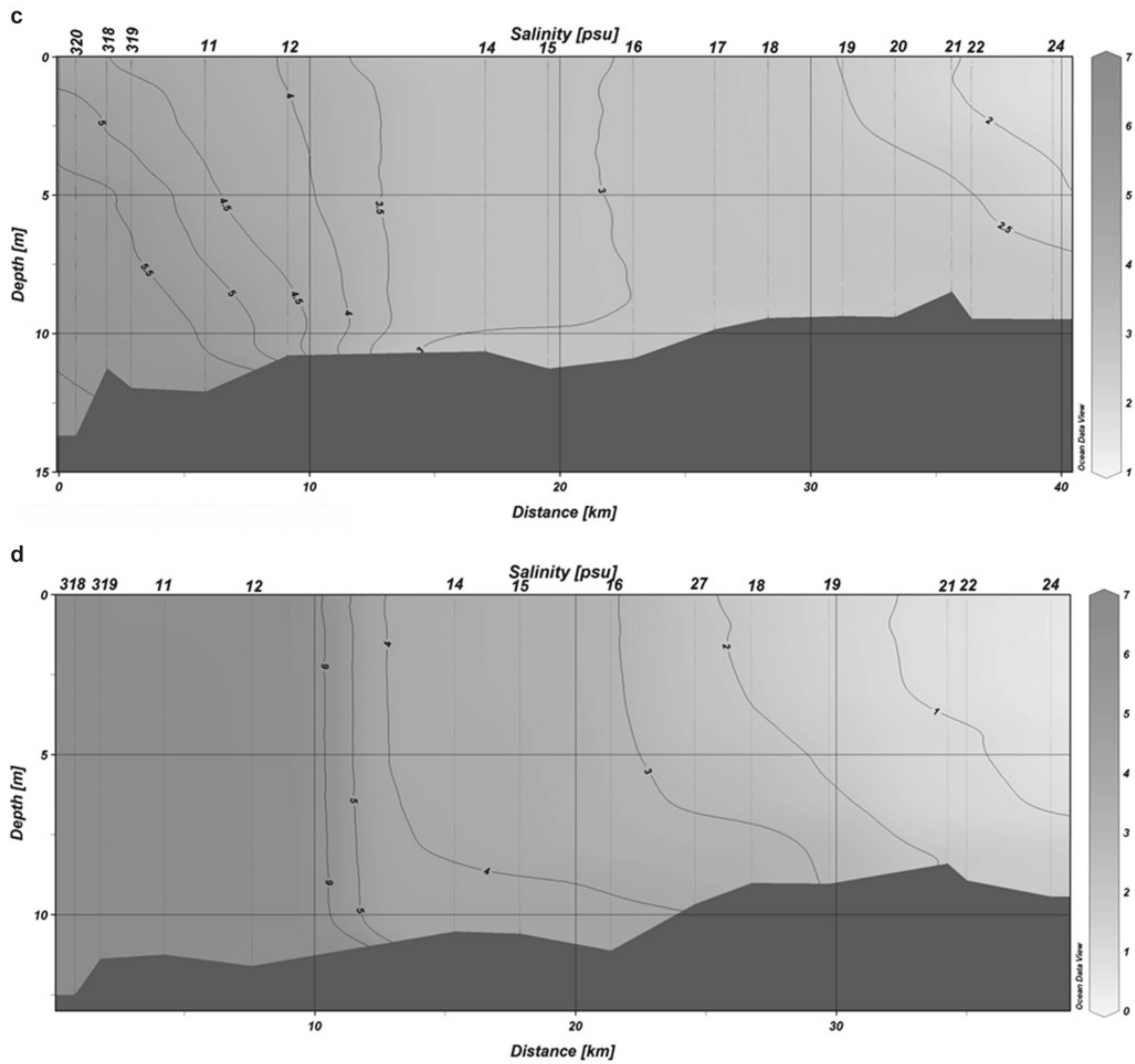


Fig 16.7 (continued)

appeared in deeper parts of the bottom in the northeastern part of the lagoon and the Primorskaya Bight.

Areas covered by sandy silt have generally reduced, from 23 % to 17 %. As before, this type of sediment is the most widespread in the northeastern part of the lagoon and the Primorskaya Bight. Areas covered by sand have increased, from 21 to 29 %. Coastal areas and the zone opposite the lagoon inlet have also been subject to such changes, i.e., are places where active wave impact on bottom sediments re-suspends and removes fine material, leaving only the coarser ones.

Comparison of the two schemes showed that the redeposition of sediments, i.e., the sorting and redistribution of material within the basin, is characteristic of contemporary sediment accumulation in the Vistula Lagoon (Chubarenko et al. 2005a). Coarse fractions are located in the most actively energetic areas of the lagoon proper – in shallows and in the coastal zone, while fine material has accumulated in deeper, calmer areas. The deep area near the inlet is covered by coarse material because fine sediments are brought out into the sea by water exchange currents (Chubarenko and

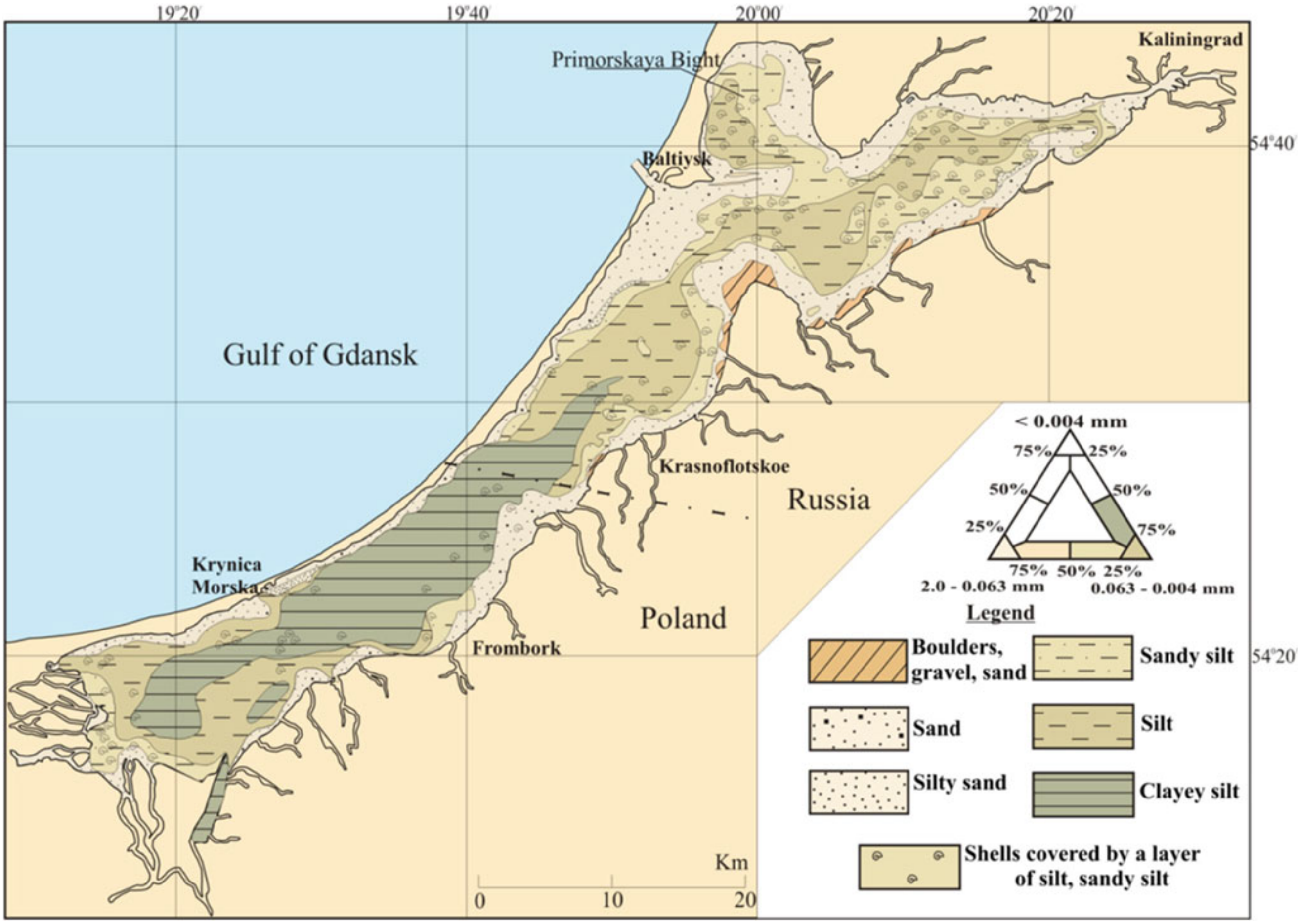


Fig. 6.18 Scheme of distribution of the surface (0–5 cm) sediment types in the Vistula Lagoon in the 1990s to the 2000s, developed according to Shepard's classification (Chechko 2008). The Polish part of the lagoon was compiled from (Zachowicz and Uscinowicz 1996)

Chubarenko 2001). Basic changes in spatial distribution of bottom sediments in the Vistula Lagoon were caused by regulation of the Vistula River drain at the beginning of the nineteenth century, which resulted in a change of evolution of the Vistula Lagoon as a single whole system and, in particular, in its natural regime of sedimentation.

6.8 Shore Line of the Russian Part of the Vistula Lagoon

The length of the coastal line of the Russian part of the Vistula Lagoon is 148 km. There is some variety in the current day morphology, genesis and existing coastal processes along the coastline. The eastern, western and northern shores of the Vistula lagoon are different according to their geomorphology. The northern shore is artificially man-made. Stable segments covered by reeds dominate on the east shore.

The eastern shore along the segment from Mamonovo to Ladushkin (Fig. 6.19a) is relatively aligned and high. Cliffs are bordered by narrow beaches, which are folded by large-scale sediments with multiple enclosures of boulders. From Krasnoflotskoe to the North Cape (which is located opposite the lagoon entrance), the cliff is active (Fig. 6.19a), despite the fact that the shore is protected by a wide boulder bench. Rate of erosion there is 0.1–0.4 m/year (Bobykina and Boldyrev 2007). East of the North Cape, the majority of the low-lying and high mainland shores are blocked by reeds (Fig. 6.19b). This area is low-lying, swampy, completely overgrown by bulrush and reeds, and rather stable.

The northern shore of the Vistula Lagoon is separated from the lagoon area by the artificial, navigable Kaliningrad Seaway Canal, which goes from the Baltiysk to the mouth reach of the Pregolya River, passing via Kaliningrad. The island of dams bordering the canal from the lagoon side was artificially constructed, together with the canal (the shore is man-made). The

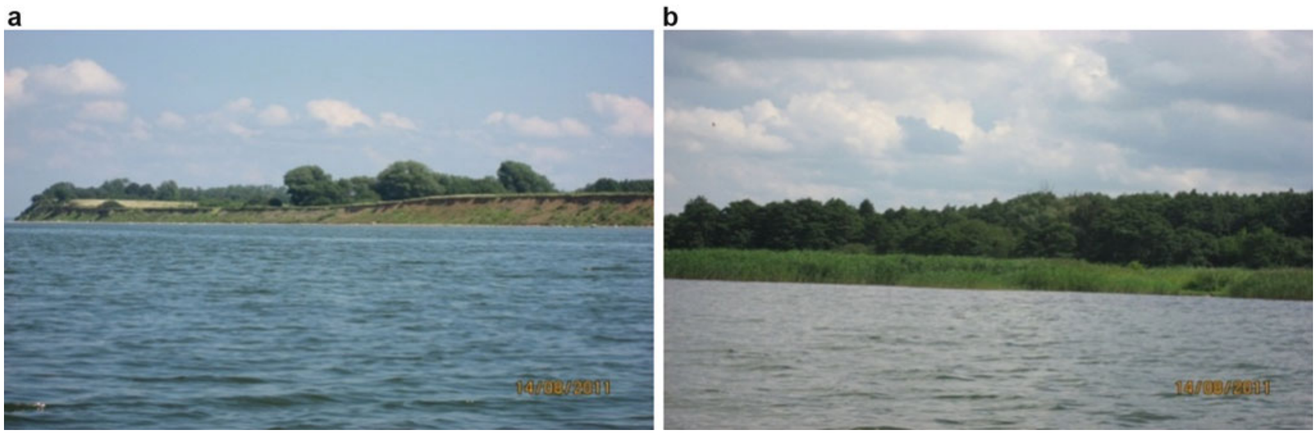


Fig. 6.19 Eastern shore of the Vistula Lagoon: (**a**) the active cliff, (**b**) reed (stable) shore (Photo – V. Bobykina)

shore facing the lagoon is experiencing intensive erosion and is only partly protected by stones or reeds.

The shore of the Vistula Lagoon is eroded (50 %), stable due to natural reed cover (33 %), protected by man-made constructions (14 %) and naturally accumulative (3 %) (Bobykina 2002; Boldyrev and Bobykina 2005). Reeds have developed in places where bottom sediments are formed by loams and lagoon-silt. They reliably protect the shore from waves, and make it stable. Erosion of open segments is caused by a combination of wind surge and wind wave influence. The maximum values of surges can reach 1.2–1.8 m here. The water reaches the eroded base of forested dunes, which leads to a slice of unconsolidated sand formations that form the shore. In addition, there is flooding of low-lying areas of the shore, which are no higher than 1.5 m.

Coastal erosion of the Vistula Spit shore is associated with waves caused by winds from the eastern direction, and that of the mainland, by winds from the western direction.

Long-term observation of the coastal dynamics of the Vistula Spit were begun by the Atlantic Branch of the P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences in 1999 (Bobykina 2008). Based on quantitative observations of the dynamics of the lagoon shore of the Vistula Spit since 1999, the average annual erosion rate is between 0.5 and 2 m (Fig. 6.20). The maximum erosion has been observed at the northern and southern segments of the Russian part of the Spit. In years with significant surges and waves (for example, the period from 2004 to 2005), the magnitude of erosion of individual sites can be up to 3 m (Fig. 6.20).

There is a reduction in the width of the spit through the recession of the shore of the lagoon at the open segments at a rate of 0.5–2 m/year. Erosion of ancient dunes on the lagoon shore of the Vistula Spit supplies significant amounts of sand material to the underwater slope, while erosion of moraine sequences on the mainland shore supply clay.

6.9 Economic Activities and Use of the Russian Part of the Vistula Lagoon

Navigation and fishing are major industries in the region (Andriashkina et al. 2008). Tourism and recreation are some of the most promising economic activities for the Kaliningrad Oblast and the lagoons in particular, though at the moment, the tourism sector is in its initial stages, and has to be developed further to meet high standards.

The Vistula Lagoon is used for fishery, water discharge, navigation, tourism, dredging and dumping. Other uses have not yet been developed.

6.9.1 Fishery

One of the main sources of commercial fish in the Kaliningrad Oblast is the Vistula Lagoon, where fishing is performed mostly with net gear. The commercial species abounding in the Vistula Lagoon are pikeperch, bream, roach, eel, perch, and sabrefish. Bream is a particularly productive species. In 1996, slightly more than 200 tons of bream were caught in the Vistula Lagoon, and towards 2003, the catch volume rose to 250 tons, with the peak occuring in 2002 (about 300 tons) (Bagdanaviciute et al. 2008).

6.9.2 Aquaculture

Aquaculture is represented by commodity fish-breeding in the Russian part of the Vistula Lagoon catchment.

The production of trout and sturgeon was developed by the “Kaliningrad Centre Aquaculture” company in the urban village of Pribrezhny. Fish are grown in cages installed in a flooded quarry hatchery in water enriched with oxygen with

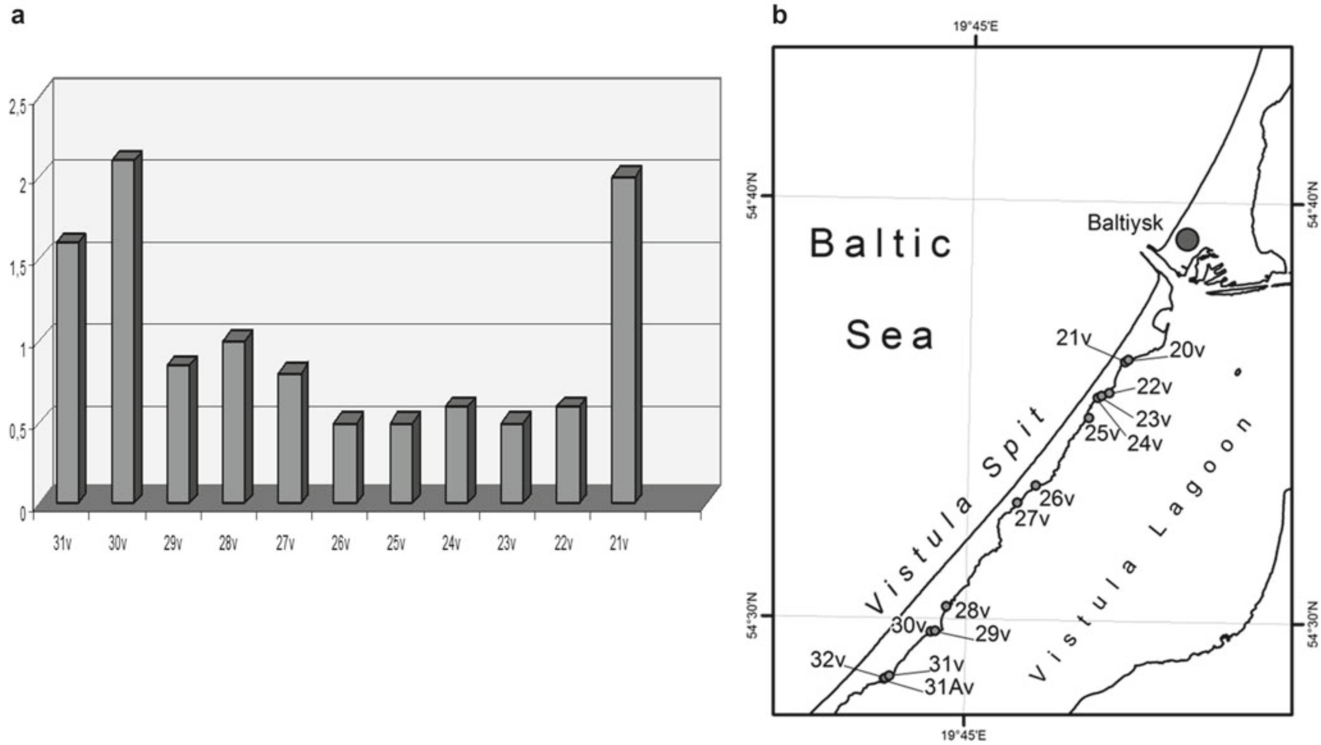


Fig. 6.20 Average annual erosion rate (**a**) of the Vistula Spit lagoon coast for the period from 2000 to 2005, and locations of the monitoring transects (**b**) (Bobykina 2008)

low temperature conditions maintained. The farm produces 9.5 tons of trout, as well as 2.5 tons of sturgeon, annually. Its sales market is a network of shops and restaurants in Kaliningrad.

The “KMP Aqua” company was established in the city of Svetly in 2007. It originated as a fish processing plant called “Kaliningrad Seafood”. The company was engaged in fish-breeding in closed water supply installations. The total plant area was 11,000 m^2. The company plants sturgeon, tilapia, catfish and eel for sale. The company’s original plan was to sell their products in Russia and abroad, but now all commercial fish grown there are sold in the domestic markets of the Kaliningrad Oblast.

6.9.3 Waste Water Discharge

Most waste water in the Vistula Lagoon comes from point sources located inland (the cities of Kaliningrad, Baltiysk, Svetly, Ladushkin, and Mamonovo). Run-off from the agricultural industry enters the lagoon through a network of smaller rivers, streams and canals. Mechanically-treated wastewaters from Kaliningrad (ca 450,000 inhabitants) are directed to Primorskaya Bay in the Vistula Lagoon by the bypass open collector (Kaliningrad Sewage Runaround Canal). In addition, wastewaters from cities and enterprises located upstream flow into the Pregolya River after mechanical treating. Sanitary conditions are good enough for bathing in the lagoon, owing to the self-cleaning capability of the river system and the lagoon. The largest hot spot, the Kaliningrad Sewage Runaround Canal, will be closed soon after the opening of Kaliningrad’s new treatment plant.

6.9.4 Tourism

The tourism-related infrastructure of the lagoon waters of the Kaliningrad Oblast has not been sufficiently developed, hence there is potential for significant growth. At present, angling has been developed. Yachting and beach rest along the lagoon shore have not been sufficiently developed. Also at present, international routes along internal waterways between Poland and Lithuania through the territory of the Kaliningrad Oblast are practically unused. In order to develop this type of recreation, it is necessary to provide a detailed assessment of the natural conditions of this water area and develop the coastal infrastructure.

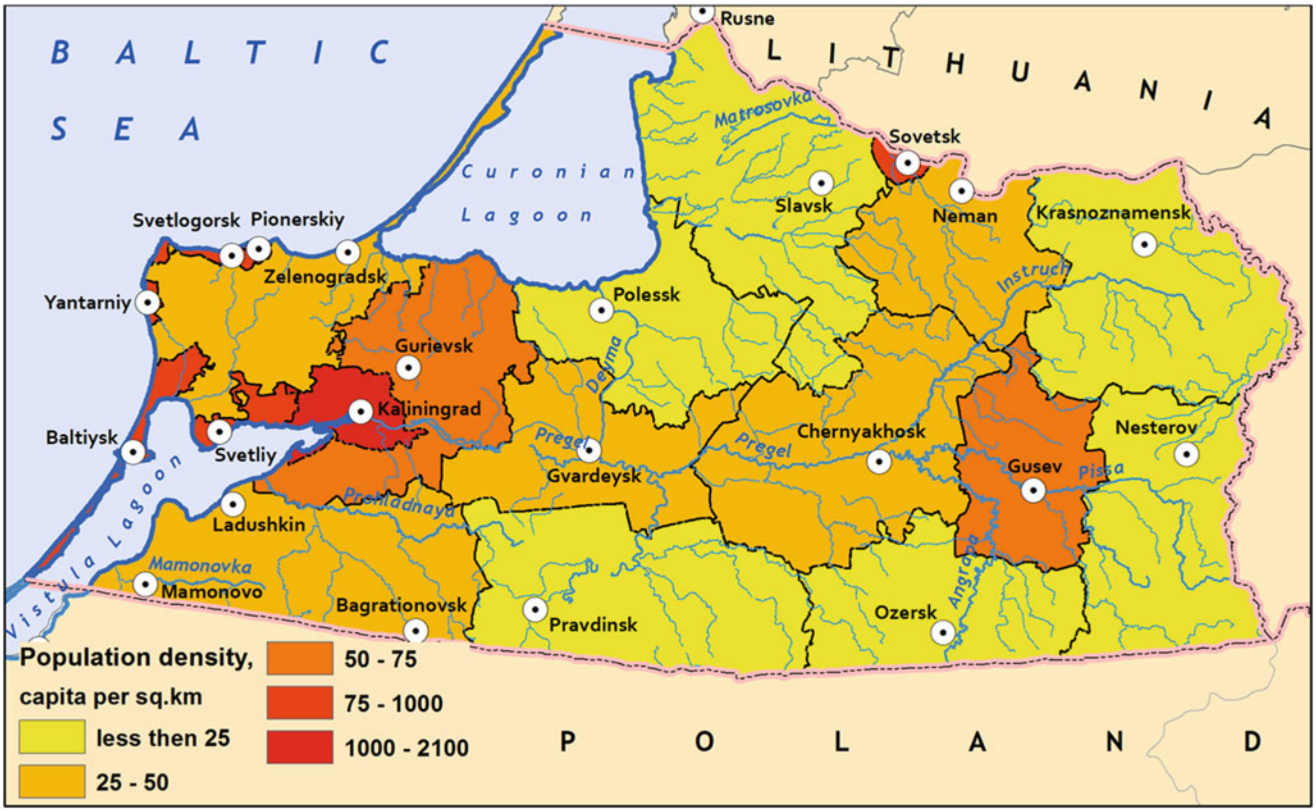


Fig. 6.21 Population density per municipal units of the Kaliningrad Oblast (Bagdanaviciute et al. 2008)

6.9.5 Dredging and Dumping

Dredging operations are constantly held in the Kaliningrad Seaway Canal. These works are needed to maintain and improve the entrance to the Canal. Clean sand is dumped into the water area of the Baltic Sea. Fine-grained soil is used to strengthen the internal portions of the islands of the protective dam of the Kaliningrad Seaway Canal.

6.9.6 Navigation

Officially, the Kaliningrad Oblast has one port at Kaliningrad, composed of four harbours (Kaliningrad, Svetly, Baltiysk, and Pionersky). The first three of them are located in the Vistula Lagoon.

In recent years, the port of Kaliningrad has witnessed steady cargo turnover, with notable growth in spring and winter, although passenger transfers have not yet been developed to the required level. Currently, the harbour of Baltiysk has a passenger terminal that processes about 12,000 passengers per year. According to the 2005–2006 data, there has been a slow increase in the number of passenger transfers along the internal route between the ports of Kaliningrad and Saint Petersburg of about 11 % (Bagdanaviciute et al. 2008).

6.10 Population, Water Use, Land-Use and Economic Activities in the Vistula Lagoon Catchment

Spatial distribution of the population in the coastal areas of the Vistula Lagoon is not homogeneous (Fig. 6.21, Table 6.10). The main concentration of inhabitants is around Kaliningrad, which is the largest city in the Vistula Lagoon region. The border areas between Russia and Poland in the southern and western parts of the Vistula Lagoon are relatively poorly populated. In all these regions, the average population density rarely exceeds 20 people per km^2 (Bagdanaviciute et al. 2008).

By the end of 2013 the average unemployment for the Kaliningrad Oblast equals 5.6 % of economically active population, 62 % and 27 % of them are employed in the firms of private and governemntal/municipal forms of property respectively. The population is mainly engaged in manufacturing, health care, education, transport and trade (more than 60 %). Employment in all other sectors is less than 20 % (Fig. 6.22).

The water consumed in the Kaliningrad Oblast comes from surface and underground water sources (Table 6.11) (Chubarenko 2007a). The highest water consumption, as well as waste water discharge (Table 6.12), is in the main

Table 6.10 Population in municipalities and cities/towns of the Kaliningrad Oblast

City/town	People, thousands	City/town	People, thousands
Kaliningrad	419.2	Pionerskiy	12.0
Sovetsk	42.6	Yantarnyy urban district	5.3
Ladushkin urban district	3.9	Mamonovo urban district	7.8
Baltiysk district (37.0 ths.)			
Baltiysk	34.1	Primorsk	2.1
Svetlogorsk district (13.6 ths.)			
Svetlogorsk	11.2	Primorie	0.7
Svetlyy district (29.3 ths.)			
Svetlyy	22.3	Vzmorie	2.1
Bagrationovsk district (33.2 ths.)			
Bagrationovsk	6.6	Yuzhnyy	2.7
Gvardeysk district (28.5 ths.)			
Gvardeysk	13.0	Znamensk	4.3
Gurievsk district (54.4 ths.)			
Gurievsk	12.1	Vasilkovo	4.8
Gusev district (37.3 ths.)			
Gusev	28.1	Mayakovskoe	0.9
Zelenogradsk district (32.5 ths.)			
Zelenogradsk	12	Pereslavskoe	1.3
Krasnoznamensk district (11.7 ths.)			
Krasnoznamensk	3.4	Dobrovolsk	1.6
Neman district (21.7 ths.)			
Neman	12.0	Zhilino	1.0
Nesterov district (17.0 ths.)			
Nesterov	4.6	Chernashevskoe	1.2
Ozersk district (16.1 ths.)			
Ozersk	5.0	Sadovoe	0.6
Polessk district (19.4 ths.)			
Polessk	7.6	Zalesie	1.2
Pravdinsk district (21.7 ths.)			
Pravdinsk	7.3	Zheleznodorozhnyy	2.9
Slavsk district (21.6 ths.)			
Slavsk	5.0	Bolshkovo	2.3
Chernyakhovsk district (51.2 ths.)			
Chernyakhovsk	39.8	Mezhdurechie	0.7

cities – Kaliningrad, Sovetsk, Neman, Svetlyi and Baltiysk (Fig. 6.23). Most of the water is discharged to the surface waters without appropriate cleaning.

Agricultural areas cover less than half (46 %) of the Russian part of the Vistula Lagoon catchment. Coniferous, deciduous and mixed forests cover 8 % and 16.5 %, respectively. More than 22 % is taken by other crops. Lakes and other non-crop lands occupy less than 1 %. Urbanized land takes up just over 5.5 % (Figs. 6.24 and 6.25).

The waters of the Kaliningrad Oblast do not include any areas protected under the NATURA 2000 programme and the Ramsar convention. There are four reserves in the Russian part of the Vistula Lagoon catchment, namely the Novoselovsky, Kamensky, and Maysko-Krasnopolaynsky State Nature Reserves and the Vishtynecky Nature Park. The Vistula Spit is scheduled to be designated as a nature conservation area.

The natural potential of the inland waters of the Kaliningrad Oblast would seem to predict increased production of aquaculture ten times over (about 30 tons of commodity fish are currently grown in the inland waters).

Analysis of social and economic development strategies for municipalities around the Vistula Lagoon in the Kaliningrad Oblast for the period up to 2016 show that the following priorities exist for the direction of development:

– Industrial production
– Agriculture

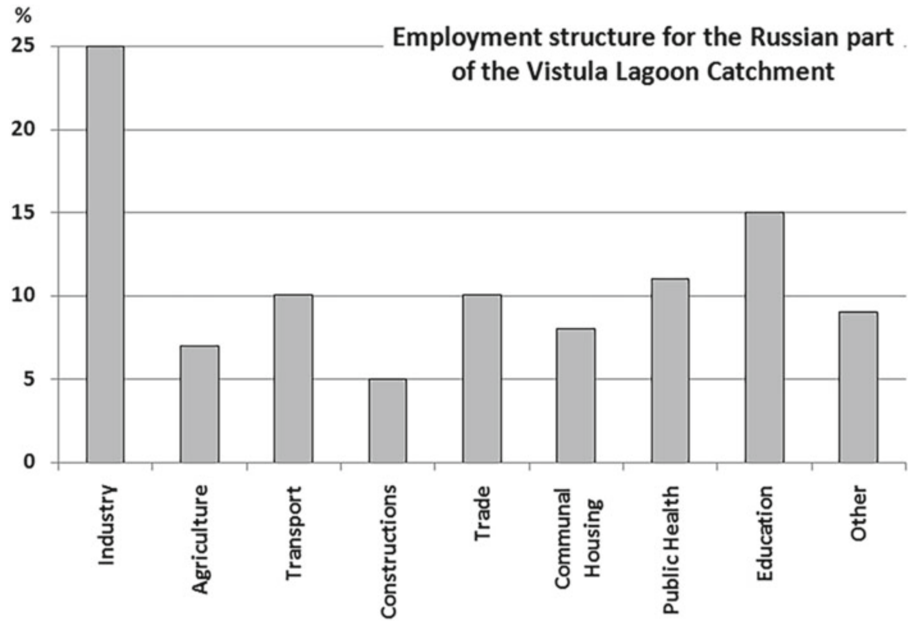


Fig. 6.22 Employment structure for the Russian part of the Vistula Lagoon catchment

Table 6.11 Main characteristics of water supply in the Kaliningrad Oblast (10^6 m^3/year)

Year	Issues of water supply				Irrevocable part of water supply
	Total	Surface fresh waters	Marine waters	Underground waters	
2006	200	121	12	67	45
2007	172	88	16	68	32
2008	169	77	22	70	35
2009	143	59	17	67	29

– Transport
– Recreation and tourism
– Environmental protection

Each municipality selects its own strategic developmental direction depending on its economic and geographical situation and social conditions. The variety of economic preferences is presented in (Fig. 6.26).

Almost all coastal municipal units (Baltiysk, Kaliningrad, Ladushkin, Mamonovo, Bagrationovsk, Gurievsk and Zelenogradsk) have assigned tourism and recreation as priorities for development (Domnina and Chubarenko 2011). Some coastal municipalities plan to develop their port and transport complexes (Kaliningrad, Svetly, Mamonovo, Baltiysk), as they have a historical basis for them. Municipal units that don't have a connection to the lagoon, or have minimal connection to it, consider 'industry production' and 'agriculture' to be their main priority for development (Gurievsk, Bagrationovsk, Pravdinsk, Ozersk, Nesterov, Krasnoznamensk municipal districts). Municipal units around Kaliningrad mainly plan to develop industrial production. Thus, industrial production, agriculture and tourism are the most popular directions of development for the municipal units of the Kaliningrad Oblast.

6.11 The Basis for Spatial Planning of the Curonian and Vistula Lagoons

The Russian parts of the Vistula and Curonian lagoons (about 470 km^2 and 1300 km^2, respectively) have a juridical status of inner marine waters. The area of the lagoons is much less than those of the Exclusive Economic Zone (5000 km^2) and the territorial waters (2800 km^2) of the Russian Federation in the southeastern Baltic, but has significant importance for local and regional development. Navigation and fishing constitute the greatest amount of use of lagoon areas. Offshore oil extraction (already existing) and windpower engineering (currently under planning) will be further developed only at the open Baltic waters. The sector of water tourism is at the initial stage of development, but the number of personal motor boats and yachts increases day by day. For the successful growth of all maritime activities, it is necessary to develop maritime spatial plans to avoid conflicts and contra-

Table 6.12 Main characteristics of wastewater discharge in the Kaliningrad Oblast

Discharge, 10^6 m^3/year	2006	2007	2008	2009
Sewage to surface water bodies, total	152	137	129	110
Including:				
Partly purified	131	116	103	87
Purified	21	21	26	23
Discharge to ground water objects	3	3	4	4
Discharge to landscape	5	5	5	5

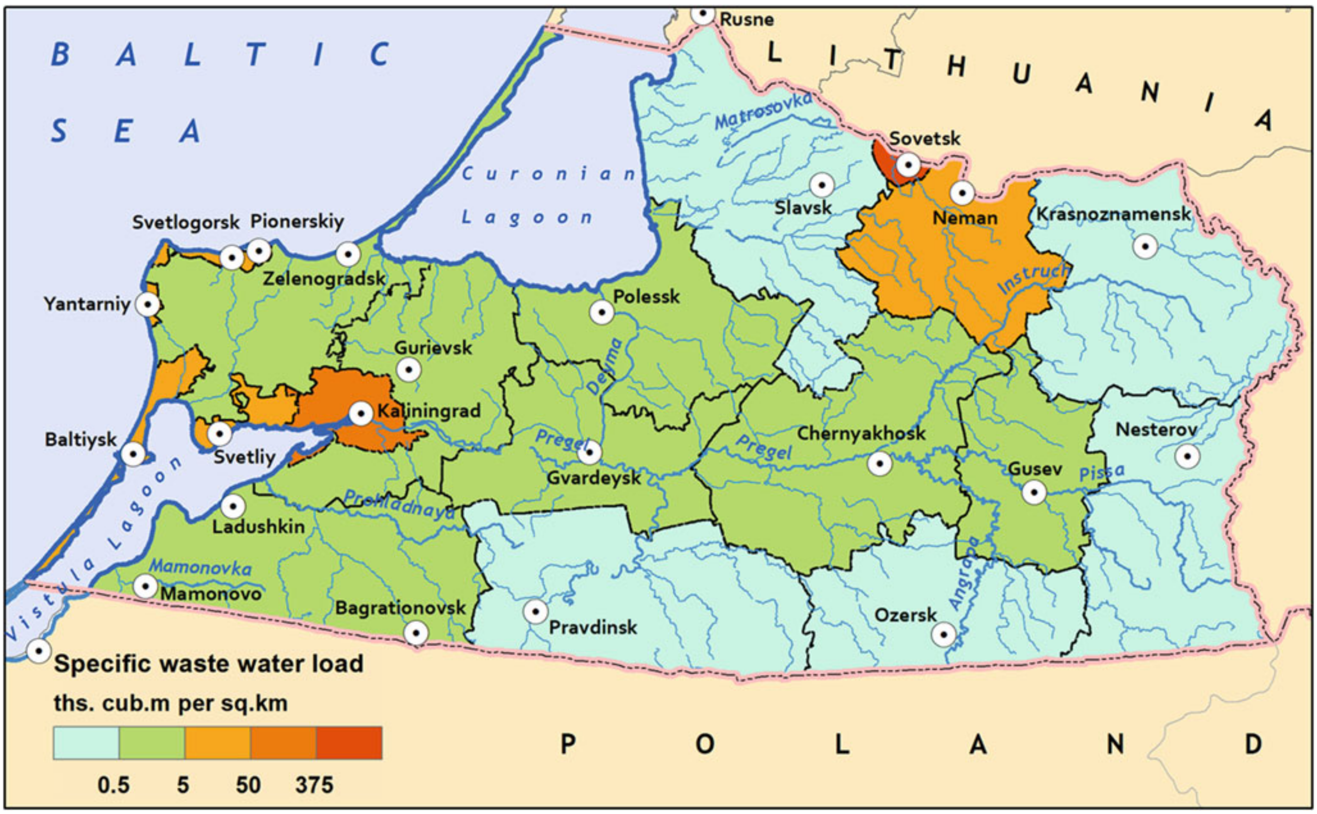


Fig. 6.23 The load from waste water discharge (data for 2006) estimated as a specific value for municipal unit, i.e., the ratio of the amount of waste waters discharged into the water bodies in a municipal unit to the area of the municipal unit

dictions. The first stage and the basis of this planning process is an analysis of existing use of water space and potential conflicts of interest (Domnina et al. 2009).

Considering the human activity that already exists or is potentially possible in the Curonian and Vistula Lagoons, we may select the following key words to describe these activities and the conditions for them: cable lines, coastal protection, dredging and dumping, fishery, harbours and ports, aquaculture, nature conservation, navigation danger, nutrient (agriculture-born) run-off, offshore windfarms, oil extraction, oil spills, protected areas, areas of restricted use (e.g., devoted to military purposes), sand and gravel extraction, shipping, spawning areas, tourism, waste water discharge, and water supply. Figures 6.27 and 6.28 present the main uses and certain natural conditions for the Russian sides of the Curonian and Vistula Lagoons. It is easily seen that the Vistula Lagoon, having less space, is used much more intensively than the Curonian.

To describe the potential conflicts between the activities listed above, one may introduce three qualitative characteristics: activities are compatible (no conflict), partly or conventionally compatible (activities should be regulated), or incompatible (conflict is very probable). The results of the expert judgment of relations between the activities for both lagoons are presented in Table 6.13. There are some activities which are not at present being realized in the Vistula Lagoon – sand and gravel extraction, oil extraction, aquaculture and water supply; these activities are also not currently being realized in the Curonian Lagoon. There are three additional activities, namely dredging and dumping, waste water

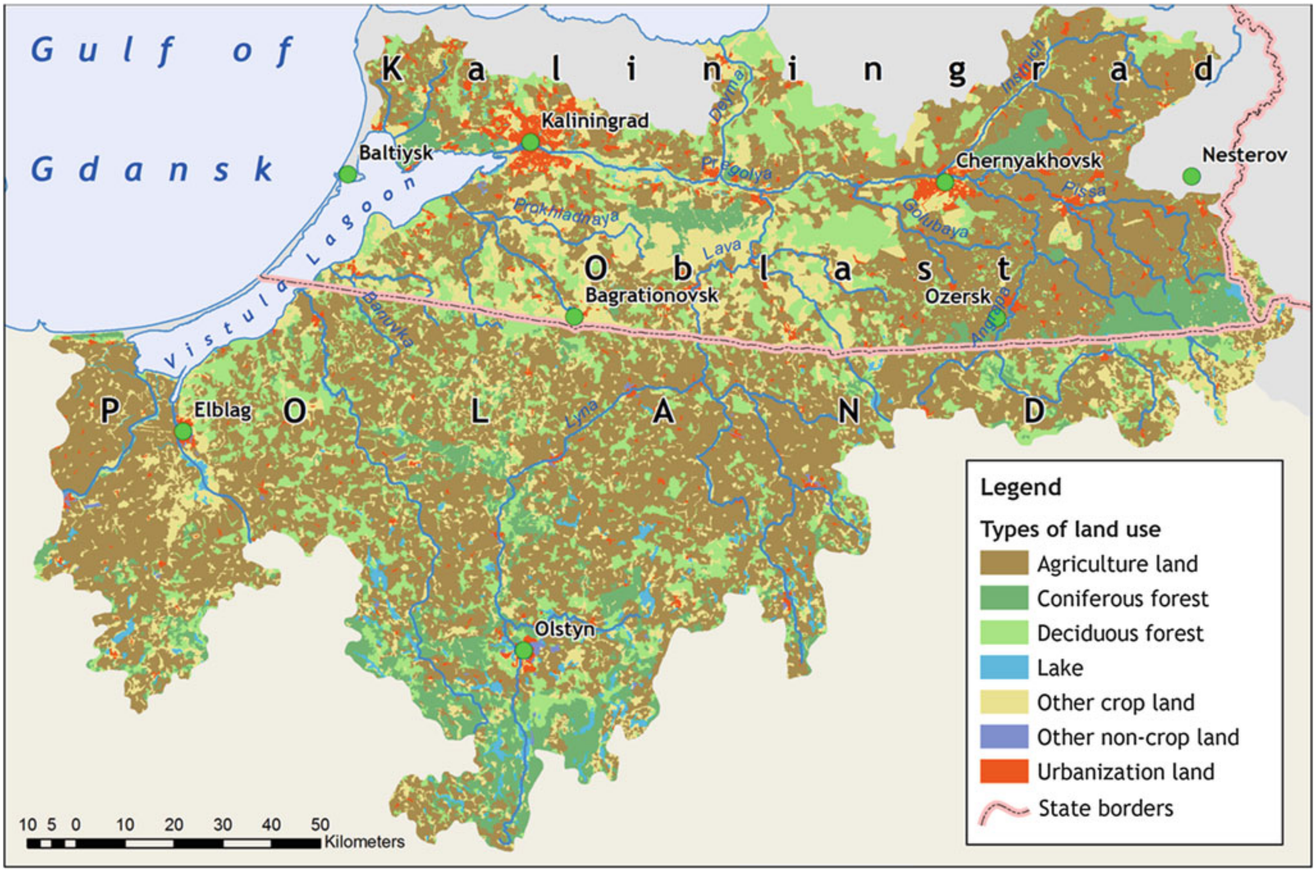
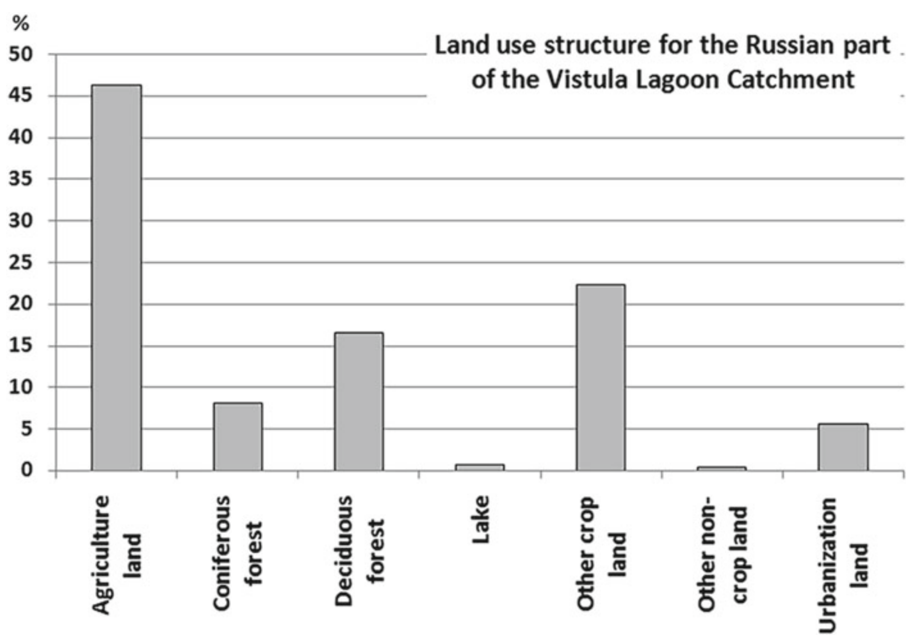


Fig. 6.24 Land use scheme of the Vistula Lagoon catchment (Map was prepared by D.Domnin as part of the LAGOON Project (Hesse et al. 2015))

Fig. 6.25 Structure of uses of land for the Russian part of the Vistula Lagoon catchment



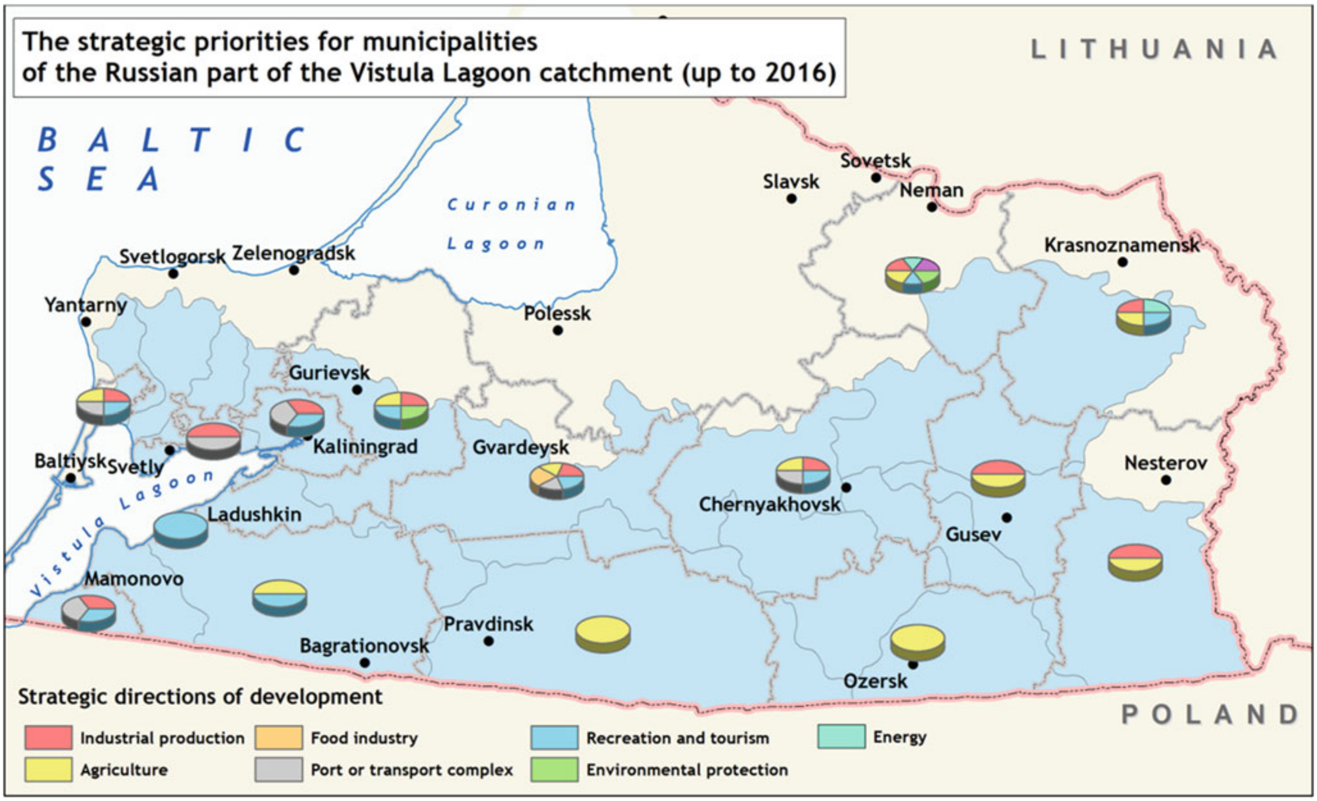


Fig. 6.26 Strategic priorities for future economic development of municipal units of the Russian part of the Vistula Lagoon catchment are presented as round diagrams per municipal unit. *Thin lines* are boundaries of municipal units (the main city is also indicated for each municipal unit); the area of the Vistula Lagoon catchment is colored in *blue*; the state border around the Kaliningrad Oblast is presented as a coupled *thin-thick line*

discharge and restricted use, which are completely absent within the Curonian Lagoon area.

Analysis of the tension inherent in potential conflicts was also made (Domnina et al. 2009), based on expert judgments and using the following approach. All potential conflicts were divided into three groups: "Use – Use" (e.g., dredging and dumping – fishery), "Use – Natural environment" (e.g., small vessel traffic – spawning areas) and "Permanent danger" (threat of oil spills, navigation danger, euthrophication, etc.). The tension for any potential conflict was evaluated in terms of four grades: high (3), moderate (2), weak (1) and absence of conflict (0). The grades have been calculated for every water area within the Curonian and the Vistula Lagoons. In the results, the Vistula Lagoon was characterized by the highest potential tension in general, the lagoon's estimated conventional 'tension value' being nearly two times higher for "use-use" conflicts and 30 % higher for indicators of "Permanent danger", but practically equal for potential conflicts between use and natural environment.

The reason for the high tension of potential conflicts for the Vistula Lagoon is in the large number of uses in smaller water areas. There is also the threat of oil pollution and numerous navigational dangers there. Use of the Curonian Lagoon is not as intensive as that of the Vistula Lagoon. Therefore, values of tension for "Use – Use" and "Use – Natural environment" conflicts is less within the Curonian Lagoon. However, even though there is no threat of oil pollution in the Curonian Lagoon (no oil tanker traffic), the level of permanent potential danger was estimated as being rather high, owing to strong eutrophication.

To conclude, it should be noted that the waters of the Curonian and Vistula Lagoons are used for different purposes – industrial fishery, navigation, environmental protection, shore protection, tourism, etc. There are certain activities for which the lagoons have definite potential, but which do not currently exist or are not yet well developed, such as aquaculture, wind power engineering and yachting or boating.

However, despite intensive use of the lagoon waters and the threat of potential conflicts of different values of tension, there are no real conflicts or unregulated relations. All conflicts analyzed are merely potential, and have to be taken into account when planning the future of the water areas of the Curonian and Vistula Lagoons. Moreover, in the best possible case, the use of lagoon waters should be agreed upon with the neighboring states – Poland and Lithuania – and this

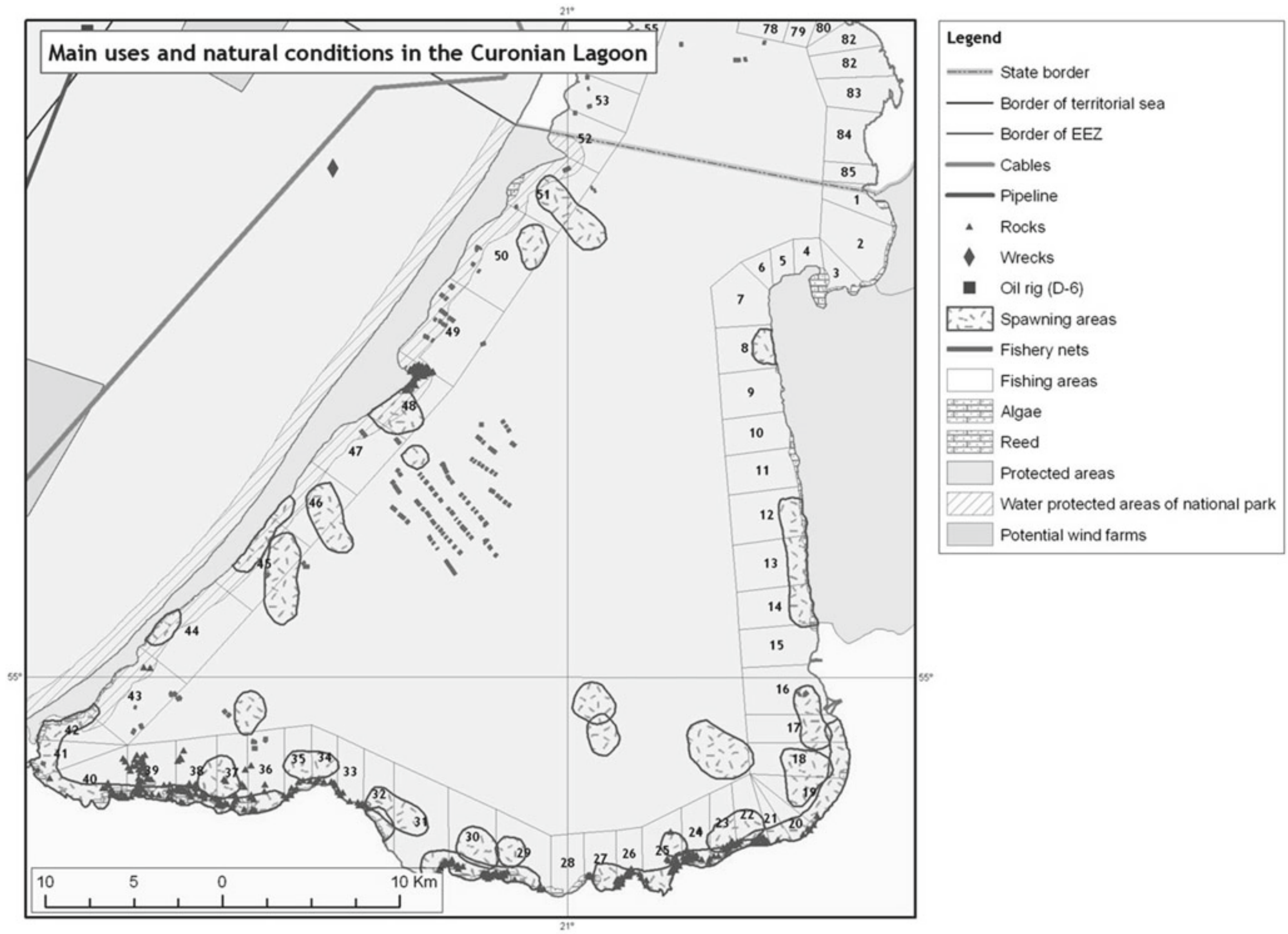


Fig. 6.27 Main use and certain aspects of the natural conditions on the Russian side of the Curonian Lagoon (Domnina et al. 2009)

transboundary aspect may both stir potential new conflicts and open new promising prospects.

6.12 Expected Changes in Use of the Vistula Lagoon and Catchment Due to Climate Change

Climate change has begun to affect certain aspects of the economic use of the water area of the Vistula Lagoon and its catchment, directly or indirectly. In the future, the impact of climate change will grow. However, the disadvantage of all strategies currently being considered either in municipal units or at the level of the regional government of the Kaliningrad Oblast is the scant attention being paid to environmental protection and climate change. In addition, the scenarios of climate change are not mentioned in any of the documents of strategic development. Meanwhile, climate change will affect virtually all economic sectors of the region (Karmanov et al. 2010; Piwowarczyk 2012).

6.12.1 Agriculture and Food Industry

Ones of the sectors most sensitive to climate change are agriculture and the processing of agricultural products. The development of agriculture depends on temperature and moisture. For the Vistula Lagoon, warmer summers and longer growing seasons are projected, and therefore, the possibility of obtaining higher yields will increase (Bates et al. 2008).

Making an estimation of temperature regime shift based on data obtained from modeling of the air temperature field for the Baltic Sea area within the ECOSUPPORT project (2009–2011, http://www.baltex-research.eu/ecosupport), it can be concluded that an increase in temperature of 4 °C by the end of the twenty-first century might lead to a prolongation of the vegetation period of approximately 1 month–2 weeks in the spring time and 2 weeks during autumn for the Vistula Lagoon area.

On the other side, warming and an increase in extreme weather events (e.g., the duration of high temperature and

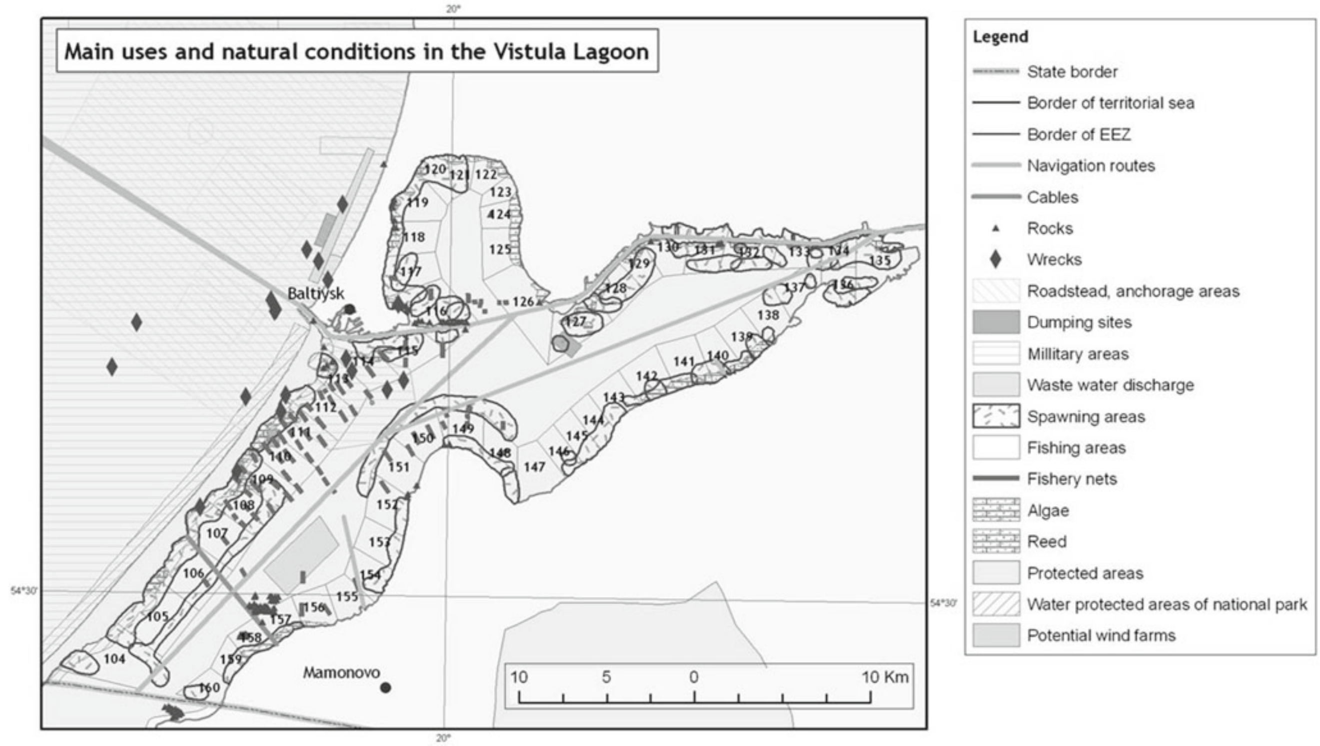


Fig. 6.28 Main use and certain aspects of the natural conditions on the Russian side of the Vistula Lagoon (Domnina et al. 2009). Offshore windfarms do not currently exist, but are planned within the area

drought) may increase the variability of crop yield, and even lower average yield. In particular, an increase in the frequency of extreme climatic events in the region during certain stages of culture growth (e.g., heat stress during the flowering period, rainy days on the dates of sowing) with higher intensity rainfall and more prolonged dry periods will likely reduce the yield of summer crops. Also, heavy rainfall, intensive soil moisture and flooding can hinder the reception of a large yield (Bates et al. 2008).

Negative aspects of climate change may interfere with the active development of agriculture in Bagrationovsk, Gurievsk, Zelenogradsk and the Baltiysk regions in the Kaliningrad Oblast (Domnina and Chubarenko 2011).

One of the ways to overcome the effects of climate change is the selection of more resistant crops for food production, repair, construction and maintenance of drainage canals and dikes.

6.12.2 Port and Land Transport

Flooding caused by rising water levels, and an increase in the intensity of extreme weather events (such as storms and hurricanes), pose a threat to transportation networks in some areas (localized street flooding, flooding of underground communications, damages associated with flooding and landslides for bridges, roads and railways (Bates et al. 2008)). Acknowledgement of this will be needed to recover, observe and increase the capacity of the storm drain system, which is especially important for the municipalities of the Vistula Lagoon area (Domnina and Chubarenko 2011).

Municipalities choosing port activities as their developmental priority should take into account the adverse effects of climate change, because beach erosion and sediment movement, the rising of sea levels and an increase in salinity are significant stresses for port structures.

6.12.3 Tourism and Recreation

The impacts of climate change on tourism include, on the one hand, prolongation of the tourist season in the Vistula Lagoon area, and on the other hand, a change in water quality conditions (Domnina and Chubarenko 2011).

Evaluation of tourist season prolongation, based on data obtained from modeling of the air temperature field for the Baltic Sea area within the ECOSUPPORT project (BALTEX 2009–2011), showed that, as in the case of agriculture, duration of the tourist season could be enlarged by approximately

Table 6.13 Potential compatibility of different types of use and natural peculiarities for the Vistula (left lower side) and Curonian (right upper side) Lagoons

Legend: activities (conditions) are: – compatible (1), – conventionally compatible (0), – incompatible (−1), – do not exist or are planned (-)	Offshore windfarms	Protection areas	Fishery	Cables	Tourism	Shipping	Harbours and ports	Nutrient run – off	Sand and gravel extraction	Oil extraction	Dredging and dumping	Aquaculture	Nature conservation	Navigation danger	Water supply	Oil spills	Waste water discharge	Spawning areas	Coastal protection	Resricted use
Offshore windfarms	!!!!	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Protected areas	1	!!!!	−1	0	0	0	−1	−1	–	–	–	–	1	1	–	–	−1	1	1	–
Fishery	−1	−1	!!!!	0	0	−1	1	0	–	–	–	–	−1	−1	–	–	0	−1	0	–
Cables	1	0	0	!!!!	1	–	1	1	–	–	–	–	1	0	–	–	1	0	0	–
Tourism (yachting)	0	0	0	0	!!!!	1	1	0	–	–	–	–	0	0	–	–	−1	0	0	–
Shipping	−1	−1	−1	0	1	!!!!	1	1	–	–	–	–	0	−1	–	–	1	−1	1	–
Harbours and ports	1	−1	1	1	1	1	!!!!	1	–	–	–	–	0	−1	–	–	0	−1	1	–
Nutrient run off	1	−1	0	1	0	1	1	!!!!	–	–	–	–	–	0	–	–	1	–	−1	
Sand and gravel extraction	–	–	–	–	–	–	–	–	!!!!	–	–	–	–	–	–	–	–	–	–	–
Oil extraction	–	–	–	–	–	–	–	–	–	!!!!	–	–	–	–	–	–	–	–	–	–
Dredging and dumping	1	−1	1	1	1	1	1	1	–	–	!!!!	–	–	–	–	–	–	–	0	–
Aquaculture	–	–	–	–	–	–	–	–	–	–	–	!!!!	–	–	–	–	–	–	–	–
Nature conservation	0	1	−1	1	0	−1	0	1	–	–	–	–	!!!!	1	–	–	−1	1	1	–
Navigation danger	1	1	−1	1	−1	−1	−1	1	–	–	–	–	1	!!!!	–	–	1	1	1	–
Water supply	–	–	–	–	–	–	–	–	–	–	–	–	–	–	!!!!	–	−1	–	–	–
Oil spills	1	−1	−1	1	−1	1	1	1	–	–	–	–	−1	1	–	!!!!	1	–	–	–
Waste water discharge	0	−1	0	1	−1	1	0	1	–	–	–	–	−1	0	–	1	!!!!	−1	1	–
Spawning areas	1	1	−1	0	0		0	0	–	–	–	–	1	1	–	−1	−1	!!!!	0	–
Coastal protection	1	1	0	0	0	1	1	1	–	–	–	–	1	1	–	−1	1	0	!!!!	–
Restricted use	1	0	0	1	0	0	1	1	–	–	–	–	0	−1	–	−1	1	−1	1	!!!!

1 month in the spring time and 2 weeks in the autumn. Duration of the swimming season, related to an increase in water temperature in the lagoon, will become longer by about 1 month as well.

Rising temperatures will cause an increase in eutrophication of the Vistula Lagoon, leading to an expansion of algal and reed bed areas along the coast. In general, the negative impact on tourism and recreation activities due to a change in water quality may be not very large, because this economic sector is very flexible and well-organized. An account of both the municipalities' existing capacities and market interest will help to mitigate the negative impacts of climate change.

Infrastructure in low-lying coastal areas is vulnerable to sea level rise, floods, hurricanes and other extreme atmospheric events (Bates et al. 2008). The number of coastal infrastructure objects at risk is growing rapidly in Kaliningrad Oblast, due to the development of small ports and harbors along the Kaliningrad Seaway Canal.

6.12.4 Fishery

Taking into account the total analysis of climate change effects on freshwater aquaculture and fishery made in (Bates et al. 2008), we may formulate the following issues for the Vistula Lagoon:

- rise in temperature, drop in oxygen content and, possibly, drop in pH
- worsening of quality
- extreme meteorological elements
- water level rise and conflicts of interest between fishing and transportation functions of the lagoon due to the expansion of shipping;
- potential change in biodiversity of the lagoon.

Positive effects include an increase in growth rate and efficacy of food resource use; increase in duration of the growing period; range expansion.

6.12.5 Industrial Production

Climate change does not directly affect industrial production, apart from the danger of under-flooding of working areas (situated on the floodplain) and extreme meteorological events. The exceptions are industrial facilities for products susceptible to climate (for example, food industry enterprises) (Bates et al. 2008). Danger of underflooding is not an actual problem for municipalities around the Russian part of the Vistula Lagoon, as the facilities are situated in a territory more than 2 m above sea level.

6.12.6 Environmental Protection

Protection of the environment is one of priorities for development in certain municipal governments. Strictly speaking, environmental protection itself can not be a direction for economic development, but should rather be considered an essential condition for any economic development. At any rate, this is an important activity, which could also be affected by local climate change (Domnina and Chubarenko 2011).

Abrasion of the coastlines is the instability factor for existing and long-term development of protected natural territories. In particular, this is true for the Russian part of the Vistula Spit, which has no conservation status, but has an especially strong problem of coastal erosion in some segments, where it is a danger for local roads. Climate change may also cause a gradual changing of plant formation on the Vistula spit that, despite actually being a natural phenomena, must still be subject to measures for nature conservation by necessity.

6.13 Conclusion

The Curonian and Vistula Lagoons should be considered to be a part of one natural hydraulic system. They are connected via two branches of the Pregolya River – the Pregolya River proper and the Deyma arm, a branch of the Pregolya River 56 km upstream from its mouth. Practically, this means that the Pregolya River catchment upstream of the point of bifurcation of the Pregolya River into these two branches belongs to both lagoons. Aside from the joined Pregolya River catchment, both lagoons have their own catchments: they are (a) 98,200 km^2 of the Neman River catchment (Lithuania and Belarus) for the Curonian Lagoon and (b) 8600 km^2 of numerous small rivers entering the Vistula Lagoon from Russia (Kaliningrad Oblast) and Poland.

Under average conditions, the Pregolya River proper brings 60–64 % of the water to the Vistula Lagoon, and the Deyma branch takes about 36–40 % of it to the Curonian Lagoon. Under very extreme wind surge conditions (several days of strong and constant western winds), waters from the Vistula Lagoon may even overflow into the Curonian Lagoon via the Deyma branch. Thus, the Vistula and Curonian Lagoons and the downstream of the Pregolya River form a partly-connected system, with water steams regulated by differences in the water level both at the lagoons and at the upper part of the Pregolya River. The water level in the lagoons (at the very mouths of the Pregolya and Deyma Rivers) is forced by water level variations in the Baltic Sea and local wind, and the river stream is forced by rainfall, and therefore, the behavior of the system depends on a combination of marine (water level), atmospheric (wind, rainfall) and terrestrial (river run-off) factors, and all of them exhibit climate change variability.

During preparation of this book, another publication (Lilebo et al. 2015) about European lagoons was issued. The problem of future changes in the environmental conditions of the Vistula Lagoon (Rozynski et al. 2015a) and its watershed, which was one of the test site areas, was discussed in the context of future changes in climate and management issues (Rozynski et al. 2015b). It was found that changes in management practice (intensity of agriculture and related land use changes), especially in the watershed area (Hesse et al. 2015), may bring more crucial changes in water quality than possible climate changes around the lagoon (Bielecka et al. 2015). But concerns such complex systems as the Vistula Lagoon – Pregolya River – Curoniuan Lagoon system, the hydraulic conditions and balances in it are very sensitive to possible climate changes, and consequences will be revealed in exact area of contact – the downstream portion of the Pregolya River. For example, a process such as autumn saltwedge intrusion upstream in the Pregolya River, which influences the civil infrastructure of the City of Kaliningrad by blocking the water intakes of the drinking water supply system in the Pregolya (Fig. 6.29), may be synergetistically enhanced by a water level rise in the lagoon on one hand and a lowering of the river stream due to a decrease in rainfall (point 5.3 of this chapter) on the other.

While the Curonian Lagoon has mostly maintained the same environmental conditions over the ages, the Vistula Lagoon experienced considerable anthropogenic modification at the end of the nineteenth century, when the Nogat River, the branch of the Vistula River Delta, was practically closed by sluice. After that, the Vistula Lagoon's evolution was changed from that of a freshwater running coastal lake to an estuarine lagoon with predominant marine influence (Chubarenko and Chubarenko 2001).

Both lagoons are transboundary, belonging to countries (Lithuania, Poland and Russia) with different water management systems (EU and non-EU countries). This brings an additional challenge to the implementation of principles of sustainable development of human activity in the lagoons and their catchments. Both lagoons are most intensively used for fishing, but the Vistula Lagoon is also very much used for other purposes. There is a deep, navigable canal passing along the northern shore of the Vistula Lagoon, a navigable route between Russia and Poland passing along the main thalweg of the lagoon, and waste waters from the City of Kaliningrad (Russia) and other small towns are discharged into the Vistula Lagoon after treatment at different levels. All of this means that the Vistula Lagoon, as well as being viable for different types of use of the lagoon area, is also more vulnerable in terms of different kinds of potential conflict between environment and anthropogenic uses.

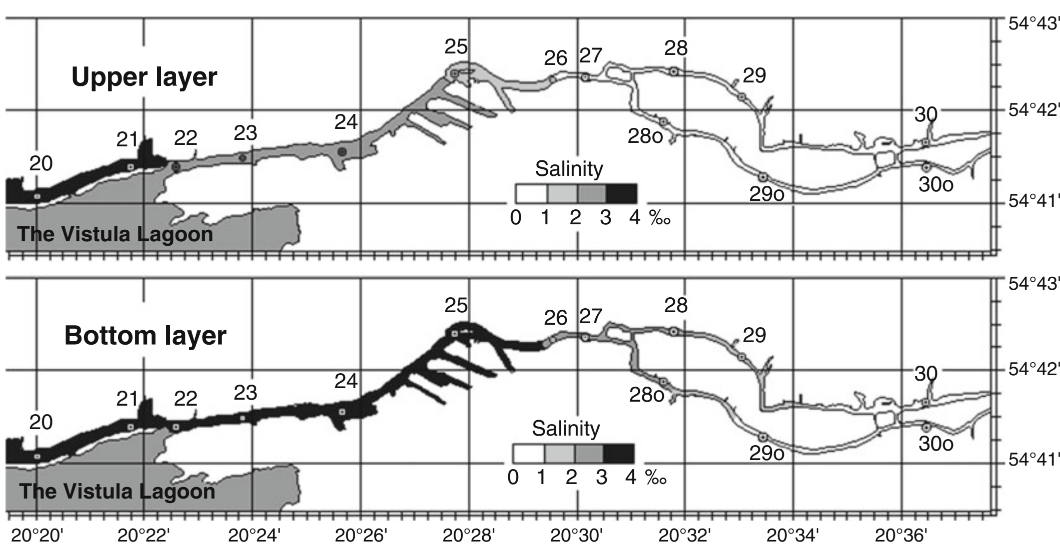


Fig. 6.29 Scheme of the most probable location for the boundaries of water with different salinity on the eve of the autumn storm surge period at the surface (**a**) and the *bottom* (**b**) layers in the Pregolya River downstream area. Once a storm surge has lasted several hours, saline water intrusion will easily go upstream, blocking the intakes of the drinking water supply of the city of Kaliningrad, located at the 29o and 30o points

References

Andriashkina A, Domnin D, Chubarenko B (2008) Potential and conflicts of marine water area use in Russian part of the South East Baltic. In: Zaucha J, Fedorov G, Limonov L, Oding N (eds) North East of Russia in the Baltic Sea region: problems and perspectives of economic cooperation and collaboration. Kant's RSU, Kaliningrad, pp 230–257

Andrulewicz E, Witek Z (2002) Anthropogenic pressure and environmental effects on the Gulf of Gdansk: recent management efforts. In: Schernewski G, Schiewer U (eds) Baltic coastal. Ecosystems. Structure, function and coastal zone management. Springer-Verlag, Berlin/Heidelberg, pp 119–139

BACC Author Team (2008) Assessment of climate change for the Baltic Sea Basin. Regional climate studies. Springer-Verlag, Berlin/Heidelberg. ISBN 978-3-540-72785-9

Bagdanaviciute I, Blazauskas N, Brzezinska A, Chubarenko B, Cieslak A, Dailidiene I, Domnin D, Gajewski J, Gilbert C, Gulbinskas S, Kalas M, Matczak M, Mikelenaite J, Mileriene R, Rybka K, Staskiewicz A, Stawicka I, Szefler K, Visakavicius E (2008) In: Gilbert C (ed) State of the Coast of the South East Baltic: an indicators-based approach to evaluating sustainable development in the coastal zone of the South East Baltic Sea. Drukamia WL, Gdansk

BALTEX (2009–2011) The Baltic Sea experiment. ECOSUPPORT (Advanced tool for scenarios of the Baltic ECOsystem to SUPPORT decision making). Last update of this page: 18 Dec 2015. http://www.baltex-research.eu/ecosupport/

Barinova G (2002) Kaliningrad region. Climate. Yantarny Skaz, Kaliningrad. (In Russian)

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (eds) (2008) Climate change and water. Technical paper of the international panel on climate change. IPCC Secretariat, Geneva

Bielecka M, Robakiewicz M, Zalewski M, Khokhlov V, Tuchkovenko Y, LIoret J, Lencarte Silva J, Dias JM, Lillebo AI, Chubarenko B, Staroszyk R (2015) Lagoons impacts integrated scenarios. In: Lillebo AI, Stalnacke P, Gooch GD (eds) Coastal lagoons in Europe. IWA Publishing Alliance House, London, pp 155–167

Bobykina V (2002) Coastal reeds of the Vistula Spit and geoecology lagoon shore. In: Ecological problems of the Kaliningrad region and the Baltic region. Kaliningrad State University, Kaliningrad, pp 151–155. (In Russian)

Bobykina V (2008) Coasal morphodynamics of the Vistula Spit. In: Dynamics of the coastal zone of non-tidal seas. Terra Baltica, Kaliningrad, pp 37–38

Bobykina V, Boldyrev V (2007) Present state of the Vistula lagoon coast as the coastal ecosystem's component. Paper presented at the conference Estuarine ecosystems: structure, function and management, Kaliningrad-Svetlogorsk, 16–22 September 2007 (In Russian)

Boldyrev V, Bobykina V (2005) Current condition of the Curonian and Vistula Spits Lagoon Coasts and their interaction with the Lagoon waters. Paper presented at international conference European lagoons and their watersheds: function and biodiversity, Klaipeda, 4–9 October 2005

Bulycheva E, Stont Z, Bukanova T (2015) Variations of sea surface temperature and ice conditions in the South-eastern Baltic over the last decade. Paper presented at IEEE/OES Baltic international symposium: measuring and modeling of multi-scale interactions in the marine environment, Tallinn, 26–29 May 2015

Chechko V (2002) Analysis of spatial-temporal variability of suspended matter of the Kaliningrad Bay of theBaltic Sea. Russ Water Resour 29(4):425–432. Moscow: IAPC Nauka/Interperiodica

Chechko V (2004) Characteristic features of sedimentation in estuaries of lagoon type (by the example of Vistula and Curonian lagoons of the Baltic Sea). In: Alimov A, Ivanova M (eds) Regularitis of hydrobiological regime of water bodies of different type. Science World, Moscow, pp 172–175. (In Russian)

Chechko V (2008) Spatial structure and evolution of bottom sediments in the Vistula Lagoon. In: Chubarenko B (ed) Transboundary waters and basins in the South-East Baltic. Terra Baltica, Kaliningrad, pp 244–249. ISBN 978-5-98777-031-3

Chechko V, Blazchishin A (2002) Bottom deposits of the Vistula Lagoon of the Baltic Sea. Baltica 15:13–22. Vilnius: Publisher Lithuanian Academy of Sciences

Chubarenko B (2007a) Watershed management in the Russian federation and transboundary issues by example of Kaliningrad Oblast (Russia). In: Gonenc E, Vadineanu A, Wolflin J, Russo R (eds) Sustainable use and development of watersheds, NATO Science for peace and security series, sub-series C - environmental security. Springer, Dordrecht, pp 133–149. doi:10.1007/978-1-4020-8558-1_9. ISBN 978-1-4020-8557-4

Chubarenko B (2007b) Monitoring physical processes. In: Gonenc IE, Koutitonsky VG, Rashleigh B, Ambrose RB, Wolflin J (eds) Assessment of the fate and effects of toxic agents on water resources, Security through science series C: environmental security. Springer, Dordrecht, pp 109–126

Chubarenko B (2008) The Vistula Lagoon. In: Chubarenko B (ed) Transboundary waters and basins in the South-East Baltic. Terra Baltica, Kaliningrad, pp 37–57. ISBN 978-5-98777-031-3

Chubarenko B, Alexeev F (2005) Trans-boundary character of water resources in the South-eastern Baltic as the basis of the strategy for sustainable development of water resources. In: Perspectives of interregional cooperation development: Kaliningrad Oblast within the Euro-region "Baltic". Kaliningrad State University, Kaliningrad, pp 202–223

Chubarenko B, Chubarenko I (2001) New way of natural geomorphological evolution of the Vistula Lagoon due to crucial artificial influence. In: Emeliayanov E (ed) Geology of the Gdansk Basin, Baltic Sea. Yantarny Skaz, Kaliningrad, pp 372–375

Chubarenko I, Chubarenko B (2002) General water dynamics of the Vistula Lagoon. Environ Chem Phys 24(4):213–217. Vilnius: Institute of Physics

Chubarenko B, Chubarenko I (2003) The transport of Baltic water along the deep channel in the Gulf of Kaliningrad and its influence on fields of salinity and suspended solids. In: Dahlin H, Dybern B, Petersson S (eds) ICES cooperative research report, vol 257. ICES, Copenhagen, pp 151–156

Chubarenko B, Margonski P (2008) The Vistula Lagoon. In: Schiewer U (ed) Ecology of Baltic coastal waters. Ecological Studies, vol 197. Springer-Verlag, Berlin, pp 167–195

Chubarenko B, Chubarenko I, Kuleshov A (1998a) The results of 1994–1997 investigations of hydrological structure and transparency of water in the Russian part of the Vistula Lagoon. Paper presented at symposium freshwater fish and the Herring population in the coastal lagoons: environment and fisheries, Gdynia, Poland, 6–7 May 1998

Chubarenko B, Kuleshov A, Chechko V (1998b) Field study of spatial-temporal variability of suspended substances and water transparency in Russian part of Vistula Lagoon. In: System ecology, vol 2. Klaipeda University, Klaipeda, pp 12–17

Chubarenko B, Lund-Hansen LC, Beloshitski A (2002) Comparative analysis of potential wind-wave impact on bottom sediments in the Vistula and Curonian lagoons. Baltica 15(2):31–39. Accepted November 14, 2002. http://www.geo.lt/geo/index.php?id=726

Chubarenko B, Koutitonski VG, Neves R, Umgiesser G (2004) Chapter 6: Modelling concept. In: Gonenc IE, Wolflin J (eds) Costal lagoons: ecosystem processes and modelling for sustainable use and developments. CRC Press, Boca Raton, pp 231–306

Chubarenko B, Chechko V, Kurchenko V (2005a) Suspended sediment studies in the Vistula Lagoon and its navigational canal. In: Sediment transport in rivers and transitional waters. Institute of Hydroengineering, Gdansk, pp 40–45

Chubarenko B, Chubarenko I, Baudler H (2005b) Comparison of Darss – Zingst Boden Chain and Vistula lagoon (Baltic Sea) in a view of hydrodynamic numerical modeling. Baltica 18(2):56–67. Accepted December 14, 2005. http://www.geo.lt/geo/index.php?id=721

Chubarenko B, Navrotskaya S, Stont Z (2012) Long-term trends of meteorological and hydrological characteristics for coastal zone of the Kaliningrad Oblast (Russia): report of subcontract work within the BaltAdapt project between the Permanent International Secretariat of the Council of the Baltic Sea States (CBSS), the client, and the Baltic Institute of Ecology of Hydrosphere (BIEH), the contractor. AB IO RAS, Kaliningrad

Climate (2015) Climate data Kaliningrad Airport (1931–2014). http://en.tutiempo.net/climate/ws-267020.html. Accessed 4 June 2015

Dailidiene I, Davuliene L (2008) Salinity trend and variation in the Baltic Sea near the Lithuanian coast and in the Curonian Lagoon in 1984–2005. J Mar Syst 74(1):20–29. Elsavier. doi:10.1016/j.jmarsys.2008.01.014

Dailidiene I, Baudler H, Chubarenko B, Navrotskaya S (2011) Long term water level and surface temperature changes in the lagoons of the southern and eastern Baltic. Oceanology 53:293–308. Moscow: IAPC Nauka/Interperiodica

Davies JL (1972) Geographical variation in coastal development. Oliver and Boyd, Edinburgh

Domnina A, Chubarenko B (2011) Discussion on the Vistula Lagoon regional development considering local consequences of climate changes. In: SMHI oceanography series, vol 112, pp 1–44. ISSN 0283-7714

Domnina A, Chubarenko B, Domnin D (2009) Potentials and conflicts in the Russian part of the South-East Baltic. In: Ciesliak A, Jakubowska P, Scibor K, Staskiewicz A, Zaucha J (eds) Compendium on maritime spatial planning systems in the Baltic Sea Region. Maritime Institute, Warsaw-Gdansk, pp 114–129. ISBN 978-83-85780-96-0.

Fisher HB, List EJ, Koh RCH, Imberger J, Brooks NH (1979) Mixing in inland and coastal water. Academic, New York

Floderus S (1988) On the spatial distribution of wave impact at the Kattegat seabed. Geografiske Annaler A 70:269–272. Sweden: Publisher SSAG

Gasiunaite ZR, Daunys D, Olenin S, Razinkovas A (2008a) The Curonian Lagoon. In: Schiewer U (ed) Ecology of Baltic coastal waters. Ecological studies, vol 197. Springer-Verlag, Heidelberg, pp 197–216

Gasiunaite ZR, Daunys D, Olenin S, Razinkovas A (2008b) The Curonian Lagoon. In: Chubarenko B (ed) Transboundary waters and basins in the South-East Baltic. Terra Baltica, Kaliningrad, pp 58–67. ISBN 978-5-98777-031-3

Handbook on climate of the USSR (1969) Cloud cover and atmospheric phenomena 6(5). Hydrometeoizdat, Leningrad (In Russian)

Hesse C, Krysanova V, Stefanova A, Bielecka M, Domnin D (2015) Assessment of climate change impacts on water quantity and quality of the multi-river Vistula Lagoon catchment. Hydrol Sci J 60(5):890–911. Published on behalf of the IAHS

Jurgelėnaitė A, Kriaučiūnienė J, Šarauskienė D (2012) Spatial and temporal variation in the water temperature of Lithuanian rivers. Baltica 25(1):65–76. Vilnius: Publisher Lithuanian Academy of Sciences

Karmanov K, Chubarenko B, Domnin D, Hansson A (2010) Attitude to climate changes in everyday management practice at the level of Kaliningrad Region municipalities. In: SMHI oceanography series, vol 4. Swedish Meteorological and Hydrological Institute, Norrkoping, pp 1–12. ISSN0283-7714

Kjerfve B (1986) Comparative oceanography of coastal lagoons. In: Wolfe DA (ed) Estuarine variability. Academic, New York, pp 63–81

Lazarenko NN, Maevskiy A (eds) (1971) Hydrometeorological regime of the Vistula Lagoon. Hydrometeoizdat, Leningrad. (in Russian)

Lillebo AI, Stalnacke P, Gooch D (eds) (2015) Coastal lagoons in Europe. IWA Publishing Alliance House, London

Malinin V, Gordeeva S, Shevchuk O (2010) Modern sea level variability and its causes. Proc Congr Russ Geogr Soc III(1):83–87. (In Russian)

Markova L (1999) Rivers. In: Litvin V (ed) Kaliningrad Oblast: nature sketch. Yantarny Skaz, Kaliningrad, pp 69–83. (In Russian)

Martin JL, McCutcheon SC (1999) Hydrodynamics and transport for water quality modelling. Lewis Publishers, Boca Raton

Meier HEM (2006) Baltic Sea climate in the late twenty-first century: a dynamical downscaling approach using two global models and two emission scenarios. Clim Dyn 27(1):39–68. doi:10.1007/s00382-006-0124-x. Accessed 12 Dec 2014

Navrotskaya SE, Chubarenko BV (2011) Comparison of mean and extreme water levels in the Baltiysk Strait and the mouth of the Pregolya River (Kaliningrad Lagoon) for the period 1901–2006. Trans Russian Geograph Soc 143(4):75–80 (In Russian)

Navrotskaya S, Chubarenko B (2012a) On trends in water levels in the Russian part of the Vistula Lagoon and the adjacent waters of the Baltic Sea. The regional effects of global climate change (causes, effects, projections). In: Proceedings of the international conference, Voronezh, 26–27 June 2012, pp 248–251. (In Russian)

Navrotskaya S, Chubarenko B (2012b) On raising the sea level in the Russian part of the Vistula Lagoon. Russ Meteorol Hydrol 37(1):39–46

Navrotskaya S, Chubarenko B (2013) Trends in the variations of the sea level in the lagoons of the Southeastern Baltic. Oceanology 53(1):13–23. Moscow: IAPC Nauka/Interperiodica

Phleger FB (1969) Some general features of coastal lagoons. In: Ayala-Castaneres A (ed) Coastal Lagoons a symposium, memories of the international symposium on coastal lagoons, UNAM-UNESCO, Mexico D.F, 28–30 November 1967, pp 5–26

Piwowarczyk J, Hansson A, Hjerpe M, Chubarenko B, Karmanov K (2012) Climate change in the Baltic Sea Region – a cross-country analysis of institutional stakeholder perceptions. AMBIO 41:645–655.

Port of Klaipeda (2015) Klaipėda State Seaport Authority. Information updated 2016-02-19. http://www.portofklaipeda.lt/en. Accessed 3 Mar 2015

Pustelnikovas O (1998) The geochemistry of sediments of the Curonian Lagoon (Baltic Sea). Institute of Geography, Vilnius

Razinkovas A, Bliudziute L, Erturk A, Ferrarin C, Lindim C, Umgiesser G,Zemlys P (2005) Curonian Lagoon: a modelling study, Lithuania. In: Russo RC (ed) Modeling nutrient loads and response in river and estuary systems. Report 271 of committee on the challenges of modern society, North Atlantic Treaty Organization, Brussels, pp 194–222

Repechka M, Pustelnikovas O, Chervinskas E (1980) The modern sedimentation in the Curonian Lagoon. The scientific proceedings of the Lithuanian Universities. Geography XVI, pp. 28–69. (In Russian)

Rozynski G, Bielecka M, Margonski P, Psuty I, Szhymanek L, Chubarenko B, Esuikova E, Domnin D, Domnina A, Pilipchuk V (2015a) Chapter 7: The physio-geographical background and ecology of the Vistula Lagoon. In: Lillebo AI, Stalnacke P, Gooch GD (eds) Coastal lagoons in Europe. IWA Publishing Alliance House, London, pp 57–67

Rozynski G, Bielecka M, Margonski P, Psuty I, Szhymanek L, Chubarenko B, Domnina A, Kolontseva M, Taratuk O, Przedrzymirska J, Zaucha J (2015b) Chapter 8: The management story of the Vistula Lagoon. In: Lillebo AI, Stalnacke P, Gooch GD (eds) Coastal lagoons in Europe. IWA Publishing Alliance House, London, pp 67–77

Siegel H, Gerth M, Tschersich G (2006) Sea surface temperature development of the Baltic Sea in the period 1990–2004. Oceanologia 48:119–131. Moscow: IAPC Nauka/Interperiodica

Silich M (1971) Water balance of lagoon. In: Lazarenko N, Maevski A (eds) Hydrometeorological regime of Vistula Lagoon. Hydrometeoizdat, Leningrad, pp 143–172. (In Russian)
Sly PG (1978) Sedimentary processes in lakes. In: Lerman A (ed) Lakes: chemistry, geology, physics. Springer Verlag, Heidelberg, pp 65–89
Stigebrandt A, Gustafsson B (2003) Response of the Baltic Sea to climate change – theory and observations. J Sea Res 49(4):243–256. Elsavier
Stont Z, Chubarenko B, Goushchin O (2010) Changes in hydrometeorological characteristics for marine coast of the South-East Baltic. Trans Russ Geogr Soc 142(4):48–56. UK: The Royal Geographical Society (with the Institute of British Geographers) (In Russian)
USGS Global Visualization Viewer (2015) Earth resources observation and science center (EROS). http://glovis.usgs.gov/. Accessed 21 July 2015
Wypych K, Nieczaj J (1975) Osady denne. In: Łazarienko NN, Majewski A (eds) Hydrometeorologiczny ustroj Zalewu Wislanego. Wydaw. Komunikacji i Łączności, Warszawa, pp 41–46. (In Polish)
Zachowicz J, Uscinowicz S (eds) (1996) Geochemical atlas of the Vistula Lagoon. PGI, Warszawa. (In Polish)

Neva Bay: A Technogenic Lagoon of the Eastern Gulf of Finland (Baltic Sea)

7

Daria Ryabchuk, Vladimir Zhamoida, Marina Orlova, Alexander Sergeev, Julia Bublichenko, Andrey Bublichenko, and Leontina Sukhacheva

Abstract

The chapter is devoted to the geological development, hydrology, biology and environmental status of Neva Bay – the easternmost and shallowest part of the Gulf of Finland (the Baltic Sea). After the construction of the St. Petersburg Protection Facility, which separates Neva Bay from the Gulf of Finland, it was deliberately transformed into a technogenic lagoon. Neva Bay and its coastal zone were formed during the late Pleistocene deglaciation and Holocene sea-level fluctuations. The last very important event in Holocene geological history was the Neva River's onset from Lake Ladoga. Since the founding of St. Petersburg in 1703, Neva Bay has been influenced by increasing anthropogenic impact. Intense dredging and dumping caused a transformation of the bottom relief and sediments. The silty clay mud of the sedimentation basins provides information about "pollution history" of Neva Bay as a result of the rapid development of industry in St. Petersburg in the twentieth century. The Neva Bay ecosystem has certain unique features. Despite intensive traffic, dredging and dumping, leading to the destruction of aquatic habitats, the living planktonic and benthic communities are characterized by their regenerative ability.

Keywords

Eastern Gulf of Finland • Anthropogenic load • Sedimentation processes • Ecosystem

7.1 Introduction

Neva Bay – the easternmost and shallowest part of the Gulf of Finland – is an "inner bay" of St. Petersburg – the second largest city in Russia, and an important industrial, transportation and cultural center, located on the coast of the Gulf of Finland. Construction of the St. Petersburg Flood Protective Facility, which began in the 1970s, transformed Neva Bay into a very special "anthropogenic lagoon". The Neva River – one of the largest European rivers – is a natural channel that discharges the low mineralized waters from Lake Ladoga into Neva Bay and then into the Gulf of Finland. Natural features and the multidirectional anthropogenic impact on Neva Bay have caused the formation of a very special biodiversity. A proper understanding of the environmental state of Neva Bay and its primary natural and anthropogenic processes is crucial for the regional planning of sustainable development.

D. Ryabchuk (✉) • V. Zhamoida • A. Sergeev
A.P. Karpinsky Russian Geological Research Institute (VSEGEI), 74, Sredny prospect, 199106 St. Petersburg, Russia
e-mail: Daria_Ryabchuk@mail.ru; Vladimir_Zhamoida@vsegei.ru; sergeevau@yandex.ru

M. Orlova • A. Bublichenko
Zoological Institute Russian Academy of Sciences (ZIN RAS), Univesitetskaya nab. 1, St. Petersburg 199034, Russia
e-mail: marina.orlova2012@gmail.com; abublichenko@mail.ru

J. Bublichenko
Saint-Petersburg Research Centre of Russian Academy of Sciences (SPbRC RAS), 5, Universitetskaya nabereznaya, 199034 St. Petersburg, Russia
e-mail: julandb@mail.ru

L. Sukhacheva
Research Institute of Remote Sensing Data for Geology (NIIKAM), Branch of FGUP TSNIIMASH, Pr. Kosmonavtov 27-5-40, St. Petersburg, Russia 196211
e-mail: sukhacheval@mail.ru

R. Kosyan (ed.), *The Diversity of Russian Estuaries and Lagoons Exposed to Human Influence*, Estuaries of the World, DOI 10.1007/978-3-319-43392-9_7

7.2 Physical Conditions of Neva Bay

7.2.1 Physical Geography and Hydrology of Neva Bay

Location Neva Bay is the most eastern and shallowest part of the Gulf of Finland (Fig. 7.1). It is 21 km long; its maximal width is 15 km, its water surface area is 329 km^2, its average depth is 3.5 m, and its water mass volume is about 1.2 km^3.

The maximal natural depths have been observed in the center-western part of the bay (5–6 m). Nearby, within a portion formerly used for underwater sand-mining that is still filled with craters, the water depth reaches 10–12 m. Neva Bay can be considered to have been a deliberately technogenic lagoon since the 1980s, when it was practically separated from the eastern Gulf of Finland by the St. Petersburg Flood Protective Facility. At present, the total width of six channels (gates), including the Main Marine Channel connecting Neva Bay to the open sea, is about 1 km.

Hydrology The hydrological regime of the bay is very variable, owing to frequent changes in its hydrometeorological parameters, shallow-water conditions and the strong influence of the current of the Neva River (the largest river of the Gulf of Finland, with a water discharge of 80 km^3/year (Nezhihovsky 1988)). Water level fluctuations, wind waves and currents are the most important hydrodynamic factors here. The surface water current (up to 10 cm/s) of Neva Bay flows in a western direction. The brackish water current near the bottom flows along the southern coast of the bay to the east. Neva Bay water has a very low salinity (0.07–0.34‰), and as a result solely of the strong currents at the bottom flowing in an eastern direction, it can grow periodically up to 3‰ (Nezhihovsky 1988). These measurements were produced during the periods from May-October at stations for monitoring biological pollution in 2004–2008 and 2013–2014, in the context of the TOPCONS project (ENPI grant contract No 2011-022-SE511). Ice cover is formed every year, but due to warmer winters, the time of solid ice development has recently shortened. Fast, extreme rises in the water level (floods higher than 1.6 m above the average level) caused by a complex combination of several hydrometeorological factors are a specific phenomenon in Neva Bay. The most significant sea level rises in the Eastern Gulf of Finland were caused by storm run-up as a result of the combined effect of drift currents and long waves. During the period since the founding of St. Petersburg in 1703 up to the present, more than 300 floods have been observed. The maxi-

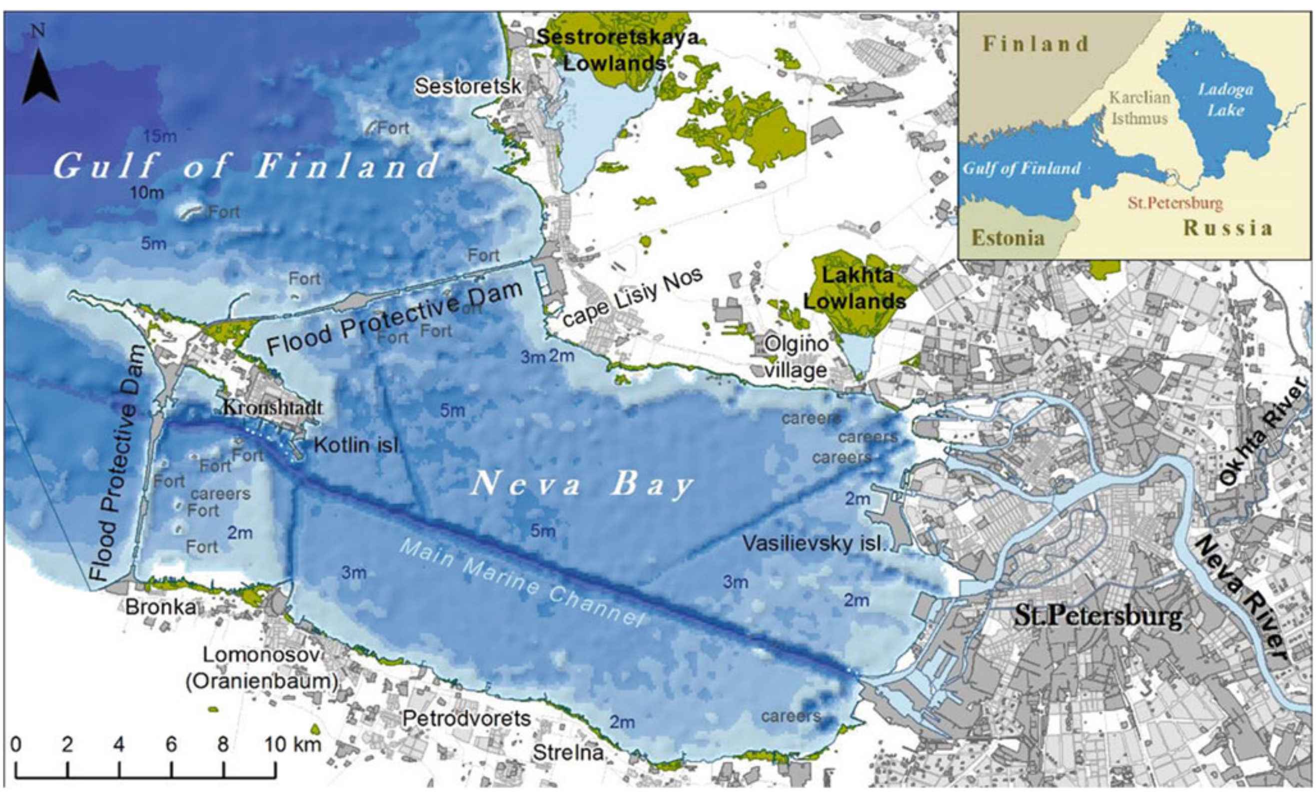


Fig. 7.1 Map of Neva Bay

mally catastrophic floods took place in 1777 (3.21 m), 1824 (4.21 m) and 1924 (3.80 m). The average stormy wave height from March to August is about 1 m, and from September to February, up to 2 m. The annual number of stormy days (with a wind speed over 15 m/s) is from 40 to 50. Waves can affect the Eastern Gulf of Finland's bottom up to depths of 3–3.5 m (Leontiev 2008), so practically all of Neva Bay's bottom can be influenced by waves.

Water Chemistry and Hydrooptical Conditions Neva Bay is a highly urbanized lagoon. This is also an area of intense ship traffic, as several harbors of the St. Petersburg port are located here. Numerous industrial, agricultural and transportation objects on the coasts of Neva Bay and along the Neva River, which has a large catchment area, contribute high concentrations of nutrients to the water of Neva Bay. Shipping is a source of such hazardous substances as TBT.

Hydrooptical conditions, mainly determined by concentrations of suspended matter, are important for the development of phytobenthos, planktonic and macrozoobenthos communities. These conditions are highly variable, both due to natural seasonality and such anthropogenic impact as that recently caused by dredging and dumping, e.g., the creation of new territories and the reconstruction of shipping infrastructures, accompanied by intense bottom sediment disturbance and the redistribution of hazardous substances, previously buried in sediments (Pitul'ko 2014; Spiridonov et al. 2014) (also see Sect. 7.3 below). Those sediment spills and the consequent increase in suspended inorganic matter concentration in the water column are recognized as a negative factor, controlling planktonic and benthic living communities in Neva Bay (Maksimov 2014). As the result of continuous satellite monitoring data from 2003 to 2012, we have identified three major periods of drastic changes in the hydrooptical conditions in Neva Bay and the adjacent areas of the Gulf of Finland (Sukhacheva and Orlova 2014). The variability in the interaction between anthropogenic and natural (seasonal) driving forces of hydrooptical conditions is shown in Figs. 7.2 and 7.3.

These pictures represent three major periods (from the beginning of the 2000s until now) of hydrooptical regime formation: (a) satellite image from August 10, 2004 – PERIOD 1, before the beginning of hydrotechnical activity in the new St. Petersburg harbor "Marine façade" project; (b) satellite image from October 29, 2005 – at the very beginning of the dredging activity in autumn 2005; (c) satellite image from September 21, 2006 – PERIOD 2 – showing intensive dredging in Neva Bay with sediment dumping in underwater pits; (d) satellite image from September 30, 2007 (also PERIOD 2) – showing intensive dumping along the Northern coastline; (e) satellite image from September 21, 2008 (PERIOD 3) – showing dredging in the area of construction of the new terminal; the excavated sediments are transported into the transitional zone, and anthropogenic influence in the Eastern Gulf of Finland is accompanied by a clearly expressed upwelling situation; (f) satellite image from September 6, 2013 (also PERIOD 3) – Neva Bay is now an area of hydrotechnical activity related to the construction of a terminal in the "Bronka" seaport, accompanied by increased concentration of suspended matter in the south gate of the Flood Protection Facility, and extreme development of phytoplankton in aquatic territories, adjacent to Neva Bay, where upwelling is also present.

Bottom Relief The natural features of Neva Bay bottom relief are characterized by an increase in sea depth in the western direction, and by local risings around Kotlin Island, stretching to the southern and northern coasts of the bay. At present, as a result of anthropogenic activity, the bottom relief has become sharper. Again, from the date of St. Petersburg's founding in 1703, some artificial islands with fortresses and quite a few crib-bars were constructed to the south and north of Kotlin Island. Fairways (ship channels), both those currently explored and those currently out of use, also contribute to the complexity of the bottom relief and its hydrology (e.g., penetration of salt waters into Neva Bay), as well as the distribution of benthic species.

7.2.2 History of the Neva Bay Bottom and Coastal Studies

Neva Bay has been shown on geographical maps since the first half of the seventeenth century. On the Swedish map edited by Olaus Magnus in 1539 from the University library of Uppsala and on the map by Gerard Mercator printed in 1595 in Mercator's Atlas, we can see Vyborg Bay and the Neva River, but there is no Neva Bay yet. On the map of Russia edited in 1614 by Gessel Gerard for Fiodor Gudonov, the son of Boris, the coastal line of the Eastern Gulf of Finland, e.g., Neva Bay and Kotlin Island, is depicted far more correctly. A very similar coastal line contour can be seen on the Swedish maps of Erik Nilsson Aspegeen (1643) and Ioghann Monsane (1644).

The battles of the Northern War, the founding of St. Petersburg, and the building of fortresses for the defense of the new Russian capital initiated hydrographical studies of the Bay bottom. In 1701, hand-made plans created in Sweden of the Neva delta and the Neva Bay fairways indicated depth. In October 1703, Peter I himself participated in a depth measuring to the south of Kotlin Island (Razdolgin and Skorikov 1988). By 1740, Captain Alexey Nagaev had become the head of "sea depth measurements from the Neva mouth to Kronshtadt". He was the author of the first large-scale bathy-

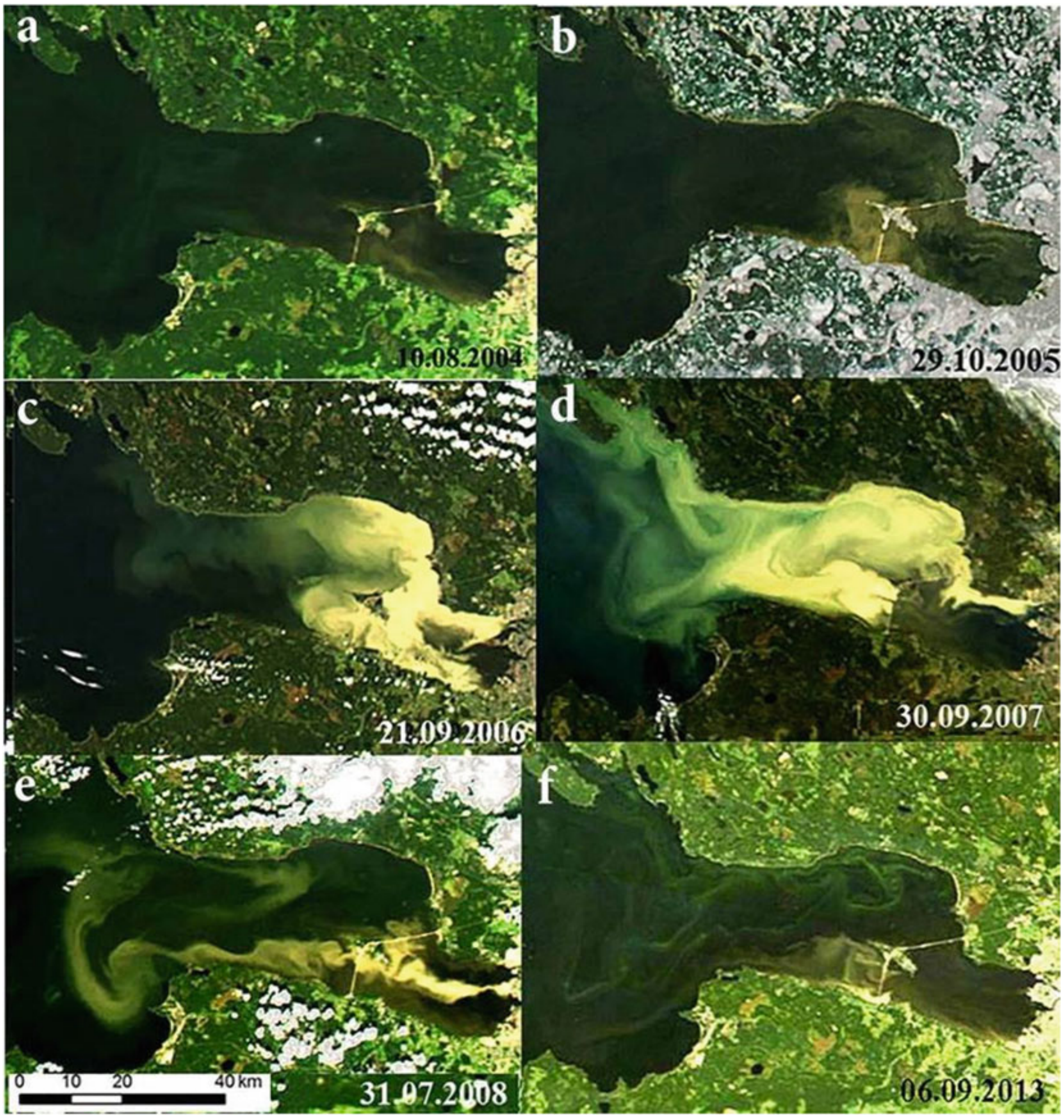


Fig. 7.2 Distribution of optical heterogeneities in the Eastern Gulf of Finland recorded by MODIS sensor: (**a**) from August 10, 2004; (**b**) from October 29, 2005; (**c**) from September 21, 2006; (**d**) from September 30, 2007; (**e**) from July 31, 2008; (**f**) from September 6, 2013

metric charts of Neva Bay, printed in 1742 (Russian National Library) and 1750. Captain Nagaev published the first descriptions of the Bay coast for the Coast Pilot. During the eighteenth and nineteenth centuries, detailed hydrographical surveys were conducted here by the special Department of the Russian Naval Ministry. A survey of Neva Bay was finished by 1859; its result was the basis for the majority of the maps edited between 1860 and 1911. It is noteworthy that "repeated measurements" have been carried out here practically every year.

From the middle of the eighteenth century, the hydrographical survey has been accompanied by sediment descriptions. The first descriptions of Neva Bay bottom sediments were carried out by officers of the Russian Navy's Hydrographic Survey as long ago as 1751. Such sediment types as sand, gravel and boulders ("stones"), and mud are mentioned in the pages of the vessel's journal by skippers Vasily Karpov and Matew Verkhovtsev (Fig. 7.4). According to the instructions of the Director of the Hydrographical Department of the Russian Naval Ministry, General Shubert, in his piece, "About the Baltic Sea Survey", there is a request that a depth, the vessel's location and "a quality of the bottom ground" be written into the journals for each station. Special signs for sediment type (stones, sand, fine sand, gravel, mud) have been marked on the bathymetric charts since 1860 (bathymetric charts of Neva Bay, 1860, 1911).

Fortification construction in Neva Bay (forts, crib-bars, Kronshtadt's harbors) initiated the bottom investigations, which can be considered one of the first marine geotechnical works in Russia. In 1836, the committee in charge of construction of the "Alexander I Fortress" decided to study the geological structure of the bay bottom around the building of

Fig. 7.3 Distribution of suspended matter in the Eastern Gulf of Finland under conditions of seasonal cooling and the intermixing of water masses (PERIOD 2): (**a**) satellite image by MODIS taken on November 24, 2007; (**b**) satellite image taken by MODIS on January 2, 2008. The optical heterogeneities, registered by satellite, are evidence that pollution of Neva Bay and adjacent areas by a fine fraction of suspended sediments continues for a relatively long time (up to 2 months) after the dredging and dumping has finished

the fort. "For this purpose casing tubes with the wooden pile were hammered. The ground taken out from the piles have shown that up 2.1 meters of the bottom was covered by fine sand, under it there was the layer of muddy clay, below 9–10 meters – dense (hard) land clay" (Razdolgin and Skorikov 1988, 112). Later, bottom investigations accompanied the construction of other forts, the building of St. Petersburg port and the excavation of ship channels, and the railway project between Cape Lisiy Nos and Kotlin Island. In 1885–1886, 30 boreholes were drilled near the Galley (Galerny) ship channel (Pel 1888).

Thus, by the middle of the nineteenth century, a large amount of geotechnical data concerning the Neva Bay bottom had been compiled. In 1911, Professor A. Inostrantsev studied the Quaternary sequence 559 m long and 18.9 m deep that had been uncovered by excavations during the building of the dry dock in Kronshtadt (Inostrantsev 1912). Inostrantsev stratified and described the sequence, established its genesis, and studied petrographic constituents of the till.

Scientific investigations in the bay became more active, and were also expanded to include studies of biodiversity, in the period between 1919 and 1930 (V. Lyahnitsky, M. Rosen, K. Deryugin). In 1928 and 1929, in the context of the construction of the Flood Protection Facility project, 13 boreholes were drilled between Oranienbaum and Kotlin Island and 10 more between Kotlin Island and Cape Lisiy Nos. Grain-size and physical property analyses of 417 sediment samples were carried out. The first transect of a Quaternary sequence up to 12 m in depth was compiled there (Rosen 1930). In 1920–1924, the expedition of Professor Konstantin Deryugin conducted hydrochemical, hydrobiological and hydrological works in Neva Bay. At the 10 sampling stations and about 40 drag (dredge) points, surface sediment sampling was produced. For all the samples, grain-size analysis was carried out (Deryugin 1923).

After the Second World War, investigations into Neva Bay sediment were conducted by the Russian Hydrometeorological Survey, the State Hydrological Institute, LenHyproTrans, Leningrad (St. Petersburg) State University, the Institute of Limnology RAS, MORNIIPROEKT, and other organizations. Detailed multidisciplinary works were organized during construction of the Flood Protective Dam.

Systematic on-land (Auslender et al. 2001) and marine (Spiridonov et al. 2007) geological surveys carried out from 1980 to 2000 have enabled researchers to study the distribution, composition, structure, and thickness of Quaternary deposits in the Eastern Gulf of Finland and adjacent areas. Since 1987, scientists of the Department of Marine and Environmental Geology of the A.P.Karpinsky Russian Research Geological Institute (VSEGEI) have carried out geological surveys, environmental investigations and geological mapping of Neva Bay bottom sediments (Petrov 2010). As a result, more than 1000 surface sediment samples were collected; a considerable amount of grain-size and geochemical analysis was conducted; and seabed sediments, litho-facial and Quaternary maps of the Bay bottom at different scales (from 1:200,000 to 1:25,000) were compiled. Since 1993, annual environmental geological monitoring within 30 sampling stations has been carried out by the VSEGEI and Sevmorgeo Institutes and the State Hydrometeorological Survey. By 2014, a significant dataset

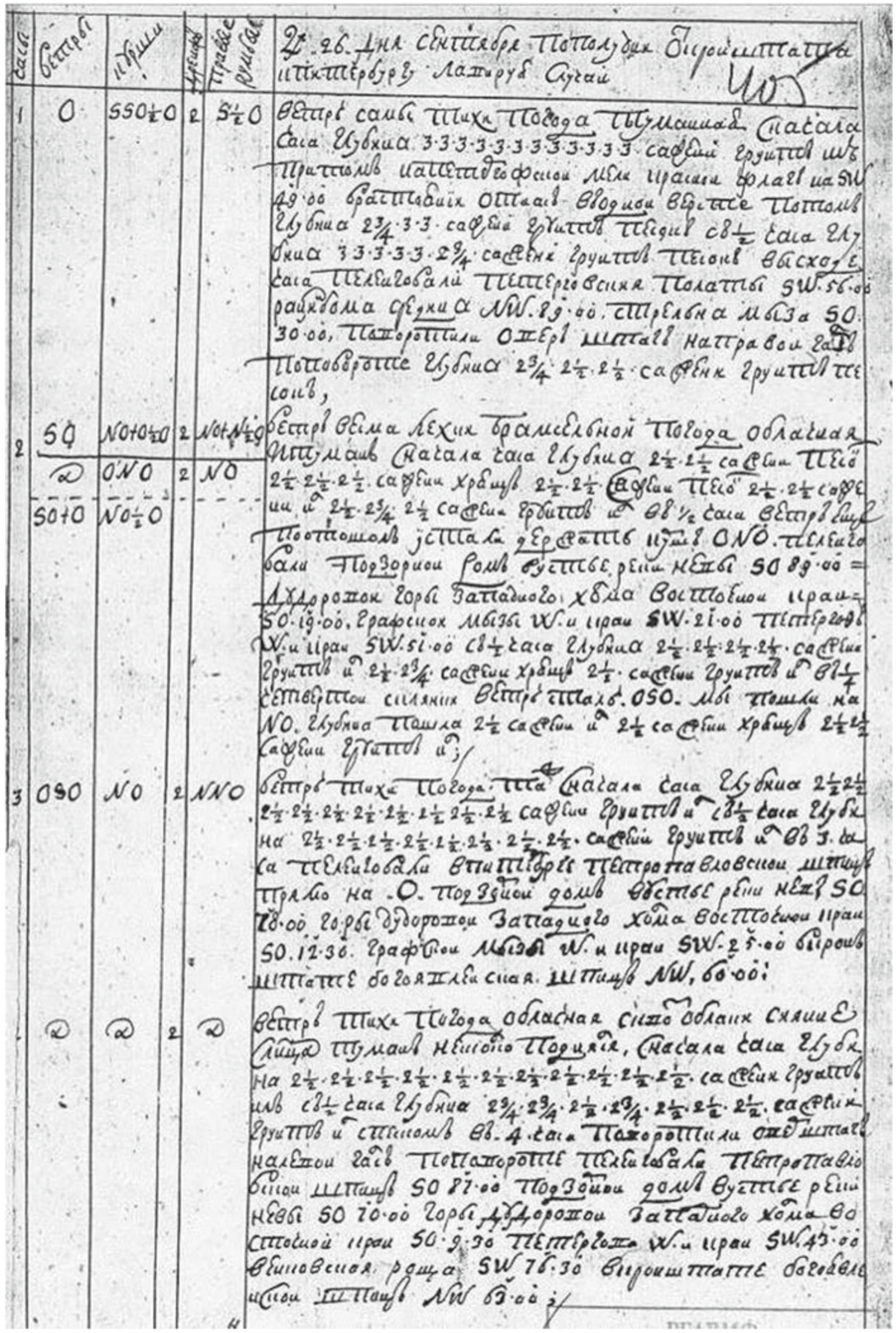


Fig. 7.4 Page from the hydrographical journal of skippers Vasily Karpov and Matew Verkhovtsev with a description of the Neva Bay depths and bottom sediments, 1751

of sedimenthologic and geochemical data had been collected. Between 2004 and 2006, in the context of the Russian-Finnish project SAMAGOL ("Sediment geochemistry and natural and anthropogenic hazards in the marine environment of the Gulf of Finland"), the specialists at VSEGEI and the Geological Survey of Finland (GTK) organized a joint scientific cruise (Fig. 7.5). Eight sediment cores were taken using a Niemisto gravity-corer and sub-sampled. After gamma spectrometry, the samples were totally digested and analyzed through ICP-AES and ICP-MS techniques. The chemical analyses of the samples revealed much for the study of the «pollution history» of Neva Bay (Vallius 2007). Since 2011, in a monitoring study carried out by VSEGEI, special attention has been paid to coastal zone dynamics and pollution.

Biodiversity studies of Neva Bay began more than 100 years ago with the studies of benthic fauna by A.S. Skorikov (1910). He had emphasized its similarity to the benthos of Lake Ladoga and the Neva River. In the 1920s, K.M. Deryugin (1922, 1923, 1925) provided a basis for further observations of benthos (Salaskin 1982). The macrozoobenthos of the first half of the twentieth century was represented by more

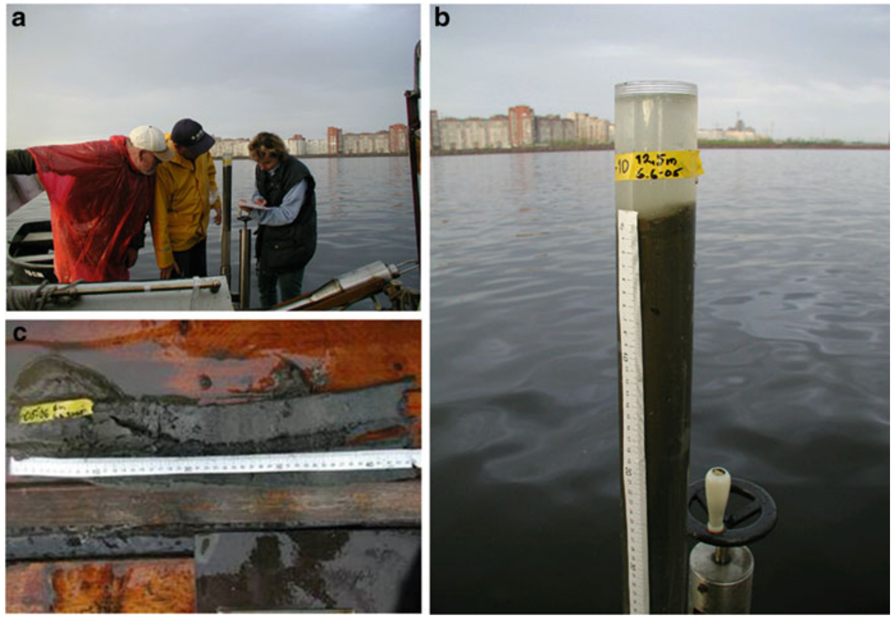


Fig. 7.5 Silty-clay mud sediment sampling during a joint scientific cruise of VSEGEI and GTK, Neva Bay, 2004. (**a**) Sediment core description on board the R/V "Risk"; (**b**) core 04-NG-10 (near Lakhta) sampled by a Niemisto corer; (**c**) core of Neva Bay muddy sediments

than 100 species, among which chironomids, oligochate worms and mollusks were predominant. Studies of the biodiversity of Neva Bay, including the coastal zone and macrophyte beds, were carried out on a fairly regular basis in the 1970s and 1980s (Vinberg and Gutel'makher 1987; Korelyakova 1997).

Biodiversity studies of terrestrial vertebrates inhabiting the Neva Bay coastal areas started at the end of the nineteenth and beginning of the twentieth centuries (Fisher 1873; Bihner 1884; Bogolubov 1895; Bianki 1903, 1913; Alferaki 1906, 1907). However, primary attention was devoted to the local avifauna and bird migrations. Very scarce data were collected about amphibians, reptiles and mammals (Fisher 1873; Bogolubov 1906; Bianki 1909a, b). The first observations of the bird and mammal fauna of Kotlin Island were carried out by N.F. Bogolubov (1895, 1906). After the Second World War, Russian scientists once again actively joined in Gulf of Finland avifauna research, among them such ornithologists as A.A. Malchesvsky, G.A. Noskov, and many others. Detailed works connecting bird migrations through the Gulf of Finland began in the 1960s (Noskov 1960). The most detailed investigations of all the coastal terrestrial vertebrates in the Neva Bay area began in the period from 1990 to 2000 (Khrabryi 1991; Kouzov 1993; Orlov and Ananjeva 1995; Noskov 1997; Bublichenko and Bublichenko 1999) and are still in progress nowadays. Monitoring is connected with the constantly increasing pollution level, the transformation of coastal habitats and the necessity of the conservation of biodiversity (Bublichenko 2008, 2010 etc.).

Investigations have become especially extensive since the mid-2000s due to an increased interest in the problems of eutrophication and biological pollution and the suggested impacts of dredging and dumping on the development of aquatic communities (Technical Reports 2004, 2008; Ecosystem…, 2008; Dynamics of biological diversity…, 2012; Regional Ecology…, 2014). Along with scientific publications, the annual volumes of the Environmental Assessment sections of hydrotechnical projects (creation of new territories and renovation of traffic infrastructure) can also be considered to be sources of information about the biodiversity of Neva Bay and its coasts, and the distribution of rare, threatened and red list species of plants and animals, both terrestrial and aquatic. Over the last decade, the satellite monitoring of Neva Bay has provided important spatial visual information for use in the interpretation of sampling of hydrophysical and biological data (Sukhacheva and Orlova 2014).

7.3 Regional Geology, Geomorphology and Geological History

The Gulf of Finland, including its eastern portion, is located at the boundary between the Russian Plate and the Baltic Crystalline Shield along its southeastern margin. A peneplain surface (very gently sloped south-south-east) was developed over Paleo-Mesoproterozoic basement units prior to the commencement of Late Vendian – Early Paleozoic terrigenous sedimentation. Tertiary denudation, including dominant glacial erosion, produced the present bedrock topography to a valuable degree, in both the southern sediment-covered part and the shield areas. One of the important features of the preQuaternary surface is the long, narrow (1–2 km) and deep (up to 200 m) paleo valleys, two of which can be traced along the northern coast of Neva Bay (Petrov 2010).

7.3.1 Late- and Postglacial Geological History of the Eastern Gulf of Finland

The late- and postglacial geological history of the Eastern Gulf of Finland and its coasts has been described in many publications (Kvasov 1979; Krasnov and Zarrina 1982; Spiridonov et al. 2007). During all phases of the late- and postglacial development (Baltic Ice Lake, the Yoldia Sea, Lake Ancylus, and the Littorina Sea), the study area was always the paleo basins in the easternmost part of the Gulf of Finland. Regional tectonic movement, together with several high pan-Baltic amplitude transgressions and regressions, caused significant change in the relative sea-level and formation of numerous terraces during the late Pleistocene – Holocene, both on land (at altitudes up to 100 m) and off-shore (up to a water depth of 20 m).

Recurring Quaternary glaciations over Northern Europe have repeatedly covered the entire Baltic Sea Basin (Andren et al. 2011), including its eastern part. The majority of the study area nowadays is covered by sediments of the most recent glacial cycle. Traces of the previous glacial and interglacial periods can only be found within paleovalleys. The area of the Eastern Gulf of Finland was covered by an ice-sheet by the time of the so-called Neva (Pandivere) stage of Weichselian glaciation (about 13,300–13,500 cal.BP) (Saarnisto and Sarinen 2001) (Fig. 7.6a).

By the time of the next stop of the ice-sheet's retreat in the south of Finland – the Salpausselka stage (about 12,300 cal. BP) – the entire area of the Gulf of Finland became free from ice. According to the most recent investigation of the varved clay sediments (Subetto 2009), deglaciation of the Neva Bay area occurred between 13,450 and 13,400 cal.BP. Near the ice margin, a huge Baltic Ice Lake (BIL) formed (Fig. 7.6b); within the study area, during the maximal phase, its water covered the Gulf of Finland and the Ladoga Lake bottom, as well as the Karelian Isthmus (with the exception of the top of its Central Height, this having been an island). Most typical sediments of the BIL were varved and homogenous clays (Fig. 7.6).

At about 11,700 cal. BP, the level of the BIL dropped drastically. The regional water level drop of at least 25–30 m caused extensive, dramatic landscape transformation and deep erosion of surficial deposits. During the portion of the geological survey of Neva Bay concentrating on the upper sediment boundary of the BIL clays, a layer of peat was found, dating to 11,050 ± 760 BP (C14), indicating that after the final drainage of the BIL, Neva Bay was most probably completely dry. Deposits from a low water level stage (11,700–10,700 cal. BP) are represented inland by layers of peat in the vicinity of St. Petersburg and within the Lakhta depression (altitudes −6.5 to −10 m) (Guide-book 1982). In the western direction, peat layers of the same age are found at altitudes from 0 m (near Sestroretsk) to 1 m (bank of the Tchernaya River) (Subetto 2011).

The next stage of development of the Baltic Sea basin – the Yoldia Sea – did not leave traces in the sediment history of Neva Bay, as its level was most probably relatively low. An increase in salinity due to the existence of a connection to the ocean did not reach the Eastern Gulf of Finland.

Around 10,700 cal. BP, a shallowing of outlets west of Lake Vanern stopped the Baltic basin's connection with the sea (Andren et al. 2011), and the water level started to rise. Within the study area, maximal water level of Lake Ancylus reached an altitude of +11 m to +13 m to the west of Neva Bay and about 10 m within St. Petersburg (Fig. 7.6c). Lake Ancylus covered the western part of the modern St. Petersburg area and was linked with Lake Ladoga by the so-called Henijoki Strait in the northwestern part of the Karelian Isthmus (Subetto 2009). In the fresh water of Lake Ancylus, mostly grey clays were formed, enriched by distinct, black hydrotroilite inclusions.

The subsequent regression phase (with a maximum of about 8800–8500 cal.BP), according to onland research, was marked by peat layers at altitudes of +4.5 m in the Karelian Isthmus (Mittinen et al. 2007), and from 0 to −2 m within the St. Petersburg area (Krasnov and Zarrina 1982). Based on discoveries of peat layers, K.K. Markov (1931) and S.A. Yakovlev (1925) assumed that, during the pre-Littorina regression, the water level in the Eastern Gulf of Finland was lower than it is nowadays (−2.4 m and −6 m, respectively). An analysis of the morphology and geological structure of the submarine terraces shows that, at that time, the relative sea-water level was, in fact, at least 5–6 m lower (Ryabchuk et al. 2014). Therefore, during that time, Neva Bay became been dried again (Fig. 7.6d).

Since about 8500 cal. BP, the connection of the Baltic Sea Basin to the ocean had been constant, the water level had started rising, and the marine stage of the Holocene development – Littorina Sea had started. During the maximum stage of the Littorina transgression for the easternmost part of the Gulf of Finland (dating from 7600 (Miettinen et al. 2007) to 7200 cal. BP (Rosentau et al. 2013)), several open bays were formed within local depressions of the glacial till (e.g., in the Sestroretskaya Lowland, the Lakhta Lowland, and within the central part of modern St. Petersburg). Glacial and glaciofluvial ridges transformed into numerous islands and peninsulas (Fig. 7.6e). The width of the simultaneous terrace is

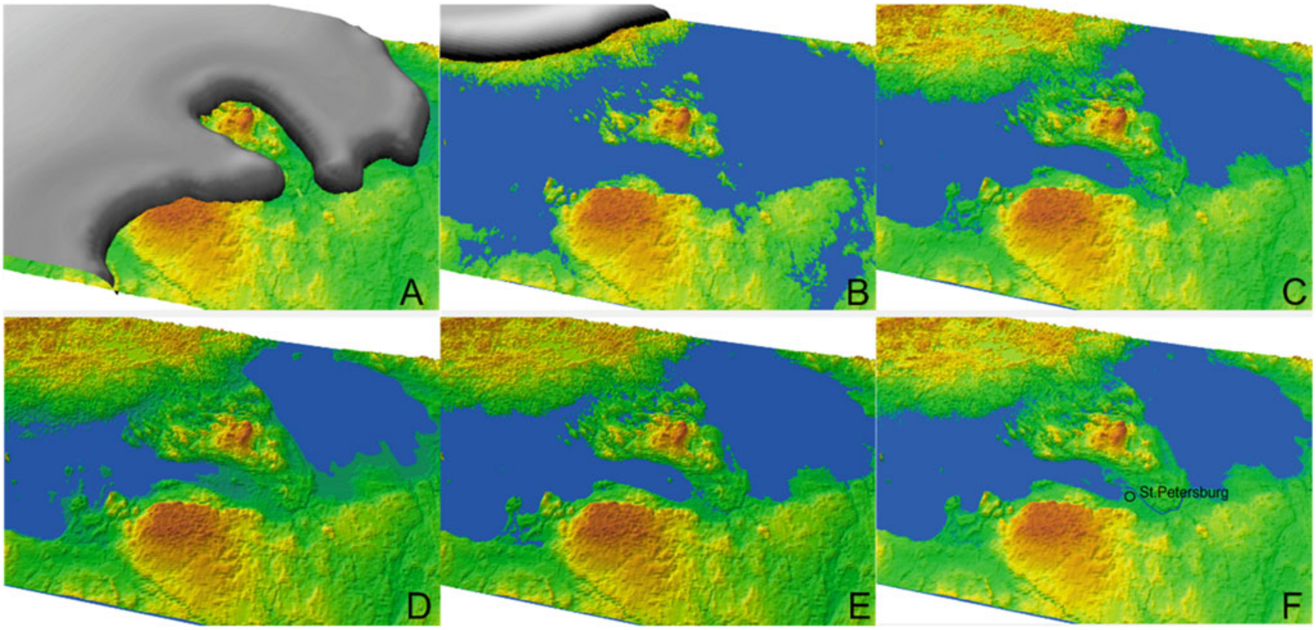


Fig. 7.6 Paleoreconstruction of study area development. (**a**) Neva (Pandivere) stage of Weichselian glaciation (about 13,300–13,500 cal. BP); (**b**) Salpausselka stage (about 12,300 cal.BP) and the Baltic Ice Lake; (**c**) Lake Ancylus (about 10,000 cal. BP); (**d**) pre-Littorina regression (about 8500 cal. BP); (**e**) maximum of Littorina transgression (about 7600 cal. BP); (**f**) modern situation

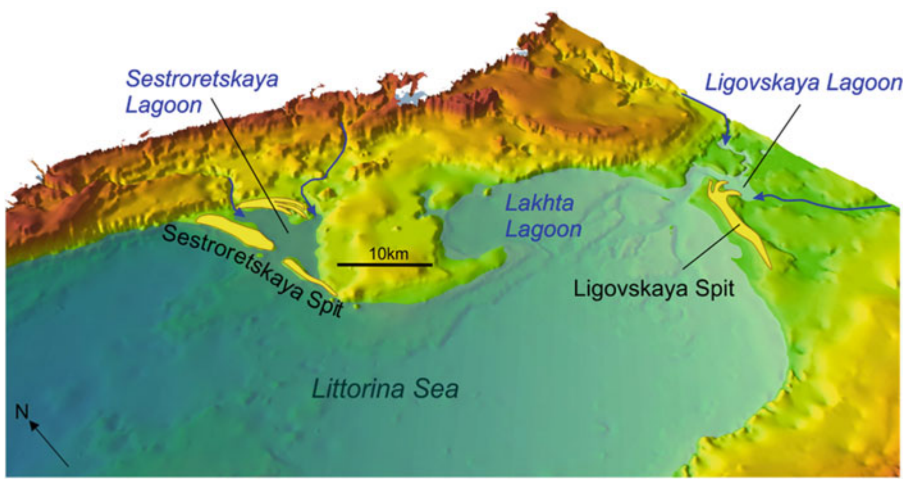


Fig. 7.7 Lagoon systems of the Eastern Gulf of Finland in the Late Holocene

from 0.4 km in the west to 2.5 km within the Sestroretskaya and Lakhta Lowlands, where erosion escarpments alternate with beach ridges of the same age.

The rate, time, and character of the subsequent regression (7600–7300 cal. BP–5400 BP) are debatable (Miettinen et al. 2007; Rosentau et al. 2013; Sandgren et al. 2004). The main feature of the regional lithodynamics of this stage in the Eastern Gulf of Finland was the development of large accretion bodies (bars and spits) and lagoons, partly connected to the sea (Fig. 7.7). Three relict lagoons (within the Sestroretskaya and Lakhta Lowlands and on the eastern coast) were located around the area of the modern Neva Bay.

Recent archeological studies of the coastal areas of the Eastern Gulf of Finland have resulted in the discovery of numerous unknown Mesolithic and Neolithic archeological sites and the restudy of many settlements found at the beginning of the twentieth century (Gerasimov 2003). It was established that, during the time of the Littorina (8500–4500 cal BP) in the Eastern Gulf of Finland, lagoon systems were most favored for fishing activity by the ancient population. Along the inner coasts of ancient lagoon systems, such archeological sites as Riigikula and Kudrukula were situated within the fluvial plains of the Narva and Luga Rivers (southern coast of the Gulf of Finland), and the Sestroretskaya and Lahta sites on the northern coast (Gerasimov 2006; Rosentau et al. 2013). In 2008–2009, as a result of archaeological research organized by Dr. Petr Sorokin at the mouth of the Okhta River, the right tributary of the Neva River

(Sorokin 2011), there was discovered an Early Iron Age, Early Metal Epoch and Stone Age archeological site (Okhta 1). The obtained archaeological collection includes about 12,000 items. Several types of pottery were defined as belonging to the Stone Age – Early Metal Epoch collection based on typological and morphological studies. Interdisciplinary investigation of the Okhta 1 site included lithological, mineralogical, geochemical, pollen, and diatom analyses. Over 150 radiocarbon dates were also obtained for different purposes (Kulkova et al. 2012). Micro-relief features, the distribution of archeological findings, and a considerable number of radiocarbon dates allowed researchers to divide the study area into "habitable" and "fishing" zones. A joint analysis of new geoarcheological data and published materials about the regional geological history permitted the creation of paleoreconstructions for the area around Okhta-1 for the time period 7700–2300 cal.BP (Kulkova et al. 2012).

Late- and post-Littorina relative sea level changes are still disputable, but since 4500 cal. BP, it has generally been decreasing (with some possible fluctuations), the lowlands around the bay have been swamping, and the modern coastal zone of Neva Bay was formed.

The last, very interesting problem of Holocene geological history is the question of the Neva River onset. The age of the Neva River has been debated for more than a century, with different authors imagining a wide time lap for this event – from the beginning of the Pleistocene (Verzilin and Kleimenova 2010) to 2000–2300 cal. BP (Kvasov 1979). But there is a recent consensus, based on studies on land, that the river was formed around 3000 cal. BP, due to the shift of the Lake Ladoga outlet from the Heinjoki waterway to its present route as a result of the differential post-glacial land uplift of the Lake Ladoga basin and its surroundings (e.g., Saarnisto and Grönlund 1996; Saarnisto 2008, 2012; Dolukhanov et al. 2009; Kulkova et al. 2014; Virtasalo et al. 2014).

The upper part of the geological sequence in the vicinity of the Neva Bay shoreline, both on the dry beach and in the near-shore, consists of relatively soft Quaternary deposits (Fig. 7.8).

Landward from the shoreline, they are represented by Late-Pleistocene glacial, glaciolacustrine and Holocene lacustrine, marine and alluvial deposits, mainly loam, clay, sand and peat. In the nearshore surface glacial till, glaciolacustrine clay and Holocene sand dominate (Spiridonov et al. 2007). All these deposits are easily erodible. The natural

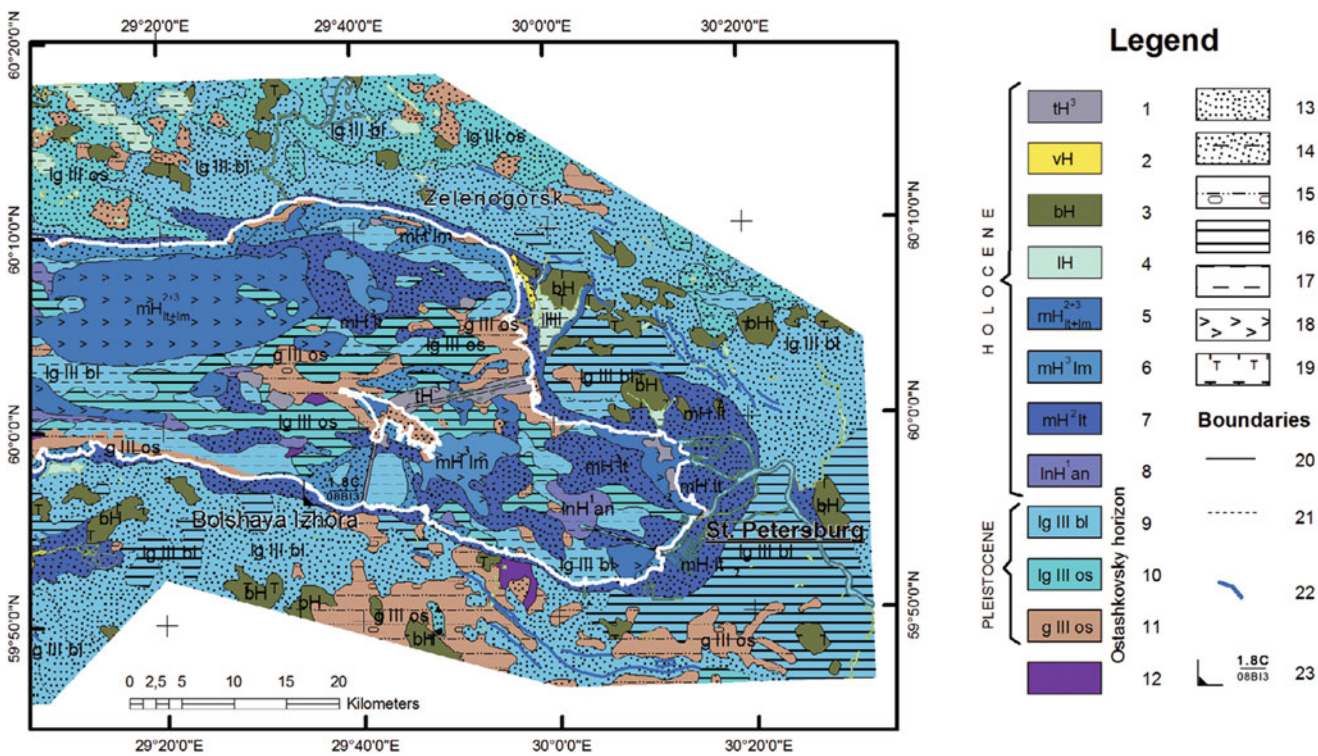


Fig. 7.8 Map of quaternary deposits in the Neva Bay area. Legends 1–8 represent Holocene deposits and 9–11 represent Pleictocene deposits. *1* Technogeic deposits, *2* Aolian deposits, *3* biogenic deposits, *4* lacustrine deposits, *5* Limnea marine deposits, *6* Littorina and Limnea marine deposits, *7* Littorina marine deposits, *8* Lake Ancylus deposits, *9* Baltic Ice Lake deposits, *10* limno-glacial deposits of the Luga stage, *11* glacial deposits, *12* pre-Quaternary bedrocks, *13* sand with gravel and pebble, *14* sand, *15* sandy till, *16* varved clay, *17* clay, *18* mud; *19* peat, *20* stratigraphic boundaries, *21* lithologic boundaries, *22* coastal sand ridges, *23* sites of dating (age in thousands of years, method/sample number) (Ryabchuk et al. 2011)

Neva Bay coasts are very low, modern erosion escarpment having not been very well developed in relief. Along the northern coast of Neva Bay, there are glacial moraine outcrops. The coast contains a large number of pebbles, cobbles and boulders. In the process of its erosion, the finer sediments are carried away relatively rapidly by waves and currents. The pebbles, cobbles and boulders are mostly immobile and, after some time, form a belt of stones of various sizes on the beachface and in the nearshore bottom (Ryabchuk et al. 2011). Sediment material, eroded from the glacial till, is moving eastward alongshore and forming narrow sandy beaches and short spits. Along the middle part of the northern coast of Neva Bay in the water, plants cover the nearshore bottom.

The same low coasts with a dense population of water plants are the most widespread type in the southern shore of the bay. The eastern coast can be classified as completely anthropogenic, because, since the founding of St. Petersburg, as a result of comprehensive engineering work, the level of the natural coasts was uplifted and new territories were created.

7.4 Bottom Sediments of Neva Bay and Recent Sedimentation Processes

In the eastern part of Neva Bay, the accumulation of bottom sediments is mostly controlled by the Neva River sediment discharge. The total annual volume of bedload Neva River transport reaches 65,000 tons, while the volume of suspended material is about 510,000 tons. The majority of the Neva River sediment load accumulates within Neva Bay (Raukas and Huvarinen 1992). From east to west (according to the decreasing current speed), sands (from fine to very fine), silty-sands and silts are forming. Accumulation of silty-clayey mud occurs within the bottom relief depression, with a water depth of 4 m, located in the centre of the western part of the bay. The natural sedimentation rate is about 0.5 mm/year (Spiridonov et al. 2004). Consequently, sands and silty-sands (Fig. 7.9(8)) cover most of the Neva Bay bottom. It is noteworthy that, due to the domination of silt fraction (0.05–0.005 mm) in the Neva River's sediment load, these sediments are very widespread along the Neva Bay bottom in comparison with other areas of the Eastern Gulf of Finland.

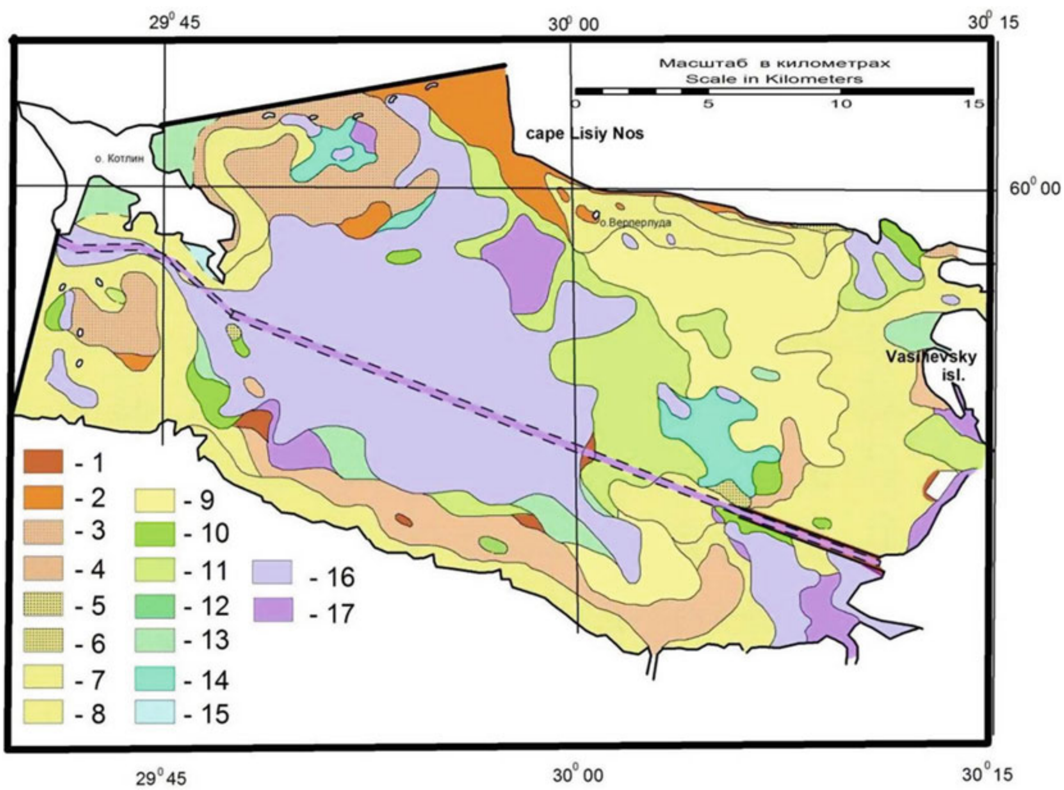


Fig. 7.9 Sea-bed map of Neva Bay. *1* Boulders, pebbles, *2* sand with gravel; sands: *3* unsorted, mainly coarse-grained, *4* unsorted, mainly fine-grained, *5* coarse-grained, *6* medium-grained, *7* fine- to medium-grained, *8* fine-grained, *9* very fine grained, *10* silty sandy, *11* sandy silt, *12* clayey sand, *13* sandy clay, *14* silt, *15* sandy-silt with clay, *16*- clayey silt, *17* Pleistocene clay outcrops

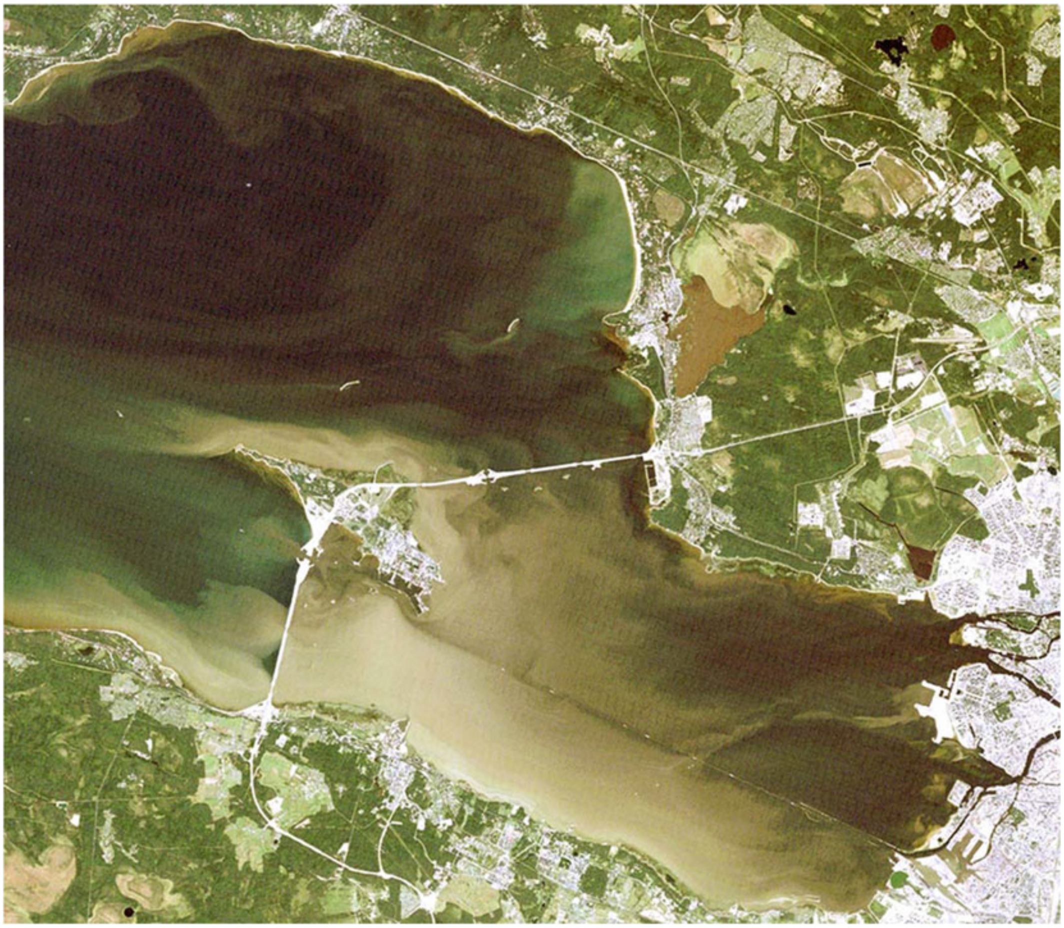


Fig. 7.10 Landsat-5 Image from August 19, 2010. Areas of high turbidity in Neva Bay and adjacent areas of the Eastern Gulf of Finland, caused by re-suspension of bottom sediments in the lagoon under the influence of strong winds (up to 10–12 m/s) from a south-south-west direction under the conditions of low sea level (−28 cm BS). In the Eastern Gulf of Finland, the upwelling and development of phytoplankton have been registered

Long-term consequences of the impact of large-scale dredging activity in Neva Bay during implementation of the "Marine Façade" Project (2006–2008 period) have been revealed as a result of satellite monitoring. From analysis of satellite images from LANDSAT and MODIS for the years 2009–2012, after hydro-technical activity has been completed in Neva Bay and adjacent areas of the Eastern Gulf of Finland, in the absence of dredging activity, increased levels of turbidity are often revealed. According to our estimates, the concentrations of suspended solids in these zones are two to four times higher than the background value of suspended matter concentration in Neva Bay water (10 μg/l). Such phenomena is indicated by periodic forcing of a (secondary) increase in suspended solid concentrations, arising due to wind-wave actions under unconsolidated clay layer of sediments accumulated in the period between 2006 and 2007. Such property and behavior of modern seabed sediments identified as a result of satellite monitoring of Neva Bay has been confirmed by the data from hydro-meteorological observations in the area study conducted by «Saint-Petersburg's Hydro-meteorological Center» (Sukhacheva and Orlova 2014).

Processes of re-suspension of bottom sediments in Neva Bay registered by LANDSAT-5 on August 19, 2010, are presented in Fig. 7.10. It is evident that, despite some years having passed since the event, a large anthropogenic impact has occurred; the ecological state of the estuary has not fully recovered.

7.5 Biological Characteristic of Neva Bay and Its Coast

Neva Bay biota is spatially heterogenous and relatively diverse due to the above-mentioned geological diversity, extended coastal zone and the presence of hydrodynamic and hydrochemical barriers. Its temporal variation is also dependent on human activities. As a result of the combined effects of natural driving forces and anthropogenic impact, the harbor habitats of Neva Bay include hundreds of aboriginal and ten common alien species (e.g., two plant species, two fish species, three species of oligochaete worms and three amphipod species). Coastal habitats also serve as migratory areas for birds and fishes, spawning areas for fishes, and nursery areas for seals. That is why within Neva Bay and its coastal zone, there are several protected areas in spite of the high level of human activity. The coexistence of technogenic and protected natural landscapes is one of the distinctive ecological features of Neva Bay, and is very important for territorial and marine spatial planning.

The species composition of aquatic living communities is strongly dependent on the Neva River run-off. Thus, the majority of planktonic species is in common with those of Lake Ladoga and the Neva River. Benthic life is sufficiently contributed by heterotopic species – the aquatic larvae of insects. Species of marine origin (e.g., the non-indigenous ponto-caspian bivalve mollusk zebra mussel (*Dreissena polymorpha*)) with a biphasic life cycle have a very limited distribution in Neva Bay. Their populations and pseudopopulations are restricted by localities, close to the storm surge barrier, where salinity is some degree higher than at the main part of Neva Bay (Technical Reports 2004, 2008). The most disturbed littoral zone is dramatically impacted by biological invasions – alien amphipods contribute up to 50 % of the biomass in summer (Berezina 2007), and there are areas occupied by alien aquatic plants: *Elodea canadensis* and *Acorus calamus* (Technical Reports 2004, 2007). Neva Bay is a highly productive biological region, which also plays an important role in the formation of fish resources of the Eastern Gulf of Finland. In general, its biota is also characterized as relatively vulnerable, through the high variability in quantitative characteristics of communities under the impact of industrial and transportation projects.

7.5.1 Phytoplankton

Planktonic microalgae that are photosynthetic and/or myxotrophic organisms are an important counterpart to the level of producers in any aquatic ecosystem. Species content and the quantitative development of phytoplankton so far form a basement for biological productivity and determine the functioning of an entire ecosystem. Regular researches and monitoring of the phytoplankton of Neva Bay and the shallow areas of the Eastern Gulf of Finland have been carried out since the 1980s (Nikulina 2008). Cyanobacteria, Bacillaryophyta, Cryptophyta and Dynophayta, and Chlorophyta are the predominant groups contributing more than 90 % of total phytoplankton biomass with very few exclusions (in 2004, Crysophyta were registered as the dominant group) (Nikulina 2008). Green algae are the most diverse group. The Flood Protection Facility construction, hydrothechnical activities and eutrophication have changed species diversity. In the 1980s, diatoms were the predominant group of phytoplankton. This was succeeded by the dominance of the oscilatoria group *Planktothrix agardhii* and *Limnothrix planctonica* in late 1990s/early 2000s. Nowadays, species of the summer phytoplankton complex are capable of fixing molecular nitrogen from the atmosphere, releasing toxic substances into the water (e.g., *Aphanizomenon flos-aquae*, *Anabaena flos-aquae*), forming a large portion among cyanobacteria. A considerable increase in biomass of Cryptophyta and Dynophyta with some decrease in the dominance of cyanobacteria has been observed since the late 2000s (Nikulina 2012; Nikulina and Gubelit 2011). Long-term data on the seasonal dynamics of phytoplankton in Neva Bay show that the period of predominance of cyanobacteria has also increased. In the 1980s, cyanobacteria were predominant only in July and August. Since the late 1990s, they have been predominant during the entire summer and into September (Nikulina and Gubelit 2011).

Quantitative characteristics of phytoplankton have been changing locally and along the entire Neva Bay over time in response to a change in the flow regime (construction of the Flood Protection Facility) and hydrooptical conditions (sediment spills). The decrease in biomass in the 1980s was attributed to the increase in turbidity on the south side of Neva Bay due to hydrotechnical activities (Nikulina 2012), the same effect that would be observed in the mid-2000s (period 2, as shown in Fig. 7.2) along the entire Neva Bay (Technical Report 2004, 2007). Our measurement of the composition of photosynthetic pigments in the summer of 2014 also showed a drastic decrease in the quantitative development of phytoplankton accompanied with the proposed prevalence of Cyanobacteria in areas polluted by sediment spills near Kotlin Island.

Natural driving forces are also important for the quantitative development of phytoplankton. First of all, there are impacts from Lake Ladoga and the Neva River (as mentioned above). Irregular short-term events, such as storms and periods of calm weather, are also important for phytoplankton dynamics (Nikulina 2008). Comparison of phytoplankton biomass and production values in the Eastern Gulf of Finland in the summer periods of the 2000s (period 1 in Fig. 7.2) with those of the 1980s shows their two to threefold increase (Golubkov 2009; Nikulina 2012). Primary production exceeded 2.0 g C m^{-2} d^{-1} at the top of the Gulf in the 2000s and corresponds to highly eutrophic water (Golubkov 2009). Such an increase in productivity and changes in the predominant complex of phytoplankton suggest eutrophication of the system, determined by both anthropogenic and natural hydrological-climatic factors.

7.5.2 Macrophytobenthos

More than a hundred species of aquatic vascular plants, macroalgae and filamentous algae have been recorded in Neva Bay and the Eastern Gulf of Finland in the present day (Korelyakova 1997; Gubelit and Kovaltchuk 2010; Zhakova 2008). A detailed study of the composition and distribution of aquatic and semiaquatic vascular plant species has been done during monitoring of non-indigenous species (Technical Reports 2004, 2005, 2006, 2007, 2008). This time, 68 common, widely distributed species have been registered, while rare species or typically terrestrial species were not taken into consideration. The majority of aquatic flora of phanerogams was represented by 58 species from 29 families and 44 genera. Spore vascular plants were represented by five species from four families. Macroalgae were represented by five species of charophytes from two families and green filamenthou algae Cladophora glomerata. Among phanerogams, six families are the most diverse: Cyperaceae – eight species, Potamogetonaceae – six, Ranunculaceae – four, Poaceae – four, Hydrocharitaceae – three, Lemnaceae – three. All other families are represented by one to two species. The class of monocotyledonous is represented by a somewhat greater number of species than the class of dicoyledonous, while the latter class is prevalent in number of families. These ratios by species and family are typical for inland water bodies. The prevalence of Cyperaceae and Potamogetonaceae is also typical for continental waters.

In the twenty-first century, 13 species of higher plants and 3 species of charophytes have been registered. Most of them (ten species) are considered hydrophytes – plants characteristic to the middle flood zones. Of these species, the first registration of the non-indigenous *Acorus calamus* L. took place in 2004, with several flowering patches being discovered for the first time in patches of reeds and canes along the northern coast of Neva Bay (Technical reports 2004, 2007).

In the context of submerged and aquatic vegetation, 18 of the most common plant associations, belonging to nine formations and three classes (Formation class), were revealed (Technical Report 2004). The most important and widely distributed in Neva Bay, up to the present day, are associations of reed (reed beds) (*Phragmites australis*) and cane (*Scirpus lacustris*) from formation groups of aquatic-aerial vegetation (*Aquiherbosa amphibia*), while submerged meadows had several periods of dramatic depression. At the beginning of the twentieth century, submerged macrophyte meadows were widely distributed in the coastal zone of Neva Bay. By the 1980s, most of these meadows had been lost. The meadows were replaced by reed beds, which are resistant to poor hydrooptical conditions. The reason for the deterioration of the submerged vegetation is intensive dredging activity related to the creation of new building lots in St. Petersburg along the eastern coast of Neva Bay, and construction of the storm-surge protection barrier (the Dam) in the mid-1980s and the mid-2000s (period 2 in Fig. 7.2). Some areas are occupied by alien species – *Elodea canadensis* and *Acorus calamus. E. canadensis* patches were also depressed by an increase in suspended matter in the mid-2000s (Technical Report 2007), but were restored several years later (Technical Report 2012). Macrophytobenthos plays an important role in fish nursery areas (see below and Technical Reports 2004, 2007, 2012).

7.5.3 Zooplankton

A total of 394 species of zooplankton were recorded in Neva Bay, with the highest diversity being registered in the period from 1911 to 1984 (Telesh 2008). The high diversity of species of zooplankton in Neva Bay in comparison to westward parts of the Eastern Gulf of Finland is promoted by hydrological and temperature regimes favorable for freshwater and lacustrine species coming into Neva Bay from Lake Ladoga and the Neva River and species associated with areas occupied by maprophyte beds. The composition of zooplankton species is balanced between Ladoga zooplankton and zooplankton of the Eastern Gulf of Finland to the west of the storm surge barrier. The dominant groups are Rotifera, Copepoda and Cladocera.

One fourth of all zooplankton species are common and have a constant presence in Neva Bay during a corresponding season. The complex of dominant groups has changed over the time. The most remarkable changes have been revealed in the periods from 1982 to 1984, the entirety of the 1990s, and Period 2, as reflected in Fig. 7.2 (Telesh 2008; Technical Report 2008). These changes are mostly explained by natural changes and man-made impacts, but to some degree by present knowledge. Thus, the number of planktonic crustaceans identified by Rylov (1923) that were characterized by him as rare (e.g., *Bosmina longirostris*, *Chydorus sphaericus*, *Mesocyclops leukarti*) or occasional (many species of Ritifers) are nowadays common or dominant, especially in areas with macrophyte beds. It is proposed (Telesh 2008) that these species were no less common in the past, and that the most probable reason for their status as rare or occasional is the restriction of planktonic studies in open parts of Neva Bay (while coastal areas only began to be investigated in the 1980s).

Salinity is one of the major driving forces that form the biota of estuarine systems, and the Eastern Gulf of Finland is no exception: the remarkable difference between Neva Bay and the seaward areas of the Gulf of Finland is an absence of established populations of the invasive zooplankton species *Acartia tonsa* (Copepoda) and *Cercopagis pengoi* (Cladocera) from Neva Bay. Those species are common and play an important role in the above district and to the west in many parts of the Baltic Sea. However, as confirmed in personal communications (Dr. O. Susloparova), *C. pengoi* can occur in areas of Neva Bay where periodic intrusion of salt waters occurs. By our suggestion, there is also a pool of resting eggs of *C. pengoi*, which can also be a source for the above-mentioned records. Larvae of the benthic species are also absent from Neva Bay, as its mineralization and especially low concentration of calcium limits early development of byphasic invertebrates (Technical Reports 2004, 2007).

Zooplankton, both in taxonomic diversity and quantitative characteristics, follow the spatial and temporal variations of suspended material concentrations and natural driving forces (Technical Reports 2004, 2008). In a way, this is similar to responses from phytoplankton (see above).

As suggested (Golubkov 2014), hazardous materials may also have a negative effect on the zooplankton in terms of hystopathological changes and other abnormalities in individuals of the dominant species of cladocerans in areas adjacent to St. Petersburg.

7.5.4 Macrozoobenthos

Macrozoobenthos is the leading biotic group of the benthic compartment of an aquatic ecosystem. More then 200 species and taxa of zoobenthos were recorded in Neva Bay during the annual monitoring of alien species in the period from 2004 to 2008 (Technical Reports 2004, 2008). They belong to taxa occurring in freshwater and oligohaline waters, both true aquatic and amphibiotic (aquatic larvae of insects). Freshwater species prevail in the modern Neva Bay; however, the formation of pseudopopulations of oligohaline species is not excluded. Thus, in the summer of 2004, brackish water naidid oligochaetes (*Nais elinguis*, species from genus *Paranais*), with dominance by *N. eliguus*, were found in benthos near Petrodvoret (Technical Report 2004).

Among the large taxonomical groups, the most diverse are the Chironomidae (Insecta, Diptera) and the Oligochaeta among true aquatic invertebrates (54 species of Oligochaeta from 5 families). The macrozoobenthos of Neva Bay is significantly different in its central part, coastal zone and littoral zone. The central part is populated by a community, formed of Oligochaeta and Chironomidae. In the coastal zone, in some localities, beds were found formed by filter-feeding bivalve mollusks (Maksimov 2014). The littoral zone communities are the most diverse, represented by Turbellaria, Oligochaeta, Hirudinea, mollusks (Bivalvia, Gastropoda), crustaceans (Amphipoda, Isopoda) and insect larvae (Chironomidae, Ephemeroptera, Trichoptera, Hydrocarina, Ceratopogonidae, Coleoptera, Megaloptera) (Technical Reports 2004, 2008, 2012). In the summertime, the modern littoral communities are dominated by alien amphipods, *Gmelinoides fasciatus*, *Pontogammarus robustoides* and *Gammarus tigrinus*. Altogether, they contribute up to more than a half of the total biomass of the zoobenthos in the shallow littoral of Neva Bay and the Eastern Gulf of Finland and negatively affect the benthic animal community in the shallow coastal zone, suppressing and replacing native species (Berezina 2007). The macrozoobenthos in the littoral zone and shallow areas is characterized by high quantitative development up to 17,000–20,000 ind. m^{-2}, in abundance and 30–40 g m^2. Thus, vertical zonation of Neva Bay plays an important role in the distribution of macrozoobenthos diversity. Climatic fluctuations mediated by discharge from the Neva River also affect the zoobenthic community; there are positive relationships between the average run-off of the Neva River and the biomass of bottom animals in Neva Bay (Golubkov 2014).

Modern and historical observations show the strong dependence of the macrozoobenthos on human activities. For instance, the glacial relict crustaceans *Monoporeia affinis and Saduria entomon*, typical for the Eastern Gulf of Finland and recorded in Neva Bay at the beginning of the twentieth century (Skorikov 1910), are absent here now, the probable reason being the construction of the Flood Protection Facility, which partly prevents saltwater intrusions into Neva Bay. The abundance of the zoobenthos is affected by the dredging and dumping of bottom sediments for the creation of new building lots in St. Petersburg. For instance, creation of the new Passenger Port in the eastern part of Neva Bay in the mid-2000s resulted in a considerable increase in suspended matter in the water. This, in turn, led to a manifold decrease in the abundance of large mollusks Unionidae in the zoobenthos of the bay (Maksimov 2014).

7.5.5 Fish, Fish Spawning and Nursery Habitats

Coastal fish surveys in Neva Bay and in the Eastern Gulf of Finland carried out from 2011 to 2013 have revealed 33 species from 13 families, including 5 alien species. The Cyprinidae family was represented by 15 species (45 % of the species list); fam. Gobiidae, four (12 %), fam. Percidae, three (9 %), fam. Gasterosteidae, two (6 %), and the other nine families were represented by one species each (Uspensky and Naseka 2014). Aboriginal species – perch, bleak, gudgeon, ruff, roach and the invader *Proterorhynus nasalis* – are common in Neva Bay. The average number of species per locality was 8.0 ± 1.0.

Most of the dominant cyprinid fishes spawn in Neva Bay around the end of May – beginning of July in relatively warm coastal habitats with macrophyte beds at depths of 0.5–3 m. Their spawning habitats are mostly situated along the mainland southern coast of Neva Bay and along the eastern coast of Kotlin Island (EIA 2008). Pike-perch is an important commercial fish species. Its spawning localities are in areas with slow flow (no more then 0.2 m/s), at water depths of 1.5–2.5 m. Their main locality is in the stony bank between the cities of Lomonosov and New Peterhof. The efficiency of fish nursery areas, situated along the above-mentioned coasts, is relatively high in comparison with the northern coast of the Neva Bay areas, as follows from observations on the distribution of fish larvae and juveniles (EIA 2008).

Neva Bay is a transitional area for fish migrations. The migratory routes of whitefish, wither lampreys, and salmon from the Baltic Sea to the Neva River go across Neva Bay. These species enter the rivers beginning in late spring until the eventual freezing-over (EIA 2008).

7.5.6 Terrestrial Vertebrates in Coastal Habitats

Nowadays, 76 bird species (about 120 species including the coastal forest habitats) from 9 orders, 15 mammal species from 5 orders (including 3 introduced species, *Ondatra zibethica*, *Neovison vison*, and *Nyctereutes procyonoides*, the last two being the most aggressive predators in the coastal area), 3 amphibian species from 1 order, and 1 reptile species are registered in the Neva Bay coastal and island habitats. However, fauna composition, abundance and spatial distribution are very dynamic characteristics and depend on many components, including such external factors as the effects of intrapopulation-regulating mechanisms.

Six mammal species and 25 bird species registered during the breeding, wintering or migratory seasons in the aquatic and coastal areas of Neva Bay are included in the Red Data Book of Saint Petersburg Nature (2011), while 44 terrestrial vertebrates (including migratory birds) are included in the Red Data Book of the Leningrad Region (2002); 12 species are listed in the Red Data Book of the Russian Federation (2001), 62 species are included in the Red Data Book of the Baltic Region (1993); 25 species in the Red Data Book of the Eastern Fennoscandia (1998); 21 species on the Helcom Red List of Baltic Sea species in danger of becoming extinct (2014), and 1 species (Osprey *Pandion haliaetus*) on the IUSN Red List (2014) (Fig. 7.11).

In speaking of the terrestrial vertebrates of Neva Bay, we have to mention the importance of this area not only in terms of breeding habitats, but also for the seasonal migrations of birds. The Gulf of Finland is located in the exact flight trajectory of a vast number of birds which, having been bred in Russia's European North, fly to spend the winter in Southern Europe and Africa. The Belomor-Baltic Migration Route, one of the branches of the Arctic Migration Route, runs through the Neva Bay aquatory and coastal areas. On the way to their breeding or wintering sites, birds not only fly in transit through the Gulf of Finland, but also form huge stopovers on the water and coastal areas, where they gather food and rest before the next stage of their flight (in the "Northern Coast of Neva Bay" and the "Strelninsky coast" Nature Protected Areas, for example).

As to two seal species that inhabit the Gulf of Finland, both species (the Baltic Ringed Seal *Pusa hispida botnica* and the Gray Seal *Halichoerus grypus*) disappeared from Neva Bay area practically right after the dam construction was finished. However, gray seals have sometimes been registered close to Kotlin Island in recent years. The Baltic Ringed Seal's abundance is decreasing catastrophically in the entire western part of the Gulf of Finland.

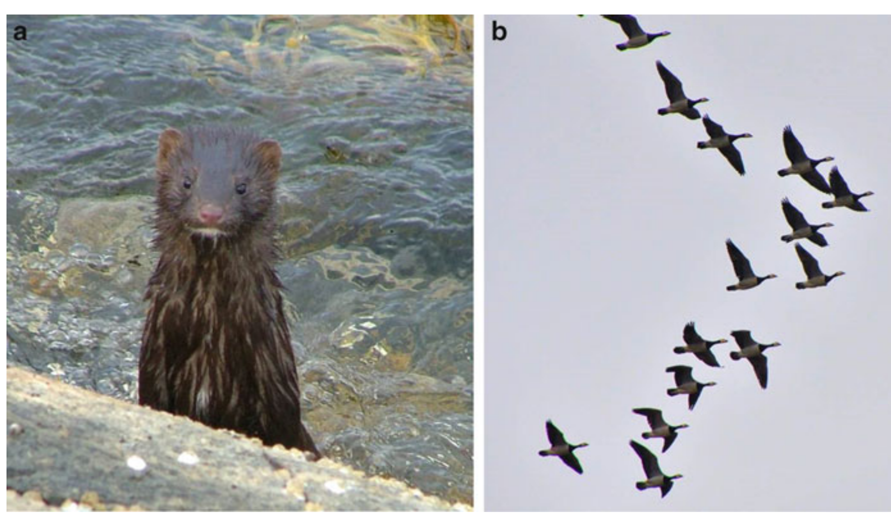


Fig. 7.11 (**a**) American mink *Neovison vison* – one of the most dangerous predators in the coastal area; (**b**) Barnacle geese *Branta leucopsis* migrating over the Flood Protection Facility

7.6 Anthropogenic Impact on Neva Bay. Vulnerability Assessment of Lagoons to External Factors of Natural and Technogenic Character

The impact on the Neva Bay ecosystem by the city of St. Petersburg is quite considerable, given the city's industrial and transport waste water, the constant development of the harbor's infrastructure, the Flood Protection Facility, which completely changed the hydrodynamic and sedimentological regimes of the bay, dredging and dumping activity, creation of new territories, and intense navigation. Actually, anthropogenic activity nowadays has become just as important a driving force of environmental development as natural factors.

7.6.1 Anthropogenic Impact on Bottom Relief

The intense anthropogenic impact on Neva Bay and its coasts started from the time of the founding of St. Petersburg by Peter the Great, in 1703. Construction of the old capital of Russia was accompanied by a technogenic uplifting of low, swampy territories, and a changing of the river network. For the city's defense in the western part of Neva Bay, several artificial islands with 17 fortresses were built (Kronstadt 2015). The first fortress, "Kronshlodt", was constructed in 1704 with the personal participation of Peter I. The bay bottom was crossed with special defense constructions – wooden crib-bars for the prevention of ship movement outside the fairways. As the natural water depth within the majority of Neva Bay is about 2 m, and St. Petersburg harbor is located in the easternmost part of the Bay, for navigation purposes, the dredging of ship channels has been constant. In 1885, the so-called Marine Channel – the main fairway to St. Petersburg – was constructed. Water depth in the channel before 2006 was 12 m; now it reaches 14 m. In the twentieth century, St. Petersburg became a huge city, with a population of 5 mln and a highly developed industrial and transport infrastructure (including several ports). This caused an enormous increase in the anthropogenic load on the Gulf of Finland's ecosystem. Dredging and dumping has continued: in the 1970s, submarine sand extraction took place in the nearshore close to Lahta Bay, causing significant bottom relief transformation with the forming of depressions up to 12 m deep (Fig. 7.12).

Since the founding of St. Petersburg, hazardous floods have threatened the population of the city. That is why the first plans for city protection were discussed right after the catastrophic flood of 1824. In 1858, in the Report to The Russian Geographical Society, E. Tillo presented eight different projects for the flood defense of St. Petersburg. One such project developed in 1824–1827 by Professor Pierre Dominic Basen resembles the project of the Flood Protective Facility, which is being constructed now (Fig. 7.13). It was proposed that they would build "a stone dam from the Cape Lisiy Nos to Kotlin Island, through the western part of the island and to Oranienbaum. Whole length should be 21 verst (1 verst is about 3500 ft.)" (Tillo 1893).

In the nineteenth century, an idea for flood protection had not yet been realized, but after the Second World War, the discussion started again at a new technical level, and in 1979, construction began on the huge hydrotechnical structure – the Flood Protection Facility. In the 1990s, construction was interrupted due to a need for ecological risk assessment, but in the late 2000s, it was continued, and since 2011, one of the hugest hydrotechnical constructions in the Gulf of Finland has been functioning.

In 2006, a new stage of intense anthropogenic impact on the Neva Bay environment began. In the eastern part of the bay, near Vasilievsky Island, 476.7 ha of new territory for the St. Petersburg Passenger harbor was created using sand-dredging technology (CJSC Terra Nova 2015). To deepen the ship channel for huge ferries up to 14 m, large amounts of bottom sediments (e.g., clayey material) were dredged, removed and damped within former carriers of sand extraction in the bay nearshore.

Among the recent examples of a technogenic impact on Neva Bay and adjacent areas of the Eastern Gulf of Finland, there is the construction of a multifunctional maritime shipping complex called «Bronka». The harbor will include several terminals. For its construction, new territories are being created and active dredging work carried out. The project will be finalized in 2020. Hydraulic engineering works have been carried out in the southwestern part of Neva Bay. In this case, scenarios for the distribution of suspended sediment in the Eastern Gulf of Finland have mainly been defined by dredging and dumping activity and by hydro-meteorological conditions. The water stratification and upwelling events have often caused the redirection of water masses contaminated by suspended sediments from the southern to the northern coast of the Gulf (Fig. 7.14).

7.6.2 Anthropogenic Impact on the Coastal Zone

The coastal environment of the eastern part of the Gulf of Finland, and especially Neva Bay, is thus very important, both for nature conservation and for the development of the recreational infrastructure of the entire northwestern region

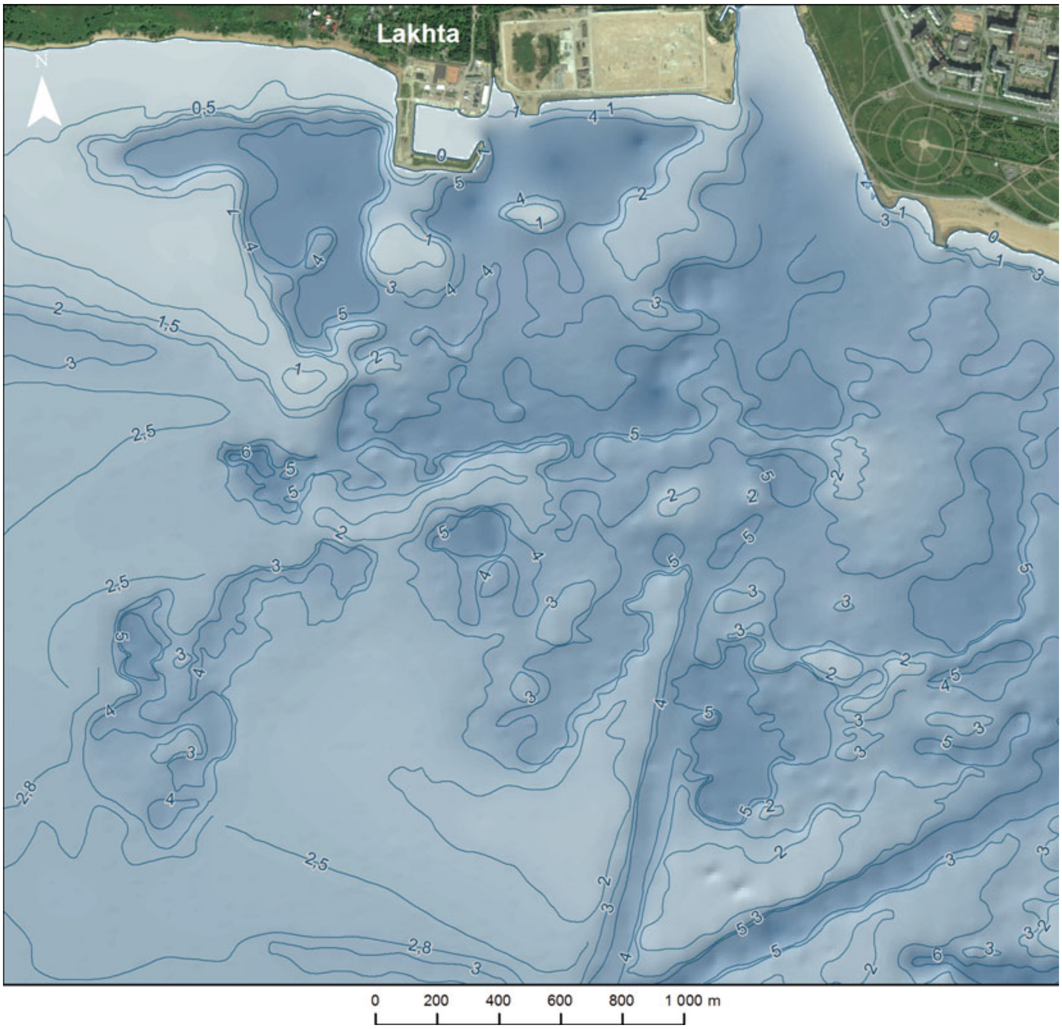


Fig. 7.12 Bottom relief in front of Lahta Bay transformed by submarine sand extraction

of Russia. This environment, however, is extremely vulnerable and experiences pressure of gradually increasing intensity (Ryabchuk et al. 2011).

Transformation of the Neva Bay coastal zone started as early as the eighteenth century, but in many cases, it could not be assessed as "negative". The southern coast of Neva Bay is one of the best known examples of harmonious coincidence of both natural and anthropogenic elements in the coastal landscapes of Europe. Several beautiful parks featuring the Russian Imperator's Country Palaces are located here. Among them, the pearl of landscaping architecture – Petrodvorets, with its park, palaces and numerous fountains – and the Strelna and Oranienbaum parks and palaces should be mentioned (Fig. 7.15). It is also worth mentioning that the architects used the natural landscapes and geological features of the area. The Littorina sea terrace is elongated along the southern coast; its escarpment divides the "upper" and "lower" parts of the park ensembles, while the area's hydrogeological features are used for the functioning of the system of fountains.

On the other hand, the eastern coastal zone of Neva Bay presents several examples of the horrible results of anthropogenic impact. Together with industrial and harbor areas, which are still one of the main sources of pollution, there are parts of the shoreline represented by "waste beaches" (Fig. 7.16). Purification, regeneration and the use of such coastal segments for any construction activity is a very difficult task, as the former methods of waste disposal are characterized by a very high level of assorted pollutants (e.g., heavy metals and radioactive material).

The coastal areas of the Eastern Gulf of Finland suffer from coastal erosion (Ryabchuk et al. 2011). However, the lower level of wave impact minimizes the negative influence of this factor on the Neva Bay coastal development. As for the influence of the huge coastal engineering structure, the Flood Protective Facility, its impact on the coast is opposite to that of the construction going on in the east (in Neva Bay) and outside it. The higher water level (in comparison with the natural situation) outside of the facility during extreme floods leads to a more frequent occurrence of extreme ero-

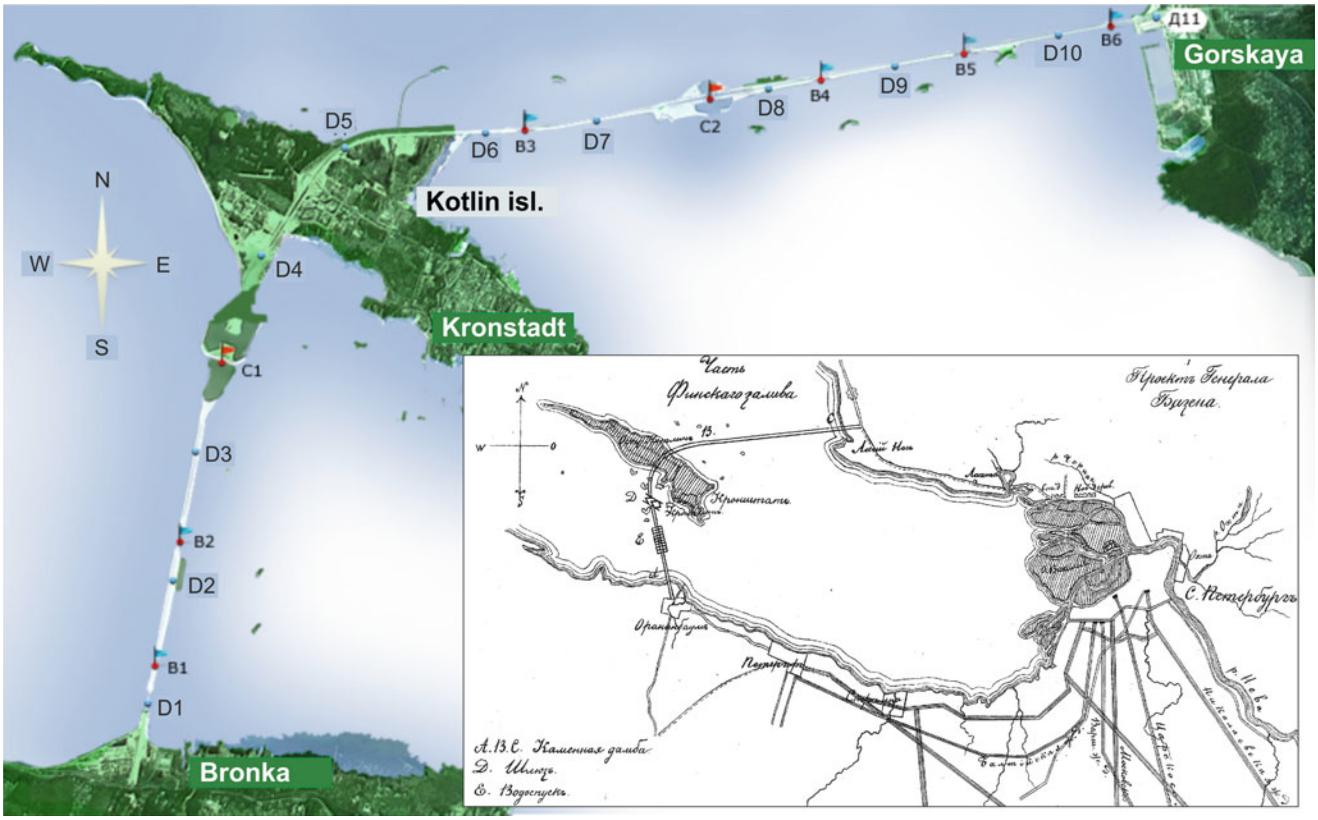


Fig. 7.13 Modern plan of the St. Petersburg Flood Protection Facility (C1, C2 – gates for vessels; B1–B6 – water gates; D1–D11 – dams) and first project of protection contracture by Federic Basen (1824–1827)

sion events. Contrastingly, within Neva Bay, the Protection Dam prevents active erosion on the coasts.

7.6.3 Anthropogenic Impact on Sedimentation Processes

One of the most important environmental problems is the modern clayey mud accumulation in Neva Bay. As was mentioned above, in Neva Bay, there are silty-clay accumulative zones at depths of 4–6 m, while to the west of the St. Petersburg Flood Protection Facility, mud accumulation occurs at depths of 10–15 m.

Interesting data concerning "sedimentation history" were found on historical maps and in archive materials. According to the data of a hydrographical survey conducted in the eighteenth century (from the funds of State Archive of the Russian Navy) within the modern mud accumulative zone of the western part of the Bay, 200 years ago, the bottom was covered by sands. As Neva Bay was always very important both for trade and the defense of St. Petersburg, hydrographic measurements accompanied by sediment descriptions have been carried out here annually since the beginning of the nineteenth century. All maps from 1830 to 1911 show the sandy bottom in this part of the bay.

The first scientific expedition of Professor Derugin (1920–1924) found silty-clay mud in several sampling sites of the central part of Neva Bay. One of the conclusions of Professor Derugin's report was that the old maps and descriptions for them were wrong, but a comparison of his data with the results of the geological survey of the 1990s indicates significant sharing of the mud accumulation area (Fig. 7.17). Recent monitoring has shown that the process continues.

A joint VSEGEI and GTK study of the sedimentation rate and sediment pollution, undertaken in 2004–2007 in the context of the SAMAGOL project, confirmed that the entire 40–50 cm silty-clay layer was formed during the last 100–150 years (Ryabchuk et al. in press). So, both the analytical data and an investigation of the archive materials permit us to conclude that, during the last two centuries, sedimentation processes in the bay have changed and a special condition for the accumulation of mud has developed. Surely, one of the main factors influencing it has to be human-related processes.

During the Russian-Finnish investigation in the context of the SAMAGOL project (Vallius 2007), it was revealed that

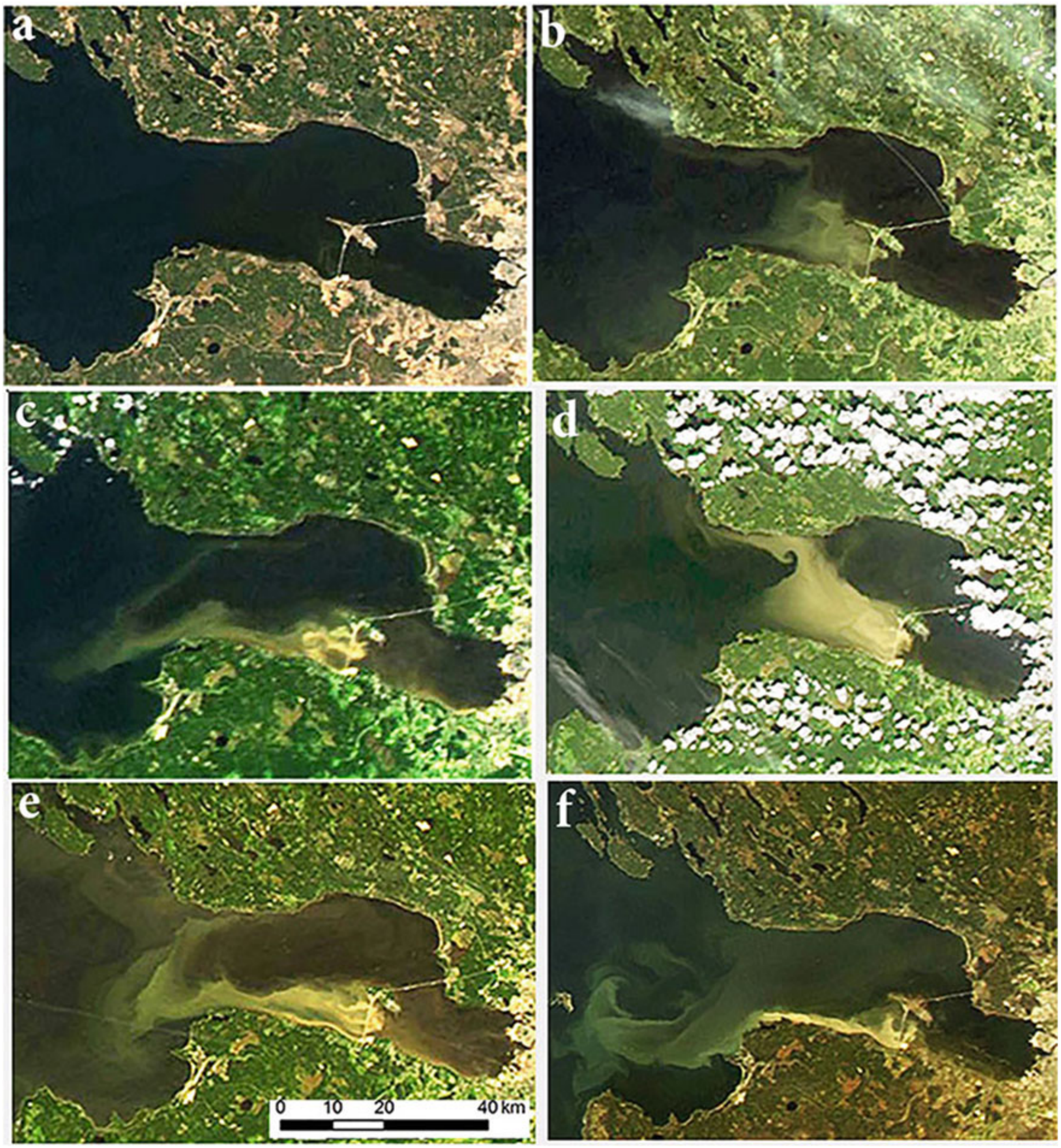


Fig. 7.14 Satellite images obtained from sensor MODIS: (**a**) image from April 20, 2014, the usual view of the aquatic system before hydro-technical work has started: (**b**) from may 17, 2014, hydro-technical works, already started, can be observed in the stratification of water masses and the presence of upwelling; (**c**) image from June 15, 2014, presence of hydro-technical works, winds of northeastern direction, decreasing of the sea level; (**d**) from July 7, 2014, intensification of hydro-technical works, presence of stratification and upwelling, winds of northwestern direction; (**e**) from July 11., 2014, hydro-technical works, stratification of waters masses, winds of northeastern direction, low sea level; (**f**) from September 18, 2014, hydro-technical works, presence of water stratification, winds of northeastern direction, decreasing stage of the sea level

the coastal sedimentation basins of Neva Bay are a unique source of information about its "pollution history". The concentration curves of most of the heavy metals studied (e.g., Cd, Zn, Pb, Cu) show similar concentration trends throughout the sediment profiles. When looking at the temporal trend, we see that metals started to accumulate rather rapidly in the first half of the previous century. The first metals to have reached concentrations of strong contamination were zinc, lead and copper, probably an indication of a surging base metal industry, while the very strong increase in cadmium a decade or two later indicates a similar increase in the chemical industry (Fig. 7.18). The highest concentrations can be found in the upper halves of the cores, probably representing a time span from the 1950s to close to the end of

Fig. 7.15 Fountains of Petrodvorets park, located on the Littorina terrace

Fig. 7.16 Waste disposal on the eastern coast of Neva Bay

the century. The last decade and a half has clearly been a time of return, as concentrations of all metals have decreased significantly (Vallius et al. 2006).

In the 1990s, one of the reasons for the decrease in concentrations of heavy metals was the economic depression in Russia, but nowadays, this positive trend is mainly the cause of the significant efforts of the VODOKANAL State Enterprise in their development of the St. Petersburg water waste purification system.

7.7 Characteristics of Anthropogenic Impact Assumed in Future Prospects

Neva Bay is an inner lagoon of St. Petersburg, so the complex anthropogenic impact on its bottom and coast will continue to increase indefinitely. Among the most important projects being realized today is the construction of Bronka harbor, started in 2010, in the southwest of Neva Bay. As mentioned above, the other important source of disturbance

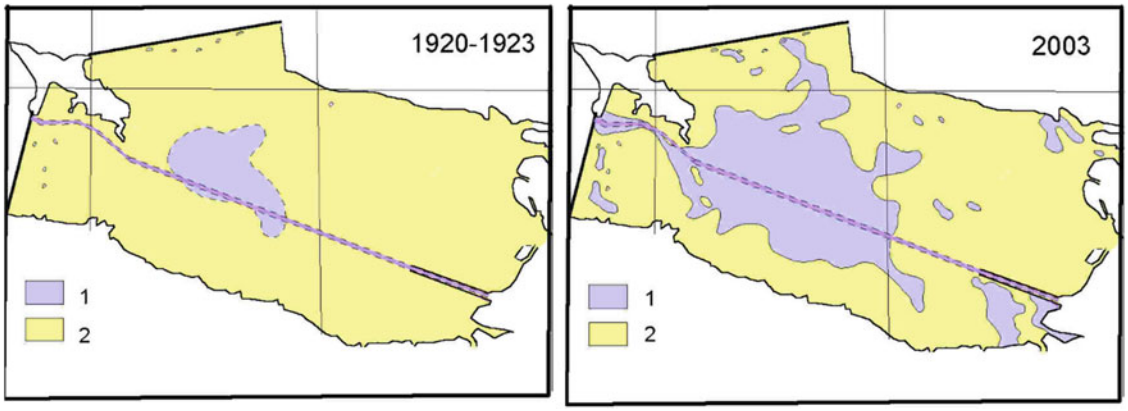


Fig. 7.17 Sharing of silty-clay mud accumulation area during the twentieth century, based on a comparison of Prof. K. Derugin's expedition (1923) and the results of a geological survey (1989–2003). *1* Silty-clay mud, *2* other sediment types

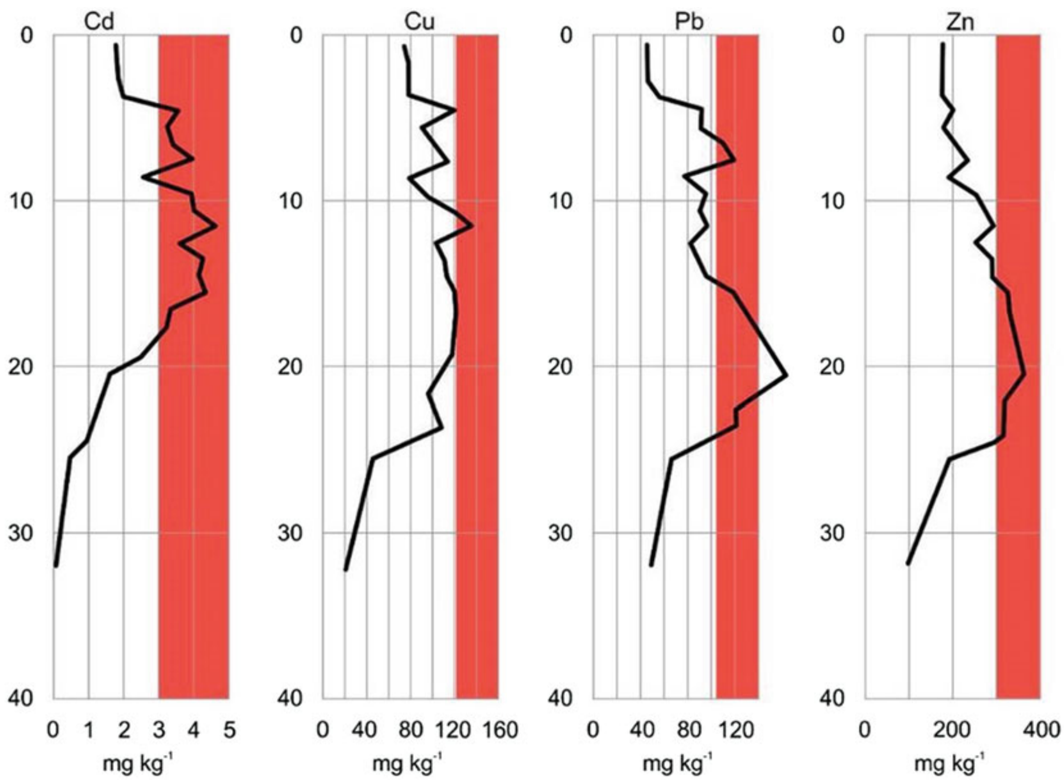


Fig. 7.18 Concentration curves of Cd, Cu, Pb and Zn in the Neva Bay soft sediment core. Vertical axe – sampling interval, cm; *red line* – level of "very high pollution" for bottom sediments (Swedish EPA) (Vallius et al. 2006; Ryabchuk et al. in press)

for the Neva Bay ecosystem is the constant dredging caused by necessity of deepening ship channels for big cruise vessels and ferries. In the northern coast of Neva Bay, in 2012, construction of the GAZPROM "Lahta-Center" complex was begun. According to the project, a 500-m high skyscraper, amphitheatre, park and other recreation and business infrastructure will ultimately be built.

The coastal zone of Neva Bay between Cape Lisiy Nos and Olgino village is part of the "North Coast of Neva Bay" state reserve. On a narrow strip along the coast of the bay, neighborhoods unusual for the St. Petersburg oak forest can be observed. At the beginning of the eighteenth century, one of Peter I's travel palaces was located here, and some of the old oaks planted during that period are still here. The list of vascular plants in the state reserve includes 432 species. Among them, 47 need special protection.

In the shallow nearshore area, there is some highly developed aquatic vegetation, including reed and rush beds, thus it is a very important stopover for waterfowl along the White Sea-Baltic migration route (Fig. 7.19).

Especially large stopovers take place during the spring migration, when it is possible to observe up to 300 swans simultaneously (*Cygnus cygnus* and *C. bewickii*) and about 3000 ducks per day. Ove the last decade, for the entire period of the spring migration, up to 60,000 waterfowl and shore birds were registered at these sites (Rymkevich et al. 2009). In total, 47 species have stopovers or feeding places here. There are also many species included in the Red Data Book of various rank: 15 species are included in the Red Data Book of Saint Petersburg Nature (2011), 14 species in the Red Data Book of the Leningrad region (2002); 5 species – in the Red Data Book of the Russian Federation (2001), 19 species in the Red Data Book of the Baltic Region (1993); 7 species in the Red Data Book of the Eastern Fennoscandia (1998); 6 species on the Helcom Red List of Baltic Sea species in danger of becoming extinct (2014); and 1 species (*Pandion haliaetus*) on the IUSN Red List (2014).

The sanctuary plays an important role during the autumn seasonal migrations and as a breeding habitat for local avifauna too (more than 60 bird species breed here, including in the portion of the coastal area with forests). In spite of its closeness to roads and the dam, and the proximity of tourists and fishermen, five species of amphibian, three species of reptile and ten species of mammal can be found in the reserve (Fig. 7.20b).

On the northern coast near Lake Lahta, and not far from the "North Coast of the Neva Bay" nature protected area (NPA), sits the "Yuntolovsly" state nature reserve. One hundred and eighty nine terrestrial vertebrate species have been revealed there (including migratory birds and very rare species). This area has many habitats and migrant stopovers: Lake Lahta, bogs, marshes, different types of forest, meadows, etc. However, nowadays, the local fauna is in danger because of highways and building construction close to the NPA. Additionally, this area has lost its importance as one of the most significant places for migratory birds in the Leningrad region.

Within the southern coastal area, there are objects of natural heritage such as the "Strelna Coast" and "Sergievka Park". The "Strelna Coast" was well known as an important area for migratory birds for more than 20 species, but its local fauna is scarce in comparison with "Sergievka Park" and other NPAs in Neva Bay: 2 amphibian species, 1 reptile species, 85 bird species and 13 mammal species. In the 1990s, this area was occupied by farmers, fishermen, and tourists, and biodiversity decreased significantly. But in the twenty-first century, this territory received the status of a strictly protected area. This means that no people may visit the "Strelninsky Coast", and it has subsequently come to play an important role as a stopover for many migrants once again. As to "Sergievka Park", the NPA is a very significant place for local sylvatic biodiversity: about 500 fungi, 500 vascular plants, 200 lichens species, etc., have been discovered there, while 3 amphibian species, 1 reptile species (Fig. 7.20a), 188 bird species and 34 mammal species inhabit this area. The coastal habitats are represented solely by reed beds.

In total, seven main coastal habitats of terrestrial vertebrates have been determined in Neva Bay:

1. **Reed beds**. Within the study area, reed beds occur in numerous shallow waters along the shoreline and represent the most extensive potential breeding habitat, by size and length. They constitute a nesting biotope for 22 bird species, and a habitat/feeding place for four mammals and one amphibian (*Rana tempotraria*).

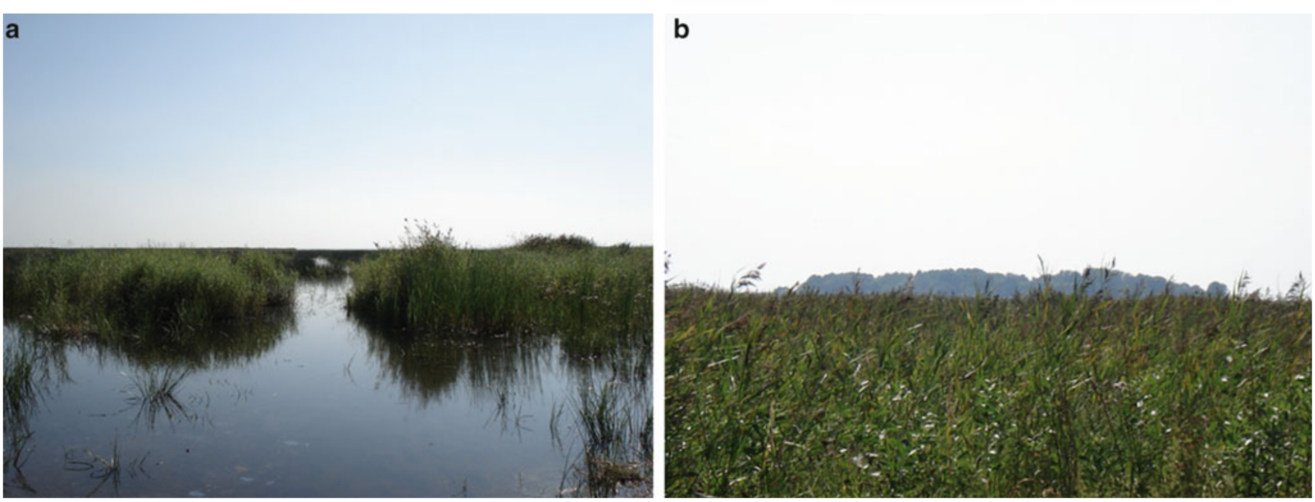


Fig. 7.19 Hydrophyte plants in the nearshore of the "North Coast of Neva Bay" state reserve

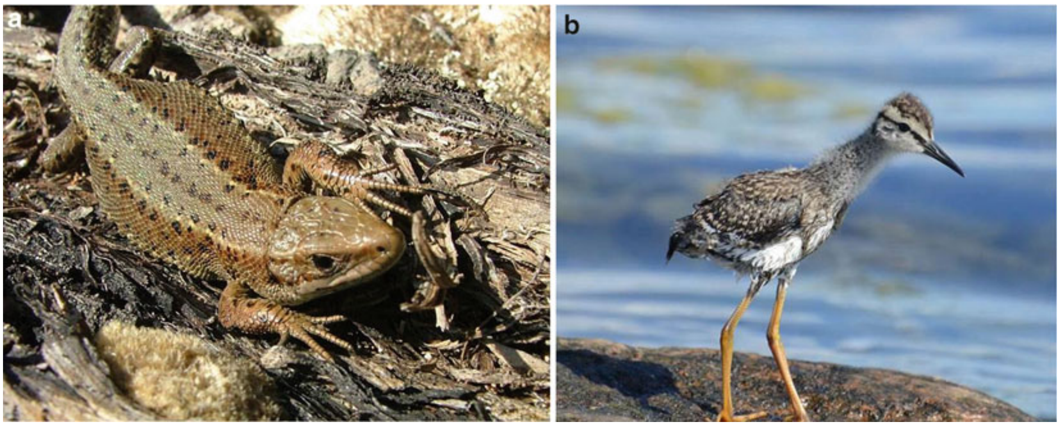


Fig. 7.20 (**a**) Viviparous lizard (*Zootoca vivipara*) on the mainland coast; (**b**) Common Redshunk's chick (*Tringa totanus*), a species included in the four Red Data books of various rank

2. **Bulrush beds**. During the breeding season, 11 bird species and one amphibian have been recorded here. Despite the obvious attraction for birds, rush beds present a certain risk for nesting. These habitats may be completely flooded during storms and, while the waves are less noticeable to birds situated in the center of dense reed thickets, almost all nests in the rushes get washed out, especially those built on the bent plants, for example, in *Chlidonias niger*, while nests on hummocks, or big mats (such as those of gulls and grebes) are more likely to be spared.
3. **Coastal meadows**. By "coastal meadows", we mean the coastal zone, heavily overgrown with grasses and shrubs, and periodically flooded during storms. Spatially, coastal meadows occupy the largest coastal areas of Kotlin Island, but at the mainland, the coastal areas are very small. The meadows these have been greatly transformed, or are actively visited by people, so the species composition (four to six species) and the number of animals are considerably lower, as compared to similar biotopes located at Kotlin Island (one amphibian species, eight bird species, seven mammal species). Coastal meadows with rich vegetation provide the perfect nesting camouflage from predators and humans, and mortality in egg batches as the result of tides and storms is significantly lower here than in the reeds and rushes. A lot of mammals use coastal meadows as seasonal feeding biotopes. The main limitation to «populating» such biotopes, from our point of view, is the extent of recreational pressure.
4. **Boulder ridges and stony places** along the shoreline provide permanent breeding places for only a few species. They are most common at the islands (the forts and Kotlin Island). In the full absence of vegetation, up to eight bird species breed on rocky banks. Boulder ridges and stony places ensure good camouflage for nests, but the majority of waterfowl and shorebirds rarely occupy such biotopes. The maximum abundance is taken up here by passerine birds (*Motacilla alba* and *Oenanthe oenanthe*). Mammals (*Neovison vison* and *Vulpes vulpes*, generally) hunt there sometimes.
5. **Sandy and sandy-shingle beaches**. Sandy beaches refer to one of the most typical biotopes in the surveyed area. However, the sandy beaches of the mainland and Kotlin Island are widely used for recreation and, for this reason, have almost completely lost their attraction for vertebrates as breeding habitats and feeding places in this region. Moreover, these biotopes provide the least possible nest camouflage from predators. No breeding of vertebrate species was registered in the mainland coastal zone. Reptiles (one species, the Viviparous lizard (Fig. 7.20a)) and mammals are rare in these areas.
6. **Forests at the shoreline** are very typical for the mainland coastal areas and the northern part of Kotlin Island. They can be divided into three main groups: forests growing on Klint terraces, old parks ("Sergievka Park", Aleksandria, Peterhoff parks) and damped black alder forests. Their fauna is very rich and different. In most cases, it is represented by typical sylvatic vertebrates (up to 220–230 species).
7. **Anthropogenic habitats** of the coastal zone are very different and can be divided conventionally into two types. The first includes residential buildings located on the shores. They provide an opportunity for a number of species, uncommon to the coastal zone (*Passer montanus*, *Hirundo rustica*, *Delichon urbica*, *Sturnus vulgaris*, *Muscicapa striata*, *Mus musculus*, *Rattus norvegicus*, etc.), to breed in close proximity to the Gulf of Finland and use the coast as a feeding biotope (*Vulpes vulpes*).

The second one includes man-made landscapes (= artificial habitats): the Flood Protection Facility and old fortresses (Fig. 7.21), which are widely represented in Neva Bay. Artificial islands were constructed about 150 years ago from boulders and sands to serve as fortresses and fortifications. Therefore, on the artificial islands, five main habitats were determined: plots with trees and scrub, manmade sandy banks, grasslands, boulder ridges, old buildings and storm surge barriers. In total, one amphibian and one reptile species, 28 bird species and 9 mammals have been found out there.

Five of these species are included on the Helcom Red List of Baltic Sea species in danger of becoming extinct, four species – in the Red Data Book of the Leningrad region. The most preferable nesting habitats are boulder ridges (31 %, 12 species), grasslands (25.5 %, 10), "park" areas (23 %, 9), at the storm surge barriers (8 %, 3), an inside fortresses (10 %, 4). The only ones to inhabit manmade sandy banks (2.5 %) are sand martins (*Riparia riparia*) (Fig. 7.22a), but their abundance numbers up to 100 pairs (Fort Totleben). The most common species are Black-headed gulls *Larus ridibundus*, Common terns *Sterna hirundo*, Arctic terns *S.paradisaea* (Fig. 7.22b), Tufted ducks *Aythya fuligula*, and goosanders *Mergus merganser*.

Thus, many different types of coastal habitat used by terrestrial vertebrate animals are represented in the Neva Bay area. However, the fauna composition and species abundance are very different, often within similar habitats. In our opinion, human impact plays the primary role in changes in biodiversity. On one hand, as a result of human activity, three coastal NPAs exist in Neva Bay nowadays and one more (the "South Coast of Neva Bay") is in the works. Besides, artificial habitats attract new species atypical of the coastal areas, to breed or feed there (passerine birds and rodents, as a rule). However, in most cases, these artificial habitats are used by common species, which have gotten used to living near people. On the other hand, the pollution level is increasing; dredging works not only destroy certain breeding habitats, but also change them, devastating many feeding areas and annihilating food (aquatic plants, fish, invertebrates). Disturbance is a huge problem for animals in all coastal habitats (including NPAs). The press of anthropogenic activity in this territory (seaport activities, dredging, construction, and permanent noise from these activities, as well as poachers, fishermen, tourists, etc.) has increased over the last 20 years. All coastal areas, and NPAs most of all, require that nature protection be improved and that complex monitoring investigations be continued.

7.8 Vulnerability Assessment of the Neva Bay Environment to External Factors of Natural and Technogenic Character

Anthropogenic transformation of Neva Bay and its coastal areas as a result of sharing of the urban area (e.g., high-rise business districts), development of industrial and transportation infrastructure (dredging, dumping, marine harbor construction, expansion of high-way construction, etc.) will cause an increase in the technogenic load on the lagoon. On the other hand, it is obvious that sustainable regional development, the implementation of nature protection and a

Fig. 7.21 Totleben fortress

Fig. 7.22 (**a**) Sand Martin's nest in the tube at Milutin fort; (**b**) Arctic tern's nest on the flood protection facility

healthy and safe environment for the St. Petersburg population demand the choice of "environmentally friendly" technologies.

Construction of the St. Petersburg Flood Protection Facility has solved the problem of coastal erosion and floods within Neva Bay. However, the level of coastal pollution (e.g., waste disposal beaches) is still very high.

The City Administration and the St. Petersburg Vodokanal has implemented a set of ambitious activities targeted at the reduction of untreated wastewater discharges and the removal of nutrients (nitrogen and phosphorus) from wastewater. In June 2011, St. Petersburg fully met the new recommendations of the Helsinki Commission: content of phosphorus in the total municipal wastewater discharge did not exceed 0.5 mg/l. Construction of the Northern Tunnel Collector was complete as of October 2013. Channeling of the remaining untreated wastewater discharges to the collector will enable the ensured transportation of 98.4 % of all municipal wastewater for treatment (SUE Vodokanal 2015) (Fig. 7.23). The trend towards a decrease in the phosphorus load from the Neva River and other rivers entering the Eastern Gulf of Finland from the 1970s onwards, which has decreased by approximately twice that since that time, has been observed by biological monitoring as well (Golubkov 2014).

The other problem, which should be kept in mind, is the high level of Neva Bay sediment pollution. Any dredging activity could cause secondary pollution of the water by heavy metals, petrochemicals, and sediment transport in the western direction.

Neva Bay has an outstanding position among the other lagoons of the Baltic Sea as the result of the artificial separation of the uppermost part of the Gulf of Finland from the western part of the extended Neva River estuary. Thus, Neva Bay is now the permanent lagoon-like freshwater part of the Neva River estuary and is characterized by specifics peculiar to lagoons. The Flood Protection Facility, which serves as an analogue of the spits, e.g., in the case of the Vistula or Curonian Lagoons, enforces the influence of the Neva River run-off and restricts the impact of marine hydrological processes (upwellings and inflows) and has, so far, also formed specific conditions for aquatic life and bioresources, as well as for water and sediment qualities as prerequisites for human health and constituents of commercial values of this area.

7.9 Discussion

Analyses of geological and biological research have revealed that anthropogenic activity has intensely affected not only the ecological status and biota, but also the geological environment and sedimentation processes of Neva Bay. During the geological mapping carried out by VSEGEI in the period from 1987 to 1989, it was suggested that the silty-clay muds of the bay are very young, because all the layers (40 cm to 1 m) are very homogeneous in regard to chemical compounds and are high technogenically polluted from top to bottom. Usually, only the upper 5–10 or 15 cm of the mud sediments in small depressions to the west of the Flood Protection Facility are polluted. Our monitoring study, carried out here since 1993, has confirmed this supposition.

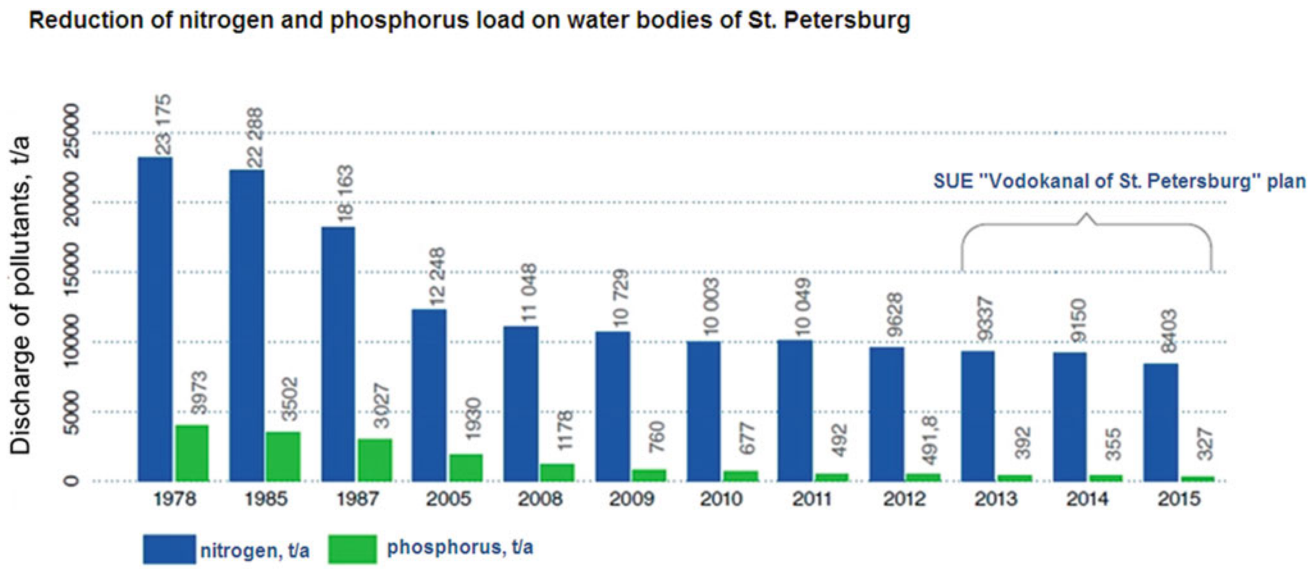


Fig. 7.23 Reduction of nitrogen and phosphorous load on the water bodies of St. Petersburg (SUE Vodokanal 2015)

Results of analyses of the archived data (Sect. 7.6.3) have shown that the area of mud accumulation in Neva Bay has been expanding over the last 200 years, most actively since the second part of the twentieth century. Recent trends of change in sedimentation processes are linked to dredging activity, which can be traced through remote sensing data analysis.

The main natural source of fine-grained material in the eastern Gulf of Finland is the washing-out of lake-glacial and lake sediments of both the bottom surface and the mainland. However, at the end of the 1980s and the beginning of the 1990s, the hydro-engineering works in Neva Bay (for the creation of new territory) caused an increase in suspended matter concentration in the upper water layers of Neva Bay as high as 200 mg/l – ten times greater than natural. Besides, in the 1970s, construction of the Flood Protective Dam began. As a result, silty-clay accumulative processes became more active. In 1993, hydro-engineering work in the Bay was stopped and dredge concentration decreased (becoming three to four times less by 1998), so the sedimenthological situation in the bay changed as well.

The next change in the sedimenthologic trend was observed after the hydro engineering work of 2006–2008. As a result of dredging and dumping processes, the concentration of suspended matter in the water was extremely high by 2007 and the trace of suspension reached Vyborg Bay (Fig. 7.3). VSEGEI's study of the near-shore bottom showed that a clayey layer up to 3 cm thick had formed on the sand surface. The concentration of fine particles in the beach sands of resort areas increased by up to 5–7 % in 2007–2008. The sedimentation system of the Eastern Gulf of Finland was significantly disturbed. The monitoring study of 2011–2013 has shown that the sedimentation system is very slowly returning to its natural conditions. The other important aspect of anthropogenic impact on the geological environment is heavy metal accumulation in the bottom sediments, which reflects the industrial development of St. Petersburg (Fig. 7.18).

Significant changes in the abiotic characteristics of Neva Bay (e.g., bottom relief, surface sediment types, sedimentation rates, geochemistry, hydrooptical and chemical properties of the near-bottom water) have led to a dramatic transformation of the benthic communities (Sect. 7.5).

7.10 Conclusion

Since the founding of the city of St. Petersburg in 1703, Neva Bay and its coasts have developed under the growing anthropogenic impact of the former Russian capital and its industry. After construction of the St. Petersburg Flood Protection Facility in 2011, Neva Bay has been transformed into a deliberate “technogenic lagoon”.

Results of marine geological investigations in the Eastern Gulf of Finland, as well as analysis of remote sensing data, archive and literature data, permit us to conclude that, over the last three centuries, the sedimentation processes in the Eastern Gulf of Finland, and especially its eastermost part, Neva Bay, have changed. Special conditions of mud accumulation in the western part of Neva Bay have developed. Investigation from 2007 to 2008 has shown that the majority of the bottom has been completely transformed by technogenic processes. Ongoing active hydro-engineering works have caused the formation of a clayey layer up to 5 mm thick on the sandy surface of the Neva Bay bottom.

Neva Bay continues to be an area of active nature use, including both large-scale projects related to shipping infrastructure and the creation of new multi-purpose territories on one hand and the functioning of nature protection areas and improvement of water quality due to the implementation of new technologies decreasing nutrient loads on the other hand. Despite intensive traffic and the above-mentioned large-scale transformation leading to the destruction of aquatic habitats, the living planktonic and benthic communities are rather resilient, being contributed to by freshwater eurybiotic and amphibiotic species that can restore themselves over several months or years after the disturbance is reduced. This is not true for fish resources, which degrade along with the irretrievable loss of spawning and nursery areas during the current and planned transformations of the coastal zone.

Acknowledgements Investigations were supported by the Federal Program of State monitoring of the geological environment (funded by the Rosnedra Agency), biological monitoring was funded by the Committee on Nature Use, Ecological Safety and Environmental Protection of the St. Petersburg city government, TOPCON's project of the ENPI Russian-Finnish program of 2007–2013 and the Gulf of Finland, 2014.

References

Alferaki SN (1906) About ornithological fauna of Saint-Petersburg region (K ornitologicheskoj faune Sankt-Peterburgskoj gubernii) Dogs and gun hunting (Psovaja I oruzejnaya ohota) 25:7–12

Alferaki SN (1907) Ornithological notes about Saint-Petersburg region in 1906 (Ornitologicheskie zametki po Sankt-Peterburgskoj gubernii v 1906 godu). Ann Zool Mus Russ Acad Sci (Ezegodnik Zoologicheskogo museja Akademii nauk) 11:1–3

Andren T, Bjork S, Andren E, Conley D, Zillen L, Anjar J (2011) The development of the Baltic Sea basin during last 130 ka. In: Harff J, Björck S, Hoth P (eds) The Baltic Sea basin. Springer, Heidelberg/Dordrecht/London/New York, pp 75–98

Auslender VG, Yanovsky AS, Kabakov LG, Pleshivtseva ES (2001) Novoye v geologii Peterburga (New facts in geology of St. Petersburg). Mineral 1(4):51–58. St. Petersburg. (in Russian)

Berezina NA (2007) Invasions of alien amphipods (Crustacea, Amphipoda) in aquatic ecosystems of North-Western Russia: pathways and consequences. Hydrobiologia 590:15–29. Springer International Publishing

Bianki VL (1903) New and rare birds of Saint-Petersburg region (Novie I redkie ptitsi Sankt-Peterburgskoj gubernii). Ann Zool Mus Imp Acad Sci (Ezegodnik Zoologicheskogo museja Akademii nauk) 8(2):XXV–XXXII. St. Petersburg: Imperial Academy of Sciences

Bianki VL (1909a) Reptiles and Amphibians of Saint-Petersburg region (Reptilia и Amphibia Sankt-Peterburgskoj gubernii). Ann Zool Mus Imp Acad Sci (Ezegodnik Zoologicheskogo museja Akademii nauk) 14(1-2):131–135. St. Petersburg: Imperial Academy of Sciences

Bianki VL (1909b) Notes about mammals inhabit coastal area among Lebjazje and Chernaja Lahta villages (Petergofskiy district) (Zametki o mlekopitajushih, vodjashihsa v beregovoj polose mezdu derevnjami Lebjazje I Chernaja Lahta Petergofskogo uezda). Ann Zool Mus Imp Acad Sci (Ezegodnik Zoologicheskogo museja Akademii nauk) 14(1–2):107–118. St. Petersburg: Imperial Academy of Sciences

Bianki VL (1913) The list of birds observed during the warm season in 1897–1913 at the coastal area among Lebjazje and Chernaja Lahta villages (Petergofskiy district) (Spisok ptiz, nabludavshihsa v tepliy period 1897–1913 gg v beregovoj polose Petergofskogo uezda mezdu derevnjami Lebjazje I Chernaja Lahta). Ann Zool Mus Imp Acad Sci (Ezegodnik Zoologicheskogo museja Akademii nauk) XVIII:545–561. St. Petersburg: Imperial Academy of Sciences

Bihner EA (1884) Birds of Saint-Petersburg region: data, literature and criticism (Ptitsi Sankt-Peterburgskoj gubernii: materiali, literature I ktitika). Proc Saint-Petersburg Nat Soc (Tr SPb Obshestva Estestvoispitatelej) 14(2):624, St. Petersburg

Bogolubov NF (1895) About migratory birds of Kotlin isl. SPb (O pereletnih ptitsah o.Kotlin), St. Petersburg

Bogolubov NF (1906) Kotlin island as a zoologiacal habitat (Ostrov Kotlin v zoologicheskom otnoshenii). Nature and Hunting (Priroda I ohota) No 10–12, St. Petersburg

Bublichenko A (2008) Coastal and island theriofauna of the eastern part of the Gulf of Finland. 7th Baltic theriological conference, Lepanina, Estonia, 1–5.10.2008. Abstracts, pp 15–17

Bublichenko A (2010) Coastal and island theriofauna of the eastern part of the Gulf of Finland. Russ J Theriol 8(1):37–46. Moscow: Scientific publishing KMK

Bublichenko JN, Bublichenko AG (1999) Fauna of "Oranienbaum" reserve-museum and its vicinity (Fauna muzeja-zapovednika "Oranienbaum" i ego okrestnostej). 7th Annual scientific conference: XXI century – youth, education, ecology, anthroposhere (7 ezegodnaya nauchnaya konf. XXI vek: molodez, obrazovanie, ekologia, noosphere), St. Petersburg, pp 177–178

Dolukhanov, P.M., D.A. Subetto, KhA Arslanov, N.N. Davydova, G.I. Zaitseva, E.N. Djinoridze, D.D. Kuznetsov, A.V. Ludikova, T.V. Sapelko, and L.A. Savelieva. 2009. The Baltic Sea and Ladoga Lake transgressions and early human migrations in North-Western Russia. *Quat Int* 203(1–2): 33–51

EIA (2008) Preliminary impact assessment in content of project documentation "Creation of territories in the eastern aquatory of the Gulf of Finland on the area from storm surge barrier on the north of Lisiy Nos settlement to Sestroretsk town" (Predvaritel'naja ozenka vozdeistvija, vypolnennaja v sostave projecta "Sozdanije iskusstvennykh territorij v vostochnoj chaste akvatorii Finskogo zaliva na uchastke, raspolozhennom severnee posiolka Lisii Nos ot kompleksa zashchitnykh sooruszenij do goroda Sestroretsk"): 651-1-OVOS. Petrohimtechnologia, St. Petersburg (in Russian)

Fisher J (1873) Reptiles and amphibians of St-Petersburg vicinity: (Die Reptilien und Amphibien des St-Petersburg Gourvernements). Zool Ann (Der Zoologische Garten) 14(1):324–328. Frankfurt: Zoologische Gesellschaft

Gerasimov DV (2003) Istoriya izucheniya, chronologiya I periodizatsiya pamyatnikov epochy neolita na yuge Karelskogo peresheika (History of research, chronology and periodization of Neokithic archeological sites in the south of the Karelian Isthmus). Arheologicheskoye naslediye Sankt-Peterburga (Archeol Herit StPetersburg) 1:12–24. St. Petersburg (in Russian)

Gerasimov DV (2006) Kamenniy vek Karelskogo peresheyka v materialach Kustkamery RAN (Stone age of Karelian Isthmus in materials of Kunstkamera Museum). Svod archeologicheskich istochnikov Kunstkamery (Collection of archeological sources of Kustkamera Museum) 1:109–188. St. Petersburg (In Russian)

Golubkov MS (2009) Phytoplankton primary production in the Neva estuary at the turn of the 21th century (Pervichnaja produkzija fitoplanktona v estuarii htrb Neva v nachale 21 stoletija). Inland Water Biol (Biologija vnutrennikh vod) 4:312–318. St. Petersburg: IAPK Nauka/Interperiodica (in Russian)

Golubkov SM (2014) Ecosystem of the easterm Gulf of Finland: biodiversity and ecological problrms. Reg Ecol 1–2(35):15–20. St. Petersburg: RAS

Gubelit YI, Kovaltchuk NA (2010) Macroalgal bloom and species diversity in the transitional zone of the Eastern Gulf of Finland. Hydrobiologia 656:83–86. Springer

Inostrantsev AA (1912) Geological structure of Kotlin Island (Geologicheskoye stroeniye ostrova Kotlin). Issues St Petersburg Nat Soc (Trudy SPb obschestva estestvoispytateley) XXXV:5. St. Petersburg

Khrabriy VM (1991) Birds of Saint-Petersburg and its vicinity (Ptitsi Sankt-Peterburga i ego okrestnostej), St. Petersburg

Korelyakova IL (1997) Higher plants of the Eastern Gulf of Finland (Vysshie rastenia vjstochnoj chasti Finskogo zaliva). GOSNIORKH, Leningrad (in Russian)

Kouzov SA (1993) Waterfawl and shore birds of the northern coast of Neva bay (Vodoplavajushie I okolovodnie ptitsi severnogo poberezja Nevskoj gubi). In: Ecology and fauna of Palearctic birds. Proceeding of ZIN RAS. 252, St. Petersburg, pp 60–83

Krasnov II, Zarrina EP (eds) (1982) Leningrad and Leningrad region: guide-book of geological excursion A-15, C-15. XI INQUA congress. VINITI, Moscow (in Russian)

Kronstadt. Virtual tour. http://kronshtadt.info. Accessed 29 Sept 2015

Kulkova M, Gusentsova T, Nesterov E, Sorokin P, Sapelko T (2012) Chronology of neolithic-early metal age sites at the Okhta river mouth (Saint Petersburg, Russia). Radiocarbon 54(3–4):1049–1063. Arizona

Kulkova MA, Gusentsova TM, Sapelko TV, Nesterov EM, Sorokin PE, Ludikova AV, Ryabchuk DV, Markova MA (2014) Geoarchaeological investigations on the development of the Neva River delta (Gulf of Finland) during the Holocene. Mar Syst 129:19–34. Elsevier

Kvasov DD (1979) The late-quaternary history of large lakes and inland seas of Eastern Europe. Ann Acad Sci Fenn Ser A III Geol Geographyca 127:71. Helsinki

Leont'yev IO (2008) Budget of sediments and forecast of long–term coastal changes. Oceanology 48:428–437. Moscow: IAPK Nauka/Interperiodica

Maksimov AA (2014) Macrozoobenthos of the Neva Bay under conditions of intensive hydrotechnical works (Makrozoobentos Nevskoi Guby v uslovijakh intensivnykh gidrotechnocheskikh rabot). Reg Ecol (Regional'naja Ekologija) 1–2(35):39–47. St. Petersburg: RAS (in Russian)

Markov KK (1931) Development of the relief in the North-Western part of the Leningrad District (Razvitiye reliefa severo-zapada eningradskoy oblasti). Leningrad (in Russian)

Miettinen A, Savelieva L, Subetto D, Dzhinoridze A, Arslanov K (2007) Palaeoenvironment of the Karelian Isthmus, the easternmost part of the Gulf of Finland, during the Litorina Sea stage of the Baltic Sea history. Boreas 36:441–458. Accessed 28 June 2008

Nezhihovsky RA (1988) Problems of the Neva Bay hydrology, Leningrad (in Russian)

Nikulina VN (2008) Phytoplankton of the Neva River estuary (Fitoplankton estuarija reki Nevy). In: Alimov AF, Golubkov SM (eds) Ecosystem of the Neva river estuary: biological diversity and ecological problems (Ecosistema estuarija reki Nevy: biologicheskoie raznoobrazje I ecologicheskije problemy). KMK Press, Moscow, pp 77–96 (in Russian)

Nikulina VN (2012) Change in species composition and abundance of planktonic algae under anthropogenic impact (Izmemenija vidovogo sostava planktonnykh vodoroslei pod vlijanijem antropogennykh vosdeaistvij). In: Alimov AF, Golubkov SM (eds) Dynamics of biological diversity and bioresources of inland water bodies (Dinamika biologicheskogo raznoobrazija i bioresyrsy kontinental'nykh vodoyiomov). Nauka, St-Petersburg, pp 145–155 (in Russian)

Nikulina VN, Gubelit YI (2011) Cyanobacteria and macroalgae in ecosystem of the Neva estuary. Knowl Manag Aquat Ecosyst 402:1–12. France: EDP Sciences

Noskov GA (1960) Bird migration in north-western regions of Leningrad oblast (Migratsii ptiz v severo-zapadnih rajonah Leningradskoj oblasti). In: Proceedings of IV Baltic ornithological conference, Riga, pp 72–73

Noskov GA (1997) Migration of waterfowl and shorebirds in the north-western region of Russia and tasks of their study. In: Proceedings of the Programme on "Study of the status & trends of migratory bird population in Russia", vol 1, St. Petersburg, pp 12–19

Orlov NL, Ananjeva NB (1995) Distribution of amphibians and reptiles and their relict populations in the Gulf of Finland and Lake Ladoga. Memoranda Soc Fauna Flora Fenn 71:109–112. Helsinki: Helsingfors

Petrov OV (2010) Atlas of geological and geoecological maps of the Russian part of the Baltic Sea. VSEGEI, St. Petersburg

Pitul'ko VM (2014) Large-scale projects in the EGOF: principles and presumptions for preparation of environmental protection measures (Masshtabnyje projecty v vostochnoi chasti Finskogo zaliva: principy i presumpcii dlya podgotovki prirodozashchitnykh meroprijatij). Reg Ecol (Regional'naja Ekologija) 1-2(35):96–105. St. Petersburg: RAS. (in Russian)

Raukas A, Huvarinen H (eds) (1992) Geology of the Gulf of Finland. The Academy of Sciences of the Estonian SSR, Tallinn (in Russian, summary in English)

Razdolgin AA, Skorikov YA (1988) Kronshtadt Fortress (Kronshtadskaya Krepost'), Leningrad (in Russian)

Rosen MF (1930) Geological structure of the Gulf of Finland bottom along the transect Oranienbaum – Kronshtadt – Lisiy Nos (Geologicheskoye stroeniye dna Finskogo Zaliva po profilu Oranienbaum – Kronshtadt – Lisiy Nos). Proc Cent Hydrometeorol Bur (Izvestiya Tsentralnogo Hidrometeorologicheskogo Byuro) X:139–178. Leningrad: NKPS

Rosentau A, Muru M, Kriiska A, Subetto DA, Vassiljev J, Hang T, Gerasimov D, Nordqvist K, Ludikova A, Lõugas L, Raig H, Kihno K, Aunap R, Letyka N (2013) Stone Age settlement and Holocene shore displacement in the Narva-Luga Klint Bay area, Eastern Gulf of Finland. Boreas 42(4):912–931. doi:10.1111/bor.12004. Accessed 17 Jan 2013

Ryabchuk D, Sukhacheva L, Spiridonov M, Zhamoida V, Kurennoy D (2009) Coastal processes in the Eastern Gulf of Finland – possible driving forces and connection with the near-shore zone development. Estonian J Eng 15(3):151–167. Tallinn: Estonian Academy Publishers

Ryabchuk D, Kolesov A, Chubarenko B, Spiridonov M, Kurennoy D, Soomere T (2011) Coastal erosion processes in the Eastern Gulf of Finland and their links with geological and hydrometeorological factors, vol 16. Boreal Environment Research, Helsinki, pp 117–137 (Suppl. A.)

Ryabchuk D, Zhamoida V, Amantov A, Sergeev A, Gusentsova T, Sorokin P, Kulkova M, Gerasimov D (2014) Development of the coastal systems of the easternmost Gulf of Finland, and their links with Neolithic-Bronze and Iron Age settlements. In: Harff J, Bailey G, Luth F (eds) Geology and archaeology: Submerged landscapes of the continental shelf. Geological society. Special Publications, London. First published online September 29, 2014, doi:10.1144/SP411.5. http://dx.doi.org/10.1144/SP411.5

Ryabchuk D, Vallius H, Zhamoida V, Kotilainen A, Sukhacheva L, Orlova M (in press) Sedimentation processes and pollution history of the Neva Bay (Eastern Gulf of Finland, the Baltic Sea)

Rylov VM (1923) Zooplankton of Neva Bay (Zooplankton Nevskoj Guby). In: Investigations of the Neva River and its drainage basin. Petrograd, pp 1–85

Rymkevich TA, Rychkova AL, Antipin MA, Kotkin AS (2009) Spring migratory birds stopovers in the Neva Bay of the Gulf of Finland

(Vesennie migratsionnie snojanki gnbz v Nevskoy Gube Finskogo zaliva). In: Investigations of populations dynamics of migratory birds and their trends in changing in the North-West of Russia (Izuchenie dynamiki populyatsij migrirujushih ptiz I tendentsij ih izmenenij na Severo-Zapade Rossii), vol 6. Tuskarora, St. Petersburg, pp 6–26

Saarnisto M (2008) Emergence history of the Karelian Isthmus. In: Karelian Isthmus – stone age studies in 1998–2003. Iskos 16:128–139. Helsinki

Saarnisto M (2012) Late Holocene land uplift/neotectonics on the island of Valamo (Valaam), Lake Ladoga, NW Russia, Quaternary International, pp 143–152. , doi:10.1016/j.quaint.2011.09.005

Saarnisto M, Grönlund T (1996) Shoreline displacement of Lake Ladoga – new data from Kilpolansaari. Hydrobiologia 322:205–215

Saarnisto M, Sarinen T (2001) Deglacialtion chronology of the Scandinavian Ice Sheet from the Onega Lake basin to Salpausselka end moraines. Glob Planet Chang 31:387–405. Elsavier

Salaskin AA (1982) Benthic fauna of the Neva Bay and some peculiarities of its distribution (Donnaya fauna Nevskoi Guby i nekotoryje osobennosti jejo raspredelenija), vol 192, Proc. of GOSNIORKH (Isvestija GOSNIORKH). GOSNIORKH, St. Petersburg, pp 70–77 (in Russian)

Sandgren P, Subetto DA, Berglund BE, Davydova NN, Savelieva LA (2004) Mid-Holocene Littorina Sea transgressions based on stratigraphic studies in coastal lakes of NW Russia. GFF 126:363–380. Stockholm

Skorikov AS (1910) To the fauna of the Neva Bay in the vicinity of the Kotlin island (K faune Nevskoi Guby v okrestnostiakh ostrova Kotlin). Yearb Zool Mus R Acad Sci (Ezhegodnik Zoologicheskogo museja Imperatorskoi academii nauk) 15:474–490. St. Petersburg: Imperial Academy of Sciences (in Russian)

Sorokin PE (2011) Archeological sites of the Okhta Cape. Sci Russ 3:19–25. Russia: Russian Academy of Sciences

Spiridonov MA, Ryabchuk DV, Shakhverdov VA, Zvezdunov SI, Nesterova EN, Suslov GA, Grigoriev AG (2004) The Neva Bay. Geoenvironmental issue (Nevskaya Guba. Geoecologicheskiy ocherk). St. Petersburg (in Russian)

Spiridonov M, Ryabchuk D, Kotilainen A, Vallius H, Nesterova E, Zhamoida V (2007) The quaternary deposits of the Eastern Gulf of Finland. Geol Surv Finland Spec Pap 45:5–18. Edited by Henry Vallius, Finland: GTK

Spiridonov MA, Malysheva NB, Pitulko VM (2014) Natural and technogenic transformation of marine coastal zone of St. Petersburg (Prirodno-technogennaya transformatsiya morskoy beregovoy zony Sankt Peterburga). Reg Ecol 1–2(35):106–118. St. Petersburg: RAS

Subetto DA (2009) Lake sediments: Paleolimnological reconstructions. Publishing House, St. Petersburg. "A.Herzen Russian State Pedagogical University" (in Russian, resume in English)

Subetto DA (2011) Paleogeographiya poslelednikovya I golocena. Priroda Sestroretskoy Niziny (Paleogeography of late glacial and Holocene. In nature of Sestroretskaya Lowland). In: Volkova EA, Isachenko GA, Khramtsov VN (eds). Publishing House, St. Petersburg, pp 25–30. "A.Herzen Russian State Pedagogical University" (in Russian)

SUE (2015) Vodokanal of St. Petersburg. Official site. http://www.vodokanal.spb.ru/en. Accessed 14 Nov

Sukhacheva LL, Orlova MI (2014) About application of the results of satellite observations in the Eastern Gulf of Finland for the assessment of natural and men-mediated impacts onto ecological state of the quatic area and biotic components of the ecosystem (O primenenii resultatov sputnikovykh nabludenij vostochnoj chsti Finskogo zaliva dlya ozenki vosdeistvija estestvennykh I antropogennykh faktorov na sostojanije akvatorii i bioticheskikh kompomemtov ecosistemy. Reg Ecol (Regional'naja Ekologija) 1–2(35):62–76. St. Petersburg: RAS (in Russian)

Technical Report (2004) Development of the system of monitoring of biological pollution for aquatic ecosystems of the Gulf of Finland basin (Sozdanije sistemy monitoringa biologicheskogo zagryaznenija vodnykh ecosystem basseina Finskogo zaliva). Governmental contract. St. Petersburg (in Russian)

Technical Report (2005) Approbation of the system of monitoring of biological pollution for aquatic ecosystems of the Gulf of Finland basin (Aprobacija sistemy monitoringa biologicheskogo zagryaznenija vodnykh ecosystem basseina Finskogo zaliva). Governmental contract. St. Petersburg (in Russian)

Technical Report (2006) Monitoring of biological pollution for aquatic ecosystems of the Gulf of Finland basin (Monitoring biologicheskogo zagryaznenija vodnykh ecosystem basseina Finskogo zaliva). Governmental contract. St-Petersburg (in Russian)

Technical Report (2007) Monitoring of non-indigenous species. Governmental contract. St. Petersburg, (in Russian)

Technical Report (2008) Monitoring of non-indigenous species (Monitoring chuzherodnykh vidov). Governmental contract. St. Petersburg (in Russian)

Technical Report (2012) Arrangement and carrying out the fieldwork, aimed to creation of project documentation for mapping and express-assessment of modern state of aquatic and coastal landscapes in the Gulf of Finland at areas, adjacent to St.-Petersburg for ensuring of environmental safety (on the example of natural and technogenic portions of the Neva Bay and the Gulf of Finland in Primorsky and Resort districts (Obespechenije i vypolnenije polevykh rabot dlya sozdanija projektnoi dokumentacii dlya kartirovanija i ekspress-ozenki sovremennogo sostojanija vodnykh i beregovykh landshaftov Finskogo zaliva na akvatorijakh, prilezhashchikh k gorody Sankt-Peterburg dlya obespechenija ecologicheskoi bezopasnosti (na primere estestvennykh i technogennykh uchastkov Nevskoi Guby i Finskogo zaliva v Primorskom i Kurortnom rajonakh). Governmental contract. St. Petersburg (in Russian)

Telesh IV (2008) Species diversity and community structure of Zooplankton in the estuary of the Neva River (Vidovoje raznoobrazije i struktura soobshchestv zooplanktona v estuarii reki Nevy). In: Alimov AF, Golubkov SM (eds) Ecosystem of the Neva river estuary: biological diversity and ecological problems (Ecosistema estuarija reki Nevy: biologicheskoie raznoobrazje I ecologicheskije problemy). KMK press, Moskow, pp 144–145 (in Russian)

Tillo EI (1893) Proekt predohranenija S.-Peterburga ot navodnenija (Project of St.Petersburg Flood Protection). In: Proceedings of the Imperial Russian Geographical Society on general geography (Zapiski imperatorskogo Russkogo geograficheskogo obshhestva po obshhej geografii) XXV(2). St. Petersburg

Uspensky AA, Naseka AM (2014) A survey of coastal shallow-water fish communities in Russian sector of the Eastern Gulf of Finland (K izucheniju rybnogo naselenija pribrezhnykh melkovodij rossiiskogo sektora Finskogo zaliva). Reg Ecol (Regional'naja Ekologija) 1-2(35):58–55. St. Petersburg: RAS (in Russian)

Vallius H (ed) (2007) Holocene sedimentary environment and sediment geochemistry of the Eastern Gulf of Finland, Baltic Sea. Geological Survey of Finland, Special paper 45 Finland: GTK

Vallius H, Ryabchuk D, Kotilainen A, Spiridonov M, Suslov G, Zhamoida V (2006) Pollution history of thr Neva Bay since the foundation of the city of St. Petersburg (1703 AD), The Baltic Sea geology: The ninth marine geological conference. Extended abstracts. University of Latvia, Riga, pp 115–116

Verzilin NN, Kleimenova GI (2010) Problema suzhestvovaniya reki Nevy v Golotcene. Vestnik Sankt-Peterburgskogo universiteta, Seriia 7. Geologiia, geografiia, vol 4. St. St. Petersburg University Press, Petersburg, pp 74–80 (in Russian)

Vinberg GG, Gutel'makher BL (eds) (1987) Neva Bay. Hydrobiological investigations. Nauka, Leningrad (in Russian)

Virtasalo JJ, Ryabchuk D, Kotilainen AT, Zhamoida V, Grigoriev A, Sivkov V, Dorokhova E (2014) Middle Holocene to present sedimentary environment in the easternmost Gulf of Finland (Baltic Sea) and the birth of the Neva River. Mar Geol 350:84–96. Elsevier

Yakovlev SA (1925) Relief and sediments of Leningrad area (Relief I nanosy Leningrada), Leningrad (in Russian)

Zhakova LV (2008) Macrophytes: vascular plants and macroalgae (Makrofity: vysshije vodnyje rastenija i makrovodorosli). In: Alimovm AF, Golubkov SM (eds) Ecosystem of the Neva river estuary: biological diversity and ecological problems (Ecosistema estuarija reki Nevy: biologicheskoie raznoobrazje I ecologicheskije problemy). KMK Press, Moscow, pp 105–125 (in Russian)

The White Sea as an Estuarine System

8

Evgeniy Ignatov, Oleksiy Kalynychenko,
and Anatoliy Pantiulin

Abstract

The White Sea is Russia's inland sea. The chapter contains a description of a new model for structural organization of the White Sea as an estuarine system and characteristics of the main factors forming the sea's regime. Following an overall typification of the coast, the chapter presents general characteristics of the coastal structure, landscapes and biological features, as well as the development of morphodynamic and lithodynamic processes. A description is provided on the morphology of the landscape and coastal marine areas, including lagoons and the estuarine coast. The data on unique natural objects, rare and endangered species and anthropogenic impacts on the White Sea coasts are discussed.

Keywords

Estuarine system • Diversity of estuaries • Vertical water structure • Types of coast • Landscape and biological diversity • Hydrology of lagoons • Fjords • Morpho- and lithodynamics • Nature monuments • Red data book • Human impacts • Biological disaster

8.1 Introduction

The White Sea is located in the north of the European part of Russia in the basin of the Arctic Ocean. From a structural geomorphological respect, it belongs to the marginal shelf seas (Nevessky et al. 1977; Vareychuk and Ignatov 1989), while its oceanology classification (Zubov 1956; Dobrovol'sky and Zalogin 1982) defines it as an enclosed sea. This follows from the unique peculiarity of the White Sea, which is located among the Eurasian Arctic seas, yet is not related to them due to the absence of the main typological feature of the latter – year-round ice cover. The White Sea is not similar to the neighboring Barents Sea, and is also 16 times smaller in area and 50 times smaller in volume; the two seas are connected by a long mutual boundary.

E. Ignatov (✉) • O. Kalynychenko • A. Pantiulin
Faculty of Geography, Lomonosov Moscow State University (MSU), GSP-1, 1 Leninskiye Gory, Moscow 119991, Russia
e-mail: ign38@mail.ru; okalynychenko@yahoo.com; apantulin@newmail.ru

Without exaggeration, the White Sea can be considered to be a microcosm of physical, chemical, biological, geological, and other processes and phenomena of the widest spectra: classical, anomalous, and even unique. These processes and phenomena are distributed in a concentrated form over a relatively small space. Naturally, these phenomena are attractive for researchers with different areas of interest, as demonstrated by the increased expedition activity in the White Sea over the last decade. At the same time, certain problems have appeared that are related to the interpretation and generalization of the observations and a need to overcome the traditional marine science stereotypes. Under such conditions, multidisciplinary interaction acquires a particular importance. Along with being desirable, such interaction becomes mandatory, because every discipline has to cooperate with the other disciplines in order to solve its own individual problems. The key role in the formation of a systematized conception of the White Sea belongs to hydrology. The main goal of this paper is to create an up-to-date hydrological conception of the White Sea based on the principles of individuality, integrity, and comparability. The structure of the paper

R. Kosyan (ed.), *The Diversity of Russian Estuaries and Lagoons Exposed to Human Influence*,
Estuaries of the World, DOI 10.1007/978-3-319-43392-9_8

includes three main sections: a characterization of the factors forming the regime of the sea; the accumulated knowledge and classical conceptions about the hydrology of the White Sea; and finally, a description of the new systematic approach.

8.2 Main Factors Governing the Regime of the White Sea

The hydrological regime and peculiarity of the White Sea are due to three external factors related to the "water body" of the sea and one internal factor. The first three factors are the following: the morphometric properties of the sea (the size, area, and volume of the sea as a whole and of its parts, its bottom topography, and the shape of the coastline); its meteorological regime and climate (above all, heat exchange with the atmosphere and wind regime); and its freshwater exchange (continental run-off, precipitation, and evaporation). The main internal factor is represented by the tides, whose energy is distributed over the entire volume of the sea (Fig. 8.1).

8.2.1 Morphometric Characteristics of the White Sea

Among the marine basins surrounding Russia, the White Sea only exceeds the Sea of Azov in regards to size. The area of the sea is relatively small, approximately 90,000 km^2; the volume is 6000 km^3. It is important to note their distribution in individual parts of the sea.

The form of the sea is strongly aportioned and the connection with the adjoining Barents Sea is not typical of enclosed seas. The boundary between these seas runs along the line from Cape Kanin Nos to Cape Svyatoi Nos, a length of 160 km, which is comparable to the maximum width of the sea (450 km along the Kandalaksha–Arkhangelsk line). The Voronka (funnel) is located further along. Its configuration corresponds to its name. It ends at Mezen Bay and becomes a real strait, called the Gorlo, which is 150 km long and 50–60 km wide. In the opinion of Timonov (1950), the middle of the Gorlo is the morphological boundary of the White Sea.

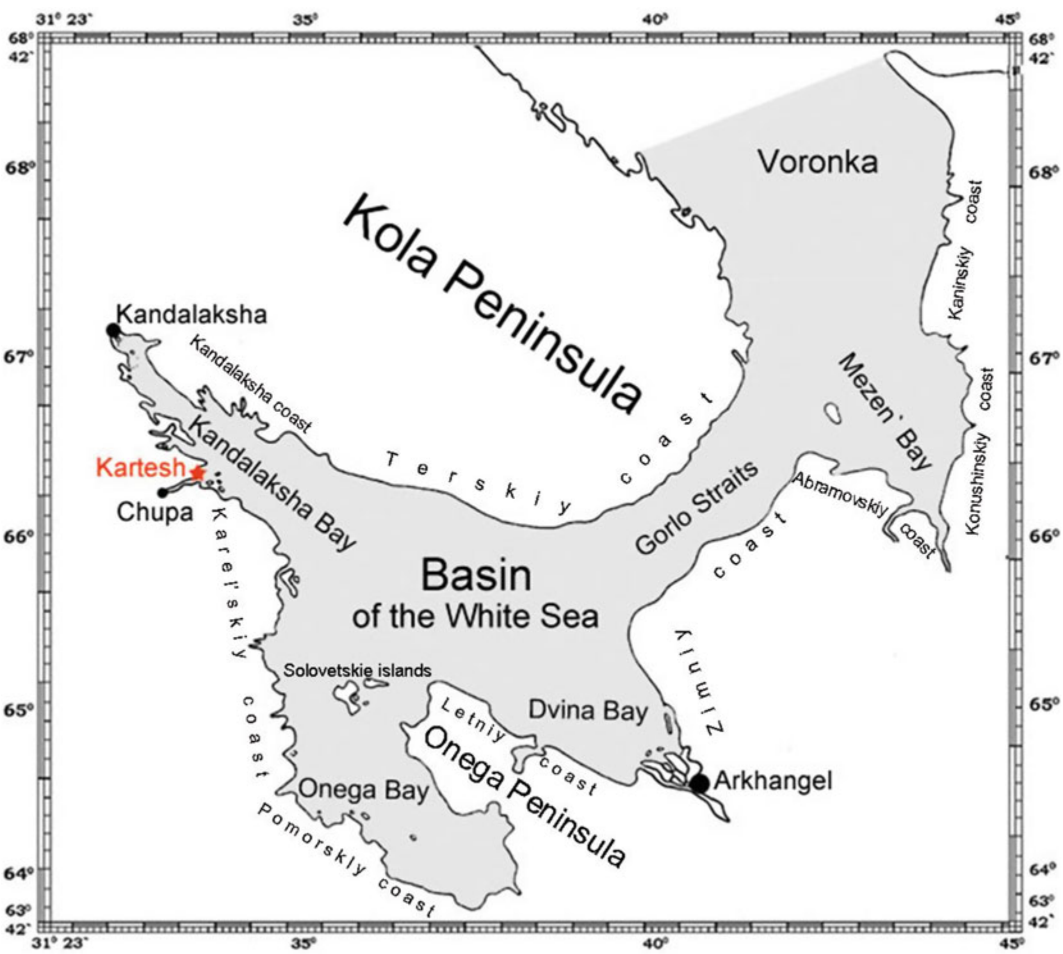


Fig. 8.1 Map-scheme of the coasts of the White Sea (Composed by O. Kalynychenko after Nevessky et al. 1977)

The three regions mentioned (the Voronka, the Gorlo, and Mezen Bay) form the northern part of the White Sea, with characteristic depths of 30–50 m. This is actually an extensive region (40 % of the total area of the sea) of the strait type, and it is simultaneously a threshold zone open to the north in the direction of the adjoining basin. It divides the Barents Sea from the southern part of the White Sea by a distance of 335 km. The southern part is the most individual part of the sea, which includes the Basin and three bays (Dvina, Onega, and Kandalaksha). A deep depression is located here with a maximum depth of 350 m; this occupies a small volume but plays a very important role in the ecosystem of the White Sea.

The bays of the White Sea significantly differ in their morphometric properties. Mezen Bay has a relatively regular conic shape and only one island, Morzhovets. Depths shallower than 10 m occupy over one-half of the area. Only in the center of the bay is there a depression, limited by the 20-m depth contour. The maximal tides of the White Sea have been observed in this region, causing great cyclic variations in the depths and horizontal displacements of the coastline (the width of the intertidal in certain regions of the coast reaches 5 km and more). In addition, most of the coast of the bay is subject to abrasion and is receding at a rate of 2–5 m per year.

Dvina Bay is distinguished by having the most regular morphometric structure. Smooth-leveled steep coasts gradually approach each other in the apex of the bay. Their monotonous shape is distorted only by the small Unskaya Inlet. The basin of the bay is open to the sea, with only one island, Mud'yug, located near the northern coast. The bottom of the bay is even, with depths gradually increasing to 100 m. Together, all these peculiarities minimize the influence of topographic factors on the oceanological processes occurring in the bay. The processes in the apex of the bay are different. Here, the bay terminates into the mouth region of the largest river flowing into the White Sea – the Severnaya Dvina River. This is a classical multi-channel delta with a multitude of islands, channels, and complex internal dynamics. At the marine edge of the delta, the river outflow is separated into three channels, which overflow the marine bar, detach from the bottom, and interact with the seawaters of the bay.

In contrast, Onega Bay is characterized by a complex morphometric structure. The near-shore zone is shallow and has a typical skerry structure. Besides islands and ludas (small stony islands), there are many underwater and above-water rocks. At certain places, the width of the intertidal area reaches 1–1.5 km. There are also many islands in the open part of the bay. The largest archipelago of the White Sea, the Solovets Archipelago, is located near the outlet from the bay. Relatively deep depressions (50–70 m) separated by thresholds and banks stretch out along the central part of the bay and the straits around the Solovets Islands.

Kandalaksha Bay notably differs in its form from the other bays; it is more elongated and has a smaller mean width. The coasts of the bay are related to the skerry-fiard type, so that even without the dense rim of rocky islands, the coastline would still be characterized by intense ruggedness. Numerous inlets (a total of approximately 50) of the glacial–tectonic type resemble fjords with the glacial erosion of their coastal slopes, their bottom topography, and their confinement to fracture lines and fragmentation zones. However, unlike fjords, the coasts of these inlets are not high and their depressions and thresholds are not deep; therefore, they are classified as fiards, and frequently as guba in the local dialect. The longest inlet of Kandalaksha Bay, Chupa Inlet, is 37 km long, while its mean width is 2 km and the depths of the depressions are approximately 65 m.

With respect to its bottom topography, Kandalaksha Bay is divided into two parts. The inner part is characterized by a background depth shallower than 50 m and an uneven relief, consisting of a complex alternation of depressions with depths gradually decreasing towards the apex of the bay (80 m, 50 m, and 30 m) and thresholds between them of different depth. Frequently, the numerous islands – which are located here along the entire width of the bay – play the role of thresholds. The outer part of the bay is separated from the inner part by a sharp increase in depth, and is almost twice as wide as the inner part. The deepest point of the White Sea (335 m) is located here, off the Turii Peninsula. A sharp depth increases the borders along a significant part of the coastline in this part of the bay.

The coasts of Kandalaksha Bay are in a regime of vertical motion. The greatest upward velocity of the coasts (4.5 mm/year) occurs in the Kovda region (Pobedonostsev and Rozanov 1971). This process results in the gradual separation of small inlets from the sea and their transformation into inland basins. In the regions of the southern coast of Kandalaksha Bay, there are a great many basins of this type, at different stages of transformation.

8.2.2 Climatic and Meteorological Characteristics of the White Sea

The White Sea is located in the north of the temperate climatic zone, but some features of the subarctic climate manifest themselves in its transpolar part (the Voronka).

The sea is surrounded by land and, at the same time, is open to the ocean. It is located at approximately equal distances from the Atlantic and Polar baric centers, and its climate combines both marine and continental features. The climate is characterized by spatial variability and significant seasonal and interannual variations.

From April to September, the radiation balance of the sea is positive; the maximum is reached in June, when daylight hours are longest. From October to February, the balance turns negative, and in March, it is close to zero (Zatichnoi and Gershanovich 1991). The annual value of the total solar radiation increases from north to south by approximately 10 %.

The average monthly air temperature in the warmest month (July) grows from 8.6° near Cape Kanin Nos to 15.6°near Arkhangelsk. The mean temperature of the coldest month is distributed differently: it is highest in February (−9.6°) near Cape Kanin Nos, and lowest in January near Mezen (−14.3°), while reaching −12.9° in Arkhangelsk at that same time. The amplitude of the annual air temperature variations is minimal at the northern boundary of the sea (18°). It increases in the southern direction, reaching its maximum values (26–28°) in the apexes of all four bays of the sea.

In all the seasons, frequent changes of air masses related to the passage of baric formations are characteristic of the White Sea. On average, the weather in the sea throughout the year is determined by cyclones 71 % of the time and by anticyclones only 29 % of the time. A dynamic weather change – with strong winds, precipitation, and temperature jumps – accompanies the propagation of the fast western cyclones (12 %) and the so-called "cyclones diving from the north" (12 %). The greatest recurrence is characteristic of anomalously propagating cyclones (33 %), which can induce correspondingly irregular weather situations.

The wind regime over the White Sea is determined by the seasonal state of the atmospheric pressure field. In the winter, southerly and southwesterly winds pre-dominate. Their joint recurrence is 40–50 %, while the most infrequent winds over the sea blow from the northeasterly quarter. In the summer, northerly and northeasterly winds (easterly winds at selected stations) represent the greatest recurrence. The characteristic wind speed is 5–10 m/s. Strong winds (greater than 15 m/s) most frequently blow in the autumn and winter. Over the course of a year, the number of days with such winds can be as high as 100–120 in the northern part of the sea. In all the seasons, the recurrence of calm weather does not exceed 2–3 %.

Overcast skies are typical of the White Sea throughout the entire year. The number of overcast days (with a cloud amount of 8–10) increases from 170 in the south and west to 210 in the north of the sea; by the same token, the number of clear days (with a cloud amount of 0–2) decreases from 21 in the south to 11 in the north. Fog is also a characteristic weather property of the White Sea. The number of days with fog is maximal in the northern part of the sea (100–110), while in the southern regions, this value decreases to 30–50.

8.2.3 Freshwater Contributors

Fresh waters are transported to the sea from various sources, including the following: riverine run-off, subsurface drainage, distributed slope run-off, and atmospheric precipitation. A certain portion of fresh water is removed from the sea through evaporation. The riverine run-off is the main input component of the freshwater budget in the White Sea.

The total catchment area of the White Sea is 714,420 km^2, of which 540,000 km^2 falls into the catchment basins of the three largest rivers of the sea: Severnaya Dvina, Mezen, and Onega (Elshin 1979). The largest catchment area belongs to the Severnaya Dvina, equal to 357,000 km^2. The catchment area of the Kola Peninsula rivers equals 65,460 km^2, while the catchment area of the Karelian and Pomorian coasts is 108,960 km^2.

The rivers of the White Sea are predominantly fed by melting snow, with a characteristic regime of spring floods and low-water winter periods. However, they differ in the character of their interannual run-off distribution. The regime most clearly manifests itself for the lowland rivers of the eastern part of the sea. For example, 52 % of the Severnaya Dvina annual run-off enters the sea during the flood (May–June), while only 3.7 % (February–March) enters it during the low-water winter period. The distribution for the Kola Peninsula rivers is somewhat more even: 38.7 % occurs during the high-water, and 7.6 % during the low-water periods. This is because of the lakustrine-marsh run-off regulation in this region. This effect is even greater for the waters of the Karelian and Pomorian coasts. Here, the corresponding numbers equal 28.9 % and 8.5 %, respectively (Zatichnoi and Gershanovich 1991).

In the basin of the White Sea, there are freshwater run-off systems with a special regulation regime related to operating hydraulic engineering constructions. These include the Neva River, which has a cascade of hydroelectric power stations and water discharge along the riverbed and bypass channel; the Kovda River, with a cascade of hydroelectric power stations; the Knyazhegubskii channel, with a cascade of hydroelectric power stations and river discharge directly into the sea through the overflow pipe of a dam; the Kem River, with a cascade of hydroelectric power stations connected to the system of the White Sea–Baltic Sea canal; and finally, the Vyg River, with a cascade of hydroelectric power stations. The general peculiarity of these systems lies in their more uniform annual run-off distribution. The mean maximum run-offs exceed the minimum run-offs by only 1.5–3 times. The difference is manifested in the distribution of the run-off extrema. For example, in the Neva, the Knyazhegubskii channel, and the Kovda, the maximum run-off is in September; in the Kem, it is in May; and in the Vyg, one can distinguish three approximately equal maxima in January, June, and October. In addition, one must keep in mind possible deviations from the mean values of the run-off due to technological factors.

Reliable estimates of the subsurface drainage and slope run-off into the White Sea are not available. We can assume that the run-off is insignificant in the western part of the sea, where the coasts are composed of crystal rocks of the Baltic Sheet, without sedimentary cover. In the spring, numerous brooks, springs, and swamp seepages can be observed over the entire Karelian coast.

Annually, between 500 and 600 mm of precipitation falls over the surface of the White Sea, of which 350–400 mm falls during the warm period of the year. This equals a mean volume of 47.8 km^3 per year. Evaporation from the surface has been approximately estimated as 23 km^3. Thus, the excess of precipitation over evaporation is 24.8 km^3, while the annual sum of all the freshwater components of the sea budget is 252.8 km^3. The ratio of this volume to the sea area yields a freshwater layer 2.8 m thick, which is the greatest relative value of freshening among the seas surrounding Russia.

We can judge the interannual variations in the freshwater components by the variability of the riverine run-off. A statistical estimate of the interannual deviations of the riverine run-off amplitude (at a reliability of 1 % and 99 %) reaches 35 % of its mean value.

8.2.4 Tides and Tidal Energy

Tides are the most important factor forming and affecting the White Sea water body regime and water mass dynamics. Tides count as an external factor, since tidal waves propagate here from the Barents Sea, while the White Sea serves as a receiver, transformer, and dissipater of their energy. On the other hand, tidal phenomena are so inseparable from other marine processes and so deeply interwoven with them that they become their own essential category. Thus, this section is only devoted to a background characterization of the tides in the White Sea, and their diverse internal roles will be analyzed in later sections. Tides propagate into the White Sea from the Barents Sea as regular semidiurnal waves, with the elevation of the tide and the velocity of the currents increasing along the wave front from east to west by a factor of 1.5–2 (a property of Kelvin waves). Over the length of the Voronka and even in Mezen Bay, the wave front becomes narrower and the energy is concentrated, manifesting itself in the increasing tidal height and current velocity. Thus, the maximum velocities of the tidal currents over the entire White Sea (up to 250 cm/s) have been observed at the boundary between the Voronka and Mezen Bay, while the maximum tide height is located at the apex of Mezen Bay (9.8 m). The propagation of the waves into the Gorlo and the Basin with its bays occurs with their partial reflection, diffraction, and interference, resulting in a complex system of waves of different character: progressive, progressive–standing, and amphidroms. The resulting distribution of tidal energy into the White Sea is as follows. 33 % of the total energy transported across the input section dissipates within the Voronka, 47 % remains in Mezen Bay, 20 % is transported into the Gorlo, but due to reflection, only 6 % propagates into the southern part of the sea. Here, the energy distribution is also not uniform: 4 % falls on Onega Bay, while the Basin and the two other bays get only 2 %. In general, the extreme values of the tide heights and the velocities of tidal currents in the sea regions correspond to the energy distribution. The deviations are related to the influence of morphometry and are better reflected in the currents. We have already noted that the absolute extrema of these characteristics are observed in the Voronka and Mezen' Bay. In the Gorlo, the tide height is 3 m, while the velocities of the currents reach 100–120 cm/s. Transverse irregularity is conserved here; along the Terskii coast, both characteristics are 1.5–2 times greater. In the Basin, the tide height decreases to 1.5 m and the velocities of the currents do not exceed 20 cm/s. Approximately identical tides have been observed in Dvina Bay, but the velocities of the currents at the apex are greater – up to 30–60 cm/s. In Kandalaksha Bay, the topographic effect leads to an increase in the height of the tide up to 2.5 m, but it manifests itself more notably in the tidal currents: in numerous inlets, narrownesses, and thresholds, the velocities of the currents can reach 80–120 cm/s. In Onega Bay, the tide increases from 1.2 m at the inlet to 3 m at the apex of the bay. The complex mosaic-like bottom topography forms a corresponding structure in the tidal currents in the bay, with maximal velocities reaching 200–250 cm/s (Zatichnoi and Gershanovich 1991).

It is important to note certain peculiarities of the tides in the White Sea. The age of the tide is 2 days, on average; that is, the spring maxima of the level and the currents are late by 2 days with respect to the astronomical full moon and new moon. The differences between the spring and neap tides are better manifested in the currents (2–3 times) than in the level (1.5–2 times). Tidal currents in the open parts of the sea have a rotating character, while in the Gorlo, straits, and inlets, they are reversible. Different types of tidal wave deformations have been observed in the White Sea. These include the "manikhi" phenomenon in Dvina Bay, which is characterized by a temporal delay in the rise of the sea level and even a short-term drop in the tidal phase. In Kandalaksha Bay, the same effect is observed in the ebb phase. Asymmetry of tidal waves is observed in the coastal zone, inlets, and skerries: the duration of the tide phase is 1–2.5 h shorter than the ebb phase, and correspondingly, the mean and maximum velocities of the currents are greater during the former than during the latter.

8.3 Systematic Approach to the Hydrology of the White Sea

The proposed approach is based on three principles: individuality, integrity, and comparability. Let us consider them one at a time.

Out of the enclosed seas, the White Sea is distinguished by a variety of peculiarities. Let us note only some of them, which are among the sea's more atypical features. The salinity spectrum of the sea is unique (25–30); it is located outside both the freshened (1–24.7) and oceanic (33–37) ranges.

The form of the connection between the typical estuaries of the White and Barents Seas has no analog among other enclosed seas: the length of the strait region exceeds half of the longest part of the sea, and its volume equals almost a quarter of its total volume.

The realization of water exchange through the vast zone of intensive mixing is unique among straits with water exchange. The velocities of the "tidal noise" exceed the velocities of exchange currents by one order of magnitude.

Certain properties of the seasonal transformation of the water structure in the deep-water part of the sea are extremely unusual. The summertime waves of heat propagate to greater depths (90 m) than the wintertime waves of cold (30 m). In the winter, the cooling of the water structure is performed from above (convectively) and from below (advectively), leading to a temperature close to freezing. A warm intermediate layer, formed as a result of this process, is also an exception from the usual rules. All the known warm intermediate layers in various oceans and seas have an advective origin. In the White Sea, the warm layer has a local genesis, and it contains the "oldest" waters in the structure, in the sense of how much time has passed since their contact with the surface.

It is necessary to clarify what we mean by an estuary model. The estuary branch of oceanography has existed for more than 50 years. During this time, more than 40 definitions of an estuary (Dyer 1997) have been suggested, while the image of an estuary has become very wide through the inclusion of the northwestern part of the Pacific Ocean, the Baltic Sea, and the Great Lakes in this definition. Above all, the classical estuary is a semi-enclosed coastal basin that has a certain form, within which both riverine and marine waters are observed. In this paper, we use an inversion of this image; that is, an estuary is defined as the processes of interaction between water masses of different properties under certain topographic conditions with the participation of external energy. This approach gains additional flexibility from the inclusion of any and all boundary cases, when one of these components is not present (for example, one of the water masses, an estuarine shape, or tides). For a better understanding of the sense of this estuarine image, let us analyze two analogs: fronts in the open ocean and exchange straits. Both cases are based on the interaction of water masses with different properties; but the former is not influenced by the topography of boundaries, so that motions along the front predominate, while in the latter case, the influence of boundaries is so great that the main motion takes place along the gradients of the characteristics. In this respect, exchange straits are closer to estuaries, but their number is very small compared to the enormous variety of estuaries.

As seen before, the authors suggest that the White Sea is a "hierarchic" estuarine system. The sea as a whole occupies the upper level of the hierarchy, which includes the interaction of two water masses (White Sea water with a salinity of 25–30‰ and Barents Sea water with a salinity of 34–35‰), an estuary of the fjord type with a prolonged threshold zone in the north and a basin in the south, and a powerful tidal energy flux. If we change the scale of consideration, we can see that the sea is not a mono-estuary, but an estuarine system consisting of four sub-systems. Each bay shows specific individual characteristics and possesses individual properties.

Mezen Bay is a wide, nonstratified estuary with riverine run-off at its apex and extremely strong tides. Dvina Bay is a wide, stratified estuary with the maximal riverine run-off delivered at its head. Onega Bay is an estuary with the most mosaic-like structure of its bottom topography, islands, tidal dynamics, water stratification, and three large sources of riverine waters. Kandalaksha Bay is wide and is the deepest estuary, with the most irregular coastline and distributed riverine run-off.

If we increase the scale again, we find that Kandalaksha Bay is also an estuarine system: a large part of its coastline consists of a number of estuaries (a total of 40) with a range of sizes of 1–37 km. The bay itself is not uniform. It is divided into three parts: the skerry, middle, and outer deep water. Among the estuaries of the bay, there are a number of complexly organized estuaries (Chupa with Keret'; Velikaya Salma with Rugozerskaya Guba; Por'ya Guba), which comprise the next level of estuarine systems. The last size scale of the estuary is the category of micro-estuaries (0.01–0.5 km), which includes littoral reservoirs (inlets–festoons, pools) and a large number of reservoirs at different stages of separation from the sea due to the uplift of the coast. Organized in this manner, the estuary system of the White Sea has a great deal of potential for effective integration, since it is based on the same foundation – the estuary model – which unites the objects in a wide range of scales, and allows us to carry out their comparative analysis. The hierarchic structure of the system – in which individual parts are not connected in a series, but instead, nested inside one another – provides its complete interrelationship. It is known that a hierarchic structure is also very characteristic of the structure of many biocenoses, and this undoubtedly provides a perspective for multidisciplinary approaches.

The estuary system possesses a well-manifested property of self-similarity of scale, or fractality. It starts with factor similarity, i.e., the factors initiating the estuarine processes (different water masses, the basin of interaction, and sources of interaction energy) are found at all scales. Next comes the geometrical similarity, or non-decreasing complexity, of the estuarine structure at different levels, and the repeated forms of estuaries at a number of scales. For example, one of the most widely spread forms of fjord is found at all levels of the system (from the sea as a whole to the littoral pools).

The hydrological structure also possesses a key similarity at different scale levels. This is the alteration of mixed and stratified zones, which starts from the sea scale (the northern and southern parts) and continues at subsequent levels. In Onega Bay, the mixed region around the Solovets Archipelago is adjacent to the stratified region in the apex of the bay. In the estuaries of Kandalaksha Bay, a similar pattern of alternation is found where deep-water regions alternate with shallow-water regions, for example, in the Velikaya Salma–Rugozerskaya Guba system, where a stratified region adjacent to the sea in the threshold area changes to a mixed region. Along Rugozerskaya Guba, the entire water volume is transformed with respect to temperature without restoring the stratification. In this part of the inlet, the temperature and salinity stratifications only exist within separating reservoirs.

Fronts formed at the boundaries of different regions are related by their origin to the shelf fronts. Such a front located at the boundary between the Gorlo and the Basin can clearly be seen in satellite images of the surface temperature. Another front can always be seen in images of the boundary between Onega Bay and the Basin. The fronts of lesser scale are not recorded remotely, but can be found in typical estuaries during hydrographic surveys and even detected by sonar. All fronts are subject to displacement; wind forces can either sharpen or mask them. Tidal currents represent the main mechanism of transfrontal transport; they oscillate in the direction transverse to the fronts of all the different levels.

The other type of front, the salinity front, is also repeated at different scales. One such front is located in the southern part of the Voronka, another one at the outlet from Dvina Bay. Such fronts are also found in typical estuaries (for example, in Kolvits Guba).

Another type of similarity, the dynamical one, indicates a combination of the tidal and gradient (estuarine) currents at all scales, as well a similarity between dynamic elements (vortices, counter-currents, and convergences).

The joint effect of this self-similarity scale manifests itself in the recurrence of biotopic combinations in the estuarine system of the White Sea. All the elements of this hierarchy possess both similar and specific functions.

The macro-estuary (i.e., the sea itself) provides for the formation of the background salinity field, the vertical structure of the White Sea waters, and interaction with the Barents Sea.

In the deep stratified part of the sea, the water structure is formed by processes of both a convective and advective character. Practically all the information about winter convection was obtained through two methods: calculation using the N.N. Zubov method of applying the data to autumnal stratification, or observations of its results during the spring and summer periods. In the spring, the structure consists of four layers: the slightly warmed and freshened surface layer, the cold intermediate layer (CIL), the warm intermediate layer (WIL), and the cold deep layer. The location of the CIL core corresponds approximately to the depth of the convection penetration. According to observations made in recent years, this is located in the 30–50-m interval. Judgment on the temperature and salinity of the CIL and the conjugated WIL is less definite. Seasonal and interannual transformations influence both of these layers, and systematic observations are needed to separate them. However, the following conclusions can be made on the basis of uncoordinated observations made in different seasons and years:

1. The CIL and WIL are typical peculiarities of the White Sea's hydrological structure. The sea's fundamental three-layered structure is confirmed by the fact that these layers have been regularly observed (Pantyulin 1974, 1983, 1990, 2001, 2003). In its elementary form, the three-layered structure can exist only at the end of winter – it consists of a convective layer in the upper part and an advective layer in the lower part, separated by a relatively warm intermediate layer. While the cold layers are fully determined by the winter conditions during their formation, the warm layer can still conserve "signals" from the previous warm period.
2. The transformation of the layers is determined by different processes. In the early spring, for example, the convective layer is divided into the warm and freshened surface part and the CIL, with a sharp pycnocline between them. During the summer, the pycnocline and the axis of the CIL have a downwelling tendency, while the characteristics of the intermediate layers are smoothed by mixing. Advective processes of structural transformation related to the transfrontal transport and water spreading from mixed regions to the stratified zones are very important. This occurs in the regions of fronts in the southern part of the Gorlo, around the Solovets Islands, and at the threshold intervals of estuaries in Kandalaksha Bay. The mixed waters are entrained into the stratified structure of the layer of the corresponding density and are usually found from the step-like inverse distribution of characteristics. The mechanism of "pushing" the water is generally

determined by tidal oscillations across the front; hence, the pulses have semidiurnal and half-month periods. Also, there is no doubt that wind significantly influences the water transport. The advective factor facilitates the transformation of the entire intermediate layer, but in a mosaic-like way. It can even influence the surface layer: the formation of mixed waters, whose density is close to that of the surface waters in the Basin, is possible in Onega Bay due to the riverine run-off. These waters spread over the surface and can form a patchy structure of the sea surface temperature field, which is frequently observed in satellite charts.

3. According to the available data, the temperature and salinity of the CIL and WIL are characterized by significant spatial and temporal variability. The general interval of the temperature variations in the CIL is from −1.3 to −0.2 °C, while the salinity varies from 27.0 to 28.2‰. In the WIL, these values range from −1.0 to 0.6 °C and from 27.6 to 28.8‰, respectively. A survey of 25 stations in Kandalaksha Bay, carried out at the end of May 2001, revealed an unusual state in the intermediate layers. The CIL was distinguished by its spatially uneven temperatures (generally within the limits of −0.2° to −1.0 °C), which are significantly higher than the freezing point, and its decreased salinities (from 27.0 to 27.5‰). The WIL was also warm (at 15 stations, the temperature of the core was positive, with a maximum of 0.6 °C) and less saline. The other survey, carried out at the end of June 1991, revealed a different pattern. The CIL had a characteristic temperature (from −1.1 to −1.3 °C) and salinity (from 27.8 to 28.2‰). The WIL was more uniform in terms of temperature (from −0.9 to −1.0 °C) and less uniform in terms of salinity (from 28.2 to 28.8‰). According to the available data, the duration of the intermediate layers' existence is limited to the beginning of September. At the same time, a survey carried out in the middle of June 2000 did not reveal any signs of intermediate layers, while their spatial niche was occupied by various step-like inversion structures.

The deep waters of the sea (below 150 m) are distinguished by their comparatively monotonous thermohaline structure; their renewal is definitely related to winter advection from the Gorlo. Their volume is not great (12% of the volume of the sea), but this does not imply annual replacement. In 1991, a two-layered structure with respect to oxygen was observed at several stations, with a difference of 20% in the relative concentrations. The "newest" waters did not replace the "old" ones from the bottom layer, but instead were located above them.

Thus, during its maximum development, the summer hydrological structure of the White Sea can consist of six layers.

Meso-estuaries (bays) realize two important functions: they initiate horizontal circulation and facilitate exchange between layers. This occurs fully in Dvina Bay. In the terminology of estuarine processes, this is a wide stratified estuary with a circulation of the horizontal type. The Dvina Current, the strongest and most stable current of the White Sea, flows along the northern coast. It manifests itself through many indicators (measurements, thermohaline distributions, optical properties, chemical indicators). The characteristic velocities of the current are 20–40 cm/s, its width ranges from several to 10–15 km, and in the periods of its greatest development, it can be traced up to the middle of the Gorlo.

The structure of the waters in the region of the gravity current clearly demonstrates two peculiarities: the effect of the entrainment of underlying sea waters, and the transverse inclination of the isosurfaces of its characteristics. In general, the circulation pattern in the bay is determined as follows. The compensation current is located not over the gravity current, and not next to it at the surface, but in the deeper central part of the bay under the pycnocline. It is more correct to call it water transport, since the velocities here are very small. Nevertheless, due to this motion, the waters from the intermediate layers of the Basin are driven into Dvina Bay. During their motion along the sloping bottom of the bay, they rise close to the surface, which is additionally facilitated by the dynamic rise of the isosurfaces of characteristics along the left-hand periphery of the current of the Dvina (in the classical interpretation, this is the "cold pole"). As a result, the water structure in the bay is elevated with respect to the Basin, which corresponds well to the vertical zonality in the benthos distribution. The surface layer of the bay beyond the gravity current is not distinguished for its stable dynamics. Selected data indicate the episodic appearance of a weak gravity current along the southern coast of the basin. In periods of increased riverine run-off, the plume of freshened waters covers the entire surface of the bay, and its dynamics are generally determined by irregular wind forces.

Mezen' Bay is a shallower estuary with extremely strong tidal dynamics, which excessively realize the function of water exchange between the layers by means of mixing. The character of the distribution of different waters in the absence of stratification is clearly seen in satellite charts of water temperature. As a rule, freshened and warmer waters are distributed in two tongues along the coasts of the bay, while cool and saline waters from the Voronka wedge themselves into the central depression.

Onega Bay is separated from the Basin by a buffer zone of intensive tidal mixing around the Solovets Islands; in principle, this blocks the possibility of the existence of any stable (permanent) current in the straits. The water exchange through these straits is of an oscillating character. It is determined by mixing and horizontal water transport during tidal cycles. Thus, the waters from the mixed zone are entrained into the stratified structure of the Basin and Dvina Bay. According to the available data, advection is more intense through the eastern strait. The waters from the stratified region can also enter the mixing zone and return to another layer after mixing with the local waters.

Kandalaksha Bay is an estuarine system of the second order (Fig. 8.1). Morphometrically, the bay consists of three parts. The part near the apex of the bay is a skerry reservoir with approximately 50 large and small islands. Within this reservoir, the surface salinity increases from 8 to 10‰ at the apex to 20–22‰ at the outer boundary. The stratification is moderate. Circulation in the straits between the islands is complicated. The residual currents are characterized by a three to four-layered structure. The middle part is the region of the seaward transit of the surface waters. The spreading of saline seawaters towards the apex of the bay across a number of thresholds and deeper regions occurs in two ways: with or without mixing over the thresholds. In the latter case, the deep regions are filled with waters from the levels of thresholds or with partly mixed waters.

In the outer part of the bay, the most important phenomenon is the interaction of the bay waters with numerous estuaries of smaller scales. The most thorough studies have been carried out in the Chupa estuary. They distinguished the existence of a stable three-layered estuarine circulation with a surface current flowing into the sea, a countercurrent in the 5–20-m layer, and a slow seaward motion in the lower layer. Similar exchange currents were recorded in other estuaries. Thus, a series of estuaries in Kandalaksha Bay performs water exchange between the layers from the intermediate layer into the surface layer. Surface currents from the estuaries stimulate water transport along the coast and the formation of circulation cells in the bay.

The categories of typical estuaries and micro-estuaries perform other important functions as well. They effectively serve as flow filters for the matter transported from land with the distributed run-off. The widespread asymmetry of tides in these estuaries (the tidal phase is short, and the currents are stronger than in the ebb phase) operates as a "tidal pump," pumping in suspended marine matter and turning it back to the sediments.

Concluding our discussion of the hydrological system of the White Sea, we note its most important peculiarities:

1. The interaction between the continental and oceanic waters is the main system-forming process in the White Sea. In order to comprehend the scalar variety of this interaction, we can use the conception of the sea as a hierarchic estuary system. The estuary model best corresponds to the individuality of the White Sea, and it plays the role of a universal structural element with the potential for integration and comparison.
2. The hierarchy of estuaries possesses properties of scalar similarity: geometrical, factor, structural, dynamical, and functional, which serve as a basis for applying fractal concepts. A special role belongs to the straits as a natural iteration process of fractal formation.
3. The structure of the waters in the White Sea is composed of a combination of stratified and nonstratified components, with fronts between them. Practically all the structural components are renewed annually by the mechanisms of mixing and water exchange between the layers and across the fronts.
4. Circulation in the White Sea is a cardinal combination of horizontal motions and vertical displacements of the waters between different layers. Estuarine dynamics dominate in stratified structures; at the surface, wind forces are added. Tidal forces are the main transporting factor in nonstratified structures. All these factors may interact at fronts.

8.4 The Morphology of the Coastal Zone of the White Sea

The location of the White Sea at the junction of the Baltic Shield and the Russian Platform has identified dramatic differences in the geological structure of the coasts and seafloor of its western and eastern regions.

In the western regions, in the area of predominantly glacial drift, the ancient rocks of the shield are exposed, and strong schists, granites, gneisses, and other rocks smoothed by glaciers are located close to the sea. The isostatic tectonics of the fault is expressed clearly in the coastal morphology. Fracturing characterizes the rocks. Tectonic and glacial relief dismemberment have caused a strong dissection of the coastline. Fiard and skerry types of the coast are common here; such types cannot be found anywhere else on the coast of the Russian Federation.

In the east, in the area of glacial accumulation, almost all the sea coasts are composed of friable Quaternary deposits (boulder loam, sand, clay) that lie on the Paleozoic sedimentary rocks (shales, sandstone, limestone). The coasts are lined and relatively monotonous.

Special features in the morphology and dynamics of the coastal zone and shelf are caused by strong tidal currents. Tidal currents play a major role in the distribution of suspended material and silt transfer (Vareychuk et al. 2012). This phenomenon is related to the widespread boulder, sand, and silt littorals, rocky and clay drying benches, and estuaries.

West Coast **The Pomorian**, **Karelian and Kandalaksha** are cut by numerous bays and edged (skirted) by small islands, enhancing the overall ruggedness of the coast. The islands are protrusions of the crystalline fundament and form several groups, the Kandalaksha, Kemskie, and Pomorskie skerries.

The shore on the south of Onega Bay is a swampy lowland that goes to the north into the area where the clay is drying, shielded from the surface by a thin layer of sand. Occasionally, near the coastline, which has smooth contours with open bays, there are hills formed by crystalline rocks.

Further north, near Belomorsk, the coastal area increases significantly. Crystalline hills dominate in the coastal relief. Dissection of the coastline and coastal depth increases. Some bays penetrate the land for dozens of kilometers (Chupa, Kolvica bays, or "gubies", etc.), forming a fiard type of coast, which, unlike the fjord type, occurs on the relatively low coast (Zenkovich 1938; Vareychuk et al. 2012).

The relief of the coast is determined by the nature of the surface of the crystalline fundament. In the south, it is a glacially-smoothed, gently hilly terrain of the ancient peneplen, which is greatly disrupted by the crystal faults within the Kandalaksha Bay Coasts experiencing tectonic uplift at a rate that increases from south to north (Koshechkin et al. 1975). The relative weakness of the sea waves and strength of the rocks dramatically slow down the development of coastal processes. The waves just wash away loose rock and dissect the surface of the crystalline fundament.

Terskiy Coast For the south and southeast coasts, the stairs of the Quaternary marine terraces of the late post-glacial time are typical, and can be traced almost continuously from the Turiy Peninsula to the mouth of the Ponoy River, beyond which they become intermittent until reaching Lumbovsky Bay (Lavrova I960; Koshechkin et al. 1975).

The accumulative coastal terrace with a height of 3–4 m above the high tide is particularly widespread, determining the accumulative type of most of the area's coasts. There are also areas with abrasion. Where the sedimentary basement rocks (sandstones of the Terskaya formation) are being abraded, the drying benches have been developed before the cliffs (Cape Korabl', Cape Tolstik). To the north of the Ponoy River, the coast becomes rocky. Forms of frost weathering prevail over the clear abrasion (Nevesskiy et al. 1977). The rising of the coast in the southwest of the Kola Peninsula is faster than that in the east. In general, the coast of this part of the Kola Peninsula is rectilinear and predefined by faults.

Limitskiy and Letniy Coasts These two coasts run along the edge of the Onega Peninsula. They bring bright traces of the sea processing and can be attributed to the abrasive-accumulative type.

Erosional type coastal areas are located between Cape Chesmensky and Cape Glubokiy (in Onega Bay), between the villages of Lopshengoy and Yarengoy and towards the northwest and southeast of Sozmi (Dvina Bay). Most of the accumulative sites are located at the tops of gulfs and bays (Konyukhov Bay etc.). Especially thick accumulative forms with coastal ridges are located along the side of Dvina Bay. Ancient coastal dunes are widespread along the coast.

On the Limitskiy coast, one can find the last outcrop of crystalline rocks on the surface. Here, they are immersed (to the East) in the Paleozoic sedimentary rocks that are exposed on the shore, Devonian sandstones and shales. The Paleozoic fundament is covered by soft glacial and post-glacial sediments (Vareychuk et al. 2012). At the Letniy coast, such capes as Yarengsky Horn (its western part), Krasnogorskiy Horn and Cape Sosnovyi are edged by quite extensive accumulative forms – splits with lengths up to 1.5 km along the eastern shore of the Unskaya Guba. The wide zone of shallow water can be observed near the capes. At the Cape Yarengskiy Horn, the coastal ridges can be clearly observed on the beach, the littoral and in shallow coastal waters. Their pattern is determined by the change in the waves' direction, as a result of changes in the hydrodynamic conditions. Underwater ridges have been observed along the large stretch of the Letniy shore. This form of accumulative coastal relief is well represented on the satellite image.

Cape Zayachiy on the Letniy coast, in turn, is an accumulative ledge with a low sandy modern terrace. The cape can remain relatively stable over a multi-year period. Nowadays, the coast has a condensed flooring made of sawdust, because of the sawmill that has been operating here since the earlier 1930s. At the southern tip of the Cape, there is coastal erosion, related to the fact that this section of the coast is open to sea waves of southern rhumbs (directions) and is adjacent to the channel flow of tidal waters (depth is about 20 m).

At Cape Krasnogorskiy Horn on the Letniy coast, there is a fairly wide shallow (up to 1500 m in length and 2700 m in width). On the satellite images, there are several types of shallow and the adjacent elements of the underwater slope can be well-distinguished: a shallow at depths of up to 0.5 m at the low tide, developed in the boulder loams and covered with ragged, shallow sediment (with numerous large boulders); a shallow slope at depths of up to 1 m that is overlapped by sediment cover, forming a ridge; a shallow slope at depths of 1–3 m during the low water level period with single accumulative forms. Besides these relief elements, underwater ridges oriented parallel to the coastline can be clearly distinguished; a boulder ridge, overlapped by a thin cover of sand and gravel deposits, drying during the low water period; a sandy ridge at a depth of 1–1.5 m during the low water level period, which is complicating the slope of the large underwater hollow; and a spit at depths of 0.5–1 m during the low water period, composed predominantly of sandy sediments.

In the coastal zone of the study area, the gravel and boulder spits can also be distinguished, covered with sandy material at depths of 0.5–1 m during the low water level period.

The Northern Dvina Delta is located in the area described, with a clear avandelta. The delta includes a series of wide canals divided by large islands. The delta region experiences tectonic subsidence (Koshechkin et al. 1975).

Zimniy Coast To the north and south of Cape Zimnegorsky, the bedrocks represented by the soft sand and clay strata of Quaternary and Upper Devonian rocks gradually submerge under the cover of glacial deposits (Vareychuk et al. 2012). The length of the abrasive part of the coast is roughly twice that of an accumulative one.

Accumulative areas on the coast are confined primarily to river mouths (Meghra River, Nizhnyaya River, Zolotica River, etc.), but there are also two major forms, the origin of which is associated with the longitudinal movement of sediment. These forms are an accumulative ledge of land in the vicinity of Cape Intsy and a sandy spit and Mud'yug Island in the south of Dvina Bay. The remaining sections of the coast are typically abrasive. The tectonic subsidence of the Zimniy coast is confirmed by the horizon of peat, located below sea level under a 3-m layer of silty-sandy sediments (Nevessky et al. 1977).

Konushinsky and Abramovskiy Coasts These coasts are abrasive for their entire length. The rate of abrasion is very high and reaches several meters per year. For the Konushinskiy coast, the common feature is the vast areas of silty and sandy-silty temporary drying areas – watts and lides (Vareychuk et al. 2012) – and for the Abramowski shore, the stepped benches developed in Permian sandstones and limestones.

Kaninskiy Coast This coast is a flat surface of marshy tundra with a height of 10–20 m in the south and up to 60–80 m in the north. In the middle of the coast, occupied by the river valleys of the Myasna, Thorna, Shoyna and Kia Rivers, there is an accumulative area marked by a line of dunes. The rest of the coasts are lined by abrasion. In the north, a cliff with a height of 50–70 m has developed in the Paleozoic schists, which form the basis of the Quaternary marine terraces. Southwards, the sea abrades the quaternary sediments that have a predominantly clay composition. In the region, there are intensive fault and landslide slope processes; also, thermo-abrasive processes of coastal destruction of the coast are common.

Types of Coast: The Example of the Kindo Peninsula The coastline of the White Sea in the Holocene was formed during the postglacial transgression of the World Ocean; its initial outlines were foreshadowed by the ingression of the sea (the penetration of sea water into the relief depressions in the coastal zone). These processes led to the formation of ingressive shores, amid the inherited Late Holocene relief with the predominance of the relict forms of residual exaration-tectonic gullies.

In the Kindo Peninsula, the fiard type of coast dominates, defined by the peculiarities of its territory relief: exaration basins and exaration-tectonic plow trays forming fiards appearing as a result of glacier activity and degradation over the past 18,000 years.

The coastal zone represents an area of interaction between hydrosphere, lithosphere, atmosphere and biosphere; thus, the processes taking place in the coastal zone are very diverse and dynamic, which leads to instability in its relief. The White Sea belongs to tidal seas. Tides here have a semidiurnal character: there are two high and two low tides per diem. The average tidal range is from 1.5 to 2 m, in syzygy, up to 2.5 m. The tides are accompanied by tidal currents, covering the entire water column.

Wind waves do not have a significant impact on the shape of the coastal zone. This can be explained by the following factors: (1) the sea is in a frozen state most of the year (from November to May); (2) the coastline is strongly indented, which leads to the appearance of zones of wave shadows; (3) the bedrocks are resistant to destruction because of their crystalline structure (at the abrasive coasts, there are outcrops of amphibolite gneisses with grenades, which belong to the first class of classification of rocks according to their degree of resistance to denudation). Abrasion on these shores is slow, and yet, on the coast, there are abrasion niches and ledges (clearly marked on the coast westbound of Cape Crestovyy and near Chernye Stcheli).

One of the most powerful processes affecting the coastal zone is tidal currents. These are characterized by asymmetry in speed: the speed of high tides is higher than the rate of low tides (high tides take an average 5 h ± 15 min, and low tides, 7 h ± 15 min). In relation to the hydrodynamic peculiarities of the tidal sea, a vast temporary drying area, the littoral, has been formed within the coastal zone. This is the territory that is submerged during high tide. The peculiarities of the geological structure, the morphostructural plan, the petrographic composition of the coast-forming rocks and the lithology of the soft sediments, and the history of the territory in the Quaternary period, as well as relief inheritance, altogether contributed to and determined the formation of the fiard-skerry type of coast. Exaration-tectonic remnants are widespread in the relatively low-lying plain surfaces in the form of numerous islands shaped like mutton foreheads and curly rocks with a subduted domed surface, where mainly granite-gneisses, schists and other crystalline rocks are revealed. Numerous fiards cut deep into the coast's wand in the form of narrow inlet canyon-like bays called

Fig. 8.2 Primary-tectonic type of coast in the Biofiltry Bay area

"gubies" (lips). The mouths of many rivers and streams coincide with the fiards.

Kindo Peninsula The Kindo Peninsula is lined with a variety of the main types of coasts, which are typical for the White Sea, such as primary exaration-tectonic slightly transformed and secondary: abrasion, abrasion-accumulative, accumulative, lagoons and estuarine.

The ***primary-tectonic type*** can be represented by the example of the eastern coast of Biofiltry Bay. A faulted-tectonic ledge up to 25 m in height runs underwater to a depth of 8 m (Fig. 8.2). The bay stretches in the sublatitudinal direction; its western shore is relatively flat and is represented by the Holocene terrace. The bedrock is composed of gray gneiss. This ledge is a paleo-seismic dislocation of nearly 1800–1900 years in age.

The abrasion type of coast is more typical westwards of Cape Crestovyi in the Chernye Stcheli area. The slopes are steep, with an inclination of up to 90°, sometimes clipped by the wave-cut niches (Fig. 8.3). The littoral is represented by a bench, developed from crystalline bedrocks. On the bench surface, the fragments of rocks in the form of pebbles, boulders and blocks can be seen.

The ***abrasion-accumulative type*** of coast is most common on the Kindo Peninsula, mainly from the southern slope of Mount Rugozerskaya. This type is transitional. It is characterized by the presence of a sandy-pebble beach, a clay bench and a gravel-boulder belt, which will eventually become eroded. In addition to these dynamic areas, a wave-cut niche has also been observed. The process of abrasion on such a type of coast predominates over the processes of accumulation (Fig. 8.4).

The ***accumulative type*** of coast in the Kendo Peninsula is the least common type, mainly due to the specific conditions of the coastal zone and the forces acting on it. The littoral is represented by a subhorizontal surface, composed of sand of different sizes and silt with inclusions of boulders and pebbles (Fig. 8.5).

The ***lagoon coastal type*** is confined to depressions on the surface of the littoral zone, to bays or coastal water areas, separated from the open sea by pereymas, splits or island bars. Such formations are typical for the Kindo Peninsula and nearby areas: Lake Ermolinskoe, Lake Kiso-Sladkoe, and the local "saucer" in the littoral. Such type of coasts can often be found among watts and marches – on the areas flooded with tidal waters covered by halophytic vegetation (Fig. 8.6).

The ***wadden type*** is widely represented along the tidal coasts, manifesting on the tidal shores of the White Sea as a broad intertidal littoral composed of sand and boulder deposits (Fig. 8.7).

The ***techogenic type*** is representative of the way that the coast has been transformed significantly due to anthropogenic activity. Coastal protection structures are often seen here in the form of piles of blocks. On the littoral territory west of Cape Crestovyi, there are multiple traces of large mechanisms. In several places, boulder belts have been completely disassembled and removed so that boats may be lowered into the water (Fig. 8.8).

There are several basic types of accumulation: tidal, surge-storm, ice and biogenic can all be found among littoral

Fig. 8.3 Abrasion type of coast in the “Chernye Stcheli” (“Black gaps”) area (Photo by N.N. Lugovoy)

Fig. 8.4 Abrasion-accumulative type of coast (Photo by E.I. Ignatov)

accumulations. The basic process of relief formation in the coastal zone is tidal activity. Alternating quadrature and syzygy tides, minimum and maximum tides, respectively, stipulate the need to separate the littoral into the upper littoral (flooded during syzygy tides) and the lower (flooded during quadrature tides). The maximum size of the fragments moved by tidal processes corresponds to that of a large pebble.

Fig. 8.5 Accumulative type of coast at Cape Crestovyi (Photo by N.N. Lugovoy)

Fig. 8.6 Littoral zone in Kislaya Guba (Photo by E.I. Ignatov)

Fig. 8.7 Wadden coast (Photo by N.N. Lugovoy)

Fig. 8.8 Technogenic type of beach, piles of blocks at Cape Crestovyi

The storms and surges, the activity and the repetition frequency, which is high only in those areas of the coastal zone exposed to the open waters of the White Sea, can significantly change the littoral relief, as well as moving large debris and sand, creating ripples.

Landfast ice, which contains rocky fragments of different size, can move even larger fragments. The mechanism for moving the pebbles is the constant changing of the tidal movements of the level of fast ice, so that the fragments are accumulated and new ones are captured. As a result, the fragmented rocky material and landfast ice form layers.

A biogenic littoral terrain can be divided into two types according to its relief formation, where either infauna and epifauna or subaqueous flora plays the major role. The activity of Lugworms in the intertidal pools can be attributed to the first group of processes (Fig. 8.9), while the release of fukus mats during the storms and surges can be attributed to the second (Fig. 8.10).

Fig. 8.9 Accumulative pyramids and denudation funnels of suction of the Lugworms in the intertidal zone westward of Cape Krestovyi (Photo by S.K. Yarovoy)

Fig. 8.10 The release of algal mats during the stormy movement of waves near Cape Crestovyi (Photo by N.N. Lugovoy)

8.5 The Landscape and Geomorphological Characteristics of the White Sea Coast

The southern coast of the Kolskiy peninsula is known as the Terskiy coast (Fig. 8.1). It is mostly lowland that rises up to a plateau with a height of nearly 140 m above sea level. The plateau occupies the central part of the Kolskiy Peninsula. Small mountains being located near the mouth of the Varzuga River (the Komusansky Mountains) and near the village of Sosnovka (Sokolya Mountain), the rest of the coastal terrain is either low hills or flat. Therefore, wetlands, formed here due to favorable climatic conditions, occupy large coastal areas and waterlog forests. In the east, bogs cover all lowlands, while "islands" of forest vegetation remain only on the hills and in the mountains. The forest's polar boundary passes to the east of Sosnovka village, where forests border subarctic tundra. Barren soil and harsh climate conditions limit the formation of dense forest cover. Coniferous forests are sparse and undersized. The forests of the Terskiy coast are not much different from the forests of the southern coast of the White Sea, exept for low density, undersized trees and the development of dense lichenous cover, especially of raindeer moss.

Untrodden tundra dominates to the east of Sosnovka village, where undersized birch trees and grasslands similar to those in Alpine meadows can be found in certain sites, such as the slopes of the river valleys. The coastline is smooth, because the main crystalline rock is covered with thick layers of moraine and dune formations. Single harbors can be found near the river mouths. During the lowtide, all these harbors, even those at the mouths of the Varzuga and Ponoy Rivers, get so shallow that they become unsuitable for navigation of ships of large size. Therefore, the harbors of the Terskiy coast posesses only local significance for fishing by ships of small size. To the east of Poulonga, the terrain changes significantly: elongated rocky capes, deep bays and small rocky islands appear. The Terskiy coast is rich with rivers that cut deep and narrow valleys into the crystalline bedrock and form numerous rapids and waterfalls.

The Onega Pensinsula is characterized by the rare geomorphological singularity of its landscapes. A combination of taiga, coastal and marine ecosystems untouched by human activity creates a unique ground for the establishment of a national park on the territory. Due to the isolation of the peninsula and its relatively great distance from the large industrial centers of the White Sea region, the Northern part of the Onega Peninsula possesses historic peculiarities in development and settlement patterns. The territory is located in proximity to the Solovetskiy Monastery – the oldest cultural center in the Russian North. All these facts have led to the conservation of the material and intangable cultural heritage of the Russian Pomorye on the Onega Peninsula in the most concentrated and enthusiastic way.

In the mountain systems of the southern part of the Kolskiy Peninsula (Kandalaksha region), altitudinous vegetation zones are clearly defined. The belt of birch elfin forest is characterized by a high diversity of botanical and zoological ecosystem components. A small-sized mountain massif, the Luvengskie tundras, is located in the south of the Kolskiy Peninsula, close to the northwestern coast of Kandalaksha Bay. The relief of this part of the peninsula is characterized by the dominance of denudation-tectonic and structural-denudational forms, represented by flat-top mountain massifs, hilly mountains, low ridges, plateaus, and plinth plains. The predominant soils in the territory are illuvial-humus (humus-ferrous). Mountain illuvial soils with depleted humus prevail in the mountains. From the standpoint of botanical geography, the territory belongs to the Kolsko-Pechorskaya subprovince of the Eurasian taiga region, with a predominance of northern pine shrub-sphagnum, spruce-fir and birch, and moss-lichen forests.

From the landscape standpoint, the Luvengskie tundras massif, with its three peaks (442, 604 and 652 m above sea level), belong to the fold-block and block crystalline middle and low mountains of the Baltic shield. Sloping peaks occupied by mountain-tundra communities and slopes with forest and forest-tundra communities are typical for these landscapes.

Areas of old growth spruce-fir shrub-lichen-green moss forests are located on the slopes of sopkas (low mountains), attached to Kandalaksha Bay. Due to the well-preserved natural environment, these forests serve as habitats for rare and endangered species, including those under protection (listed in the Red Data Book of the Murmansk region, 2003). For example, it features rare species of wild orchids *Cypripedium calceolus* and *Calypso bulbosa*, which are included in the Red Data Book of the Russian Federation (2001). *Pitiguicitki villosa*, a category three species in the Red Data Book of the Murmansk region, has been found at the edge of the waterstream on the level of the spruce-fir forests.

In the mountainous belts of birch elfin forest and mountainous tundra, we find such rare species as *Arnica fennoscandica*, *Cotoneaster cirmabarinus*, *Woodsia alpina*, and *Anlhyllus kuzenevae*, all of which are included in the Red Data Book of the Murmansk region. In the small mountainous lakes on the flat surfaces of the upper part of Luvengskie tundras massif, the *Jsoeies lacustris* has been found, also included in the Red Data Book of the Murmansk region. According to the Ecological Atlas of the region, the density of rare species of vascular plants is quite high: 50 and more known habitats per 100 km^2.

The Pribelomorskaya Lowland outlines the White Sea as a stripe with a width ranging from 30 to 100 km and absolute heights lower than 100 m above sea level. The terrain is represented by a slightly wavy and swampy plain, somewhat inclined towards the White Sea. Terraces and coastal ridges have been preserved in the coastal areas of the Karelian seashore. For the northern parts of the seashore, the high, steep coasts are typical. The area is composed mainly of crystalline rocks that outcrop near the White Sea coast and form a dissected relief of "curly" rocks. Fluctuations in the relative heights do not exceed 20–30 m. Marshes and swamps occupy up to 80 % of the Pribelomorskaya Lowland.

The Pomorskiy coast in the south of Onega Bay is represented by vast swampy lowland, gradually rising towards the mainland. The relief's monotony is interrupted only near the shoreline by sparsely located hills (called "varaks"), formed by crystalline rocks that resemble the Onega Bay islands in shape and structure. The relative height of the hills is no more than 10–12 m. The Lowland of the Pomorian coast 5–10 km to the south of the sea leads to the strip of the gently hilly relief of the Onega moraine ridge. Seaward, the coastal lowland transitions into a wide (up to 1.5 km) littoral, and beyond that, into an underwater slope. The coastal line here has smooth contours with open bays.

The vegetation of the Solovetsky archipelago is represented by forests, wetlands, meadows, forest-tundras and tundras. Tundra-type plant communities are formed primarily on small islands (such as Bol'shoy, Malaya Muksalma, and Zayatskie), and on the elongated narrow capes in the north and northwest direction (Cape Kolguev on Anzere), as well as along the coast of Bolshoy Solovetsky Island. These plant communities cover nearly 4.5 % of the archipelago. Soil cover is poorly developed, with a thin layer of peat-humus, low mineral element content, and relatively high acidity (pH 3.5–3.9), all of which cause its rapid destruction under natural and anthropogenic impacts. Plants are usually undersized and have depressed life forms. The tundra plant communities were formed as the result of exposure to the cold northeast winds and the cooling effect of the sea. The tundra is characterized by a low resistance to trampling. In some places, spots of bare land and the development of erosion processes have appeared.

Forests cover about 44.5 % (182.2 km^2) of the archipelago area. Of these, 47.9 % are spruce communities and 29.3 % are pine forests. Around 19.9 % are birch and aspen forests, which represent the secondary stage of the recovering or pyrogenic successions. Other species count for 3.5 %. The tree stand in the woods, located near the seaside, bears signs of depression. During cyclone activity, windfalls occur frequently. This phenomenon is related to the fact that a significant portion of the archipelago is covered with a thick layer of Quaternary moraine sediments. Therefore, penetration of roots under the thin soil layer is rather difficult. Some areas of coniferous forest, located in the terrain depressions, are subject to gradual waterlogging, resulting in the degradation of the tree stand. Bogs and swamps occupy about 15 % of the total area of the archipelago, with a domination of swamps and transition wetlands. Meadows occupy about 0.1–0.2 % of the archipelago and are located in its central part. Coastal meadows in the form of a narrow discontinuous strip are located along the coast of the larger islands. The meadows have both natural and anthropogenic origin (e.g., in places of tree-cuttings and in slash areas of coastal forests and shrubs). Meadows in the central part of the islands have an anthropogenic origin and were formed as a result of the draining and deforestation of wetlands. Currently, the dryland grass and motley grass meadows with a mesophilic character of moisturizing dominate in the archipelago.

In the northern part of Onega Bay, the crystalline hills and highlands outcrop in the coastal relief where they can reach a height of 100 m and more in some places. To the south of Sumskiy Posad, the second moraine ridge is located, similar in its relief to the Onega moraine. To the north of Byelomorsk, the coastal lowland disappears, occurring only in small areas in the river valleys and mouths, as well as in places of former lakes and wetlands. Here, the strip of coast a few kilometers wide is almost completely rocky and marshy. The inner coastal areas have well-developed sand and other soft formations that are covered by taiga and swamps.

Wetland landscapes with glacial and marine sediments are represented from the north of the lower flow of the Vashka River (left tributary of the Mezen River) to Cape Kanin Nos. Among them are glacial-accumulative, glacial-lake, and plain landscapes, as well as mountain landscapes on the plateau-like terrain of the Kanin Kamen' highland, with a maximum height of 242 m above sea level, landscapes of the glacial coastal plain with groups of moraine hills (e.g., the Shomohovskie sopki) and landscapes of the erosion-accumulative valleys of the rivers that belong to the northern part of the Russian Plain.

From Cape Konushin to Cape Kanin Nos, the coastal land is a flat surface of swampy tundra, slightly rising to the north. In the south, its elevation marks do not exceed 10–20 m, while in the north, they reach 60–80 m.

8.6 Biological Characteristics of the White Sea Coast

The White Sea benthic fauna is rich, diverse and plentiful. In some areas, the mass of mussels (*Mytilus edulis*) reaches 50 kg per sq meter, close to the maximum value for mussel banks globally. By 1960, 56 fish and fish-like species had been found, excluding freshwater species, which are found in strongly desalinated areas of the coastal waters. In addition, in October-November 1964, young giant sharks (*Cetorhinus maximiis*) were caught in Kandalaksha Bay, a species previously not found here. So, 57 species are now known in the White Sea. Out of these, 42 species are permanent inhabitants, and the rest come here from the Barents Sea to spawn or fatten. Five species out of the permanent inhabitants are endemic: White Sea herring (*Clupea harengus pallasi natio maris-aibi*), White Sea cod (*Gadus morhua maris-aibi*), White Sea smelt (*Osmerus eperlanus dentex iiatio dvinensis*), White Sea Licodia (*Lycocles pallidus maris-aibi*), and White Sea river flounder (*Pleuronectes flesus bogdauovi*). The highest diversity of species of fish can be observed in the Voronka (Funnel) of the White Sea, in Kandalaksha Bay, and near the Terskiy and Karelian coasts, where the water salinity is higher. The Mezen, Onega and Dvina Bays possess lower species diversity, but the stocks of some of those that are there are quite significant, such as herring (*Clupea sp*.), saffron cod (*Eleginuis navaga*), and smelt (*Osmerus eperlanus*).

In numerous seabird colonies, nearly 40,000 pairs breed. The bay territory is inhabited by a significant portion of the Russian population of razorbills (3000 pairs), and the only nesting area of broody (*Larus fuscus*) (1850 pairs) in the subregion is there. The most abundant species is the Arctic tern (*Sterna paradisaea*), sometimes reaching 18,000 pairs.

Onega Bay of the White Sea is the most important site for migratory and wintering birds. In several permanent polynyas (areas of open seawater space among ice cover), the majority of the White Sea population of common eiders (30–40,000 individuals) and guillemots (*Cepphus grylle*) (about 10,000 individuals) come for the winter. The width of the intertidal zone here reaches a few kilometers. Coastal meadows, intertidal zones and shallow waters in the open sea are important resting areas for migratory birds along the White Sea-Baltic part of the Eastern Atlantic migratory route. A total of up to 150 species of birds can be observed in the White Sea throughout the year.

The waters surrounding the Solovetsky archipelago and two sites in Dvina Bay represent one of the most important breeding areas for the local group of White whales, including at least eight subgroups totaling 1000–1200 animals. During the summer, due to migrants from the Barents Sea, the number of White whales reaches 2500–3500 individuals.

Near the Solovetskiy archipelago and in the inner part of the bay, a large number of ringed seals live and breed. The presence of the frontal zone in the waters adjacent to the Solovetsky Islands determines the high productivity of phyto- and zooplankton. The benthic communities of Kandalaksha Bay are characterized by significant variety and a high level of productivity. The system of tidal currents in Kandalaksha Bay, which provides intensive growth of plankton, makes the region one of the major spawning areas for the White Sea herring (*Clupea pallasi maris-albi*) (a subspecies of the Pacific Ocean origin), and the bay's waters a valuable forage area for the herring fry. The bay has high value as a spawning site for Atlantic salmon: from Umba in the north to Keret in the south.

The Kandalaksha Bay water area is indented by skerries with many islands, inhabited by numerous colonies of sea birds. Although most of the colonies are small in size, the total number of breeding birds there is estimated at 15,000–20,000 pairs. Species diversity is high, but the most typical species is eider, whose numbers have reached 5500–6000 pairs in certain periods. They are followed by the silver and blue-gray gulls (*Larus canus*). Permanent polynyas around the large islands in the southeastern and upper parts of the bay become wintering sites for hundreds of sea ducks and other birds. White whales are the most typical cetacean here; in the summer period, they can often be found outside of the bay, near the Umba River.

A high level of species diversity is typical for small mammals in the region, adjacent to Kandalaksha Bay. Research conducted over the last decade up to July 2011 through the trap-line method allowed for the discovery of the species composition of the small mammals inhabiting pre-tundra birch forests. The dominant species appeared to be the shrew (*Sorex araneus*), with 11 individuals per 100 trap-nights. The number of the other species did not exceed 2 individuals per 100 trap-nights: the dark vole (*Microtus agrestis*), the tundra vole (*M. oeconomus*), the bank vole (*Clelhrionomys glareous*), and the Norway lemming (*Lemmus lemmnus*). In 2011, the peak of the Norwegian lemming population was marked in the Luvengskaya tundra.

Fauna inhabiting the Mezensky Bay region is not uniform: in one place, it is of the saline estuary type, in the other, the marine type. Seagrass beds and eelgrass fields (*Zostera sp*.) in Mezen Bay are absent and plankton has been depleted. Its composition accounts for only 29 species, with a biomass not exceeding 40.4 mg/m^3. The benthos is also negligible; it is represented by 165 species, mostly invertebrate filtering organisms (*Modiolus*, *Tridonta*, *Mytilus*) and detritus-collecting consumers (*Macoma*). Most of Mezenskiy Bay is occupied by sedentary filtering communities, in particular by biocoenosis of *Modiolus modiolus* + *Balanus crenatus* with a total biomass of 363.2 ± 183.7 g/m^2 (*M. modiolus* – 180.7 ± 155.2 g/m^2 and *B. crenatus* – 105.0 ± 88.9 g/m^2). Near the Mezen and Couloy River mouths in the sublittoral, the biocoenosis of *Tridonta borealis* with a total biomass of 35 g/m^2 and *Macoma balthica* with 182.0 g/m^2, where the dominant species biomass is 149.0 g/m^2, are located. At the lower littoral belt, the spots of A*renicola manna* are scattered, and below them, vast colonies of *Macoma balthica*. The densest populations of *Makoma* are found near Cape Strelnichnyy on the Abramowski coast, where clams reach a very large size. At the mouth of the Mezen River, the littoral zone is covered with a thick layer of lifeless clay (nyasha). During high tide, crabs (*Hyas araneus*) and shrimps (*Crangon crangon*) migrate to this zone, together with a rising water level. In general, the total biomass of Mezensky Bay's benthic organisms averages nearly 300 g/m^2, which is almost twice as much as the biomass in the Gorlo (Throat) of the White Sea.

8.7 Lagoons of the White Sea

Lagoons are marine coastal areas separated from the open sea by bars, splits and shoals and connected to the sea via straits, channels and tidal flows; sometimes, the areas are completely enclosed from the sea and function as coastal lakes.

The lagoon shores of the White Sea are located along the sea perimeter in the areas where accumulative relief forms prevail. Lagoon formation is associated mainly with the appearance of free forms of accumulative relief: spits, estuarine bars at the mouths of rivers, and island ridges and shoals between them. For the most part, lagoons can be found on the low shores of the east coast of the White Sea on the Zimniy, Abramovsky and Kanin shores. Less often, lagoons can be seen on the west coast: on the Terskiy and Karelian shores of Kandalaksha Bay and in the Gorlo (Throat) of the White Sea. Most typically, lagoons are represented in the spatially limited locations. For example, on the Terskiy shore, lagoons are typical for the Strelna, Chavan, and Varzuga Pyalitsa regions; on the Kandalaksha shore, in the Salnitsa and Turiy Peninsula regions; on the Karelian shore, most clearly near the Kindo Peninsula; on the Onega shore, near Letnyaya Zolotitsa; on the Zimniy shore, in the Nizhnyaa Zolotitsa, Antsy, Rouch'i, and Meghra; on the Abramovskiy shore, near Hailya; on the Konushinskiy shore, near Nizhnyaya Mgla and Konushinskie Corgi; and on the northernmost Kaninsky shore, in the area of the Lesna and Thorna.

The structural peculiarities of lagoons and the specifics of their hydro-biological evolution are best described by the example of newly-formed coastal lakes – the lagoons that surround the Kindo Peninsula.

8.7.1 Lake Kislo-Sladkoe (Sweet and Sour Lake)

Lake Kislo-Sladkoe (Sweet and Sour Lake) is one of the most amazing bodies of water not only in the vicinity of the local biological station, but in the whole world (Krasnova 1997; Beck et al. 2001). It is located on the Kindo Peninsula, 2 km from the White Sea Bio-station. The lake is small: 100 m in length, 60 m in width, with an average depth of only 1–1.5 m and a maximum depth of 4.5 m. The lake serves as an examplarery watershed that recently lost its connection to the sea.

The connecting channel that used to serve as the route for the flow of salty marine water into the lake during high tide dried up. The second connecting channel has also been closed, and the bottom boulders are covered by forming soil with corresponding vegetation. The uplift of the Karelian coast, with an average rate of 4 mm per year, contributes to the process of the channels drying.

Less than half a century ago, the lake used to be a bay, or rather, a narrow strait between the mainland and a small island with underwater output rapids. Uplifting together with the shore, these rapids have become an obstacle to water exchange between the sea and the strait. This is most interesting for science, representing a further scenario of change that will inevitably occur in the hydrological regime of the new lake and in its ecosystems. One manifestation of the change is the gradual transformation of the lake into a fresh watershed, with the replacement of marine communities by freshwater ones. A similar process has occured, for example, in Large Ershovsky and the Small Ershovsky lakes. In the past, these lakes used to be sea bays, and even earlier (about 700 years ago), represented one strait that separated "Kindo Island" from the mainland. Conversion into a freshwater lake is only possible if there is a source of fresh water. This is not the case with Lake Kislo-Sladkoe. While there is a swamp near the lake on the mainland, the outflow from this swamp is very small: in summer, it is just 0.01 l per second. Refilling of the lake with fresh water occurs mainly during periods of snow melt and rain offs, when the rocky bed of the rapid is filled with fresh water which flows in only one direction – towards the sea.

Currently, the balance of the inflow of fresh swamp water and salty water that leaks under the rapid's stones favors the salty water, which is supplied in amounts ten times greater than the fresh (1–1.5 l/s). Desalinated water, with a salinity of 10–20 ppm in summer, can only be found at the surface at a depth of 1 m, while below 1.5 m, the water is not simply sea water but, in fact, has a salt concentration higher than the sea. Scientists believe that the source of the additional salt is at the bottom of the lake, namely groundwater brines, which are formed in the winter. When freezing, the sea water becomes stratified. Ice absorbs the fresh water, while the concentrated bottom brine provides excess salt for the water.

In the lake, there are bordering layers with different gas content. One layer is over-saturated with extreme concentrations of oxygen up to 25–30 mg per liter, which is 300 % saturation, and the other layer, just below, is over-saturated with hydrogen sulfide, with a concentration even higher than that in the dead zones of the Black Sea.

All these phenomena happen at a maximum lake depth of only 4.5 m.

The lake waters having stratified, several layers have formed. The top layer, corresponding to the epilimnion, is a freshened, 1-m surface layer. Below it is a thin (only 50 cm) transitional layer, with sharp vertical gradients of hydrological and hydro-chemical indicators. The highest found here is a gradient of oxygen-content of 30 mg per liter per meter, extremely rare for natural watersheds. Lower is the hypolimnion, the warmest layer over-saturated with oxygen, and much saltier than sea water. And at the bottom, there is a layer of cold water saturated with hydrogen sulfide in a single funnel-shaped depression, where the depth is difficult to define because of the lack of boundaries between the clay slurry and the bottom mud. The temperature of the bottom layer does not exceed +9 °C, even in summer. The presence of a hydrogen sulfide depression makes Lake Kislo-Sladkoe similar to some of the Novaya Zemlya lakes.

In the summer, the surface of the lagoon is covered with a yellow-green film of filamentous algae. The algae are considered to be the cause of the hydro-chemical uniqeness of the lake. The algae grow not only on the lake surface, but also on its bottom: living algae occupy shallows, while the rotting dead algae accumulate in the depression. The depth at which the living algae mats grow matches the hypolimnion; namely, the algae produce this oxygen-enriched layer. The overlying transition layer prevents it from mixing with the surface layer, so all of the oxygen is in a kind of hydrological trap. While dying, the algae accumulate in the bottom depression and decompose. The vertical stratification is preserved under any wind conditions in any season of the year. The differences in the density of these main layers of water are so significant that the whole system is very stable and resistant to external perturbations. The surface layer is substantially desalinating: its salinity is 5–10 ppm lower than that in the hypolimnion, causing the low density of the upper layer. The next layer, the hypolimnion, is warmer but saltier. Warming occurs mainly due to the absorption of sunlight by the dark bottom surface. The prevailing depth underlies the hypolimnion, causing its warming, and making Lake Kislo-Sladkoe similar to Lake Mogilny and the American Oyster Lake. The intermediate layer, or pycnocline, prevents the transfer of the heat accumulated by the hypolimnon, as well as the oxygen from flowing upward. In the depression, the bottom water layer is denser due to its low temperature, so it does not mix with the hypolimnion either.

8.7.2 Ermolinskaya Guba (Inlet Bay)

Ermolinskaya Guba (Inlet Bay) has been studied in detail. The water dynamics in Ermolinskaya Guba are mainly defined by the tides and stands out owing to its current's asymmetry. The quick high tide, when the rate of flow above the rapid can be up to 60 cm/s, and the extended and slow low tide, at a rate of several times smaller, together create an "estuarine pump". The "pump" regularly pumps marine slurry and dissolved organic matter into the bay, along with particles of such size that the current can drag them over the bottom. The summer freshwater run-off to the bay is small, and does not affect the structure of the water or the salinity; the freshwater flow towards the sea appears only in spring. But the flow brings a surprisingly small amount of slurry. Contrary to the standard estimation, which assumes that a vigorous spring flood has to wash out a rather large amount (within a few dozen tons) of organic-mineral compounds of terrigenous origin from the shore, soil analysis indicate that traces of terrigenous organic compounds in the bay have momentarily disappeared.

Specifics of the hydrological regime lead to the conclusion that Ermolinskaya Guba is not smoothly transforming into a new state, as is typical for most of the coastal boundary waters that either become a lake or dry out. Rather, the bay is experiencing processes of degeneration. Typical marine macrofauna can still be traced here, but at limited spots, and the rest of the bay space is occupied by only a few species, those that can tolerate the current state of the bay. Areas typically occupied by sandy seashells *Mya arenaria* are decreasing in size, as well as those of the sea lugworm (*Arenicola marina*), which is being replaced by salicornia. Their populations are already incapable of reproducing themselves and are completely dependent on external larvae income. Littoral snails *Littorina litorea* and *L. andsaxatilis* are in favourable conditions. The first is plentiful in the silt, and can withstand its weight, and the second flourish on the rocky surfaces.

Ermolinskaya Guba is shallow and gets warm in summer; the bottom slit is being drained and does not create dead zones. Between the rocky upper littoral and the gelatinous shaky sublittoral, there is nyasha – a liquid sludge, layered with plant fragments. Its brown surface layer is oxidized and thus inhabitable. In addition to the lobworm *L. littorea*, anohipodes-pontoporeys can be observed there, as well as oligochaete in pits with coarser detritus. There is a kingdom of microorganisms. In lower layers, the only bacteria that reduce sulfates predominate in a restored black layer. All of this attracts birds and fish. During low tide, flocks of shorebirds can be encountered in Ermolinskaya Guba: sandpipers, cranes, and flocks of ducks and geese stop here to rest and spawn. During high tide, fish rush into the muddy littoral in search of food; this fact is well known to ichthyologists, who study the nutrition of stickleback and flounder, as well as to employees of the biological station, eager to ice fish for saffron cod.

Eelgrass (*Zostera marina*) flourished in the bay a few decades ago. Eelgrass is one of the few species of higher plants, known as hydrophytes (plants that are completely immersed in the water), that are adapted to life in salt water. All stages of the eelgrass's life cycle, including flowering, pollination and seed germination, take place in a marine environment. Only the fruits of this plant briefly float to the surface of the water, which contributes to their spread by winds and currents, but they soon open and their seeds fall out and grow up on the bottom. This plant plays a very important role in the White Sea ecosystem. In the first half of the twentieth century, in the western part of the sea, where 97 % of the White Sea eelgrass stock was concentrated, its total wet weight reached about half a million tons, which exceeds the stock of all other benthos plants combined. Sea grass beds provide food and serve as a biotope for a variety of marine animals by attracting spawning fish: many species spawn in its thickets, including herring, the staple food for Pomors (Russian sub-ethnos, settled on the White Sea coast). Eelgrass have very thin and delicate root fibrils, which can be protected from damage only in the bottom silt, so Ermolinskaya Guba is particularly comfortable for the plant. In the early 1960s, eelgrass began inexplicably to disappear in the White Sea shallows, and its mass collapse led to an environmental disaster. In the 1930s, that same issue had taken place in the seas of the Atlantic Ocean, where myxomicetis *Labyrinthula macrocystis* was recognized as being responsible for the eelgrass collapse. Near the White Sea Biological Station of Lomonosov Moscow State University, the first dead plants were only found in 1975; here, the eelgrass damage was caused by *Labyrinthula*. The lower part of the zone of eelgrass thickets at a depth of 1–2 m was severely affected, where in previous times, a 1.5 m high eelgrass carpet had flourished. After this disaster, the boundaries of the eelgrass habitat zone shrunk and its rare and short stems survived only at the lower edge of the littoral. In many places, eelgrass disappeared completely.

Eelgrass is a rhizome plant, but the rhizome is short-lived, because, due to its fragmentation, the individual stems become isolated. It provides only for the growth of existing thickets, but not their spread: if the stem is off the ground, it will not be able to take root again. There is another method of reproduction through fragments of rhizomes; they do often float on the water surface and can be carried out by currents. Slowly, sea grass beds started to recover, however, at the end of the twentieth century, three more crises happened for the eelgrass.

According to one version, reduction of freshwater run-off in the rivers after the construction of water reservoirs and an increase in the salinity of coastal waters should have, first of all, affected the coastal shallow waters where eelgrass stocks are concentrated. At this time, the fungus *Labyrinthula* actively multiplied and spread with the increase in water salinity. *Labyrinthula* does not resist desalination, so spring floods had saved the eelgrass earlier. After filling the reservoirs with water, the restored run-off could have led to elimination of the *Labyrinthula*, but this did not happen. For some time, the relationship between the sea grass and its parasite could be built on the well-known principle of "predator-prey": where the number of one depends on the abundance of the other, and fluctuations occur in the number and abundance of both species, shifted in time, these fluctuations can occur repeatedly.

There are other versions explaining what happened to the eelgrass. The collapse of sea grass beds can be a natural process that occurs regularly. The eelgrass's weakness is that it can grow only in clay substrate. At some point, under wave influence, the bottom becomes eroded and water washes the turbid clay out of the shore, and then sends replacement clay there. It is possible that the eelgrass beds were destroyed as a result of one of these cycles. The clay accumulation and its subsequent removal and replacement with sandy deposits do not occur simultaneously in different parts of the White Sea, which explains some discord in the dating of the eelgrass collapse. Precipitation dynamics, in turn, are created by larger cyclical processes, covering the entire region, in a particular climatic, which affect the amount of the annual surface run-off, the weathering rate, and the activity of the sea.

At the beginning of the twenty-first century, eelgrass communities confidently started to expand, and can now be found beyond Ermolinskaya Guba. Restoration of eelgrass led to an increase in the number of three-spined stickleback, whose life is dependent on the well-being of the plant.

8.7.3 Kislaya Guba (Sour Inlet Bay)

Kislaya Guba (Sour Inlet Bay) has always attracted researchers (Krasnova 1997; Beck et al. 2001). On three sides, Kislaya Guba is surrounded by wooded coast, sheltering the bay from the wind. On the fourth side, it faces the sea, with a corga (an accumulation of stones on the slopes that penetrate into the water) protecting the coast from large waves. There is neither strong surf, nor turbulent currents. Even the ice shield that covers Kislaya Guba in winter does not separate and float away in spring, as it does in other places, but rather melts in place. Therefore, water organisms live here under less disturbed conditions, for example, annelids, a.k.a. Lugworms (*Arenicola marina*), that have formed an independent population in Kislaya Guba.

Lugworms are observable inhabitants of the littoral. They do not inhabit the entire littoral area, but only those parts which are submerged by sea water for at least 18 h a day, and the subtidal zone to a depth of 5–6 m. They only settle where the thickness of the sand layer reaches 15 cm or more. On the wide beaches, composed of the fine-grained sands and silts that are the most suitable soil combinations for Lugworms, these organisms create continuous colonies, thickly covered with bunches of their ejections. The ribbon-shaped colonies are located in the narrow strip of fine sand that stretches above the waistband of the boulders. Sporadic colonies are located inside the small spots of suitable soil among the stones, alluvial sludge or rocky outcrops. Sustainable Lugworm reproduction occurs only in continuous colonies covering a sufficient area (100 m^2) and in a sufficient density of colony (at least five individuals per sq. m). Kislaya Guba is such a place. In the peak, which comes after the settling of the juveniles, the Lugworm population in the Kislaya Guba sands can reach nearly a million.

Lugworms feed by passing the detritus through their gut, absorbing the necessary nutrients. Comparison of the distribution of Lugworms with data on the content of organic substance in the substrate has demonstrated that worms in the littoral depend on the quantities of organic substance. The correlation appears to be most clear with humic acids, which come to the littoral zone from the soil on the land. Contrastingly, in the sublittoral, Lugworms do not depend on the distribution of organic substances; evidently, other factors prevail here. Although seemingly sedentary, Lugworms do not, in fact, stay in one place. They are constantly moving. The most mobile are those Lugworms that are less than 1 year old; their burrows are small, only 2–5 cm deep, and fragile. Even a weak surf wave can wash away the burrows or cover them with sand, and they rarely stay in one place for more than 3 days. For Lugworms of age around 1 year, the hole is longer – up to 12 cm deep, and they use it for a period of half of a month. During such a long period, the walls of the hole become well-soaked with the mucus from the worms' skin glands, which becomes a substrate for growing diatoms. For the construction of a new burrow, Lugworms crawl from one place to another inside the thickness, although they can occasionally swim. "Movement" of Lugworms in nature (like the "movement" of Nereis) is rare, and few have a chance to observe it, except the gulls, whose stomachs sometimes contain many Lugworm remains.

In the White Sea, Lugworms can live up to 5 years. During the first year of life, they gain about 1.5–2 g in weight, in the second year, 3–4 g, and in the third, 5–6 g. At the age of 2 years, the worms begin to breed, and then some die, but not all of them. Many of them live up to 3–4 years (and, rarely, to 5). Throughout their lives, Lugworms continue to grow, and by their fourth year, can gain more than 9 g, with the largest worms gaining in excess of 50 g.

Researchers of meyobenthos (benthic animals with a size of 0.1–1 mm) especially value Kislaya Guba. Such marine animals as round worms, harpacticidae crustaceans, ostracods, flatworms, and sea-mites escaped the attention of zoologists for many years because of their small size. The small-size viviparous hromadoropsis nematode (*Metachromadora* (*Chromadoropsis*) *vivipara*) was the first species of the White Sea meiobenthos to be studied in detail. These worms of reddish, with a length of just over 1 mm, inhabit fine sands, more than a hundred individuals per square centimeter.

In summer, these worms are concentrated near the soil surface, in the millimeter-thin layer of substrate. But in winter, they burrow to a depth of 2–3 cm. This is the place where development of a winter generation of nematodes occurs. Not only are the meyobenthos in Kislaya Guba special, but so are common mussel (*Mytilus edulis*).

8.8 Estuaries of the White Sea

Typical estuaries are common for low accumulative shores and the mouths of rivers with a small draw run-off. Estuaries occupy areas of funnel-shaped openings of the river mouth branches where tidal flows penetrate. The White Sea inlet bays called "*guba*" – narrow semi-closed areas of small rivers coinciding with fiards – can be attributed to a category of micro-estuaries. Estuaries have their own two-layer stratified waters. The upper freshwater layer flows toward the sea while the salty water masses in the near bottom layer penetrate into the river. The water exchange process depends on the power of the tidal processes and the river flow forming the estuarine system. Within the system boundaries, the salinity of the waters of the mixture zone varies significantly, creating conditions for the formation of estuarine communities. Each community is characterized by its level and type of organization. Different species of living organism in the community react differently to changes in the salt content in the mixing zone.

Two hierarchic levels, the typical estuaries (1–35 km) and the micro-estuaries (0.01–0.5 km), provide for representative coastal research of macrobenthos within the estuarine model. On the Karelian coast, these researches are usually integrated into a more or less complex estuarine system – gubas (inlet bays). The first level is typical for relatively large gubas or their upper parts, the second level for the shores of large gubas and the upper parts of small inlets. Both typical estuaries and microestuaries effectively act as filters for flows of substances coming from the land (Pantyulin 2001) and this exact function organizes the communities of organisms that inhabit them: "… zoobenthos reflects modern sedimentogenesis …" (Sadikov 2001, p. 59). In such areas as littorals and shallows, the water filtration functions, and its peculiarities, related to the size of the estuaries, can be visually monitored.

In Karelia, 18 small rivers, with typical estuaries, carry (with consideration for ionic and organic run-offs) an average of 860 thousand tons of solutes per year into the sea. This corresponds to 12.8 tons of substance per sq. km of drainage area in accordance with M.P. Maksimova's estimations (1967). Evaluation of the catchment area of 4 rivers involved in the formation of higher rank estuarine systems, the mezo-estuaries of the Niva, Onega, Severnaya Dvina and Mezen Rivers, gives an approximate area of 504.73 thousand sq. km (with an area of sea surface of about 90,000 km^2). The estimations do not cover all the diversity of the catchment area (e.g., data on scattered run-off are fragmentary), but provide a general picture of one of the two main mass fluxes – the terrigenous (freshwater) flux that supports the sea ecosystem.

The relationship between the content of organic substance and the run-off is reflected by the fact that the amount of substance in the White Sea waters clearly correlates with salinity. In turn, salinity is represented by the desalination index in areas of influence of continental run-off water. The content of organic substance is represented by solid particles, most of which are small-sized: silty and pelitic fractions, colloids and solutions. Flocculation, coagulation, absorption and desorption in the mixing zones and in other border areas are processes that are still insufficiently studied in the laboratory while they acquire considerable scope in the field. For example, Varychuk et al. (2012), through these processes, have explained a significant increase in the concentration of organic substance (in the range of 2–10‰) in the areas where Karelian small river waters mix with seawater.

Khaylov and colleagues (1992) demonstrated that peculiarities of *the nearest functional space* (*NFS*) are important for different life forms, or – in modern language – for different life scenarios. For the majority of macrobenthic organisms and, especially, for meiobenthos and microbenthos, *NFS* are small amounts of sludge and slurry at the boundary of environs where the small-sized fractions play a significant role, and the colloidal component is mostly expressed. However, the role of electrostatic processes is crucial, for example, in the process of the consolidation of clay. The combination of factors is crucial here, and is particularly significant for estuarine areas. During the deposition of fine particles of clay minerals in sea water with alkaline reaction, very soft sediment is being formed with a total porosity of up to 90 %. Desalination promotes the formation of dense coagulation structures: under neutral and acidic conditions, they are cellular, with a porosity of up to 65 %.

The presence of colloids (“jelly”) is a common feature for relatively quiet littorals (intertidal zones) and shallows. Zavarzin (2004) describes the organic jelly that includes living organisms of corresponding size (microorganisms) as a colloid system ordered by important electro-static laws. With an increase in the amount of colloid particles, the inner frame is being formed that stabilizes the colloid system and consists of microorganisms together with particles equal in size, dispersing the substance that fills the space between the frame elements.

Therefore, there are conditions in the White Sea littorals and shallows for creation of the above-described colloid systems covering the sea floor (near bottom fine dispersive films), which are inhabited by life forms larger than microorganisms. The initial natural heterogeneity is influenced by processes such as landscape formation, sedimentary cover (particularly soils), and peculiarities of bio-accumulation of elements in forests, lakes and wetlands, along with specifics of atmospheric precipitation and anthropogenic disturbance.

The above-described processes can be tracked in the run-off of the White Sea water catchment basin rivers. Extreme heterogeneity of chemical composition, qualitative differences in the organic and mineral content of the run-off, and differences in the intra- and inter-annual rhythm of the run-off were indicated for the Niva, Kem, Severnaya Dvina, and Mezen rivers (Leonov and Chicherina 2004).

Kravtsova and Mit’kinyh (2013) conducted satellite image interpretation and described the morphology and the state of infrastructure development in the mouths of the large rivers of the White Sea.

8.8.1 Severnaya Dvina

The Severnaya Dvina is one of the large rivers of the northern European part of Russia. It was created by a merging of the Suhona and Yug Rivers and flows into Dvinskaya Guba of the White Sea. The river’s length is 722 km., the volume of its discharge is 103 km^3/year, and the run-off of suspended sediments is 4.5 million tons per year. The southeastern narrow part of Dvinskaya Guba, where river freshwater mixes with saline marine waters, can be considered tp be an estuary of marine type. The multi-branched tidal delta of the Severnaya Dvina, with an area of 893 km^2, is located in the upper part of the estuary. The whole mouth area is of the delta-estuarine type. The delta was formed as a result of the estuary (existing from boreal time – early Holocene) being filled with sand sediments, the delta taking its current shape where the White Sea level had been stabilized. The upper part of the delta is located near Archangel’sk, where fan-shaped branches diverge, the main branches being (from left to right) Nikol’skiy, Murmanskiy, Korabel’nyy, Maymaksa, and Kuznetchiha. They can all be clearly seen in blue on the Landsat image. There are a lot of secondary branches and channels; while they connect before joining Severodvinskaya Guba, the branches create three wide mouths: Pudozhemskoe, Murmanskoe, and Korabel’noe.

The Severnaya Dvina belongs to rivers with a spring flood and a prevailing source of water from snow. In the spring flood period (May–June), flood waters accounted for 52.5 % of the annual run-off. Severe ice conditions and long periods of ice are typical for the mouth of the Severnaya Dvina, averaging 191 days. The average date of freeze-up is November 11, the cleansing of the ice, May 7. Ice breaking coincides with a sharp rise in the spring flood; ice congestions are created during this time. In the river’s shipping arms of Maimaksa and Murmansk, ice is artificially cracked by icebreakers in a practice that has taken place since 1915. Opening of the Nikolsky and Korabel’nyy River branches still happens naturally. A characteristic feature of the regime of water levels in the estuary are the semi-diurnal tides, the average value of which is about 1 m at the lower edge of the delta. During the tidal phase, the river flow can be reversed. With surges and tides, salty water penetrates into the delta arms, posing a threat to the normal water supply. In recent decades, the water quality in the delta has worsened in connection with an influx of industrial waste water, as well as petroleum products discharged into the river.

The Landsat image (Fig. 8.11) shows the delta during a final stage of flood, under high tide conditions, when the mouths' branch extensions are filled with water, through which the system of riverbeds is easily visible. The glacial moraine plains that surround the delta with numerous lakes are covered with forests – spruce and pine (brown on the image), aspen (red), and bogs (light gray and bluish tone). The light contours of Arkhangelsk are visible at the top of the delta and Severodvinsk is correspondingly on the southern shore of Dvinskaya Guba. These are the most important centers of the wood processing industry, the chemical industry, and shipbuilding. Arkhangelsk is one of the largest ports in Europe. Severnaya Dvina is connected through the Sukhona – Lake Kubenskoye – Sheksna system to the Volga River.

A fragment of the Landsat image (Fig. 8.12) shows the southern part of Dvinskaya Guba and the widest Nichol'skiy arm, which, at the entrance to the inlet bay, forms the main mouth of the Pudozhemskoe and also the small, westernmost Nikol'skoye mouth, where the town of Severodvinsk, a major shipbuilding center, is located nearby. The Nichol'skiy arm is used for river navigation between Arkhangelsk and Severodvinsk. In the bar zone of the Nikol'skiy mouth, the approaching channel of the Severodvinsk port has been

Fig. 8.11 The estuarine system of the Severnaya Dvina River

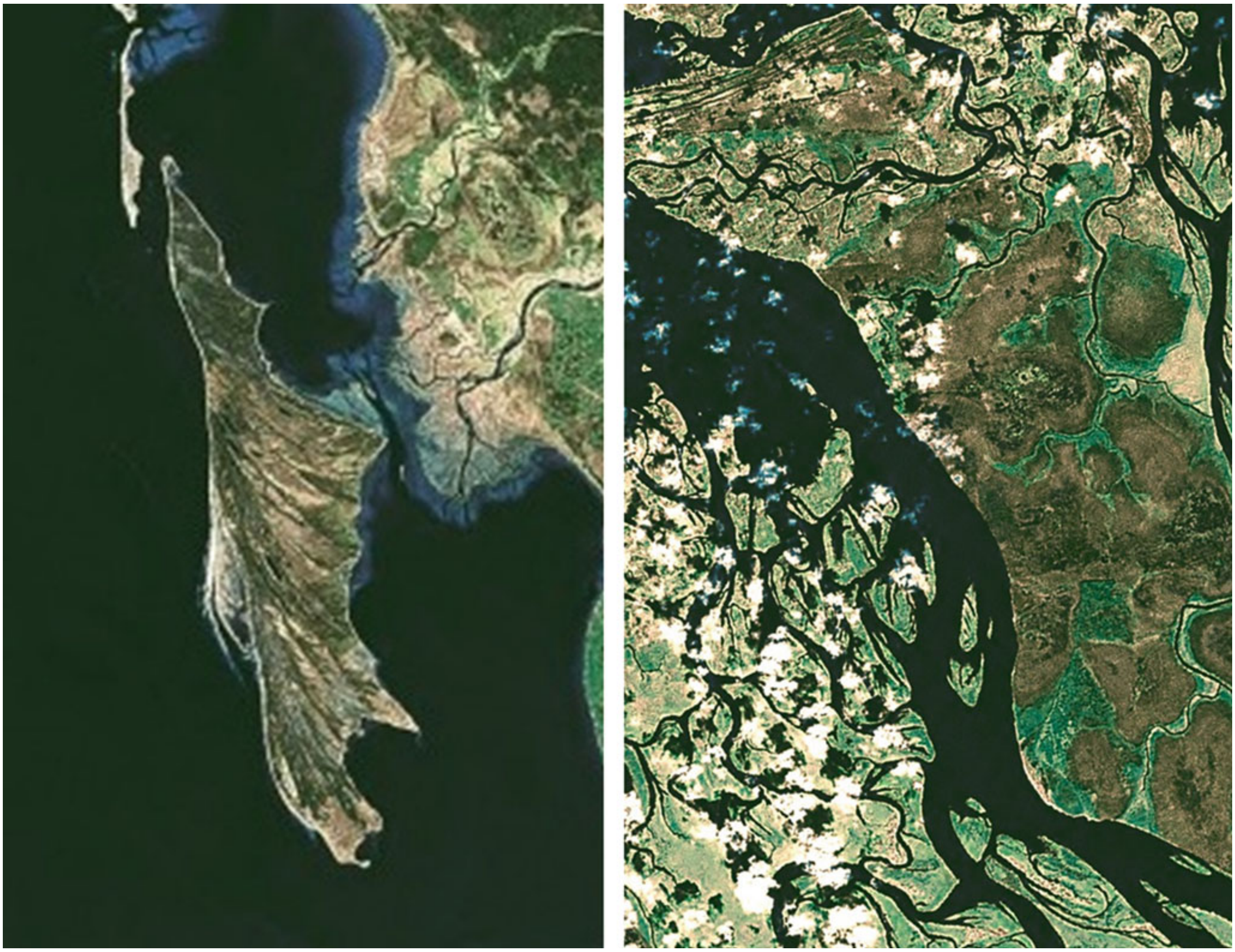


Fig. 8.12 Southern part of Dvina Bay and the Nikol'skiy branch

constructed. Shallow waters are clearly visible on the image seawards of the alignment of the main mouth. Two enlarged lower parts of the image demonstrate the increase in the alongshore accumulative splits on the east bank of Dvina Bay and the branch node of the Murmanskiy and Korabel'nyy arms of the delta.

On the enlarged parts of the satellite image (Fig. 8.13), the Korabel'noe mouth is represented. It is an estuarine expansion of the Korabel'nyy arm after its merging with the Kuznechikha and Maimaksa arms. This area of the delta riverbed network is used for maritime navigation; upstream, the main shipping route of the Arkhangelsk port passes through the Maimaksa arm. The image shows a complex picture of the bottom topography of the shallow area in which the approaching shipping sea channel has been constructed. The channel runs through the Berezovyy bar of the Korabel'noe mouth for over 6 km. The bottom part of the image covers the Murmansk mouth, which also has a complex topography. The entire Murmansk arm is used for navigation. At the bar of the Murmansk mouth, the old shipping canal can be seen. Both pictures display a series of accumulative splits, growing in the coastal zone on both sides of the mouth of the Murmansk arm.

8.8.2 Onega River

The Onega is a river in the Arkhangelsk region. It originates from Lake Lacha in the north of the East European Plain, and flows into Onezhsakya Guba (Onega Inlet Bay) of the White Sea. The river's length is 416 km, and the volume of water discharge is 15.7 km^3 per year. It has a mouth area of estuarine type with a short single-arm mouth at the river and an open shallow mouth on the seaside (Fig. 8.14). In the mouth's alignment between Capes Pihnemskiy and Pil'sky, the river's width is 2 km. At the Onega River mouth, there is an extensive bar with two hollows: Karel'skiy fairway (left) and Dvinskiy fairway (right). Between them, there are bars and

Fig. 8.13 Korabel'noe mouth

Fig. 8.14 The mouth of the Onega River

the rocky Kiy Island. Morphological processes in the modern mouth of Onega River are very slow. This can be explained by the prevalence of hard rocks resistant to erosion and the small run-off of the river's sediments. Nevertheless, the vast estuary bar is a sign of accumulation of river sediment. The Onega belongs to the rivers of the Eastern European type of regime (with spring floods); it has mixed water sources with a predominance of snow. During the spring flood (April-June), water flow is 58 % of its annual amount. During ice congestion and ice movement, the water level may rise by 2.5–3.5 m. The Onega mouth area regime is strongly influenced by semi-diurnal tides. At the mouth's seashore, their value during the ice-free period is an average of 2.4 m. Surges cause a significant increase in the tidal level – up to 2.8 m. Freeze-up begins in mid-November, and the ice starts collapsing at the beginning of May.

The Landsat images fix the state of Onezhskaya Guba (Onega Inlet Bay) of the White Sea in its different tidal phases. At the top, the wide-view and less detailed image, taken by the MSS (Multi Spectral Scanner) system at high tide, the water rises to the narrow bands of light-colored coastal ledges. On the light blue background of water in the area of the mouth's bar, there are dark stripes of hollows-fairways that can be observed. The image shows that the muddy coastal waters expand mostly along the western shore towards the White Sea Basin, which illustrates the existence of a constant counterclockwise water circulation in Onega Bay. The image displays the landscapes of surrounding territories well: predominantly forested landscapes (red on the image) on the right bank of the Onega River and wetlands on the left bank (bluish-gray). The lower, more detailed image is taken by the Landsat ETM+ (Enhanced Thematic Mapper) system during low tide. The image clearly depicts the littoral (pink) with the mouths' spits stretching along the bay coast. It is possible to trace a hollow (dark blue) at the mouth's bar; the hollow bifurcates into left and right fairways. Kiy Island is clearly visible between the fairways; it is connected to the other islands of the archipelago during low tide. A band of marine terraces with agricultural lands and adjacent wetlands is visible on the land along the shore of the bay, as well as the contour line of the city of Onega with a paper mill.

8.8.3 The Mezen and Kuloy Rivers

The Mezen and Kuloi are rivers in the Arkhangelsk Region, with a total mouth area of the estuarine type (Fig. 8.15). The Mezen originates in the swamps on the western slopes of the Timanskiy Ridge. Its length is 966 km, and its volume of discharge is 27.0 km^3 per year. The Kuloy has a length of 350 km, and its volume of discharge is 5.7 km^3 per year. Both rivers flow into the southeastern part of Mezenskaya Guba (Mezen Inlet Bay) of the White Sea, forming two expanding downstream estuaries that end at a common mouth seaside. In the past, the Mezen flowed into Cheshskaya Guba (Czech Inlet Bay) of the Barents Sea, but the river changed direction as a result of the lowering of the earth's crust and post-glacial sea transgression. Because of the small run-off of sediments of the Mezen and Couloy Rivers and strong high tidal currents, the deltas are not formed at the mouths of these rivers. There are a lot of movable sandbanks (shallows), or so-called "kosheks", in the beds of these rivers. The rivers' water source is mixed, with a predominance of snow; they belong to the rivers with spring flood, summer and autumn rain floods and low winter baseflow. Almost half of the annual flow of the Mezen takes place during 2 months of spring (May–June). The rise of the water level during the ice move is exacerbated by ice congestion. The river freezes in mid-November, and opens in mid-May. The estuaries' regime is almost completely determined by the strong influence of the tides. The amount of syzygy tide in the Mezen estuary near Cape Semzha can reach 8.5 m. Speeds of tidal currents at the mouth of the estuary are very high: up to 2–2.5 m per second. The pattern of these currents is very original, accompanied by cross flowing, and in places of convergence of the streams of current, rips ("souloi") occur. The tidal wave, moving up the estuary, is transformed, becoming close to a bore (this phenomenon is called "nakat") in its characteristics. The enormous speed of the tidal currents suspends sediment, which leads to extreme instability in the fairway and erosion of the coasts. In moments of maximum speed of the tidal currents in the bottom layers, a so-called "plug haze" is created; this zone, during high tide, moves up, and at low tide, down the estuary. This phenomenon was captured on the Landsat image, where at the bottom of the estuary, that part of the river channel is displayed with increasing brightness as a result of a sharp increase in water turbidity. Shoals, islands of deferred material in both estuaries, coastal eroded areas and the flow of turbid water (at low tide) in Mezen Bay are all visible. The image clearly displays the landscapes of the surrounding glacial plains, which are characterized by erosion and peri-glacial landforms with chains of lakes, wetlands, and streams. Here, the diversity of colors is created by interchanged sections of grass (green) and lichen tundra (pale yellow) with shrubs and swamps (brown). The Mezen mouth area is used for fishing, marine and river navigation. A project for a tidal power plant is under consideration here.

Fig. 8.15 The mouth of the Mezen and Kuloy Rivers

8.9 The Main Morphological and Lithodynamic Processes in the Coastal Zone

8.9.1 Hydrodynamic Conditions

Ice Regime The close proximity and connection of the White Sea to the extensive Barents Sea create warming conditions and salinity increase in the Barents Sea current. The current transfers nearly 26 % of the White Sea's total heat that the White receives annually. The inland location of the White Sea and the ruggedness and shallowness of some of its areas explain the strong effect of the continental influence, which is being demonstrated by the increase in annual and daily amplitudes of air temperature, the frequency of occurrence of low temperatures and the water desalination by continental run-off.

8.9.2 Distribution and Differentiation of Sedimentary Material

The supply of sediment to the coastal area of this region is insufficient, and is mainly due to the solid discharge of the rivers, which is more than three times the amount of material gained from the erosion of the coast, despite the abrasion coasts' great length. The composition of the material coming from the erosion and destruction of the coastal ledges (with the participation of phase, slope, and seismo-tectonic processes) changes in accordance with the structural features of the profile and often has granulometrically opposite features (silt-pelitic and coarse fractions for which the proportion of sand is insignificant). For alluvial sediments, the predominance of slurry siltstone and pelitic particles (quartz, feldspars and little actual clay minerals) is typical in the composition, while sediments of the accumulative, permanently dry areas (osushek) in the delta areas of medium rivers contain a significant amount of sand material (Fig. 8.16).

Strong division of the shoreline of the typical skerry areas and deep fjords combined with the uneven sea floor relief and variable angles of the underwater slope determines the sharply heterogeneous intensity of the impact of already weak hydrodynamic agents in the individual sections of the coast. Under such conditions, extended alongshore sediment flows cannot exist. The corresponding movement of material becomes dominant only on local aligned coastal segments in the period of strong alongshore northwest waves. Often, short unsaturated flows under the influence of estuarine circulation are directed from the capes (the zone of divergence) to the inner part of the bay (convergence zone), where the combination of run-off and rip currents can build on inclined underwater slope conditions that are conducive to the removal of gravel-sand size material from the shoreline to a depth of 10–15 m, even under the average intensity of waves. During periods of extreme storms, the impact of this process increases, which is one of the causes of the shortage of beach-forming sediments and the development of processes of coastal destruction, and creates the effect of an inverse distribution in the size of sediments in the cross-profile.

In open to wave areas of abrasion-accumulative and abrasion coasts with underwater slopes of moderate angles, the normal wave differentiation causes the movement of larger rock fragments in accordance with the increasing activity of waves towards the sea level boundary and removal of fine material to the outer part of the underwater slope. Nevertheless, in the eroded areas of the seabed at depths of

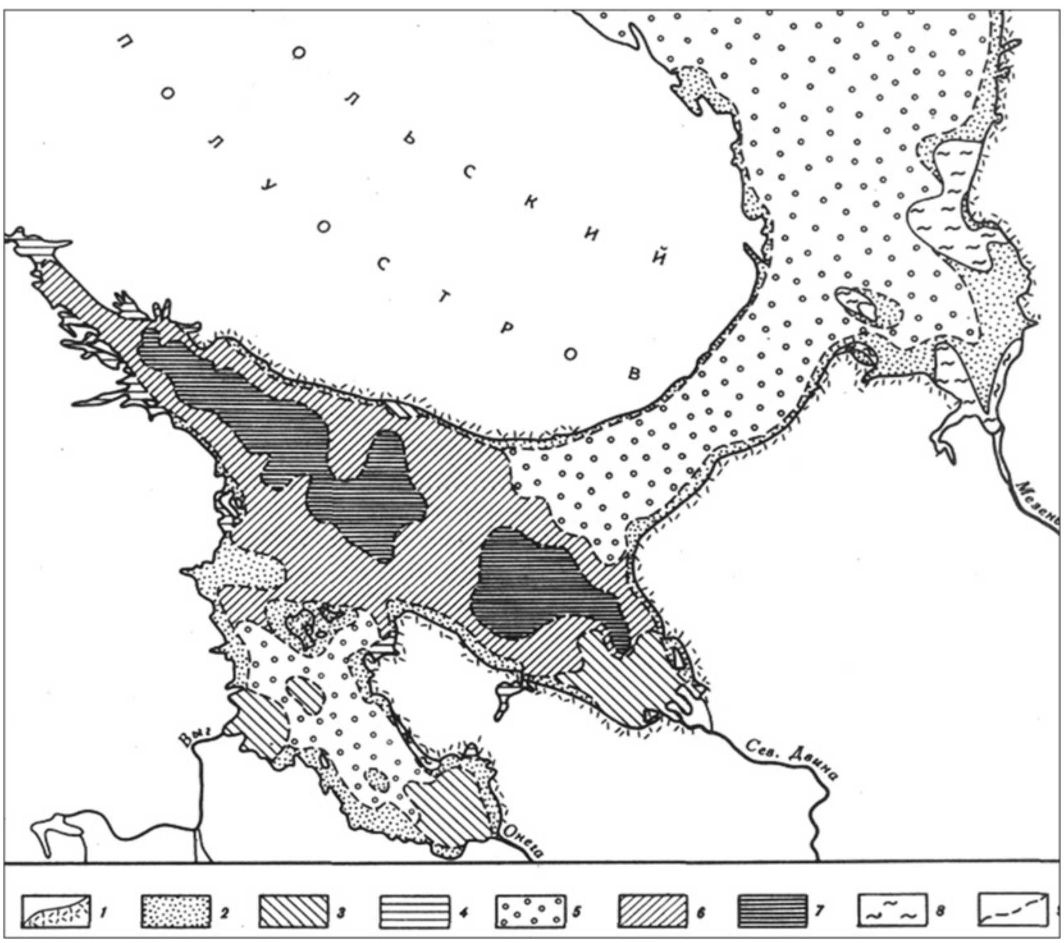


Fig. 8.16 Scheme of distribution of sedimentary facies in the area of the White Sea (Nevessky et al. 1977). One to seven – facies: (*1*) beaches; (*2*) coastal; (*3*) deltas and mouths areas; (*4*) bays; (*5*) the vast sea shoal; (*6*) the slopes of deep-sea basin; (*7*) deep-sea basin; (*8*) benches; (*9*) boundaries of the facial zones

12–14 m, the alongshore strip of sand and gravel deposits with a small amount of silt can often be seen.

At the upper part of the profile, the intensity of the processing of the material increases, and the low thick beach sediments are well sorted, by a standard deviation that does not exceed 0.9. The distribution curve is of unimodal shape with peak at a fraction of medium size sand, the contents of which, together with the adjacent fraction of coarse sand, predominates. Sediments are characterized by high values of excess and a negative value of asymmetry of the particle size distribution. This indicates that the speed of processing of the material exceeds the intensity of it income. These sands are the final product of wave differentiation in terms of the continuously varying energy of flow with a noticeable distribution of the fractions on the slope - the finest sediments being concentrated in the upper part of the beach at a level corresponding to the level of wave processing during spring (sizygy) tides. Here, the enrichment of the sediments with heavy minerals takes place: garnet ("red sands") and ore ("black sands").

Coarse material originating from eroded layers of terrestrial ice and marine ice accumulates in the upper part of the coastal profile or is moved out later by prepay (fast) ice, that represent significant expenditures (расходная часть) of the balance system. Fine material from the beach sediment and silt-pelitic material of the solid run-off of rivers and the erosion of boulder loams are mostly moved out in a suspended form beyond the wave field by the tidal, run-off and ebb currents. Distribution of the suspended sediment concentration in the plain, with the maximum in the coastal areas, indicates the predominantly terrigenous nature of the suspension. The highest saturation of water with suspended sediments (100 mg/l) occurs during the storm surge in the phase of high tide when waves abrade the coastal cliffs and, in spring, during the mass discharge of sediments. Re-suspension of the bottom sediments in relatively shallow areas is insignificant.

With the attenuation of waves, the distribution of deposited material from a suspension begins on an underwater slope in accordance with the hydrodynamic activity of the environment. Within the littoral, the most active accumulation of silt material is on the Wadden type of shores located in the wave shadow of peninsulas and islands; for the suspension to precipitate, it is enough that the calm situation last for at least one tidal cycle. The fine sediments at the bottom are compacted due to the molecular adhesion forces between the molecules of fine particles, and are not stirred up by tidal currents. Despite the seeming simplicity of this mechanism, high concentrations of suspended sediments in the waters of Kandalaksha Bay are rarely indicated; the process of accumulation on the littoral is greatly extended over time, and all the major sites are confined to accumulative bays with sources of alluvial sediments. It should also be noted that, under calm conditions, the inverse distribution of sediments according to particle size on an underwater slope occurs for relatively fine-grained material near the coast. Since the mechanical differentiation of sediments hardly ever occurs, the sediments are characterized by diverse particle size distribution and the diversity of the ratio between the fractions, all of which reach 50 %. Silt fractions often have small relative predominance over sandy and pelitic differences; gravel and other coarse gravel components can be noticed. As a result, the sediment may be related to the sand-and-silt differences with a complex composition and a very low sorting (or rather, its complete absence), which distinguishes the sediment from the above-considered sediments of predominantly wave coasts.

Another characteristic of the area sediments described is a significant amount of coarse-grained material, not associated with the differentiation process. Thus, below the zone of the wave field at depths of 10–15 m, very poorly sorted, mostly fine-grained sediments are widely developed with high content of coarse material (30–35 %). Their existence is connected to a kind of "damp" zone where coarse material slides under the force of gravity when exposed to the impact of waves and pripay (fast) ice. However, at depths of 10–20 m, the strip of coarse clastic sediments is often fixed along the shore, which canneither be associated with ice-caused redistribution, nor with "damp", since the size of the individual units is too large. Most researchers explain their formation as the product of the erosion of glacial deposits, similar to the process of formation of boulder areas in the intertidal zone. Some of these deposits may be products of seismic landslides, whose development in the Holocene proceeded very intensively.

8.9.3 Southern Coast of the Kol'skiy Peninsula

Despite the relatively aligned character of abrasion, abrasion-accumulative and accumulative shores east of the Turiy Peninsula, the shallow water is only in a relatively narrow band, due to peculiarities of the board part structure of the Kandalaksha graben. The structure of material income is similar to that in the coastal zone on the western part of the Kandalaksha coast, but the total volume of material coming from the river flow, as a result of coastal abrasion, is several times more. Among the secondary factors of the lithodynamics, in some areas, the roles of aeolian transport and the income of material from the underwater coastal slope increase.

In the context of the relative lowering and stability of shores with underwater slopes at a slight angle, a part of the solid run-off accumulates in the mouths of rivers, blocking them with spits and island or coastal bars of complex alluvial-marine origin or forming considerably wide accumulative littorals. For deeper shores, the direct confluence of the rivers and the prevalence of transit, denudation and unstable accumulation are typical.

In the coastal zone, terrigenous material is processed by waves far more intensive than those in the western part of the Kandalaksha coast. Typical for the basin seas, circumcontinental distribution of granulometric types of bottom sediment on the submarine slope can be noticed with a maximum median diameter of sediments at the top of the coastal profile. With increasing depth, tidal and other currents begin to play a critical role in the transport of sediments and the formation of morphologic and lithodynamic conditions. Accordingly, there is a gradual decrease of sand fractions in sediments – from the highest to the lowest value, and at the same time, the content of the pelitic fractions increases, and exceeds 90 % in the axial part of the sea.

In the middle of the underwater slope, alevritic fraction content reaches its maximum. At the same time, the association of lithological differences becomes very diverse and unstable, with significant changes over short distances, which greatly resembles the coastal area of the above-considered part of the Kandalaksha coast. Since the absolute heights of the waves are small, the boundary of silt sediments is relatively high, located at a depth of about 20 m. The large diversity of associations, with a predominance of alevritic differences of sediments, is also typical for sediments at the mouths of major rivers (Vareychuk et al. 2012).

Particle size (granulometric) analysis of sediments of beaches and littorals was conducted during the 4-year monitoring studies on the Varzuga site, which is the largest area of the Holocene and the largest modern accumulation in the studied coast. Widespread accumulative terraces of the late post-glacial time and erosive processing provide a relatively large amount of the solid run-off of the Varzuga River (up 100,000 tons). The predominance of deep erosion over the lateral one limits the possibility of the formation of a powerful alluvium, and most of the solid run-off enters the mouth of the rivers and subsequently becomes involved in the sphere of activity of marine processes. Along with the silt-pelitic material, some amount of sandy sediments is carried out to the coastal zone and participates in a longitudinal dislocation. The general direction of the river flow is southeastern; in this direction, the mouth section of sediments is shifted onto the submarine slope, reflecting the importance of the Coriolis force in the development of the mouth area. However, the reverse nature of the tidal currents and unstable wind (owing to a poorly expressed wind power median) cause the sediments to migrate near the mouth; the migration becomes unidirectional at some distance from the mouth. Most of the terrigenous material under the influence of high tidal currents is involved in an alongshore drift directed westward and can be traced at a distance of over 12 km. River run-off, tidal flow and southwest winds form the sedimentary flow directed eastward (about 8 km). At the distal ends of this lithodynamic system, a decrease in the output flow of sediments is reflected in the changing nature of the littoral surface (complete disappearance of the submerged portion) and is accompanied by a sharp change in the morphology of the coast that is in contact with the accumulative site.

Differentiation of the sediments according to their granulometric and mineralogical composition begins immediately after the alluvium intake into the coastal zone of the sea and is carried out simultaneously in the longitudinal, transverse and vertical directions. However, it takes some time before the effects appear corresponding to the "normal" wave sorting. The result of the mechanical differentiation during the alongshore movement of sediment is a decrease in the size of sediments with the distance from a point source, followed by a change in the statistical parameters of particle size of the contained sediments. During the transverse differentiation under the surf flow impact, more coarse sediments are formed at the bottom of the seaward slope of the average beach with full profile. These are the well-sorted sediments, in which neither of the two modal fractions (0.1–0.25 mm and 0.25–0.5 mm) has any explicit predominance, but which clearly dominate (up to 80–99 %) when these two fractions are combined. Coarse sand is represented by a small additional fraction content, which is significantly higher (up to 20 %) on the beaches east of the Varzuga River mouth than it is in the western segment of the system (less than 5 %). The role of gravel and silt-pelitic fractions is less visible (Fig. 8.17).

Upslope, the beach is marked by the decline in the portion of medium-size sandy material and an increase in the fraction of fine sand up to 70–90 %, with a maximum on the crest of the beach. The yield of heavy fraction is up to 80–90 %. Black colored minerals alternate with grains of quartz, feldspar, or other matrix rocks, highlighting the layered stratification, which is typical for beach sediments (Fig. 8.18).

Some researchers point to the predominance of a part of the heavy fractions loparite, zircon and ilmenite (Vareychuk et al. 2012). Apart from the beaches, the accumulation of concentrated heavy minerals occurs on underwater walls, within the dune belt bordering the zone of accumulation, as well as on the sandy shores of the lower flow of the Varzuga River impacted by tidal fluctuations of the sea level.

While analyzing beach sediments, it is necessary to note the large values of kurtosis and the negative asymmetry of particle size distribution. This points to the stable dynamic processing of clastic material with a rate exceeding the intensity of sediment input. Similar conditions can be noticed on the littoral and in the areas of three underwater walls in the Varzuga section, with the total width of the complex being

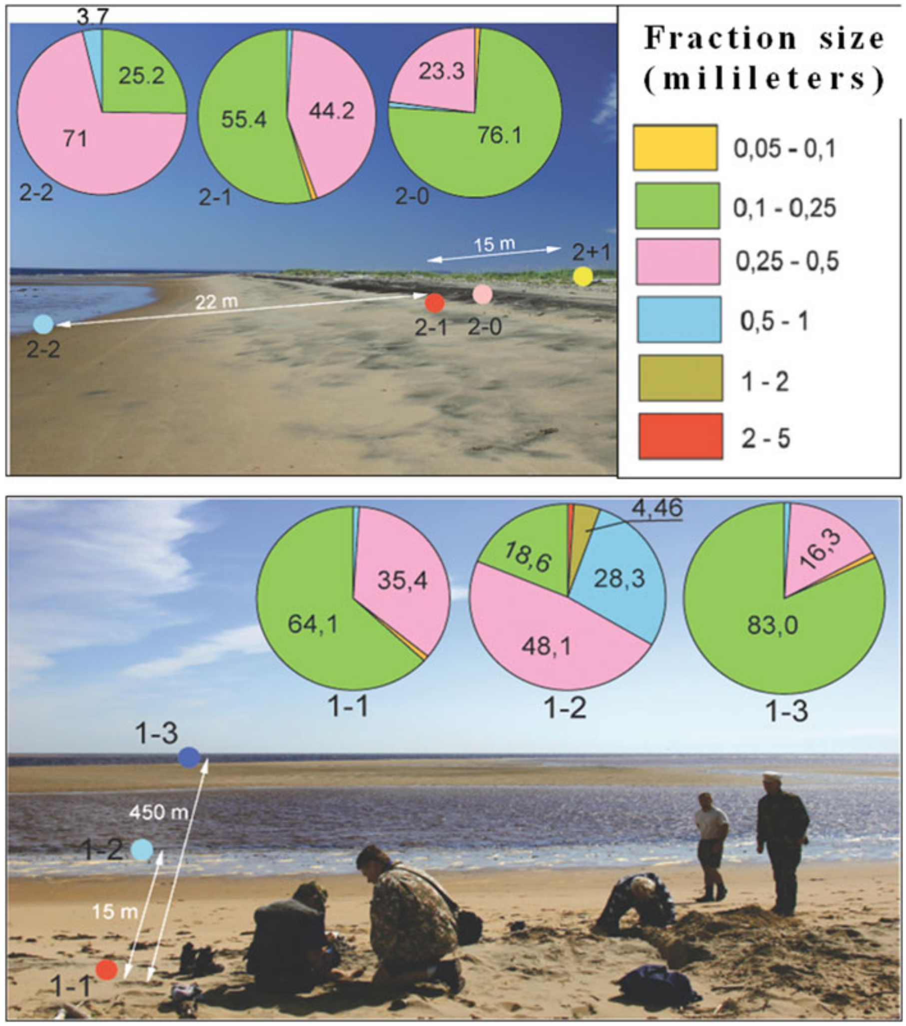


Fig. 8.17 Accumulative coast of 1.5 km (*above*) and 0.5 km (at the *bottom*) to the west of the mouth of the Varzuga River and patterns of sand deposits of size distribution. Note the increase in the concentration of heavy minerals on the crest of the beach. Legend in colors indicates the size of each fraction (in mm). Colors of the circle graphs correspond to the indicated percentage of each fraction (Foto by A.A.Ermolov)

Fig. 8.18 Modern beach sediments with layers of heavy mafic minerals on the beach at 0.5 km to the west of the mouth of the Varzuga River (Photo by N. Shevchenko)

about 60–90 m. The high mobility of the sand in the permanently drying zone, the maximum depth of penetration of wave action in the thickness of the soil and sufficient gradients of flow velocities and slopes lead to the formation of well-sorted fine sand accumulations similar to the sediments on the beach's upper part. The content of the modal fraction (0.1–0.25 mm) increases with increasing distance from the beach, and at low tide, the level reaches 80–90 %. Sands are also characterized by a negative asymmetry of particle size content, confirming the intensive rewashing of sediments and the removal of the fine-grained fractions. The relatively high content of large-medium components can be observed only in the depressions between drainable walls, where a small admixture of silt is sometimes retained. Such a particle size distribution of the material is inherent to the microrelief of shallow waters – ripple marks representing straight or curved parallel rows of small walls with asymmetrical slopes (underwater walls in miniature). In the depressions between the small walls, more coarse sediments accumulate, as does a fine-grained sedimentary material, often underlined by mafic minerals, on ridges.

Thus, the particle size analysis of sediments and sandy littorals demonstrates that even at a slight distance from the largest sources of terrigenous material under current conditions, there are low rates of sedimentation, and processing of the material by waves in the ice-free period takes place very intensively. This is determined by a very small run-off of the carried sediments. Over 90 % of the total solid discharge of the Varzuga River and other rivers consists of fine-grained particles accumulated outside the coastal zone.

Away from the major rivers on the abrasion-accumulative and abrasion coasts with stabilized cliffs, significant transformation of the sedimentary material by hydrogenic processes and, most of all, the carrying out of fine fractions lead to enlargement of the material and the formation of beaches composed of sandy sediments with a large admixture of gravel fractions (and pebble), the contents of which can reach up to 40–60 %. The largest amount of coarse material on the beaches and littorals (including buried benches) can be observed near the outcrops, which are mainly represented by red Riphean sandstones (II class of hardness).

The balance of the deposits of the coastal zone, as well as its components, is determined by local circumstances and is different on individual parts. Considering the entire southern coast of the Kola Peninsula, it can be noticed that a significant part of the relationship between the incoming and outgoing flows of sediment remains positive. Areas with a negative balance of deposits are confined to the abrasion coasts with rocks of I and II hardness classes, the destruction of which is either extremely slow or absent.

Terskiy Coast of Gorlo and Voronka In its principal features, the model of the lithogenesis of the eastern coast of the Kola Peninsula corresponds to that of the inner shelf. The main factors determining the specificity of the area are the small depth of the vast coastal shallows of Gorlo (Throat), averaging 30–50 m, and the high hydrodynamic activity of the environment covering the entire water column and providing for a high intensity of hydrogenic lithodynamic and relief-forming processes, slightly differentiated near the shore. A characteristic feature is the uncertain width of the zone that belongs to the facies of coastal sediments, because coastal sediments imperceptibly converse into the main field of similar deposits lining the middle part of this area of the sea, and are significantly monotonous.

Based on analysis of the spatial arrangement of the grain size classes of sediments at the bottom of the western part of the Gorlo (Throat), new data have been obtained that demonstrate a wide areal distribution of coarse-grained sediments (gravels, pebbles and boulders) that meets the conditions of sedimentation (high speed bottom currents) and points to the prevalence of thin material transit conditions and a rewashing of relic deposits. In addition to small-medium sands, large-coarse-grained sands, sometimes consisting of 50–80 % bio-detritus, are widespread, as well as sandy-gravel-pebble deposits with varying amounts of boulder material. The occurrence of gravel fields increases from north to south, reaching a maximum in front of the mouths of the Pyalitsa and Babia Rivers. The area of pebble fields becomes somewhat broader as the area north of the mouth of the Babya River towards the Ponoy Rover increases. The lithological analysis shows varying degrees of roundness in the material, the most rounded fragments tending to accumulate in the deep-central part of the strait. This is probably related to the displacement of coarse material that has accumulated as a result of coastal abrasion, and their diverse composition (the eroded area of the eroded complexes includes almost the entire area of the Kol'skiy Peninsula) and indicates the character of the terrigenous sediments.

In the northern part of the region, composed of hard rock formations, the abrasion and abrasion-denudation coasts are experiencing a relative elevation, and for most of the rivers, direct inflow is typical. In the south, coasts are relatively stable or lowering, so the mouths of certain rivers are partially blocked by accumulative formations. Abrasion-accumulative and abrasion coasts with soft sediments dominate here, providing for an increased inflow of clastic material in comparison with all other areas. However, in the regional structure of the sediments' sources for the coastal zone, the sediment run-off maintains a leading position, exceeding the corresponding values of abrasion by double, and its distribution in space is more even.

Th erosion of glacial and glacial-marine sediments is accompanied by the accumulation of coarse material, which almost remains completely in place, blocking benches, and does not undergo substantial differentiation in size and flotation ability. Despite the fact that loam stratas are often subject to erosion, the content of fine material on the open shores is less than 1 %, and only in the bays/sediments' traps are sediments characterized by low values of kurtosis (raw sorting) and positive asymmetry of the content's particle size. Accumulation of silt-pelitic particles under calm conditions contributes to an increased concentration of suspended substances in the northern areas, especially in the Voronka (Funnel), where its average content in the open sea is 3–5 mg/l, increasing in coastal waters up to 100 mg/l (Nevessky et al. 1977). Outside the coastal zone, silty-sandy sediments can accumulate in the estuarine areas of major rivers, which are characterized by the condition of unstable accumulation. The paleo-delta of the Ponoy River area is especially outstanding in this respect, being characterized by high values of solid discharge. But most of the pelitic and silty-sand mixture carried outside of the wave field is redistributed by currents and deposited in the deepest places. The high intensity of wave processes leads to perfect mineralogical differentiation of coastal sediments in a complex combination of longitudinal and lateral movement.

In sandy sediments, sometimes up to 80 % of the heavy fraction is composed of biotite; perovskite, sphene, magnetite, ilmenite, and fluorite can also be found. The main heavy minerals in the range of 1.0–2.0 mm are amphibole (plus pyroxene or epidote), garnet (predominantly almandine), staurolite, kyanite and sillimanite. All the minerals bear traces of their mechanical processing. This fraction consists of 50–99 % rock fragments; in fractions with a size ranging from 1.0 to 0.5 mm, their share is reduced to a few percent. The grains of most of the minerals in small fractions are rounded or subrounded, but grains of garnet are always present with a good cut-grading.

Analyzing the lithodynamics of the east coast of the peninsula, the continuing shortage of soft sediments in the coastal zone shold be noted. This looks somewhat paradoxical, given the large amount of incoming clastic material compared to the southern and southwestern part of the peninsula. However, the total length of the accumulation areas is very low, and most of them are traditionally confined to the tectonically stable estuarine areas of large rivers, or separated bays in the area of primary bracked-up fault-block coasts. This is indicated by the relative thinness of the majority of accumulative formations. The reason for this is established in the northern part of the White Sea's natural regime of dynamic equilibrium, which is based on a relatively constant amount of continuously renewing clastic material located in the coastal zone in the suspension and on the bottom. Under this scheme, the coastal zone is an area of transit of the soft sediments actively redistributed by hydrodynamic agents between areas of erosion and accumulation in the approximate equality of incoming and outgoing flows.

8.9.4 Peculiarities of the Coast Evolution Under Conditions of the Tectonic Uplift

Observations of the level of the World Ocean demonstrate that it has increased in recent decades at a rate of about 1–1.5 mm/year (Klige 1985). This is one of the reasons for activation of the retreat of the Arctic sea shore ledges, often leading to a loss of land involved in the sphere of economic use. In the study area, the relatively lowering shores are of limited development; these shores are concentrated mostly in the southeast of the peninsula. Immersion of these sites does not reflect a demonstration of the transgressive regime of the Ocean, barely noticeable against the background of seasonal and perennial tidal sea level fluctuations, so much as the negative influence of negative tectonic movements of the edge of the land. Most of the coast has a positive rate of crustal movements that is equal to or greater than the rate of eustatic sea level rise, causing a relatively stable position or lowering of the sea level.

Regressive shoreline movement causes a noticeable transformation in the relief of the coastal zone, comparable to the activity of hydrodynamic agents, and in some cases, exceeds them. The most dramatic signs of modification are marked on the indented coast of Kandalaksha Bay, where the rate of uplift of individual sections, according to some estimates, reaches up to 4.5 mm/year. As a result of this rise, the coastal areas of the seabed are becoming shallower, and waves obtain velocities sufficient for the re-suspension of muddy soil particles, which are then moved out to sea by currents. In the future, eroded areas will begin to become bare periodically at low tide, turning into permanently drying areas, and soft sediments will erode more intensely, forming the typical shape of a boulder-block littoral of Kandalaksha Bay.

The presence of numerous rock outcrops and accumulations of boulder-block material, screes and small islands in the shallow water skerry conditions contributes to the widespread mechanisms for the connection of islands, as well as their formation (Fig. 8.19). Examples are the numerous elongated capes and peninsulas formed by a system of small rocky islands, connected by land bridges not flooded during the tide (Cape Klyukova, Cape Kuzokotsky, etc.). These are low-lying (3–5 m), and often contain wetlands or lakes, and narrow strips of land connecting the former island with the mainland; they also often contain traces of salinity and can occur in a relatively short historical period of time, determined by the rate of neo-tectonic uplift. Similarly, a closure of shallow bays occurs, provided that, at the level of the quadrature low tide, there is a scree or underwater wall that has a tendency to rise. Tectonic uplift causes a gradual expansion of the scree and pushes it up to the surface, a process that, over a period of time, leads to a leveling of the coast's contours.

The lithodynamic effect of isolation of individual sections of the coast is quite significant, because the blocking effect

Fig. 8.19 The area of the Kandalaksha coast with the development of connecting forms (indicated by *arrows*), formed as a result of a tectonic uplift of the territory (Photo by A.A. Ermolov)

of the newly-formed land bridges causes a change in the sedimentation conditions in the interior parts of the new bays, including a decline in the quality of mechanical differentiation. If there is a source of alluvial material, the rate of accumulation increases, which can lead to a change in the type of coast and further transformation of the coastal contour (for example, the coast of the Malaya Por'ya inlet, near the settlement of Luven'ga, etc.).

On the coast of the eastern part of the Kol'skiy Peninsula, tectonic uplift also has taken place. However, its rate has not exceeded 2.5 mm/year. Depending on the morphology of and intensity of tectonic movements on the coast, the coastline transformation differs. On the shallow accumulative sections, the coastline moves towards the sea, as demonstrated by an enlarging of the coastal bar or marsh, rarely by separation of shallow lagoons. On erosion type coasts, the zone under the influence of active waves is shifting, and therefore slows down abrasion processes in the upper part of the coastal zone; cliff stabilization can be noticed. On relatively deep coasts, changes relative to the sea level are barely noticeable and do not impact the terrain. Rarely, abrasion forms (evorsion caldrons) can be observed, as well as semi-drift-wood located above the supra-littoral current.

8.9.5 Possible Changes to the Coast in Relation to Projected Global Climate Change

Major evolution trends of the studied coast under the conditions of global warming predicted in the new century are not only of interest from a scientific point of view, but also have a great practical importance for solving strategic problems of further development of the resource potential of the White Sea. To date, many individual articles and monographs have been published devoted to the rising of sea levels in connection to global warming that contain highly different grades (from 0–20 cm up to 4 m). Considering the available forecasts of process development, most authors accept two "scenarios" as being the most realistic, outlined in published materials of the Intergovernmental Panel on Climate Change (IPCC). One of them was adopted on the basis of assessment of the socio-economic and environmental impacts of climate change and sea level rise; it implies a 0.3–0.5 m sea level rise by 2050 and nearly 1 m by 2100. The second scenario is posited on the basis of analysis of natural climate changes and presents a more cautious assessment of future changes: 0.2 m sea level rise by 2030, and 0.65 m by the end of the century. Their effects are caused not so much by anthropogenic but natural factors. The most realistic seems to be the second scenario, which predicts a relatively small increase in the sea level in the twenty-first century.

Under conditions of current trends of vertical Earth crust movements with the previous speed, a slight increase in the relative sea level will be marked by the end of the century in the western part of the Kandalaksha coast and will average 25–35 cm. The almost total absence of low-lying coasts and the hardness of their forming rocks will limit the possible transformation of the coast zone in this region to a minimum. Similarly, the Terskiy coast to the north of the Ponoy River will evolve where sea level rise is unlikely to exceed 30–40 cm.

A number of areas in the southeast of the Kol'skiy Peninsula, under the present conditions, experience a slight subsidence, so the magnitude of the expected rise in sea level is likely to be slightly higher than that provided by the natural scenario. Under such circumstances, we should expect a strengthening of the erosion of coasts composed of soft rocks, especially in those areas where erosion was previously relatively slow (or had stopped), due to the approach of the state of equilibrium. Low-lying accumulative terraces of the Late Holocene age will be eroded especially quickly. Contrastingly, the smallest conversion of the coastline is expected to occur for the areas of abrasion and abrasion-accumulative terrace ledges composed of bedrock (I-II class hardness), which are eroding very slowly. Significant changes may occur in the regime of the Wadden type shores, where, along with a passive flooding of the narrow coastal strip, the tidal prism will increase (the volume of water moves to the shallow water and moves out during the tidal cycle), as will the removal of a small amount of fine-grained substance carried with solid run-off of rivers, beyond the coastal zone. This will lead to a noticeable reduction in the rate of increase of littoral zones and, possibly, partial erosion of their seaward sides.

8.10 Unique Natural Objects of the White Sea

A number of objects located on the coast and islands of Kandalakshskiy Bay in the boundaries of the Murmansk region belong to natural geological monuments of federal significance (Gorbatovskiy 2009). For example, on the coast of Kandalaksha Bay (Terskiy coast), 16 km eastward of the settlement of Koshkarantsy, there is a unique deposit of a stockwork-type amethyst – Cape Korabl' (Cape Ship). The deposit is a very large outcrop composed of red-color sandstones of Terskaya suites with amethyst mineralization. Zones of crushed red sandstone and siltstone contain numerous quartz lodes and leaching caverns. The central part of the stockwork is cemented by quartz, carbonate and fluorite. Amethyst mineralization is developed on the walls of variously oriented cracks, mainly in the hanging side of stockworks. In the clusters up to 500 cm^2, crystals prevail, with sizes starting from a few millimeters up to 2 cm. The intensity of the purple color of the crystals varies not only in different parts of the deposit, but even within separate individuals, from a light violet at the base to a deep purple with a smoky tinge at the top. Sometimes, needle goethite inclusion can be found inside the amethysts. In the western part of the deposit in Cape Ship (Fluorite stock), the red-colored sandstones are crossed with numerous lodes with a capacity of 5–15 cm, consisting of alternating bands of dark purple and white fluorite.

On the southern coast of Kandalaksha Bay, on the Tolstsik Peninsula, the natural geological and petrographic-mineralogical monument of federal status is located, represented by the outcrops of epidozit rocks of Cape Verkhniy Navolok. The coastal rock outcrop, with a length of 200 m and a width of 70 m, reveals the unique composition of rocks consisting almost entirely of minerals that belong to an epidote group of different mineralogical types, habits and orientation. The epidote-tsoizit gneisses and schales (epidosites) that form the outcrop have a gray and greenish-gray color, and a granoblastic, sometimes porphyryblastic structure. It is mainly presented by clinocoezit and, in small quantities, coisite, plagioclase, quartz, amphibole and garnet. The visible thickness of the layer is about 20 m. Along with this, there is also another rare phenomenon: an exposed layer of fine-grained amphibolites, unique because they have preserved the primary characteristics by which the nature of submarine lava flows can be restored. Lying below, thin-striped amphibolites indicate ancient cyclical processes of sedimentation and volcanism. In addition, on the island of Mickkow, located at the exit of Bol'shaya Kovda Guba in Kandalaksha Bay, there is a natural geological monument of petrographic types that have federal status. Here is the natural outcrop of granitoids (with an absolute age of about 2.3–2.4 billion of years), which is an example of remelting older gneisses and amphibolites, the remains of which stay among the granites in the form of fragments and boulders.

On the Karel'skiy coast, a number of geological monuments can be outlined. For instance, the natural tectonic monument of Vorotnay Uda that is represented by three small islands located in the Kem'skiy region of Karelia, 1 km east of the village of Gridino. The main feature and showpiece of the islands are dikes of olivine melanogabbronorites. The dikes' rocks, by petrographic and petrochemical parameters, are a typical example of lhertsolite-gabbronorites (2.4 billion years) that has the widest spread among the druzits of the western part of the White Sea. The object is outstanding because of the well-preserved primary shape of the dikes that allow for studying their morphology, interior structure and the peculiarities of their contact relations with other rocks.

Gneisgranits dominate among the rocks of the frame, represented by light-gray gneis-like rocks magmitized by later microcline type granites. The granites in some places form separate structures in the shape of conductors and linse-shaped structures. Before the intrusion of gabbronoritic dikes, the frame rocks were often affected by complex structural and methamorphic transformations and magmatization, which provides evidence of the Late Archaey. Pegmatic and granite conductors in the northwestern and northeastern directions transsecting gabbronorites and earlier formations are the most recent structures on the islands.

There is one more geological (geomorphological) natural monument located here – "Kuzova". The monument reveals granite domes of the Late Archaey intrusion, formed as a result of selective denudation (denudation-tectonoc relief), so-called “ram’s foreheads”, glaciers’ scars (eczartz relief), ancient coastal formations (accumulative terraces and boulder-pebble walls), man-made seids (sacred boulders) and labyrinths. Russkiy Kuzov Island is the largest island in the archipelago; it has the shape of an irregular triangle, with a size of 3 × 2.5 km, and a height of 123 m. This is the highest point in the southern White Sea region. Other islands that comprise the landsape of the zakaznik (“natural protected area”) “Kuzova” are smaller in size, with heights ranging from 15 to 117 m. The rocky domes of “Kuzova” are a part of the Late Archaey intrusion of granites that solidified in the folded thickness of the White Sea gneisses nearly 2.7 billion years ago. During subsequent geologic epochs, the long-term processes of selective rock erosion and leveling (flattening) of the terrain eroded the overlapping strata of the gneisses and exposed the granite domes of the archipelago. Finally, the relief, surface sediments and landscapes of the territory were formed during the degradation of the last glaciation and the post-glacial transgression of the White Sea.

8.11 Natural Protected Areas

There are a number of natural protected areas of different statuses in the boundaries of the White Sea coast and islands, in particular, the Kandalakshskiy State Natural Reserve in the Murmanskiy region (Kandalaksha Reserve 2014). Parts of the Kandalakshskiy State Natural Reserve are located on the marine periphery of the Kolskiy Peninsula. These are archipelagos with surrounding water areas and small coastal parts of the mainland. Most of the areas are hard-to-reach and can be accessed only by marine transportation. The total area of the Reserve is 49,583 ha (according to the forest inventory for the years 1977–1978), including 49,583 ha of marine water area. The main purpose of the Reserve foundation was the protection of nesting areas of eider and other sea birds, as well as marine mammals. The reserve was founded by Decree of the Central Executive Committee of the Karelian Autonomous Soviet Socialist Republic on September 7, 1932. On its base, the Kandalakshskiy State Reserve has been created by Decree of the Sovnarkom (Soviet People Committee) of the Russian Soviet Federal Socialist Republic (RSFSR) № 386, as of July 25, 1939, with the special goal of the protection, studying and rehabilitation of the population of eider in Kandalakshkiy Bay of the White Sea.

By further decrees and orders, the territory of the Kandalakshkiy Reserve was expanded. By Decree of the Government of the Russian Federation № 1050 as of September 13th, 1994, Kandalakshkiy Bay of the White Sea, including the Kandalakshkiy State Natural Reserve, has been included on the List of Wetlands of International Significance, mainly as waterfowl habitats. A special regime zone has been created on the islands located near the town of Kandalaksha (the Oleniy archipelago and part of the Louven’gskiy archipelago) to prevent recreational loads on the main territory of the Reserve. Visting this zone is allowed with permits issued by the Reserve according to terms established by the Reserve and strictly outlined rules.

There are many natural protected areas in the boundaries of the White Sea. Natural reserves of regional significance (called, as mentioned above, “*zakazniks*”) have been established on the islands of the western part of Onezhskiy Bay and included on the Ramsar List of Wetlands of International Significance (Ramsar List), such as the “Kuzova Islands” Zakaznik and the “Sorokskiy” Zakaznik, which have marine water areas within their boundaries. The “Kuzova Islands” Zakaznik possesses 25 km^2 of marine water area out of its total area of 36 km^2 (the area is included on the Ramsar List as a key ornithological site). The “Sorokskiy” Zakaznik has a total area of 739 km^2 (the area is included in The Emerald Network Council of Europe Program as a key ornithological site). The Shuyostrovskiy and Von’gomskiy Zakazniks have areas of 100 km^2. and 65 km^2, respectively. All these zakazniks belong territorially to the Republic of Karelia.

There is a museum-reserve located on the territory of the Solovetskiy Archipelago (Arkchangelsk region) in Onezhskiy Bay, including a zone of strict protection (area of natural significance). The zone area is 49.4 km^2 or 17 % of the Archipelago area. Cape Beluzhiy on Bol’shoy Solovetskiy Island has natural monument status; the coastal zone surrounding the cape is famous for its summer concentration of white whales and currently has special (if unofficial) protection status. The Dvinskoy (72 km^2), Belomorskiy (1130 km^2) and Ouemskiy (34 km^2) Zakazniks are located in Dvinskoy Bay, covering 54 % of the Dvina Delta. The Dvinskoy and Ouemskiy Zakazniks also have status of the Ramsar key ornithological sites.

The Moud’yugskiy Zakaznik has an area of 25 km^2. Two fishery zakazniks, Varguzskiy (387 km^2) and Ponoyskiy (1500 km^2), were established on the Kol’skiy Peninsula for salmon protection. The total area of the natural protected areas of the terrestrial part of the White Sea is 4712.5 km^2, and that of its marine water areas is 520.8 km^2.

8.12 Red Data Book of the White Sea

On the coastal zone of the White Sea, there are several species of plant and animal listed in the Red Data Book of rare and endangered species. For example, two unique endemics *Helianthemum arcticum* and *Taraxacum leucoglossum* can be found on the Turiy Cape coast of the Kandalakshskiy Reserve. The rare *Cypripedium calceolus* is found in the coastal forests; this perennial plant belongs to the *Orchidaceae* family and has large flowers in the shape of lady slippers of yellow color with red dots. Collecting the plant is prohibited in European countries. There are also other other species of orchids that have to be protected: *Epipogium aphyllum*, *Calypso bulbosa*, *Platanthera bifolia*, *Listera ovata*, *Hammarbya paludosa*. Some of the more widespread rare plant species are *Potentilla Lapponica* (*Rosaceae family*) *and Draba insularis* (*Brassicaceae family*). There are also rare ferns – *Botrychium lanceolatum*, *Botrychium multifidum*.

Amongst the animals inhabiting the White Sea, six species are listed in the Red Data Book: the European shag (*Phalacrocorax aristotelis*), the Grey seal (*Halichoerus grypus*) and the butterfly Swallowtail (*Papilio machaon*). Three species of large birds of prey are also included: the Gyrfalcon, the White-tailed Eagle, and the Osprey.

8.13 Modern Anthropogenic Impact

The modern technological transformation of the coastal zone (mooring lines, coastal protection constructions, etc.) of the White Sea and the pollution of coastal waters are caused by:

1. The existence of several very large developing sea-port complexes, particularly the Arkhangelsk seaport, and smaller harbours in the towns of Kandalaksha, Kem', Onega, Belomorsk, etc.;
2. The conduction of fairway clearance at the entrance to the Arkhangelsk seaport;
3. The dumping of significant amounts of outdated weapons (and possible dumping of chemical weapons, according to certain data) in the White Sea water area;
4. The existence in the coastal zone of two large shipbuilding factories that specialize in the building, repairing and utilization of nuclear submarines;
5. Location of the large industrial and transportation center formed by the cities of Severodvinsk, Arkhangelsk, and Novodvinsk in the Severnaya Dvina mouth;
6. River run-off that carries large masses of pollutants from the paper mills to the coastal waters.

Marine transport and seaport infrastructure with a specific set of hydrotechnic structures and activities makes its own contribution to the technogenic disturbance of the geological environment. Most of all, in this case, the sea floor sediments and coastal soils are contaminated with waste lubricants and other petroleum components.

At the same time, the port facilities (piers, mooring lines) have an impact on the geological environment of the coastal zone. In addition to the above-mentioned cities on the shores of the White Sea, there are isolated settlements, usually old semi-abandoned Pomor villages located far apart from each other. Therefore, there is a relatively small amount of hydrotechnic structures, including structures for coastal protection.

8.14 Recommendations for the Prospective Economic Development of Unique Coastal Landscapes with Definition of Appropriate Types of Economic Activity

One of the most promising areas of economic development on the White Sea coast is marine transport with the expansion of the ports of Arkhangelsk, Kandalaksha and Belomorsk and reconstruction of the White Sea–Baltic Sea canal. Restrictions on the development are related to the inability to take large ships, the need for ice-breaking ships accompanying other vessels from January to April, and the demand for constant dredging (approaching channels are quickly filled with sand). Development of the "Belkomur" transport project, a network of roads linking the Urals and Scandinavia, is of great importance for the Arkhangelsk region. Activities of shipbuilding and ship-repairing factories in Arkhangelsk have intensified. Production of trawlers, barges and drilling platforms was mastered as a result of the military conversion. The "Sevmashpredpiyatie" and "Zvezdochka" companies began to receive military orders and modernized the previously built ships, as well as utilizing ships, submarines and missiles; the world's first floating nuclear power plant is currently under construction. The "Rosshelf" enterprise plans to produce around 50 billion cubic meters of natural gas in the Barents Seas and has placed its orders for ice-resistant drilling platforms at the machine-building factories of the Arkhangelsk region. Expansion of transport and shipbuilding activities, which are extremely important for the regional economy, requires comprehensive scientific support of the projects at all stages of their development, as well as technologies to minimize possible negative impacts on the unique and fragile natural ecosystems of the White Sea coast.

The combination of unique and diverse coastal landscapes, a large number of unique historical and natural monuments, and an abundance of wildlife opens up broad prospectives for the development of different kinds of domestic and international tourism, such as cultural and educational tourism, eco-tourism, hunting and fishing, boating and rafting, river and sea cruises, event and adventure tourism, religious tourism, medical and health tourism, ethnographic tourism, etc. Development of any type of tourism must be guaranteed, first of all, by the development of transport infrastructure, development of the hotel network in 579 coastal cities and settlements, improvement of the information network, development of services to ensure security of the tourism routes (for example, warnings about unfavorable weather conditions) and rescue services. Quantitative restriction of the tourist flow is not much an issue in the region, because the flow is, in fact, very limited, except for the islands of the Solovetskiy Archipelago and, perhaps, Kandalaksha Bay within the Kandalakshskiy reserve.

A literature survey and an analysis of library material, information from online sources and, in part, results of field research indicate significant potential for the development of different types of tourism on the White Sea coasts. The unique combination of attractive continental and coastal landscapes, relatively undisturbed nature, and numerous monuments of historical and cultural heritage all combine to create the preconditions for the development of not only domestic, but also international tourism. Taking into account the capacity of the White Sea-Baltic Sea Channel and the relatively well-developed railway network, another promising area of economic development for the White Sea coastal region is maritime transportation with the construction and development of new ports and terminals. While implementing regional development plans, it is critically important to provide conditions for the careful preservation and prospective future development of unique coastal landscapes on the basis of the creation of mechanisms for conflict resolution in different branches of the regional economy.

Among the most promising areas of the White Sea coast, the following territories can be distinguished: the coast and islands of Kandalaksha Bay; the Solovetsky Archipelago area, as well as the sparsely populated or uninhabited islands of the Onega archipelago (Kondostrov, Bol'shoy Zhuzhmuy, Myagostrov and other islands); the Karelian coast and surrounding archipelagos.

References

Beck TA, Kolbasov GA, Sokolov KV (2001) The ecosystem of the white sea as upshot of Land-Ocean mass fluxes. In: Secular changes in Arctic marine ecosystems. The climate, the marine periglacial, biological productivity. KNC of Russian Academy of Sciences, Apatity, pp 71–81 (in Russian).

Dobrovol'sky AD, Zalogin BS (1982) Morya SSSR (Seas of the USSR). MSU, Moscow

Dyer KR (1997) Estuaries. A physical introduction. Wiley, Chichester

Elshin YA (1979) Riverine runoff to the white and the Barents Seas and its variations within a year and on a multiannual scale. Vodnye Resursy 2:65–69

Gorbatovskiy VV (2009) Geological natural monuments of Russian Federation. Knysh, Moscow (in Russian)

Kandalaksha Reserve official web-site (2014) Accessed 15 Oct 2016. Available: www.kandalaksha-reserve.org

Khailov KM, Prazukin AV, Kovardakov SA, Rygalov VE (1992) Functional morphology of multicellular marine algae. Naukova Dumka, Kiev (in Russian)

Klige RK (1985) Changes in the global water cycle. Nauka, Moscow

Koshechkin BI, Markov GA, Nikonov AA, Panasenko GD, Strelkov SA (1975) Postglacial and recent crustal movements in the northeast of the Baltic shield. Tectonophysics 29–1:339–344. Published by Elsevier B.V

Krasnova ED (1997) The spatial organization of the settlement of free-living nematodes Chromadoropsis vivipara II. Materials of scientific conference at WSBS Moscow State University (17–18 August 1996). WSBS of the Moscow State University, Moscow, pp 19–21 (in Russian)

Kravtsova VI, Mit'kinyh NS (2013) Mouth of Russian River. In: Mihaylova VM (ed) Atlas of satellite images. Scientific World, Moscow (in Russian)

Lavrova MA (1960) Quaternary geology of the Kola Peninsula. Publishing House of the USSR Academy of Sciences, Leningrad (in Russian)

Leonov AV, Chicherina OV (2004) Removal of nutrients in the White Sea with the river runoff. Water Resources 31(2):170–192. Moscow: Nauka (in Russian)

Maximova MP (1967) Stoke nutrients from the river waters of the Karelian coast to the White Sea. Research of the Fauna of the Seas 7(15):15–22. Leningrad: Zoological Institute of the USSR Academy of Sciences (in Russian)

Nevessky EN, Medvedev VS, Kalinenko VV (1977) The White Sea: sedimentogenesis and history of development in the Holocene. Nauka, Moscow (in Russian)

Pantiulin AN (2001) The White Sea as a large-scale estuarine system. Geophysical Research Abstracts 3:5–21.Vienna, Austria: EGU General Assembly

Pantiulin AN (2003) Hydrologiea system of the White Sea. Oceanology 43(1):1–14. Moscow: IAPC Nauka/Interperiodica

Pantyulin AN (1974) Selected features of the water structure in the White Sea. Biology of the White Sea 4:7–13. Moscow: Moscow State University

Pantyulin AN (1983) Interaction of the ocean with the waters of the continental runoff. In: Duvanin AI (ed) Interaction of the ocean with the environment. Moscow State University, Moscow, pp 129–154

Pantyulin AN (1990) On the formation and variability of the water structure in the White Sea. In: Matekin PV (ed) Biological resources of the White Sea. Moscow State University, Moscow, pp 9–16

Pobedonostsev SV, Rozanov LL (1971) Recent vertical movements of the White and the Barents Seas. Geomorfology 3:57–62. Moscow: Institute of Geography of the Russian Academy of Sciences

Red Data Book of the Murmansk Region (2003) Murmansk regional publishing house, Murmansk

Red Data Book of the Russian Federation (2001) Nauka, Moscow

Sadikov MA (2001) Retrospective monitoring of marine ecosystems. In Secular changes in Arctic marine ecosystems. The climate, the marine periglacial, biological productivity. KNS of the Russian Academy of Sciences, Apatity, pp 49–71 (in Russian)

Timonov VV (1950) Principal features of the hydrological regime of the White Sea (Yu. M. Shokal'skii in Memoriam). Moscow, pp 206–235

Vareychuk NS, Ignatov EI (1989) Geomorphology of the coast and bottom of the White Sea. In: Geomorphology. Institute of Geography of the Russian Academy of Sciences, Moscow

Vareychuk NS, Ermolov AA, Ignatov EI, Tchistov SV (2012) Outlines of geomorphology of the coast and bottom of the White Sea. SPC "ECOSI-Geophysica", Sevastopol (in Russian)

Zatichnoi BM, Gershanovich DE (eds) (1991) Gidrochemical conditions and oceanographic bases of formation of bio-productivity. In: Hydrometeorology and hydrochemistry of the seas of the USSR, vol. II: The White Sea. Hydrometeozdat, Leningrad, pp 8–112 (in Russian)
Zavarzin GA (2004) In: Kolotilina NN (ed) Lectures on natural sciences microbiology. Nauka, Moscow (in Russian)
Zenkovich VP (1938) Fishing maps of bottom soils of the Knyazhaya, Voron'ya and Belaya inlet bays. Trudy VNIRO 5:131–164. Moscow: Joint scientific and technical publishing house of the USSR NKTP (in Russian)
Zubov NN (1956) Fundamentals of the theory of the straits of the World Ocean. Geografgiz, Moscow

The Diversity of Russian Estuaries

9

Ruben Kosyan, Petr Brovko, and Jean-Paul Ducrotoy

Abstract

This paper gives an overview of the eight chapters of the book "The Diversity of Russian Estuaries and Lagoons Exposed to Human Influence" edited by R. Kosyan in the collection "Estuaries of the World". The book gives a comprehensive review of the current state of knowledge of the estuaries and marine coastal lagoons of Russia, identifying the most urgent problems concerning the management of natural resources and ecosystem services they provide. The analysis of ecological, geographical and socio-economic aspects governing the evolution of these ecosystems demonstrates that the natural features which characterize them are not currently adequately addressed. The economic development of coastal areas in Russia does not sufficiently take into account the structure and functioning of these complex natural systems. There is an urgent need for recommendations as to integrated planning and balancing of economic activities taking place in coastal municipalities and regions of the Russian Federation that include such unique coastal systems as lagoons, estuaries and limans.

Keywords

Russian seas • Estuaries • Physical geography • Anthropogenic impact • Natural processes • Technogenic processes

9.1 Introduction

Estuaries and deltas, including coastal lagoons, are well-represented worldwide. They make up 9.2 % of the total length of the coastline. Their richness in natural and mineral resources contributes to the wealth provided by coastal areas all around oceans and coastal seas. Actually, they create the conditions for flourishing economic activity based on their biological and ecological potentials. This is why they are the most promising places for economic development, carried out in the spirit of sustainability. The border position of estuaries and coastal lagoons in the contact zone between land and sea is the reason why they are so productive, but it is also why they are highly sensitive to external influences (natural and anthropogenic). As a result, their position at the interface between continental and oceanic systems determines the high dynamism of their geological and ecological functioning.

The main objective of this book is to provide a comprehensive review of the current state of the estuaries and coastal lagoons of Russia in order to detect and highlight the most pressing drawbacks affecting their natural characteristics. In order to do so, it was essential to identify which ecosystems were currently in need of urgent protection, the nature of the threats and what can be done to address them.

R. Kosyan (✉)
P.P. Shirshov Institute of Oceanology Russian Academy of Sciences (IO RAS), 1-g, Prostornaya, Gelendzik 353467, Russia
e-mail: rkosyan@hotmail.com

P. Brovko
Far Eastern Federal University, Vladivostok (FEFU), 8, Sukhanova St, Vladivostok 690950, Russia
e-mail: peter.brofuko@yandex.ru

J.-P. Ducrotoy
Institute of Estuarine and Coastal Studies, The University of Hull, Cottingham Road, HU6 7RX Hull, UK
e-mail: jean-paul.ducrotoy@hull.ac.uk

R. Kosyan (ed.), *The Diversity of Russian Estuaries and Lagoons Exposed to Human Influence*, Estuaries of the World, DOI 10.1007/978-3-319-43392-9_9

In the Russian Far East Seas, lagoons and estuaries are found mostly on the Chukotka, Kamchatka, and Koryak coasts, as well as around the island of Sakhalin. On the coast of the Arctic Ocean, there are typical lagoons, as well as individual bodies of water of the lagoon type established on shores where erosion and accumulation counter-balance.

On the Russian coast of the Baltic Sea, there are two large lagoons within the Kaliningrad region. Near St. Petersburg, in Neva Bay, artificial (man-made) lagoons were constructed in the process of coastal development.

On the coasts of the Black Sea and the Sea of Azov, a special type of coastal system is present. These are called "limans". Limans are morphologically similar to coastal lagoons, but have special features which justify the use of a particular word to designate them. They belong to deltaic systems and develop near the opening of the mouth of a river into the sea. They are more or less protected from open water by a barrier or spit. They are particularly muddy, and coastal marshes take advantage of such special conditions.

From a scientific point of view, the most important issues, which are discussed in this book, are as follows:

– The study of the structure and dynamics of bars and spits, separating lagoons from the sea;
– Research carried out on the direction and speed of movement, sediment distribution, etc., of lagoon straits, spits and coastal bars;
– The review of the current sea level, and the impact of its rising on the dynamics of the lagoon and adjacent shores;
– An assessment of the impact of current and planned economic activities on estuaries and lagoons, leading to a discussion of environmental challenges;

The analysis was conducted using results from field work carried out by Russian researchers in oceanography. Material collected throughout a long period of work is presented, including expeditions, as well as the results of recent studies, published in the scientific literature.

The complex characteristics of almost all Russian coastal systems and estuaries were systematized and presented for selected regions: the coasts of the Black Sea, the Sea of Azov, the Baltic Sea, including a detailed description of the Kaliningrad coast and the Gulf of Finland, the Okhotsk coast, the Sea of Japan, the Bering Sea, and all the seas of the Russian sector of the Arctic, as well as the unique coasts of Sakhalin. A large number of copyrighted and stock illustrative materials were used. Based on the examined data, we were able to identify the following general features of the estuaries and lagoons of every considered sea:

9.2 Positioning of Considered Estuaries, Lagoons and Limans

Most of the lagoons and estuaries in Russian seas are confined to accumulative shores, stretching hundreds of kilometers and bordering the low coastal plains of different origin. Some lagoons are also found within fjords. Estuaries are represented by funnel-shaped mouths of rivers meeting tidal seas.

9.3 General Characteristics of Estuaries, Lagoons and Limans

Estuaries, lagoons and limans are predominantly of medium and small size, i.e., 10–100 km^2. To varying degrees, they are separated from the sea by accumulative geomorphological features and connected by straits of permanent or seasonal types. The temperature and salt regime of water bodies are largely dependent on the tides, storm surges and river runoff. The river flow factor is decisive. The largest estuaries are located in the mouths of the Amur and Yenisei Rivers.

9.4 Morphodynamical Characteristics of the Coast

In estuaries, lagoons and limans with a prevalence of sediment accumulation, the range of denudation processes is widely developed, due to, i.e., wave and chemical abrasion, deflation, thermo-denudation, slope processes, and other processes. It is essential that nutrient recycling be considered, especially in the Black Sea, the Sea of Azov and the Sea of Japan. A constant flow of in-flowing rivers is of great importance. Unique geomorphological features characterize lagoons and limans, i.e., bars, braids, sand dunes, reefs, etc.

9.5 Brief Description of the Adjacent Coast

The relief of the sea coasts is extremely diverse. Estuaries, lagoons and limans are usually found on platform and orogenic areas with different directions and rates of movement. Their morphology is dependent on the climate and is formed under different zonal conditions – from subtropical to subarctic. Steppes, meadows, marshes and forests constitute common landscapes.

9.6 Biological Characteristics of Estuaries, Lagoons, and Limans

Estuaries and lagoons are characterized by a high biodiversity. Most often, the number of species and the biological productivity in estuaries is higher than in the surrounding sea areas. Wetlands of global significance are situated in the lagoon systems of the Black Sea, the Sea of Azov, the Sea of Japan, the Eastern Siberian coast and other seas. Specially protected areas have been established, including the Far Eastern State Marine Biosphere Reserve in Peter the Great Bay (Sea of Japan), where small lagoons and estuaries were formed (Brovko 2002).

9.7 Characteristics of Existing Exposure

Estuaries and lagoons in many seas are influenced by business activities in connection with the development of maritime transport and certain industries. These include energy, oil and gas, fisheries, shipbuilding, hydraulic engineering, and the building materials industry.

Of significance is the construction of berthing facilities, breakwaters, approach channels, dams, bridges, pipelines, strengthening of bank protection, and sand quarries. Indirect impacts due to the regulation of rivers, which affects the circulation of water masses, change the salt regime and the volumes of liquid and solid run-off.

9.8 Promising Directions

In the future, there will be an increasing influence of economic activities in estuaries and lagoons. Not only industrial developments are expected. Mariculture, spa resorts and thalassotherapy, tourist excursions and environmental activities are expected to pick up in the water bodies of the Baltic Sea, the Black Sea, the Sea of Azov and the Sea of Japan.

On the coasts of the Arctic and Pacific Oceans, along with the above-mentioned areas of development, the development of dredging, construction of waterworks and power plants, and the expansion of transportation and communication infrastructures are expected.

Greater attention will be paid to the creation of protected areas, i.e., marine reserves, national parks, and natural monuments expected to valorize the unique coastal landscapes.

9.9 Assessment of Lagoons' Vulnerability to External Factors of Natural and Antropogenic Charter

Among the negative influence of so-called natural factors affecting the evolution of estuaries and lagoons are climate change, secular variations in global sea level, increased storminess and wave activity, reduction of the ice cover, destruction of permafrost, and others.

Anthropogenic factors presently have a local character. They relate both to radical changes in the geomorphology of estuaries and lagoons in relation to industrial developments, and countless ecological impacts on the aquatic environment and the landscape in general.

Currently, progress is being made to adopt an integrated approach to coastal management and help promote non-impacting economic developments of estuaries, lagoons and limans in terms of the sustainability of economic activities, adapted to the acute vulnerability of such natural systems.

Issues concerning future economic development and governance considerations are discussed in dedicated sections of the book. Knowledge on the current ecological status and possible changes affecting coastlines is vital for understanding and elaborating strategies for securing the socio-economic well-being of human communities. These are tantamount to the necessary foundations for balanced business undertakings and any planning on the coast, comprising the future of unique coastal landscapes located in the vicinity of estuaries and lagoons.

9.10 Conclusion

Russia is the largest country in the world in area, and has the longest coast line. This determines the diversity of its coastal marine landscapes and, therefore, the difficulty of the differentiation of strategic approaches for their conservation and sustainable development. Using the experience of the best international practices in the field of environmental protection in developed countries, with extensive experience in the field of integrated coastal zone management (ICZM), as well as the experience of developing countries in such solutions to environmental problems by cheaper and simpler means (which are, at the same time, non-standard for other countries), may contribute to the conservation of unique coastal ecosystems.

Such countries as the United Kingdom, Belgium, Australia, Canada, the USA and others, widely use marine spatial planning (MSP) as the main tool for attaining ICZM. These countries elaborate specific plans for the development of coastal areas, using the tools of the World Food Program (WFP), based on an ecosystem approach. It is important to note that WFP began developing in Russia at the beginning of the twenty-first century. The most important document, focused on spatial planning in the Baltic Sea, was prepared by HELCOM (2007). Also, the atlas of biodiversity of the seas and coastlines of the Russian Arctic (Spiridonov et al. 2011) was developed as a basis for conservation planning in the seas and on the coasts of the Russian Arctic.

Thus, MSP for Russia is a new and rapidly developing tool to achieve ICZM. This tool has not yet received regulatory consolidation in the Russian Federation, which complicates the process of its use in practice, but in general, the principles laid down in this tool can facilitate the introduction of the best international practice experience in the field of ICZM and the sustainable development of the unique coastal landscapes of Russia, including estuaries and lagoons.

For the sustainable management of natural coastal systems, Russia needs modern coastal legislation. Within the framework of the legislation, authorized forms of economic activity and permitted forms of ownership of coastal zone areas must be clearly defined and the issue of the delimitation of powers of the Russian Federation versus its citizens for coastal zone management addressed.

Given the level of the challenge and the importance of coastlines of different morphogenetic types, including estuaries, lagoons and limans, for the sustainable development of coastal areas, it is necessary to take into account the Coastal Code, complementing other federal laws of the Russian Federation (Water Code, Forest Code, Land Code, the Law on Subsoil and so on). While developing the Coastal Code, it is deemed necessary to identify the legal and administrative status of the coasts as a whole and their individual morphological areas in particular. Overall, it is suggested that:

- Sea coasts should be recognized as a non-renewable natural resource;
- The Code should reflect the regional, natural, economic, geopolitical and other features of the coasts of each sea basin of Russia
- Zoning must be carried out using computerized Geographic Information Systems (GIS);
- For each coastal region of Russia, there should be a defined set of individually- and scientifically-based restrictions in the Coastal Code, imposed on the use of natural resources, together with an outlined set of actions to minimize the negative impacts of regional and global changes in natural factors that reduce the stability of coasts;
- The Coastal Code of Russia should include provisions on the regulation of issues related to cross-border issues, and provide the necessary "unification" of the Code of international law in the field of marine environmental protection and development of ICZM;
- For the realization of the Coastal Code and the monitoring of its implementation, it is suggested that a single administrative body be established at the federal level;
- For the preparation of the Coastal Code and to ensure its implementation, we need a multi-disciplinary research unit, which should include experts in the fields of earth sciences, economics, environmental management, and administration.

During the preparation of the Coastal Code, it is proposed that an assessment be conducted of the use of coastal zones in accordance with the priority purpose of any future development, i.e., the development of ports and industrial zones, recreation, fisheries, and the conservation of natural systems, including for special purposes. For that to be done, work on the coastal marine cadastre must be carried out. The proposed geo-referenced database could be the basis for the formation of not only the Coastal Federal Code, but also regional development programs for the coastal regions of Russia, and for the integrated management of coastal zones, including estuaries and lagoons (Kosyan 2013).

References

Brovko PF (ed) (2002) Atlas of the coastal zone of Sakhalin island. Far Eastern National University, Primorsky Aerogeodetic Enterprise, Vladivostok (in Russian)

HELCOM (2007) HELCOM Baltic Sea action plan. Adopted on 15 Nov 2007 in Krakow, Poland by the HELCOM Extraordinary Ministerial Meeting. http://www.helcom.fi/Documents/Baltic%20sea%20action%20plan/BSAP_Final.pdf

Kosyan RD (ed) (2013) Scientific support for the balanced business planning on the unique coastal landscapes and proposals for its use by the example of the Azov-Black sea coasts. Research report. SB SIO, Gelendzhik (in Russian)

Spiridonov VA, Gavrilo MV, Krasnova ED, Nikolaeva NG (eds) (2011) Atlas of the Russian Arctic seas and coasts biological diversity. WWF of Russia, Moscow (in Russian)

Index

A
Abrasion shores, 28, 46, 49, 51, 113, 132, 139
Abrasive coasts, 62, 233
Abrasive processes, 53, 63, 68, 69, 87, 233
Accumulative bodies, 16–21, 23, 24, 28, 38, 41, 44, 46, 49, 51, 53–55, 99, 101, 108, 109, 134–135, 138
Accumulative coasts, 41, 57, 109, 113, 255
Accumulative forms, 2–5, 7, 23, 62, 69, 71, 73, 112, 113, 131, 138, 143, 144, 147, 232
Accumulative processes, 32, 44, 53, 217
Accumulative shores, 4, 24, 28, 36, 71, 94, 245, 253, 266
Akhtanizovsky liman, 116, 117, 120–124
Akhtarsky liman, 116–119
Alluvial material, 73, 79, 99, 258
Anapa bay-bar, 94, 99, 100, 102, 103, 108, 109
Anthropogenic, 3, 53, 63, 69–71, 73, 88, 96, 107, 108, 123, 131, 146, 147, 186, 191, 193, 196, 201, 203, 207, 214–216, 234, 240, 246, 258, 265, 267
  impact, 23, 71, 109, 191, 193, 202, 203, 207–215, 217, 240, 261
Arctic seas, 14–56, 60, 223, 257, 266

B
Baltic Sea, 2, 149–186, 191–218, 226, 228, 261, 262, 266–268
Barents Sea, 14–18, 23–26, 55, 223–225, 227–229, 241, 250, 251, 261
Bay-bars, 2, 19, 20, 22–24, 28, 41, 43, 44, 46–53, 55, 60, 62, 64, 69–71, 73, 95, 99, 101–104, 106, 108, 113, 115, 119, 120, 122, 126–128, 139, 145
Beisugsky liman, 124–131
The Bering Sea, 4, 9, 58–60, 64, 266
Biogenic, 3, 7, 71, 76, 80, 82–84, 90, 113, 125, 138, 200, 234, 238
Biological disaster, 223
Black Sea, 2, 16, 93–109, 112, 113, 117, 121, 124, 137, 138, 141, 143, 147, 242, 266, 267
Bottom sediments, 3, 58, 65, 73, 76–80, 83–85, 89, 155, 157, 158, 170–174, 193–196, 201–202, 205, 207, 212, 217, 253, 254
Bugazsky liman, 99, 102, 104, 105

C
Chukchi Seas, 2, 14, 15, 20, 22–24, 52, 55
Climate changes, 15, 163–165, 182–186, 258–259, 267
Coastal areas, 1, 62, 67, 73, 150, 172, 176, 185, 197, 199, 204, 206, 208, 213–215, 232, 239, 240, 242, 251, 253, 254, 257, 265, 268
Coastal landscapes, 60, 71, 208, 261–262
Coast protection, 109
Conditions of estuaries formation, 2
Curonian Lagoon, 150–168, 178–182, 185, 186, 216

E
Eastern Gulf of Finland, 191–218
East-Siberian Sea, 14, 15, 19–21, 23, 40–41, 43, 55, 267
Ecosystems, 15, 23, 26, 35, 36, 53, 71, 99, 103, 107–109, 135, 138, 143, 146, 147, 197, 203, 205, 207, 212, 225, 239, 242, 244, 246, 261, 265, 267, 268
Environmental protection, 15, 71, 147, 178, 181, 182, 185, 267, 268
Estuaries, 1–8, 14–91, 95, 96, 99, 109, 115, 147, 150, 157, 202, 216, 228–231, 241, 245–251, 265–268
Estuarine system, 86–91, 204, 223–262

F
Far Eastern seas, 3, 5
Formation processes, 4, 50

G
Geological conditions, 16
Geological structure, 16, 22, 28, 59, 62, 87, 113, 137, 146, 194, 198, 231, 233
Geomorphological structures, 1, 58–62, 66–75
Geosystems, 14, 15, 86, 99, 108
Granulometric composition, 65, 96, 254

H
Human activities, 3, 15, 23, 113, 179, 186, 202, 203, 205, 215, 239
Human impacts, 215
Hydrobiological conditions, 23
Hydrodynamic, 2, 16, 66–68, 76, 80, 81, 138, 146, 157, 192, 202, 207, 232, 233, 251–253, 256, 257
Hydrological conditions, 23, 26, 36, 40, 55, 88–89
Hydrological processes, 23, 26, 216
Hydrological regime, 2, 16, 23, 30, 53, 58, 77, 78, 80, 86–88, 90, 91, 102, 117, 147, 155, 168, 192, 204, 224, 242, 243
Hydrology, 88, 89, 192–193, 223, 228–231

I
Ice conditions, 15, 35, 69, 246
Imeretinskaya lowland, 94–99, 109
Integrated coastal zone management (ICZM), 267, 268

K
Kara Sea, 14–16, 23, 24, 26–36
Kiziltashsky liman, 99, 102–105

R. Kosyan (ed.), *The Diversity of Russian Estuaries and Lagoons Exposed to Human Influence*, Estuaries of the World, DOI 10.1007/978-3-319-43392-9

Kuban River, 99–105, 112, 114–117, 119–121, 123–125, 147
Kurchansky Liman, 117, 119–120, 123

L
Lagoons, 1–8, 14–91, 93–109, 112–147, 149–186, 191–218, 234, 242–245, 258, 265–268
Laguna, 2, 71
Laptev Sea, 14, 19, 20, 23, 36–40, 54
Liman, 1–8, 23, 26, 28, 30, 35, 57–91, 99, 102, 104–106, 112–135, 142, 144, 146, 147, 266–268
Lithodynamics, 16, 53, 56, 99, 108, 109, 139, 147, 199, 251–259
Lithology, 16, 44, 53, 58, 59, 200, 233, 254, 256

M
Maritime spatial planning, 178

N
Natural influence, 15
Nature monuments, 75, 79, 146, 259–262, 267
Neva Bay, 150, 151, 191–218, 266

P
Phytoplankton, 15, 124, 130, 193, 202, 203, 205
Pregolya River, 151–154, 156–158, 163, 166, 169, 173, 175, 185, 186

R
Red Data Book, 206, 213–215, 239, 260–261
Rivers, 2, 14, 58, 94, 112, 149, 191, 225, 266
The Russian Arctic coasts, 14–56, 268

S
Sakhalin island, 7, 8, 58, 60, 62, 66–89, 91, 150, 266
Salinity, 2–5, 14–16, 23, 24, 26, 35, 57, 58, 62, 64, 84, 101, 102, 106, 108, 109, 117, 119, 131, 138, 151, 155–161, 168–170, 183, 186, 192, 198, 203, 204, 228–231, 241–246, 251, 257
Sea coasts, 7, 23, 25, 31, 37, 42, 45, 46, 51, 94–96, 100, 108, 109, 131, 231, 239–242, 244, 260–262, 266, 268
The Sea of Azov, 112–120, 124, 125, 129, 131, 138, 144–147, 224, 266, 267
The Sea of Japan, 3, 60, 62–64, 66, 86, 88–91, 266, 267
The Sea of Okhotsk, 11, 60–62, 64, 66, 73, 75, 76, 84, 86–91
Sedimentation processes, 3, 201–202, 209–211, 216, 217
Sediments, 2, 7–9, 21, 23, 30, 36, 41, 44, 49–51, 53, 54, 57–59, 61, 64, 67–69, 71, 73, 76–80, 82–84, 86–91, 95, 96, 99, 102, 108, 109, 112, 113, 117–121, 129, 138, 140, 149, 155, 157, 158, 161, 168, 170, 172, 173, 183, 193–195, 197, 198, 201–203, 207, 209, 210, 212, 216, 217, 231–233, 240, 246, 250–257, 260, 261, 266
Sediment transport, 24, 28, 36, 44, 46, 49, 51, 53, 55, 64, 69, 70, 73, 109, 155
Specially protected areas, 146, 260, 267

T
Technogenic changes, 15
Terrigenous material, 36, 50, 112, 254, 256
Transport of sediments, 24, 28, 36, 44, 46, 49, 51, 53, 55, 64, 69, 70, 73, 109, 254

U
Unique coastal landscapes, 261–262, 267, 268
Usage, 70

V
Vertical water structure, 229
Vistula Lagoon, 150–186, 216

W
White Sea, 14, 24, 223–262

Z
Zooplankton, 15, 86, 106, 124, 130, 204–205, 241