Estuaries of the World

John W. Day
G. Paul Kemp
Angelina M. Freeman
David P. Muth *Editors*

Perspectives on the Restoration of the Mississippi Delta

The Once and Future Delta

Springer

Estuaries of the World

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To all the people who live, work, and enjoy the coast

Foreword

Securing the future of estuarine ecosystems through a multidisciplinary understanding of their complexity: the added value of a holistic scientific approach.

The coastal zone is widely perceived as an important component of the biosphere—a place of diverse ecosystems and resources, and an area where multiple stakeholders develop their activities and exploit these resources. Current changes in climate (e.g. temperature and sea-level rises, extreme weather events such as floods and droughts) may increase the risk of abrupt and non-linear trends in estuarine ecosystem evolution, which would affect their composition, function, biodiversity and productivity. An increase in frequency of extreme events would likely disrupt the equilibrium of estuarine systems, predominantly as a consequence of disparities in response times of their multiple components (species, populations, communities, etc.). Estuaries are amongst the most productive, but most endangered ecosystems in the world. Pollution, eutrophication, urbanization, changes in land-use/land reclamation, over-fishing and exploitation of natural resources continuously threaten their future. The major challenge currently faced by human populations is managing the use of coastal ecosystems while simultaneously safeguarding the enjoyment of their visual, cultural and ecological resources by future generations. Such an objective presupposes that all consumers and end-users of the environment communicate their views on the basis of robust science.

There is a dearth of conclusive data to provide advocacy for a more integrated, scientific approach to coastal ecosystem management. Over the last decade there have been numerous advances in both understanding and approach to estuaries and an increasing number multidisciplinary studies have been undertaken. The available scientific information has come from a multiplicity of case studies and projects at local and national levels. Regional, international and global programs have been developed and rolled out; some are currently at the implementation stage while others have reached completion. Despite a rapidly increasing knowledge base, crucial questions on the causes of variability and the effects of global change remain unanswered. The perception of policy-makers is slowly shifting from a predominantly short-term economic agenda towards a longer-term socio-economic/ecological approach, yet there is a need to make existing scientific evidence more user-friendly for non-scientist decision-makers and stakeholders, without compromising the quality of such information

More and more courses at universities deal with coastal science and management but many fail to include or focus on estuaries. Excellent textbooks on the topic exist but they often do not reflect the variety and scope of scientific studies undertaken worldwide. Most of the time, students use ill-assorted, non-peer reviewed web sites. The situation is the same with regards to decision-makers and policy-makers who tend to consult ‘one-size fits’ all publications and material rather than refer to appropriate information on a relevant and/or context-specific estuarine site. As for the scientific community, it would greatly benefit from assembling and organising the existing evidence and knowledge-base. This book series, “Estuaries of the World” (EOTW) by Springer, achieves just that, considering scientific aspects of estuaries through a multidisciplinary approach. The series does not just attempt to catalogue pertinent case studies but also provides examples of best practice in scientific research and coastal management. The target audience consists of university students, decision-makers, policy-makers, and scientists with a direct or indirect interest in estuaries.

This book (the second in the collection) deals with the Mississippi River delta. The Mississippi is one of the largest delta systems in the world and encompasses a number of large sub-estuaries. This system provides an interesting model with which to compare other river mouth systems of the world.

Covering about 25,000 km^2, the Mississippi Delta is the largest and most ecologically productive coastal ecosystem in North America. But after expanding on a geological time scale, the delta has been shrinking since the industrial revolution and has become an unsustainable system. It has diminished in size throughout much of the last century, losing about 25 % of its coastal wetlands, because of anthropogenic impacts including separating the river from the delta plain by levees and pervasive hydrologic disruption. The example of the Mississippi demonstrates that restoring damaged habitats is the key to the ecological future of the delta. An understanding of what the delta was like before large-scale human intervention is essential, as well as what caused its decline, and whether stopping the decline is something that can and/or should be done. From the point of view of ecological restoration, the book shows how this degraded landscape might be resuscitated. However, while climate change will make coastal restoration more challenging, energy costs will limit options. These two factors will have an impact on all human activities. A solution to manage this difficult situation is to consider that navigation, flood control, and environmental management play equal roles.

In order to define strategies compatible with conservation and sustainable development at the local, regional and national levels, environmental aspects must be integrated into the management of the delta, which must rely on thorough collaboration between and mutual understanding of all actors and stakeholders. It is hoped that this book will contribute to restoring ecological function in a heavily impacted delta and will encourage a similar holistic and scientifically rigorous approach in comparable ecosystems worldwide.

The approach promoted in the EOTW book series has multiple objectives. The main objectives are to maintain coastal ecosystems in a healthy state to reduce pollution management costs and increase benefits from goods and services obtained from them. A holistic approach is needed to fulfil such objectives, whereby the system characteristics are considered in such a way that developments with negative impacts are prevented or at least minimized. This requires a major investment in research to better understand the way the system functions and the interactions between its different components and stakeholders, with a firm grounding in socio-economics, identification of ecological goods and services, and habitats needed for the delivery of such services to provide the expected benefits to humans.

Such a systemic approach to estuarine management relies upon the development of an integrative process for planning and the acquisition of scientific knowledge (based on field experiments and surveys, modelling, etc.) on hydrodynamics, sedimentology, ecology and climate change, all aspects to be covered in the new book series.

In this book on the Mississippi Delta, the editors have compiled information from a group of experts who were charged with addressing a series of questions concerning sustainable management of the delta. This effort was supported by three environmental groups (Environmental Defence Fund, National Audubon Society, and National Wildlife Federation) with funding from the Walton Family Foundation. Through a series of meetings, workshops, and presentations, the authors addressed a range of issues including an historical analysis of the delta, river morphodynamics and sediment dynamics, fisheries, flood control and navigation, wetlands and eutrophication, the socio-economic value of the delta, an analysis of human communities of the delta, and the potential impacts of climate change and energy scarcity. This book clearly presents the enormous challenges facing sustainable management of the delta and charts a way forward.

Jean-Paul Ducrotoy

Preface

In 1927, the entire Mississippi River system rose up like some angry beast and shouldered aside the levees designed to contain it. It flooded from Pittsburgh to Oklahoma City, entered the homes of nearly 1% of the entire U.S. population, absolutely devastated the region along the lower Mississippi River, shifted populations, changed Americans' perceptions of the role of government, and altered American regional and national politics.

In 1997 my book (*Rising Tide*, Simon & Shuster) about this flood was published and, fortunately, became a best seller. The single question most often asked me about the book was where I got the idea. I always gave the same answer: "I grew up in Rhode Island so it was perfectly natural for me to want to write a book about the Mississippi River."

Generally people responded with a laugh and thought I was joking. I wasn't. Anyone as interested in American history as I was–even those growing up by the Atlantic Ocean—must recognize how central the Mississippi River has been to the nation, and the river always fascinated me. And to me the river never meant just a straight line running from Minnesota to the Gulf; it did and does mean the entire Mississippi Valley, a valley which reaches east almost to Buffalo, New York, north into Alberta and Saskatchewan, and west into the Montana Rockies. I was hardly alone in recognizing that; the most important academic journal for American historians began publication titled *The Mississippi Valley Historical Review*, though it was subsequently re-titled *The Journal of American History*.

The Mississippi Valley is twenty percent larger than that of China's Yellow River, double that of Africa's Nile and India's Ganges, fifteen times that of Europe's Rhine. Within it lies forty-one percent of the continental United States, including all or part of thirty-one states. No river in Europe, no river in the Orient, no river in the ancient civilized world compares with it. Only the Amazon and, barely, the Congo have a larger drainage basin. In terms of economic activity it is by far the most important and most productive river system in the world. For its entire length and the length of all its tributaries, it pulses not only with the blood of America's history but its future.

The river is America.

It physically created part of America: by the deposit of sediment it made land in seven states all the way from Cape Girardeau, Missouri to the Gulf of Mexico, including all of coastal Louisiana. It even made land outside its floodplain, as coastal currents carried sediment west from one of several historic mouths of the river west to the Texas border. In total it made nearly 40,000 square miles.

And the river did far more than just that. It directed the nation's expansion across the continent. It spurred technological developments in fields as diverse as architecture, experimental physics, and metallurgy. It created great fortunes. It determined the path of major demographic movements. It forged America's economic might. In blues and jazz and literature, in Robert Johnson and Louis Armstrong, in Mark Twain and Richard Wright and William Faulkner, it created America's soul. T.S. Eliot called it the "universal river of human life," and wrote, "I do not know much about gods; but I think that the river/Is a strong brown god, sullen, untamed, and intractable./Patient to some degree… ever, however, implacable./Keeping his seasons and rages, destroyer…/Waiting, watching and waiting."

For me personally, as for Eliot, the river represents a mythic force, enormous and powerful and, if usually somnolent, sullen and dangerous. To me, images of paddle wheels peacefully turning over don't reflect the river; in the days when paddle wheel steamboats operated as other than tourist rides, there was little peaceful about them. They were rough and often violent worlds to themselves, as were the river ports they visited. A nineteenth century European had it right when he said of the Mississippi, "It is not like most rivers, beautiful to the sight, not one that the eye loves to dwell upon as it sweeps along, nor can you wander along its bank, or trust yourself without danger to its stream. It is a furious, rapid, desolating torrent. It sweeps down whole forests in its course, which disappear in tumultuous confusion, whirled away by the stream…, often blocking up and changing the channel of the river, which, as if in anger at its being opposed, inundates and devastates the whole country round."

That wild river seems to have disappeared. Humans seem to have taken this wild river and tamed it in order to exploit it. Humans have leveed it, dammed it, paved it with concrete, dredged canals and pipelines and drilled for oil and gas through the land it created. In reality, however, they haven't tamed it. The river is perfect. Humans are not perfect. If humans make a mistake in their battle with the river, the river will find it and it will exploit it. Patiently, barely noticed at first, almost as if determined to mock all the human efforts to control it, as if to revenge itself on humans for confining and torturing it, the river seems set on an inevitable course of giving back to the ocean much of what it created unless humans change their ways. At this writing, approximately 1,900 square miles—twice the area of Rhode Island– of coastal Louisiana has melted into the ocean, and the land loss is continuing.

The lost land was productive ecologically, economically, and culturally; it created a way of life, spawned great commercial fisheries, and served migratory birds. It also served as an important buffer protecting populated areas from hurricane storm surges.

This book focuses on the question of how to stop this land loss; it explores how humans can accommodate themselves to the river, and the river to human ways, in order to stop the process of destruction and rebuild some land in strategic areas to protect population centers. In other words, this book is about the Mississippi River's future, especially the future of coastal Louisiana, and with it the future of the United States. The book deals largely with technical issues, but it's also accessible to lay readers.

The engineering aspects of the solution are difficult. Little can be done for some areas of the coast. In some areas even if funds were unlimited little could be done. And of course funds are very limited.

But, difficult as the technical problems are, the purely human aspects of the solution—the politics– may be even more difficult. Disruption of some people's lives is inevitable, and people will fight to preserve what they have; resistance to plans for river diversions, for example, has already started and it is intense. Other political fights are also inevitable, including over the most obvious question: who's going to pay for all this? The state of Louisiana has produced a Master Plan praised by environmentalists, scientists, and the navigation and oil industries with a price tag of $ 50 billion for a bare bones minimum and an estimated $ 100 billion to do it right. But there is nothing in that plan about where the state will get $ 50 billion, much less $ 100 billion.

As I write this, in fact, I am personally engaged in the first political war to be fought over who will pay to implement the Master Plan. There are multiple causes of land loss, including the levee system itself, the shipping industry, and dams nearly 2,000 miles upriver which retain enormous amounts of sediment– but another prime cause of land loss is the oil, gas, and pipeline industry. As a member of the Southeast Louisiana Flood Protection Authority East, the board overseeing flood protection on the east bank of the river for metro New Orleans, I played a major role in its filing a lawsuit against Exxon Mobil, Chevron, BP, Shell and 93 other oil, gas, and pipeline companies for their role in destroying the coast. Paul Kemp, one of the editors of this book, is also on the SLFPAE board and has supported the suit.

This lawsuit set off a string of explosions when we filed it in July 2013. No one has disputed that the energy industry has liability, yet Governor Bobby Jindal has promised to intervene and kill the lawsuit. Because I was instrumental in bringing the suit, when my term expired on the board Jindal replaced me. (Paul's term has not expired, and our board is one of the very few whose members cannot simply be fired by the governor—that independence allowed us to bring the suit– so at this writing Paul continues to serve.)

There is an old saying, "The flag of Texaco flies over the Louisiana capitol." Chevron took over Texaco, and by the time this book is published, we may know if that old saying still holds true. Personally, I'm optimistic that a deal will be worked out, if not with this governor then with the next one. If it is, it will help solve the biggest political question: where the money will come from.

That brings us back to the technical questions. Can they be solved? Read this book and find out. And the other political problems—can they be solved? Stay tuned. This is just getting interesting.

John M. Barry
November, 2013

Introductory Quotation

The weight of this sad time we must obey; Speak what we feel, not what we ought to say.
In King Lear by William Shakespeare.

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Introduction: Perspectives on the Restoration of the Mississippi Delta

John W. Day, G. Paul Kemp, Angelina M. Freeman
and David P. Muth

Abstract

The purpose of this book is to show how the neglected and degraded landscape of the Mississippi River Delta might be brought back to life. It consists of a collection of scientific essays that focus on applying the results of a new era of scientific discovery to the prospect of large-scale delta restoration. These essays were written by members of the Science and Engineering Special Team (SEST), a group of experts chaired by Dr. John W. Day, Jr., that began to meet in the aftermath of the Deepwater Horizon disaster of 2010. While this new disaster focused attention on the iconic Birdsfoot Delta, it became clear that few were aware of the way it and the rest of the Mississippi River Delta is being managed into oblivion, largely with public tax dollars and the activities of resource users. The authors seek not only to provide information on ways to halt the ongoing loss of coastal wetlands, but also on how to restore the delta as a fully functional geological and ecological system. The eleven essays contained in this book address some of the challenges facing this process, and we hope it will make a positive contribution to present and future delta restoration efforts.

Keywords

Mississippi River Delta · Wetland · Deepwater Horizon · Estuarine ecosystem · Coastal restoration

Introduction

This book is about the Mississippi River Delta (MRD), the most ecologically productive ecosystem of its size in North America, covering about 25,000 square kilometers. Our purpose is to show how this neglected and degraded landscape might be brought back to life. To do so, it is necessary first to understand, and then to replicate the processes that originally created the vast ecological and economic values that have been exploited for centuries, from timber to shrimp and fish, to navigation, to oil and gas while throttling back twentieth century interventions that, while increasingly ineffective or counterproductive today, continue to force a downward spiral of destruction. That is old news. More recently, a new sense of urgency has arisen across the delta. This movement, born of a string of preventable disasters, from failures of levees to explosions of drilling platforms, is focused on applying results of a new era of scientific discovery on prospects for large-scale delta restoration.

The Mississippi delta that we know today developed over the past 7,500 years, during a period when sediment deposition by the Mississippi River overwhelmed relative sea level rise (RSLR). It includes wetlands, lakes and bays that in

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aggregate are the most productive estuaries on the US Gulf coast. This is a well-peopled delta, but settlement has always been confined to the low relief natural levee ridges that are the raised banks of active and abandoned river courses that separate and define the estuaries. People also settled on Chenier Ridges formed from old beach ridges. RSLR, which is the sum of global eustatic sea level rise and a spatially varying component of local subsidence or sinking, will come up frequently in these pages. Planners today are taking RSLR into account along with the ominous economic, energy, and climate trends we face in the second decade of the twenty-first century (CPRA 2012). For example, eustatic sea-level rise by the end of this century will likely become more important than subsidence, which in the past has been much higher. Against these odds, readers may be surprised to learn that the Mississippi delta ecosystem is remarkably resilient, and probably ranks among the top large, coastal landscapes of the world as a candidate for effective ecological and economic rebirth.

This collection of scientific essays arises from discussions among members of the Science and Engineering Special Team (SEST), a carefully chosen group of experts chaired by Dr. John W. Day, Jr., Distinguished Professor Emeritus of the Department of Oceanography and Coastal Science, School of the Coast and Environment at Louisiana State University. SEST was sponsored collectively by national non-governmental environmental organizations led by the National Audubon Society, Environmental Defense Fund and National Wildlife Federation. These national organizations, along with a number of local groups, were brought together by the Walton Family Foundation in 2008 to advocate for an urgent, scientifically credible campaign to restore the Mississippi River Delta (http://www.mississippiriverdelta.org). SEST was initiated in 2010 specifically to provide independent advice to the philanthropic community and non-governmental organizations on how best to support the restoration of one of North America's premier ecological assets. Our focus here is on providing a clear-eyed, objective view of what is known about the delta and the tools available to resuscitate it. It will, we hope, also serve to energize a larger audience to become engaged participants in that effort.

Our first SEST meeting occurred not long after 11 crew members were killed in the explosion of the Deepwater Horizon drilling rig that gushed about 5 million barrels of oil for three months less than 100 km from the mouth of the Mississippi. At a time when a new disaster focused attention on the iconic Birdsfoot, it became clear that few were aware of the way it and the rest of the MRD is being managed into oblivion, largely with public tax dollars and the activities of resource users. People who watched the pathetic scenes of oil-covered pelicans were moved to register concern. More than 30,000 volunteered to help save oiled birds, beaches and marshes with the National Audubon Society alone. Since then, however, many have been asking hard questions about what really can be done to reset the MRD toward a future of renewed productivity. This book seeks to answer that question at a technical level that can be appreciated by specialists of many fields, including coastal ecologists, river engineers, historians, fisheries scientists, sociologists and economists. An early SEST product titled "Answering 10 Fundamental Questions about the Mississippi River Delta," is still an excellent online source for many of the issues addressed in more detail here (http://www.mississippiriverdelta.org/files/2012/04/MississippiRiverDeltaReport.pdf).

First, we want to be clear that the delta we seek to bring back is not one that anyone alive today has ever seen. Tales of fantastic biological abundance have come down through time from the native peoples whose descendants still inhabit the delta, and from a plethora of later migrants attracted to this productivity from nearly every corner of the globe. This mixture has created the unique human cultural "gumbo" that makes the MRD so interesting a place to visit and live. But evidence to satisfy a modern sensibility for quantification is hard to come by prior to the mid-nineteenth Century. In two remarkable chapters, one relying on antique charts (Chap. 2), and a second delving even farther back into sixteenth century logs of Spanish and French mariners who were exploring the uncharted Gulf under a cloak of state secrecy, SEST eco-historians extract a new vision of the "Last Natural Delta of the Mississippi" (Chap. 4). This fully functional delta was a very different place from any we might imagine today, and this historical research provides a missing benchmark from which modern restorationists are gaining new insights.

But by the mid twentieth century, the die had been cast, and our path to control of the river was made law in the language of the Mississippi River and Tributaries Project (MR&T), adopted by Congress in 1928, a year after the transformative flood of 1927 (Barry 1997). Chapters 2 and 4 seek to bring to life the pre-colonial river ecosystem.

The geology of the MRD, which extends beyond the continental shelf and as much as 10 km below the modern surface, has produced more oil and gas than any other US province. It is also at the root of problems faced by the delta today. First, it has been artificially isolated from the river by thousands of kilometers of levees that prevent overflow and supply of sediments into adjacent wetlands. Second, the supply of mud (silt and clay) from the Mississippi watershed has been greatly reduced by dams and revetments that prevent meandering and bank caving. Finally, if the sediment could leave the river, a functioning pattern of distributary streams would be required to convey it any distance into the estuaries. But the search for hydrocarbons over the past 100 years has resulted in 15,000 km of randomly oriented canals dredged in ways that pervasively disrupt natural deltaic hydrology, whether by creating inadvertent impoundments or capturing flow from natural bayous.

So, these are issues that are being addressed today in a ground-breaking Master Plan developed by the State of Louisiana (CPRA 2012). If that were not enough, however, the US National Oceanic and Atmospheric Administration (NOAA) has determined from long-term tide gauge records that the MRD is the largest coastal landscape experiencing the most rapid relative sea-level rise anywhere on earth (http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml), 6–30 mm-y^{-1}. Wetland-loss, whether it occurs in fresh swamps and marshes of estuary interiors, or in brackish and salt marsh prairies closer to the Gulf of Mexico, has amounted to more than 1,800 km^2 in the past 80 years or about 25 % of the total wetland area at the beginning of the nineteenth century (Couvillion et al. 2011).

RSLR will continue to challenge the restoration of the MRD as it has done since long before humans arrived, but the rate of sediment supply to deltaic estuaries, now so much reduced by levees downstream and dams upstream, can be greatly augmented. Large, controlled "re-introductions" of Mississippi and Atchafalaya water and sediments into adjacent, deteriorating coastal basins through managed "diversions" will be the primary tool. Important issues addressed in two chapters (Chaps. 3, 6) are whether the reduced volume of Mississippi River sediment reaching the MRD today is sufficient to permit significant areas to be restored by diversions of water and sediment from the Mississippi and its western distributary, the Atchafalaya River, and where artificial outlets should be located to build or rejuvenate the most land.

There is no doubt that artificial activation of new distributaries carrying significant volumes of water and sediments into wetland basins will change the estuaries dramatically, particularly the distribution of habitats along salinity gradients. The dysfunctional delta created in the twentieth century is all that those who live and work in it have ever known, and this is particularly true of the large number engaged in commercial and recreational fishing. So while they lament the deterioration that they have seen over their lifetimes, they still approach the ambitious plans for diversions with much trepidation. Cowan et al. (Chap. 7) provide an excellent analysis of the trade-offs that will necessarily arise out of bringing a functional delta back into existence.

Furthermore, the river water that will be diverted into coastal estuaries is not the same as it was a century ago. It carries all of the pollutants that wash off the watershed between the Appalachians and the Rockies, many of which originate as fertilizers and weed control formulations applied to row crops in the vast agricultural lands of the Midwest. Nitrate-nitrogen levels are elevated perhaps an order of magnitude higher than they would be under more natural conditions. So, some have argued that it is best to keep these pollutants in the river rather than turning them loose in the wetlands. But, it turns out that wetland plants, and the low oxygen soils in which they live, have some unique capabilities for assimilation and treatment of nitrogen at least, and perhaps many other pollutants susceptible to permanent burial as the land subsides. Morris et al. (Chap. 8) address all sides of the science debate about "nutrients" now in progress and provide guidance for managing diversions in a way that neutralizes the risks that come with diverted river water.

The Lower Mississippi River also includes the largest ports for transport of bulk commodities anywhere in North America. The Mississippi River and the richness of the natural environment sustained important economic activities based on waterborne trade, fisheries, forestry, and agriculture during the 18th and 19th centuries. These activities are still important; port activity on the lower River is the largest in the world by tonnage and Louisiana has one of the largest fisheries in the United States (U.S.). Beginning in the twentieth century, the discovery of oil and gas led to the development of an enormous energy (Louisiana provides about 25 % of the nation's energy) and petrochemical industry. These economic activities led to dramatic environmental problems. Levees for navigation and flood control isolated most of the delta from the river and dramatically changed its hydrology. The life sustaining water and sediment of the river no longer spread out through multiple courses across the delta plain. About a quarter of its wetlands were lost in the twentieth century. This history is discussed in Chaps. 3 and 5, which lay out the progression of efforts to shape the river to service the industrial needs of the country, while limiting its propensity to flood communities and fertile farmlands throughout the watershed.

There is now a large-scale effort to restore the delta. Climate change and expensive and scarce energy will make restoration more difficult and challenging. In this book, we explore these issues and look at the prospects for successful restoration. This is important both for Louisiana and the nation as a whole.

Outline of Chapters

Chapter 1. Introduction: Perspectives on the Restoration of the Mississippi Delta

John W. Day, G. Paul Kemp, Angelina M. Freeman, and David P. Muth

The Mississippi delta is one of the largest and most ecologically and economically important coastal ecosystems in North America. The richness of this ecosystem supports many natural resource based activities including fishing, hunting, and recreation activities worth billions of dollars. Much of this activity is dependent on the wetlands of the delta. During the twentieth century,

human activities such as levee construction, pervasive hydrological alteration, and oil and gas extraction led to the loss of over 4,500 km^2 of coastal wetlands or 25 % of the wetlands of the delta (Fig. 1). The enormity of this loss along with the recognition that the coast is more vulnerable to flooding and climate change has led to the development of large scale plans for coastal restoration and protection. This book addresses a number of topical issues related to restoration of the coast and protection from flooding threats due to both hurricanes and river floods.

This chapter introduces a number of pressing questions and issues about coastal Louisiana restoration. While the challenges are technically, economically and socially complex, there are solutions and that taking no action will result in a creeping disaster of continued land loss, disruption of major navigation operations, billions in economic losses and the degradation of the most ecologically important deltas in the world.

Chapter 2. The Once and Future Delta

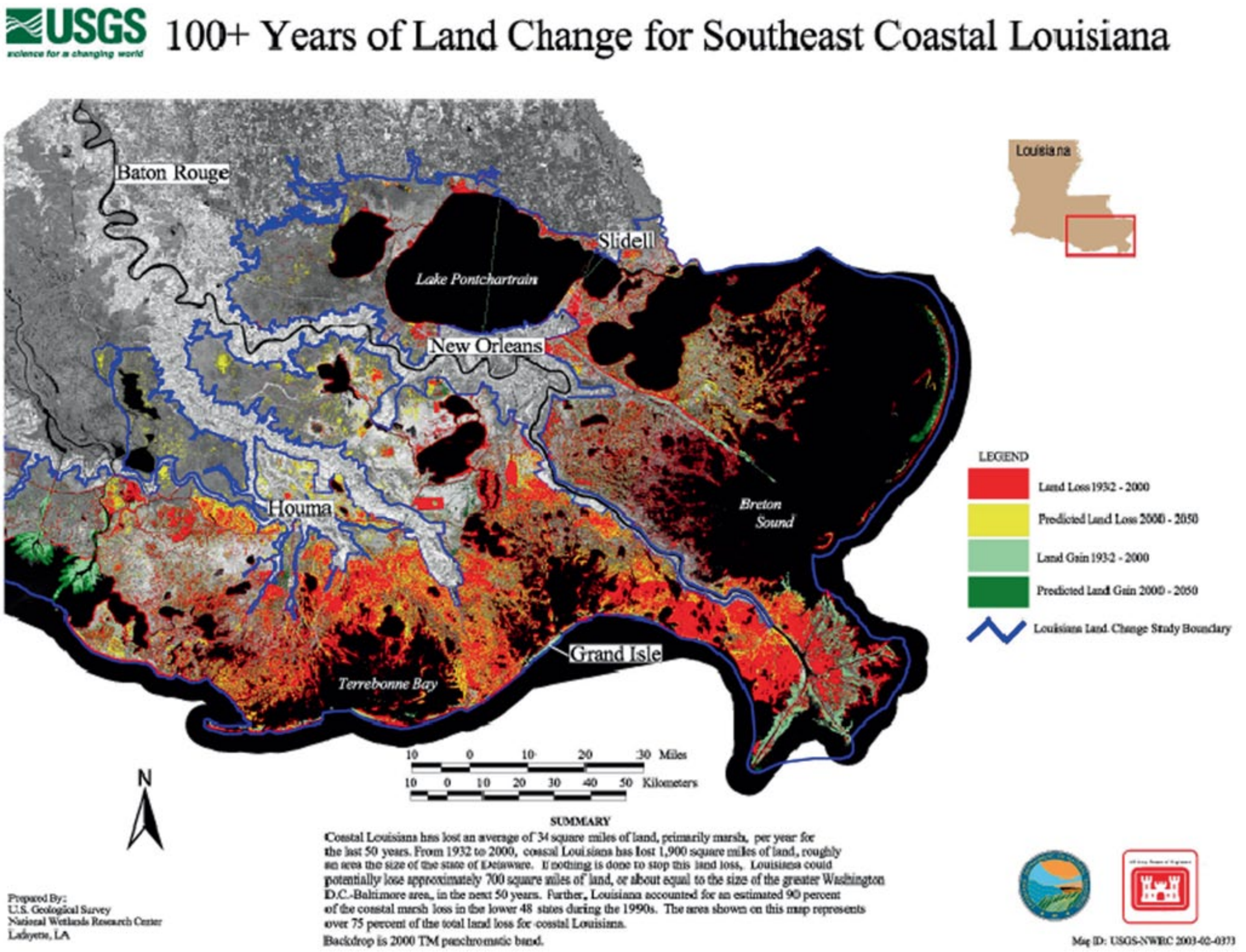
David P. Muth

It is now abundantly clear that we live in a diminished, unsustainable delta. Just as importantly, we live in a delta that diminished at an accelerating pace throughout much of the last century because of measurable anthropogenic actions. This chapter discusses what the delta was like, its decline, and whether stopping the decline is something we can and/or should do.

Chapter 3. How Deltas Work: A Brief Look at the Mississippi River Delta in a Global Context

Liviu Giosan and Angelina M. Freeman

This chapter reviews the geological development of deltas worldwide over the past several thousand years and outlines the forces that led to the development of the deltas. These include the stabilization of sea level after the ending of the last



SUMMARY

Coastal Louisiana has lost an average of 34 square miles of land, primarily marsh, per year for the last 50 years. From 1932 to 2000, coastal Louisiana has lost 1,900 square miles of land, roughly an area the size of the state of Delaware. If nothing is done to stop this land loss, Louisiana could potentially lose approximately 700 square miles of land, or about equal to the size of the greater Washington D.C.-Baltimore area, in the next 50 years. Further, Louisiana accounted for an estimated 90 percent of the coastal marsh loss in the lower 48 states during the 1990s. The area shown on this map represents over 75 percent of the total land loss for coastal Louisiana.

Backdrop is 2000 TM panchromatic band.

Fig. 1 Coastal land change in southeastern Louisiana over the past 100+ years glacial period and the successive occupation of a series of major delta lobes. The future of the Mississippi River Delta with and without major restoration efforts are outlined. Current understanding indicates that the delta will largely disappear by the end of the twenty-first century unless major restoration is undertaken.

Chapter 4. The Last Naturally Active Delta Complexes of the Mississippi River (LNDM): Discovery and Implications

Richard E. Condrey, Paul E. Hoffman, and D. Elaine Evers

Condrey et al. explore the historic record for a description of the last naturally active delta complexes of the Mississippi River (LNDM) as the most appropriate restoration model for Louisiana's coast. They focus on Alonso de Chaves' ca. 1537 manuscript. and conclude that his location of the LNDM consistent with the most authoritative first-hand accounts of the protohistoric and colonial period (Barroto, Iberville, Evía, and Dumain). The LNDM was a vast seaward-advancing arc that occupied, through four distributaries, all of the five most recent deltaic complexes of the Mississippi River and extended across all of coastal Louisiana east of the Chenier Plain. It was characterized by plumes of freshwater that extended for more than 10 km into the Gulf of Mexico during the spring flood of the Mississippi River and by a vast complex of offshore oyster reefs that functioned as both an impediment to navigation and an offshore harbor (near the reef's western end). Implications of these findings are discussed in light of Louisiana's coastal restoration plan and the 'Berms to Barriers'/post Deepwater Horizon oil spill efforts. The findings support Lamb's (1969) argument that Chaves (ca. 1537) provides the earliest comprehensive view of the coasts of the Americas and Ovieda's (1851) argument that De Soto's men sailed out the mouth of Río del Espíritu Santu—which they conclude was the Atchafalaya/Vermilion Bay complex and not the Birdsfoot.

Chapter 5. Adapting to Change in the Lowermost Mississippi River: Implications for Navigation, Flood Control and Restoration of the Delta Ecosystem

G. Paul Kemp, Clinton S. Willson, J. David Rogers, Karen A. Westphal, and S. Ahmet Binselam

In order to be politically and economically viable, coastal restoration must accommodate navigation needs. It is increasingly obvious, however, that the current navigation system is unsustainable. Increasing flow lines with the same discharge and the potential for the river to seek new outlets well inland of the head of passes are indications that the system is no longer functioning in the manner intended. Dredging and other costs are increasing, and the results are less satisfactory. Thus, a change in navigation and flood control is inevitable regardless of what is done with restoration. The 80 year-old approach of the MR&T focusing almost solely on navigation and flood control is incompatible with delta restoration, and unsustainable in and of itself. Increasing flow lines with the same discharge and the potential for the river to seek new outlets well inland of the head of passes are indications that the system is no longer functioning in the manner intended. Costs are increasing to achieve less results. Flood protection in the delta must focus on flooding threats from both the river and hurricanes. For decades, coastal Louisiana relied on the use of earthen levees in an attempt to protect developed areas from these threats. Opportunities exist for restoration, navigation, and flood control to be managed compatibly but the process of transition is not being anticipated. The transition can planned and orderly, but doing nothing on restoration is likely to lead to sudden and catastrophic loss of navigation capacity.

Chapter 6. Using What We Have: Optimizing Sediment Management in Mississippi River Delta Restoration to Improve the Economic Viability of the Nation

Samuel J. Bentley, Angelina M. Freeman, Clinton S. Willson, Jaye E. Cable, and Liviu Giosan

Although there has been a significant reduction in the sediment load to the Mississippi River Delta, there is considerable amount of sediment remaining in the system. Redesigning river operations, including the use of diversions, while maintaining navigation could help restore fairly large areas of coastal Louisiana. It is also possible that the amount of sediment reaching the Delta will increase, as the area behind upstream sediment retention wing dams fill. Moreover, if climate results in drier condition over the Missouri basin, then we can expect that erosion will increase for drier soils. In the upper Mississippi and Ohio basins climates projections are for more precipitation and thus more water coming down carrying more sediments. In a future of energy scarcity, water flows using gravity rather than pumping will likely have to be relied on to a greater extent to move sediments.

Diversions are important for rebuilding and restoring the coast, but there are issues of scale and design and conflicts with other resources. Diversions will have to become larger and specifically designed to carry more sediment. Recent experience with Wax Lake, Big Mar, and West Bay show that new land can be rapidly built after a period of subaqueous development. The orientation of the conveyance channel connecting the river to the diversion outfall area should be designed to mimic the way that water would naturally flow as it leaves the river. At West Bay, for example, the conveyance channel initially constructed pointed upstream. As the channel evolved over time, the orientation shifted towards a downstream direction. Thus, it is clear that diversion size, outlet design, and location are important factors the design of diversions. Such considerations should be incorporated into future diversions.

Chapter 7. Fisheries in a Changing Delta

James H. Cowan Jr., Linda A. Deegan, and John W. Day

The impact of restoration activities on fisheries is complicated by the fact that fishing pressure itself is perhaps the dominant impact on the community of organisms that are fished. Fisheries productivity has been related to a number of factors, including nutrient loads, wetland area, shallow depths, tidal mixing, and primary productivity. A complicating factor is that the large wetland loss in the Mississippi delta has not led, at least not yet, to a decline in fisheries. It has been suggested that one of the things that maintains the fishery is the length of the land water interface, which increases with wetland loss, at least up to a point. If however, most of the delta wetlands disappear, there will likely be major impacts on fisheries. As delta marshes disappear, many of the species that support fisheries now (shrimp, crabs, oysters, and a number of nekton) may become less abundant while those dependent on a phytoplankton food chain, such as anchovies, may become more abundant. Large river diversions for restoration could shift the spatial distribution of fishery species but not the overall productivity of coastal Louisiana fisheries.

Chapter 8. The Influence of Nutrients on the Coastal Wetlands of the Mississippi Delta

James T. Morris, Gary P. Shaffer, and J. Andy Nyman

Questions have been raised on the impact of nutrient impacts on wetlands by reducing belowground root growth and soil strength. The evidence supporting this idea is not conclusive and more study is needed. But there are a number of documented case studies where river input has not led to marsh deterioration, such as in marshes around Atchafalaya Bay and Four League Bay. Wetlands in the Bonnet Carré Spillway and sediment deposition after the 1927 man-made crevasse at Caernarvon provide additional documentation of the impacts of large diversions. Also, coastal wetlands in the Mediterranean with strong riverine input are healthier and have high rates of accretion. Future diversion projects should strive to enhance mineral sediment input. It is unclear whether marsh loss at Caernarvon during Katrina, for example, was more a factor of a large area of fresh to low salinity marsh that are inherently less stable rather than due to nutrient enrichment. In addition, nutria have been shown to strongly graze enriched marshes and thus can have a much stronger impact on root biomass than direct nutrient effects. At any rate, future diversions should strive to introduce as much sediments as possible.

Chapter 9. Complexities of Resilience: Adaptation and Change within Human Communities of Coastal Louisiana

Conner Bailey, Robert B. Gramling, and Shirley B. Laska

Historically people settled in the coastal zone to take advantage of the subsistence and employment opportunities related to the harvest of renewable and non-renewable resources. Over generations, a group of coastal communities with unique relationships to the wetlands have developed. However, for the last several decades residents have been moving away from the coast because of the disruption of these wetlands by human induced and natural processes. The environmental setting is increasingly tenuous. Coastal peoples are adjusting in several ways: relocating; staying in place with structural and non-structural adaptations; altering their spatial, physical and social processes; and by only periodically occupying the coast for the harvest of natural resources and for navigation. Further adaptations of the physical and social structures may be required to continue living along the coast as increasing climate change, land loss and energy costs bring additional challenges to coastal communities.

Chapter 10. The Importance of Mississippi Delta Restoration on the Local and National Economies

David Batker, Sarah K. Mack, Fred H. Sklar, William K. Nuttle, Mary E. Kelly, and Angelina M. Freeman

Restoration costs will be very high but the current economy is not sustainable without restoration in some form. In coastal Louisiana almost all economic activity is related directly or indirectly to the Mississippi River and delta. Restoration of the delta is required to maintain this economic activity because of the importance of the high ecosystem service values. It is likely that the structure of the economy and how it is carried out must change as the viability of coastal communities decreases. If proper planning is not in place, then the economy will be faced with a series of catastrophes that will make the economy unstable. Thus proper and aggressive planning is fundamental to maintaining the economy.

The economic health of coastal Louisiana is important to the economic health of U.S. Louisiana is vital for U.S. energy supplies, exports of agricultural commodities and coal, fisheries, and tourism. These are all threatened by coastal deterioration. The environmental infrastructure (ecosystem goods and services) supports these economic activities. It is likely that maintenance of the coastal economy and its role in the national economy will sometimes involve a shift from a place where people live to a place where people go to work and play.

Chapter 11. The Threats to the Value of Ecosystem Goods and Services of the Mississippi Delta

David Batker, Isabel de la Torre, Robert Costanza, John W. Day, Paula Swedeen, Roelof M. J. Boumans, and Kenneth J. Bagstad

This chapter discusses the benefits of investing in the restoration of the Mississippi Delta on the value of ecosystem services of the delta. The ecosystems of the delta provide at least $ 12–47 billion in benefits to people every year. If this natural capital were treated as an economic asset, the delta's minimum asset value would be $ 330 billion to $ 1.3 trillion (3.5 % discount rate). The deterioration of the delta is decreasing these values. An aggressive restoration plan will avoid $ 41 billion in losses of ecosystem services with a no action scenario and produce benefits with an estimated present value of at least $ 21 billion, bringing in an annual net benefit of $ 62 billion. Aggressive restoration will provide critical natural goods and services such as public safety, storm protection, protection of oil and gas infrastructure and thereby expand the economic base of the Mississippi Delta and the nation. Investment in delta restoration results in enormous physical, ecological, and economic benefits while doing nothing results a loss of these benefits.

Chapter 12. The Impact of Global Climate Change and Energy Scarcity on Mississippi Delta Restoration

John W. Day and Matt Moerschbaecher

Climate change impacts are projected to become more severe in coming decades. Sea-level rise by 2100 has been projected at 1 m or more. There will likely be more intense hurricanes. Climate change may also results in more large floods on the Mississippi River. At the same time, energy prices will likely rise significantly. Thus, while climate change will make coastal restoration more challenging, energy costs will limit options. These two factors will impact all of the activities discussed thus far in this paper. Planning for management and restoration needs to specifically incorporate these two factors.

Chapter 13. Summary and Conclusions: The Cost of Inaction and the Need for Urgency

John W. Day, G. Paul Kemp, and Angelina M. Freeman

This chapter melds the preceding chapters, describing the challenges facing sustainable restoration of the Mississippi delta and outlines a way forward where navigation, flood control, and environmental management play equal roles.

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The Once and Future Delta

David P. Muth

Abstract

Coastal Louisiana faces an extraordinary and unprecedented challenge: millions of people and a vast industrial infrastructure located in a disappearing landscape. The sea is re-occupying delta lobes and a coastal plain cut off from the river that built them. The decline is inexorable. Without systemic changes, coastal Louisiana, having already lost 1,900 square miles in less than a century, will disappear. Faced with this challenge, Louisiana's people are hampered by an inherent difficulty to comprehend how much the biophysical baseline has shifted. We lack an historic perspective, unaware of just how much more productive the system was and could be again. Many are engaged in a futile effort to hold onto what is doomed or put back what is already lost, rather than allow what could be: a vibrant new river management system that reignites the process that built the delta and its vast productivity in the first place. The key is unleashing the potential of the Mississippi River to build land. The challenge is to accept and adapt to the dislocations that river reintroduction will bring to navigation, fisheries, and coastal communities. The difficulty of adapting pales beside the catastrophe that waits if we do not.

Keywords

Mississippi River Delta • Shifting Baseline • Ignorance-based Worldview • Knowledge-based Worldview • Louisiana's Comprehensive Master Plan

> *It seems that the time is ripe for an enormous development of the Louisiana wet lands along new and intelligent lines, the ideal conditions to be demonstrated by observation and research, and that this development should be included in a broad program of conservation which has for its object the restoration of those conditions best suited to an abundant marsh and swamp fauna, but under some degree of control at all times.*
>
> Percy Viosca, Jr. 1928

The Baseline

Southeast Louisiana is a delta. It is a place built by sediments transported by the Mississippi River and deposited into the shallow, nearshore Gulf of Mexico and coastal bays. Since the end of the last Ice Age, land steadily emerged above the water and was colonized by plants and animals (Blum and Roberts 2012). To these sediments from the river, biological processes added organic material, mollusks built shell reefs, and marine processes redistributed sands, silts, clays, shell and organic matter. Fundamentally, this is what is known—the physical baseline. Careful study, monitoring and modeling of contemporary alluvial and marine processes, as well as examination of the sedimentary, archeological, and written record, provides us with reasonable hypotheses for explaining how these processes took place. But the indisputable tangible record we have is the physical delta, built by the interaction of the river and the sea.

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It is now abundantly clear that we live in a diminished, unsustainable delta. Just as importantly, we live in a delta that diminished at an accelerating pace throughout much of the last century because of measurable anthropogenic actions, including canal and channel dredging, confining the passes within jetties, levee building, drainage and subsurface fluid withdrawal (Day et al. 2007). While there is evidence the pace has slowed (Couvillion et al. 2011), it is likely to accelerate again if sea level rise accelerates.

Can we stop the decline? Can we pick a baseline to hold to or a restoration goal to return to and then find enough money to get us there and hold to it? Is that really what we *should* do? Or should we begin again, using the maximum resources of the river to build a new delta and hold onto whatever we can of the old?

Causes of land loss and potential responses are many. But, in the end, there is a single solution *known to have built an ecologically functional delta*: alluvial deposition by the Mississippi River (Davis 2000). Since the end of the Pleistocene the river has deposited an estimated 2,790–3,450 billion t of sediment in the former valley and on the shelf, or about 230–290 million t per year (Blum and Roberts 2009). The average depth of the delta, measured to the older Pleistocene surface ranges from less than 10 m in far upstream reaches to greater than 100 m in depth in the Bird's Foot delta (Blum and Roberts 2012; Kulp 2000). Looked at three dimensionally, from Cairo, Illinois to the edge of the Continental Shelf and the cusp of the Mississippi Canyon, the river has built a formidable land mass since sea level reached its present stand about 7,000 years ago. And the Holocene sits atop countless layers of sediment laid down by proto-Mississippi Rivers since the Jurassic, 145 million years ago. The modern delta is perched atop a sedimentary wedge that increases to more than 4,000 m in thickness at the shelf margin (Blum and Roberts 2012; Woodbury et al. 1974).

A Shifting Baseline

The diminished delta is now the subject of a concerted effort to do something to fix it. Unfortunately, in making political, economic, social and scientific decisions today about how to respond to that diminishment, we suffer from the fact that we are victims of a shifting experiential baseline—our expectations start low and get lower. No one alive today remembers a healthy, natural delta. We have been living in a sick, steadily declining delta for so long that unfortunately many believe that the delta they remember was truly healthy, rather than just less sick. Indeed, many believe that the parts of the delta today that are the most stable constitute a healthy delta. They are wrong. The baseline keeps shifting downward. Now it is shifting so rapidly that one can watch marsh disappear over the course of a few annual fishing trips. Over the course of a decade we watch the view change dramatically from marsh to open water, from swamp to marsh, from forested ridge to dead trunks standing in the scrub. The maps in our GPS devices are outdated before we first turn them on. We cruise in our boats serenely through 5 ft of water where our GPS insists there are marshes. We no longer fail to notice the shift. But we do forget that we ourselves began in a place that was far, far below where it started.

A failure to understand the implications of the rapidly shifting biophysical baseline for the Mississippi River delta has profound implications for political actions going forward. Tremendous energy is devoted to trying, fruitlessly thus far, to hold on to what remains, rather than to allow what could be. Much of the rapidly disappearing delta is in its *final* evolutionary phase. Lacking sedimentary inputs, subsiding mineral soils are now overlain by low strength organic peat soils. Marshes growing in these peat soils break free from the mineral platform and have become floating or semi-floating. Their weakened surface is breaking apart, and the length of edge exposed to erosion is increasing exponentially. The balance between land and water is tipping to the final stage of the delta life cycle—re-occupation by the sea.

A similar process is taking place on the barrier islands and headlands. As the inside marsh disappears, the volume of water that must complete each tidal cycle requires larger and larger passes through the sandy barriers, shrinking the size of the islands and headlands. The feedback loop is inexorable, land area decreases, and the bays and passes expand. Eventually the remnants of the barrier system become stranded islets, playing little further role in system hydrology, as we see today in the Chandeleur and Derniere island chains. Prior to the construction of jetties and the closing of distributaries, the barrier island cycle was driven by the delta lobe cycle. Delta front sands (those deposited at the mouths of the distributary channels) provided the material for new barrier islands. Today, barrier islands are deteriorating because sand delivery by the river has dropped by half and most of what does reach the delta is lost to deep water rather then set adrift in the littoral zone.

Added to this erosive process is relative sea level rise, steadily taxing the resiliency of a sediment starved system. Soil formation cannot keep up, even in seemingly healthy brackish marshes, absent new sedimentary inputs. Increasingly organic soils lack structural resistance to daily erosive forces, and are prone to catastrophic collapse in response to perturbations (Howes et al. 2010). These perturbations may result from both systemic changes, such as changes in hydrology or nutrient input as a result of riverine introductions, or from high energy weather events, such as hurricanes, or from combinations of systemic and episodic events. These effects are cumulative in the majority of the delta, because most of the delta no longer has the capacity to repair itself. Freshwater vegetation growing in an active delta lobe can be stripped by waves or burned by saltwater during a tropical cyclone, but recovery on the surviving mineral soil platform is rapid. The effects in the delta's end stage marshes, where tearing reaches deep into the organic soils, are long lasting, and often permanent (Morton and Barras 2011).

Meanwhile, much of the structural underpinning of the delta, the sediment load of the river, is unavailable. The nexus between ocean going commerce and the nation's largest port system along the lower river is Southwest Pass, in the Bird's Foot. Channel training to maintain this deep draft navigation system shunts much of the sediment that reaches that point to near the edge of the continental shelf, where it eventually sinks into the abyss. And less sediment reaches the delta, a consequence of dam and lock construction, primarily on the Missouri and Upper Mississippi (Meade and Moody 2010).

Most federal and state effort to date has been expended in trying to patch deteriorating brackish marsh and the barrier system, rather than to address the underlying deficit—which is the loss of deltaic function. This is the natural response for us as victims of a shifting baseline to adopt—attempt to hold on to what is known, rather than imagine what could be. To understand what could be, we need to understand just how much has truly been lost. We cannot grasp that by using contemporary conditions, even as measured over a century past, as the real baseline.

The age groups from which decision makers are drawn today, those who are roughly 35–70 years of age, are old enough to have experienced vicariously the coast their parents and grandparents knew from the early twentieth century. Most land along the "the bayou"–natural levees along the river and abandoned distributaries below New Orleans—was used for agriculture: an economic circumstance that would be unimaginable today. When flying over the delta today we can see the field lines of those farms and plantations, now so submerged that marshes grow where food was raised. Or, if presently not inundated because of forced drainage, these once productive farm fields and orchards have become pasture or subdivisions, below sea level. Rainfall inundation, high water tables, saltwater intrusion in the water table and in surface water, plus frequent tidal and occasional storm surge inundation render the agriculture remaining increasingly unproductive. Where agriculture in the coastal zone under forced drainage failed, rectangular lakes now dot the delta.

But even using the coast that our early twentieth century ancestors knew as a baseline is a mistake. The baseline had been shifting downward at that point for 200 years. Our parents and grandparents were aware that they had seen the end of an era—the slaughter of any wild terrestrial creature that could be marketed or that preyed upon other marketable wildlife: ducks, geese, herons, egrets, the last of the Louisiana whooping cranes, beaver, white-tailed deer, red wolves, black bears and panthers. They saw the early but very noticeable effects of roads, levees, and canals, driven by the pressure of population growth. Despite these signs, they overwhelmingly shared the belief that the highest and best use of any place was to tame it for human use. Though they could no longer find the abundance they once knew, they believed it had been sacrificed for a higher good—to tame the landscape for human settlement and commerce. Yet the memory of their diminished landscape now seems idyllic to us, their heirs.

We need to go back even further. The ecologically rich coast experienced in the early twentieth century pales in comparison to the delta that arriving Americans experienced a century before. One March day in 1821 John James Audubon walked to the outskirts of New Orleans and witnessed about 200 gunners bring down (he estimated) 48,000 American golden plovers in a matter of hours. Near Audubon, one hunter alone killed 63 dozen (Audubon 1929). To put that into some kind of perspective, southeast Louisiana today is well east of the main spring migration corridor for this species, and presumably was then. An avid field observer today in southeast Louisiana would be fortunate to see a dozen golden plovers in a day, and a 100 in a season, as they migrated north on their journey from Patagonia to the Arctic. Using the most generous population estimate today of American golden plover, that one afternoon's kill represents 1 % of today's 5 million total world population (Byrkjedal and Thompson 1998). Yet Audubon witnessed 48,000 plovers shot in 1 day. The plovers are a proxy for any number of species for which we have no data from that period. But it is one of many reminders of how much lower our baseline has become.

Audubon, in the delta almost two centuries ago, was witness to the beginning of the end—even he did not get to see what the first wave of Europeans 100 years before had seen. The explorers and colonists of the early eighteenth century left a frustratingly incomplete descriptive record of what they experienced in the early delta. But it is clear that they encountered a place of remarkable fecundity. It is astonishing to consider, for instance, bison living then in a landscape where today there is open water, or if still marsh today, the footing is poor or impossible for humans. Yet that is what the French encountered—herds of bison in the marshes, on both sides of the river, from a few miles above Head of Passes to the swamps below the future site of New Orleans (Campanella 2008). Early French accounts mention Indians living in New Orleans who had fish traps that supplied so much fish that little effort was involved in a families' subsistence (Penicaut 1953). Le Page du Pratz, on his first voyage by canoe upriver in the early 1720s, ran out of powder shooting alligators and other wildlife on the bank between New Orleans and Baton Rouge. He was obliged to stop and obtain more from a settler, and was thereafter careful to shoot only game for the larder (du Pratz 1774). A century later, a passenger on a ship passing the Balize noted alligators so thick along the banks of the river and in the marshes that the roar of bulls calling "had a singular effect as it rose above the breeze" (Benwell 1857). The bison and much of the game

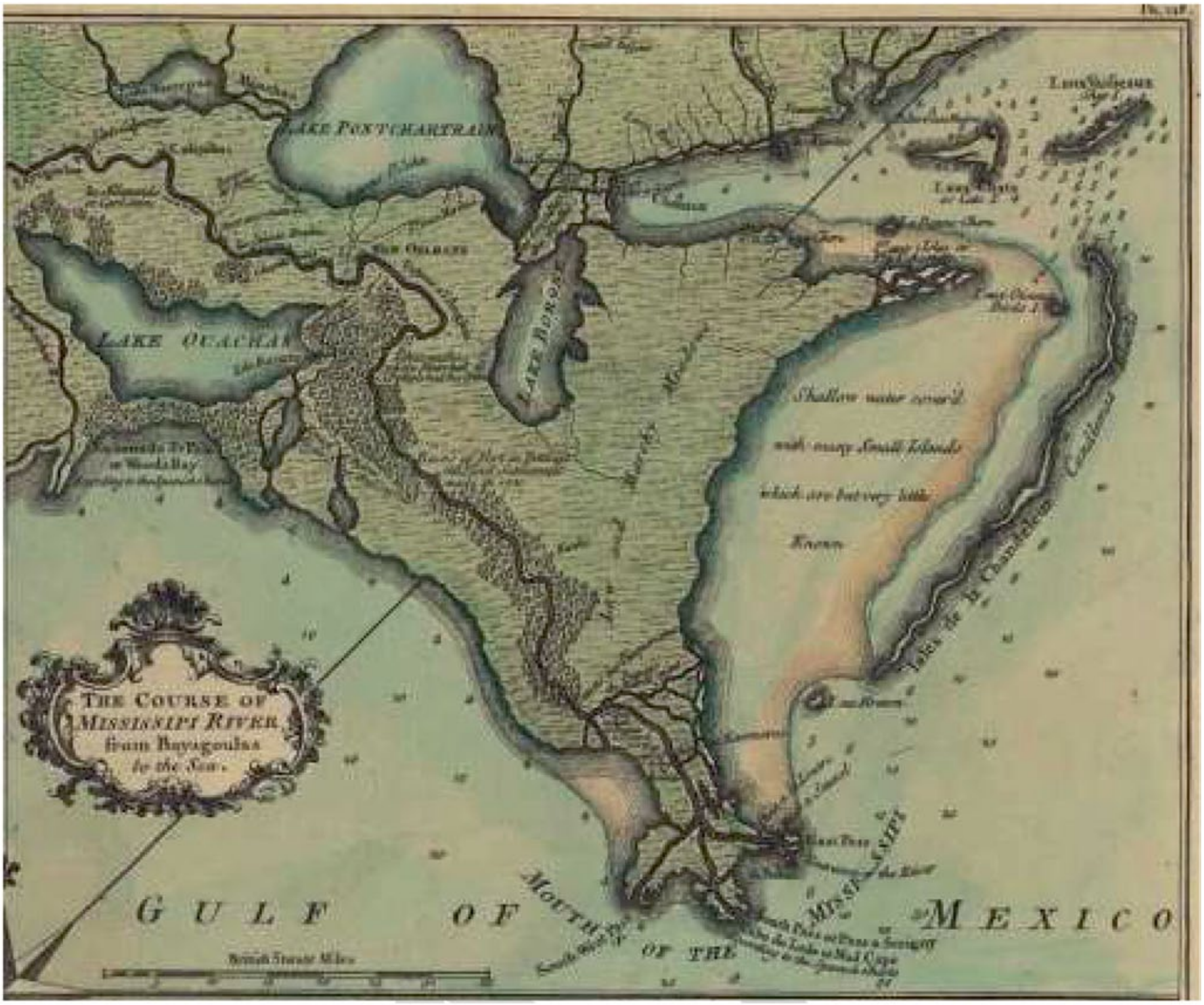

Fig. 1 The delta of the Mississippi River as depicted by Pierre Le Blonde de la Tour's survey of 1720. Lake Ouachas is Barataria Bay, Bayou Lafourche is just to its west

was gone by Audubon's time. And already by Audubon's time much of the lower river had been lined with levees, beginning the slow starvation of the delta.

The Anthropocene in the Mississippi River Delta

When France began its colonization of Louisiana in 1699, the delta covered approximately 15,000 km², with a half dozen or so major distributary channels: the Atchafalaya, Bayou Plaquemines, Bayou Manchac, Bayou Lafourche, Pass á Loutré, South Pass, and Southwest Pass. In many years the river rose and overflowed its banks to varying depths depending upon the height of the flood. During these periods of overbank flow numerous former distributaries presumably helped carry flood waters far from the main stem. The distributaries nourished virtually the entire delta with a range of freshwater and sediment inputs, which in turn mixed with seawater from the gulf to create the entire panoply of deltaic and estuarine ecosystems. Occasionally the river broke through its own confining natural levees, creating land-building *crevasses* that might flow for a season, for a decade, or might become long-lived distributaries, building new delta lobes (Fig. 1).

The French encountered two main active arms of the river, forking at present day Donaldsonville. Bayou Lafourche carried a small percentage of the flow southeast, but was navigable year round. The main stem swept broadly east past present day New Orleans, then southeast to the

Fig. 2 Terrebonne Parish, Louisiana as mapped in 1831 (Finley). Though not highly accurate, the small size of Timbalier (Tunballlier) Bay and the depiction of marsh occupying much of what is now Terrebonne Bay, indicate a landscape in which marsh dominated. Ship Island is depicted where today Ship Shoal is 12 ft deep

Bird's-foot. Each of these in turn forked into smaller active and intermittent distributary arms. To the west, the Atchafalaya, which emerged from the tangled confluence of the Red and Mississippi rivers, and Bayou Plaquemine, along with distributaries from Bayou Lafourche, like Bayou Terrebonne and its many forks, flowing towards Grand River, kept the Atchafalaya mouth fresh. As a result, there were three large areas of the delta near the gulf shoreline that were kept fresh by continuous riverine inputs: the Bird's Foot, the Lafourche delta, and the areas fed by Grand River and the Atchafalaya. In addition, smaller distributaries, crevasses, and spring overbank flooding provided steady input of river water into the vast swamps present in the upper estuarine basins—Pontchartrain—Breton (east of the main stem), Barataria (west of the main stem to the Bayou Lafourche natural levee), and Terrebonne-Atchafalaya. The river overflowed into swamps along the fringes of all of the distributary channels. From the swamps, river water filtered gulfward through freshwater marshes into pockets of brackish marsh. On the fringes of the most open bays and backs of the barrier island, saline marsh grew. Near the barrier islands and headlands, in the gulf and in the passes and bay openings—vast vertical oyster reefs grew in the brackish outflow from the estuaries, often extending miles into the Gulf. These shelf reefs formed a band from west of Vermillion Bay to Terrebonne Bay (see Chap. 4). They indicate that the ideal salinity range for oysters west of Bayou Lafourche, now found deep in the interior of the bays, used to be offshore (Fig. 2). To the east of the river, oysters occupied vast reefs in the open sounds.

European colonists, as they did everywhere they settled, set about trying to make the landscape look more like Europe. The fledgling settlement at New Orleans, laid out in 1718, had thrown up its first river levee by 1721. It became a requirement of French and later Spanish land grants that the grantees build and maintain levees along the river and its distributaries, beginning in 1722 (Smith et al. 2012). As the crown granted land in consecutive parcels near New Orleans, the man-made levee system emerged on both banks of the river, above and below the city (Fig. 3).

The man-made levee system protected the high, fertile natural levees from annual overbank flooding. Clearing for agriculture proceeded rapidly. By the time of the Louisiana Purchase in 1803 settlers had cleared the natural levees of the Mississippi from Baton Rouge to Head of Passes, and land grants indicate landowner-maintained river levees had been thrown up along the entire length (see USGS Topographical Maps). These levees failed frequently during river floods, leading to a period of less frequent but more catastrophic crevasses. The delta, though not experiencing riverine inputs during every flood, was nevertheless continuously replenished because the levee system was only as strong as its weakest, often feeble, links—plantation owner-maintained levees. And after each break, levees were rebuilt,

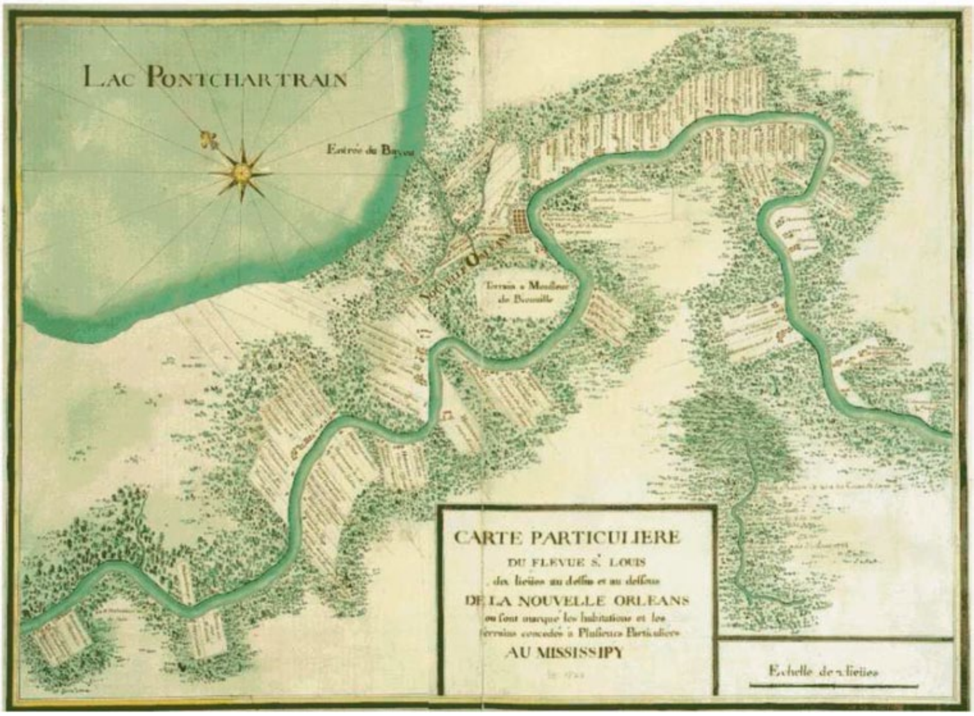

Fig. 3 Map of plantations in the New Orleans area, circa 1723. Land grants are arranged parallel to each other on the high forested natural levee, perpendicular to the river. Grantees were required to maintain an artificial levee and road along the river. Photo courtesy of The Newberry Library, Chicago. Call # Ayer MS Map 30, Sheet 80

often to improved specifications. The political and organizational response increased more or less steadily (except for a long period of decline during and after the Civil War). The frequency of system failures decreased, but the intensity of failures increased, building to the great flood of 1927.

At the same time as levee improvements were built, the many distributary channels were cut off from river flow, one by one. There are no records of the earliest closures. Presumably the intermittent distributaries like Bayou Metairie-Gentilly-Sauvage, Bayou des Familles-Barataria, Bayou Terre aux Bouefs-La Loutre, River aux Chene (east Plaquemines Parish), and Grand Bayou (west Plaquemines Parish), those that had been naturally abandoned by the main channel but presumably re-occupied in flood years, were leveed off from river overflow by individual landowners. The permanent distributaries followed: Bayou Plaquemines—1770; Bayou Manchac—1826; and in the period 1902–1904, Bayou Lafourche, the last and largest of them below Baton Rouge, was dammed (Doyle 1972). A final flurry of catastrophic crevasses during the great flood of 1927—including one created by dynamite at Caernarvon below New Orleans, led to Federal action. The Corps built a levee and spillway system that have effectively confined the river, cutting it off from two-thirds of its delta, for 80 years (Fig. 4).

In the meantime the land building capabilities of the river in the Bird's Foot were severely compromised by improvements to the navigation channels. Eventually, channel training of today's two main navigation passes, South and later Southwest, brought the channel mouths to the edge of the shelf. The effect has been to starve the rapidly subsiding Bird's Foot, perched 15 miles beyond the flanking headlands, of sustaining sediment (Blum and Roberts 2009).

Change in Worldview

Beginning with the Swamp and Overflowed Lands Act of 1849, the official policy of government at all levels (federal, state and local) in Louisiana (and nationwide) was that wetlands, including those of the delta, could and should be drained for economic use. Certainly, later national movements did lead to the establishment of small areas (refuges, parks, and wildlife management areas) to be preserved as *refugia* for ducks and other wetland dependent fauna deemed important. But it was not until the passage of landmark federal legislation including the National Environmental Policy Act (1969), the Coastal Zone Management Act (1972) and the Clean Water Act (1974), that the official support for wetland destruction began to wane.

Note that there was not just an official indifference to the fate of wetlands, as when government allowed oil companies to dredge canals. Rather, government at all levels used incentives and infrastructure development to encourage conversion of delta wetlands for settlement, agriculture and commerce. In Louisiana this included levees, drainage infrastructure, navigation canals and road building. Evidence of this can be found on interstate clover leafs that dead end in marsh in eastern Orleans Parish. During the period leading up to the shift in policy, a small minority of voices, scientists, conservationists, newly named "environmentalists", and key wetland resource

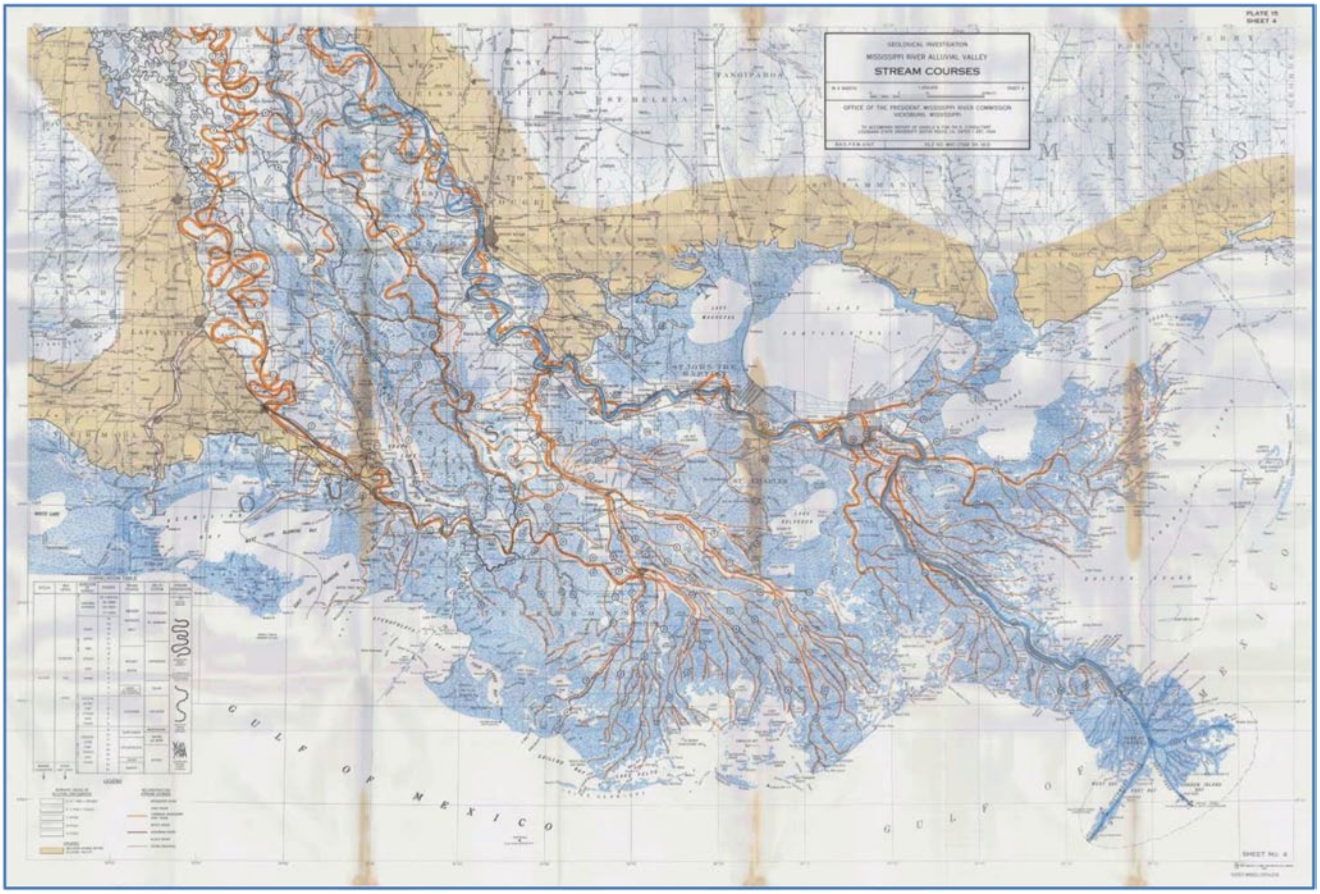

Fig. 4 Distributary courses of the Mississippi River as depicted by Fisk, 1944. Many but not all of these were still connected to the river when the French arrived to found the colony of Louisiana. Courtesy of the Mississippi River Commission

users—most notably oyster harvesters, began to raise the alarm about rapid land loss and conversion of wetlands in the delta.

It is instructive to recall that local parishes in the delta had official plans for draining most or all of their wetlands, and in some cases for draining coastal bays. Conceptually if not actually, the Dutch model was the underpinning of this way of viewing estuaries as a place to "reclaim" the land for commerce. These plans were rarely abandoned or repudiated, but were quietly superseded as the regulatory, economic and social landscape changed in the period 1980–2000. The evolution of a serious commitment to more than just paying lip service to wetland protection by state or local governments, some federal agencies, and elected representatives in Congress, took about 3–4 decades. Even when the rhetoric shifted towards environmental pieties, official actions rarely coincided, and deltaic wetlands continued to be treated as expendable nuisances. Perhaps more than anything else, measurable and predictable socio-economic costs, rather than ecosystem losses, have been the driving force behind the emerging consensus in favor of restoration.

The socio-economic future for delta communities and businesses is grim. Using only the loss rate of the past 50 years projected forward over the next 50 years, about 1,746 km^2 will be lost to erosion and subsidence (Barras et al. 2003). If moderate projections for relative sea level rise (1–1.5 m over the next century (Meehl et al. 2007)) are accurate, the current surface of the delta as a whole (10,000 and 13,000 km^2) will be inundated by 2100 (Blum and Roberts 2009). The only land left will be areas more than 1–1.5 m above mean sea level (msl), or areas behind structural flood-proofing: levees, seawalls and floodgates. Of course, the supposition that such "protected" areas might survive the loss of all fringing wetlands is conjectural, if not highly unlikely. It is entirely contingent upon the exigencies of future hurricanes, rate of sea level rise, and the level of infrastructure investment maintained over time. Increasing energy costs will likely make such systems unaffordable in the relatively near future. Thus, it is more likely that such protection will fail, as it did in Hurricane Katrina, and, unlike after Katrina, neither the money nor the national consensus will be found to rebuild it.

Despite these clear and devastating trends, everything about the delta and why it is disappearing and the potential efficacy of proposed solutions remains to varying degrees uncertain. The *relative* contributions of the various documented causes are uncertain: sea level rise; climate change; compaction of sediments; fluid withdrawal for oil and gas; fluid withdrawal for drainage; movement on geologic faults; effect of fluid withdrawal on pre-existing faults; dredging canals; saltwater intrusion; canal spoil banks; sheet flow interruption; nutrient starvation; nutrient overload; closing distributaries; preventing crevasses; blocking spring overflow with river levees; hurricane protection levees; clearing for agriculture, logging, urban, suburban and industrial development; channeling and concentrating upland run-off through pumping stations and outfall canals; point and non-point source water pollution; air pollution; exotic species; herbivory; jetties that interrupt near-shore sand transport; dredging the tidal passes for navigation; and shunting river sediment through navigation channels to the edge of the shelf. Causes abound.

Proposed solutions abound: nourish the barrier islands and headlands with sediment pumped from offshore, or from the river, or from distant shoals; build dunes; install sand-fencing; plant dune vegetation; narrow the tidal passes; divert freshwater from the river to block saltwater intrusion; stop freshwater diversion to prevent freshening of brackish marsh; move sediment from the river through pulsed diversions; re-plumb the deepwater navigation channel in the river to prevent loss of freshwater and sediment at the navigation passes; build new distributaries; re-open old distributaries; build new marsh with pumped sediments; dredge and pump sediment from the river through pipelines; require beneficial use of dredged sediment; transport sediment through long distance pipelines; nourish declining marsh or swamp with pumped sediment or with water and nutrients; deepen bays, lakes, bayous and canals by dredging and pump sediment into surrounding marsh; deny wetland development permits; require mitigation; allow more flow down the Atchafalaya; allow less flow down the Atchafalaya; remove or breach spillway guide levees; build more spillways; keeps spillways open; rebuild vertical oyster reefs; protect retreating shoreline with hard structures, or with soft structures; nourish swamps and marshes with treated sewage or with storm-water run-off; re-establish sheet-flow by degrading spoil-banks; back-fill canals; plug canals but leave spoil-banks in place; control exotics; control herbivory; remove jetties; build jetties parallel to shore; close passes with hard structures; reform agriculture to control nutrient inputs; control point source pollution from urban areas and industry; increase sediment availability in the lower river by finding ways to bypass dams and locks upstream; and fight climate change.

With this wide array of proposed causes and solutions, much of it contradictory, it is incumbent upon us to get to the heart of the ailment and seek to cure it. *The heart of the problem is anthropogenic interference in the physical functions of the delta.* The most obvious but most radical of proposed solutions involves diverting most or all of the river back into its delta. Diversions of a substantial portion of river flow promise to fundamentally alter the hydrology and salinity of the receiving estuaries. This will change water levels, change plant communities, and change the location and population of several species important to the seafood industry.

Primum Non Nocere

Disagreement over the nature of the problem, its seriousness, and the level of response needed, has led to a deep division over the efficacy of these so-called “diversions”. In the 1960s, Congress, responding to petitions from the oyster industry and the states of Louisiana and Mississippi, authorized the Corps of Engineers to build freshwater diversions to restore optimal salinities for oyster production in the Pontchartrain, Breton, and Barataria basins, as well as in neighboring Mississippi Sound. The proposed diversions were insignificant—at between 8 and 15,000 cfs each; they would have amounted in aggregate to less than 5 % of the average spring flow of the river. But for marshes that had been becoming more saline for 250 years, even these small flows were capable of profound effects. In the end, the Corps built two. A diversion at Caernarvon into the Breton Estuary with peak flow of about 8,500 cfs opened in 1991, and another at Davis Pond into the Barataria Estuary with peak flow of 10,600 cfs opened in 2001.

Controversy erupted. Even in the decades between authorization and construction, both estuaries had undergone profound changes. Oyster beds had shifted inland—in many cases placed by oyster farmers on the platforms of marsh that had eroded away. The brown shrimp harvest had moved inland as well, as had the popular recreational fishery for speckled trout. Opening the diversions caused dislocations for all three species. Ironically, the evidence is strong that total productivity in the Caernarvon influence area for all three species is improving or un-affected; only the location of harvestable quantities has shifted (de Mutsert et al. 2012).

The two freshwater diversions grew in importance all out of proportion to their intent or design. Their purpose was to allow state fisheries managers to manipulate salinities to optimize oyster production. But as they sat on the drawing board, the extent of the coastal crisis became clear to all. The freshwater diversion idea was seized upon as one of the few tangible actions the Corps was authorized and funded to take that could help. Many believed that the diversions could actually help slow or even reverse marsh loss, because saltwater intrusion through navigation and oil and gas canals was thought to be the principle cause of marsh loss. The rhetorical enthusiasm for the diversions painted a naively optimistic vision for them in the minds of people desperate for a solution.

But they were not originally designed for nor intended to build land. In fact, the Corps designed them to *minimize* sediment transport from the river. The goal was fresh water—sediment would just clog the receiving water bodies and lead to ongoing maintenance costs. Nevertheless, new land is being built in both of the diversion receiving areas—in Big Mar at Caernarvon, and in the Davis Pond ponding area. Ironically, though, the fact that these non-sediment diversions may not be resulting in overall net land gain in the entire downstream estuarine basin has been repeatedly touted as proof that sediment diversions do not work, or will not work quickly enough.

In addition, some scientists have concluded that marsh losses in the receiving basins were caused by the diversions. That is, they contend that changes in hydrology and chemistry actually led to marsh loss. This contention is debatable. There is scientific evidence for and against it, with proponents and opponents, as well as those researchers who remain neutral (Teal et al. 2012). But that contention, along with the fact that low-sediment freshwater diversions can't outpace land loss in receiving basins, has been seized upon by political opponents of future diversions.

Diversion opponents contend that these supposed failed diversions argue against using diversions for restoration. They implore that we do nothing in restoration beyond what we have tested and know to work. We are exhorted to "first, do no harm." This aphorism has been invoked to question the efficacy of large scale river diversions, because, it is argued, to build a large diversion is to *do* something that we haven't done and haven't tested. Further, because modern river water diverted by existing micro-scale[1] freshwater diversions, polluted with agricultural run-off, *may* have caused deterioration in *some* existing marsh types, this *doing* is seen as a potential harm—an unwise action.

The axiom, *primum non nocere*, "first, do no harm," borrowed from medicine, cautions physicians to refrain from intervention for intervention's sake, or intervention that risks greater harm—to first observe and discover whether nature, as it runs its course, might lead to recovery, or, at least, a better death. But the aphorism is inapt in this case. The delta is near death *because the physician has already done the harm*, and there is no future for the delta without intervention. The marshes that may or may not be harmed by modern river water are already moribund, disappearing at alarming rates, and cannot survive over the next 50 years without fundamental changes in the system or a complete cessation of relative sea level rise (Blum and Roberts 2009).

In light of this reality, the only reasonable and justifiable intervention is to undo what we have already done, to unleash the river from the strictures we have placed upon it and let it have the freedom to recover its delta. We need to remove the tourniquet that a previous physician placed around the neck of the patient. In the known geophysical equation, not only can this not be construed as *harm*, it would be to do, in contrast to the errant physician who applied the tourniquet, nothing at all.

Ignorance-Based Versus Knowledge-Based World Views

Another argument has been made that we should adopt a scientifically defensible "Ignorance-based World View" (IBWV) when it comes to restoration of Mississippi River delta, as opposed to a "Knowledge-based World View" (KBWV). In this case, it is argued, a KBWV assumes facts not in evidence, i.e. that we know how to restore a delta. This argument has been advanced in opposition to building diversions that allow the Mississippi River to flow back through its delta (Turner 2009). Again, this argument against diversion is backward. We may in fact be ignorant of what is needed for humans to *restore* a delta. But we are not ignorant about what nature needs to *build* a delta. Nature needs freedom from anthropogenic constraints.

To adopt an authentic IBWV would require us to forswear all anthropogenic intervention, anything based upon the KBWV adopted by the French who built levees, closed distributaries and tried to open the bar, which has evolved and guided anthropogenic management of the river in its delta for almost 300 years. An IBWV would teach us to reject the entirety of the KBWV that has led us to this disastrous result. It would require, in other words, undoing anthropogenic changes to the system and allowing the river to return to its delta. A management scheme that concedes our fundamental ignorance requires us to divert the river back into the delta.

Let the river build a new delta. What could be more fundamental? All we really know is that the Mississippi River built and sustained the delta until the French arrived and began tinkering with it. The rest is guesswork based upon inadequate science—inadequate by its very nature because the one dispositive data set can only be obtained by running the experiment again.

Impediments to System Restoration

The three leading socio-political impediments to restoration of delta function each involve key aspects of contemporary life in the delta. The first is resistance to changing the fundamental structure of the deep draft navigation system at the mouth of the river, which has been in place since 1879. The second is the resistance to actions which will displace key commercially important estuarine organisms, primarily speckled trout, brown shrimp, and eastern oysters. Finally,

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[1] Less than 2 % of flow.

and most importantly, is coping with changes to water level that will affect communities physically located within the delta's marshes and swamps.

Deep Draft Navigation

The Mississippi is a relatively deep river with little shoaling of the main channel. Once in the river, ships in the eighteenth and nineteenth centuries were able to reach New Orleans (as long as they could find the channel, and [before steam] had sufficient wind). The mouths, however, were a different matter. Where the river emptied into the gulf, a sand bar formed. This was caused by the slowing current in a river having reached sea level and its release from the confining channel. Mariners were faced with a continuous, nagging problem—deep water in the gulf, deep water in the river channel, but the stubborn bar in between. Throughout the eighteenth and nineteenth centuries various temporary fixes were attempted. But an effective solution awaited the construction of the jetty system, completed at South Pass in 1879. The jetties worked much like a nozzle—constricting the flow to increase water pressure at the opening. The stream of water directed by the jetty nozzle scoured a channel through the bar.

Of course, no solution is perfect. Eventually enough sand accumulated beyond the mouth of the jetties to build a new bar. The response was to extend the jetties each time this happened. Eventually, the Corps extended the jetties in South and Southwest passes until they perched on the edge of the slope of the Continental Shelf. The sand bar that formed was in deep enough water so as not to impede navigation. Indeed, on the unstable slope, the bar tended to slough down towards the abyssal plain beyond the shelf, lost to the delta completely. (As do, of course, the rock jetties. The heavy rocks sink relatively rapidly through the poorly consolidated bar deposits, requiring constant layers of new rock.)

Navigation is now wed to this primitive arrangement. Ocean going ships moving commodities (mostly grain and petro-chemicals) in and out of the gulf have access to the largest port system (by volume) in the world, extending 230 miles upriver to Baton Rouge. Navigation interests are understandably leery of any change to the lower river that might negatively affect the rather delicate equilibrium required for the jetty system to work.

But the current system is not without performance issues. Ocean-going vessels have grown steadily larger, requiring deeper draft, over the last 130 years. Southwest Pass, now the one chosen by the Corps of Engineers to maintain for ocean going ships (to a depth of 45 ft), is not naturally that deep, and can't be maintained to that depth by jetties alone. The 19.5 mile long channel has to be continuously dredged—a cost born by taxpayers, that has been steadily rising. It is rising because of the inexorable increase in the cost of fuel, which outpaces inflation because demand is outpacing supply as population grows and the third world develops. But it has also been rising because of changes to the hydrological functioning of the Bird's Foot delta. Passes and small crevasses between Head of Passes and the downstream end of the river levees (Grand Pass, Baptiste Collette, etc.) are gradually capturing a higher percentage of the flow (Allison et al. 2012). As sea level has risen, the point at which gravity overcomes inertia has also crept upstream (Roberts et al. 2012). This is changing the amount and distribution of the sediment that clogs the navigation channel, and increasing the cost to the taxpayers of annual maintenance.

More ominously, a major course change becomes increasingly more likely as the hydrology changes. One of the growing passes upstream of Head of Passes could undergo rapid channel expansion during a major flood, leaving insufficient flow in Southwest Pass to keep it open to 45 ft. Such a course change would have dramatic and expensive effects on the ability of the ports to function, disrupting the world's economy.

Reliance on this nineteenth century system has other future costs. The Panama Canal is being expanded, and will by 2014 be able to handle ships that need a 55 ft draft (Lagrange 2011). If the ports of the lower Mississippi cannot be reached by such ships, they will lose traffic as the world's fleets switch over to vessels needing a 55 ft channel. Given the difficulty and cost of maintaining the 45 ft channel, the likelihood that the present system would be converted to a 55 foot system is low—assuming it is even technically feasible.

Given these trends, we can either move proactively towards building a navigation system that does not rely on nineteenth century innovation and design (like jetties), or we can wait idly as inexorable economic forces send the tonnage to other ports or over different transportation modalities.

Fisheries

Abundant, readily available, and relatively inexpensive seafood is a key component of south Louisiana culture. Its commercial, recreational and subsistence harvest enables a way of life. Its consumption provides essential protein in coastal communities. It helps define foodways, from the simplest family meal to creole, Cajun and *nouvelle haute cuisine*, helping to drive the tourist economy. Its export provides food to the nation and brings income to the state. The most important species, in terms of volume harvested and value, are estuarine, and entirely dependent upon the existence of the still vast marsh platform in each of the delta lobes. For many of these organisms, optimum habitat is achieved during the deteriorating phase of the delta cycle, rather than during the building phase (Baltz et al. 1993). The prehistoric delta included accreting lobes dominated by fresh river water, and deteriorating lobes dominated by saline seawater, and everything in between. In the beginning phase of European colonization, the only part of the estuary where salty conditions dominated was east of the river and upstream of Head of Passes to the lower Pontchartrain estuary. Today, salty conditions dominate from Lake Maurepas to Bohemia on the east side, throughout most of the Barataria and Terrebonne estuaries on the west side, and, because of ship channels, around lakes Calcasieu and Sabine in the Chenier Plain (Linscombe and Chabreck 1997).

Because of this present artificial imbalance in that equation, where little of the delta is now accreting or fresh, species that thrive in more saline environments during harvestable parts of their life cycle are both abundant and widespread throughout the estuaries. During the last century, these species have moved inland, getting closer to harvesters (Moore and Pope 1910; Reed et al. 2007; Salinas et al. 1986; VanSickle et al. 1976). Harvesters themselves have for the most part abandoned the semi-nomadic seasonal down-estuary settlements of the early twentieth century, and settled into permanent homes in communities farther from the immediate coast. Places that were marsh just 50 years ago have become oyster reefs, open water where shrimpers trawl and fishing grounds. Places that were too fresh then, now have optimal salinities.

This shifting *geographical* baseline is as deceptive as the shifting baseline for abundance and diversity seen in other species. It has gotten easier to harvest key species, because they are found closer to home and market. As a general rule, the quantity of harvestable fish and shrimp is related to both the total area of marsh, but also to the total linear distance of marsh edge, which increases as marsh deteriorates. Ironically therefore, despite the loss of marsh, the quantity of harvestable seafood has shown no comparable measurable decline perhaps because of this relationship: deteriorating marsh may be fueling seafood production. Organic marsh material might literally be being converted to shrimp, crabs, oysters and fish—vegetable becoming animal protein as it is processed up the food chain. But the trend is toward equilibrium, which is zero in a zero sum game—once the marsh is gone, fisheries fueled by deteriorating marsh would collapse. We are, as has often been observed, living off the principal, not the interest.

But this is a game that does not have to be zero sum. As long as the Mississippi River is the only outlet for runoff of much of the precipitation that falls on the interior of North America, and as long as the sun shines, the river can go on building deltas and the sea can go on destroying them. We could begin living off the interest again, with the river as the principal.[2]

A return to the prehistoric physical baseline—a building delta with large areas of freshwater swamp and marsh—will necessarily disrupt this seafood economy as now practiced. All of the species now harvested will remain, and will continue to thrive, but the *loci* of harvest for some will shift toward the gulf, and the geographic width of the harvestable niche will narrow. Species such as eastern oyster, brown shrimp, and speckled trout, which have benefited from the conversion of fresh to saline and the break-up of the intervening brackish marshes, will undergo the seaward shift and a narrowing band of ideal salinity.

But this is not true for all species. Those with a tolerance for a wide range of salinities, such as blue crabs and redfish, will continue to occupy large areas of the estuaries, with broad areas of overlap with current conditions. Freshwater species, such as largemouth bass, alligators and red swamp crawfish, will occupy a much greater area.

Resistance to these proposed changes has been fierce among some in the communities that exploit these resources. Many shrimpers, especially smaller operators that depend upon brown shrimp inland during the spring season, object to the freshening of estuaries during spring high water. They fear reductions in brown shrimp populations, and object to the prospect of having to go farther for the harvest. Louisiana also has a robust recreational shrimp harvest which would be similarly affected. Some recreational anglers, and the charter captains and marina owners that depend upon them, object to a similar displacement of speckled trout, a much sought after game species. And, of course, most oyster harvesters, dependent upon a sessile resource that is most productive in a narrow range of salinities, fear wholesale freshening of estuaries. The band of optimum salinities would narrow, and would be found near the passes and barrier islands, rather than inshore. Many of those who harvest estuarine species tend to work on low margins, and large increases in fuel and time costs could drive some out of business, and could reduce incomes for many.

But estuarine fisheries production is also a zero-sum game. Once the estuarine platform is gone, the estuarine-dependent fisheries will collapse. We can either take actions that cause dislocation and shifts in estuarine fisheries resources now, or we can preside over the slide to zero. There is no doubt that current fisheries will be forced to adapt or die in order to make sure there is anything left for the future.

Communities

No issue is more difficult than devising a strategy for existing communities in the coastal zone now under threat, or that will come under increasing threat as sea level rises.

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[2] To keep the analogy accurate, the river would really be building up principal in separate new accounts, while old accounts, and the interest they earn, are being depleted.

Many southeast Louisiana coastal communities grew rapidly during a period, roughly from Hurricane Betsy in 1965 to Hurricane Katrina in 2005, which experienced relatively little catastrophic tropical activity. At the same time, however, exposure to smaller tropical cyclones grew as buffering coastal wetlands deteriorated. Beginning with Category 1 Hurricane Juan in 1985, flooding of areas that had no experience of storm surge except in major storms began to occur more frequently. The natural response was to call for levees. But these communities are generally located deep in the coastal zone, on linear natural levees surrounded by marsh and open water. Their very existence is tied to easy access to coastal waters. The fact that assets are dispersed and linear rather than concentrated means that the length of levees and floodwalls needed per unit asset is very high. The solution has been to propose cross basin levees with navigation gates that protect numerous scattered assets, but must perforce enclose and cut off estuarine wetlands.

Cognizant of the effect that levees have on enclosed wetlands, planners have increasingly proposed so-called 'leaky levees'—levees with floodgates and tidal openings to allow hydrological exchange during normal tidal conditions. Such levees could theoretically provide adequate flood protection when closed during surge events, but allow normal estuarine functioning at other times. But there are serious concerns about whether levees can be designed that mimic the 'leakiness' of natural systems adequately enough to mitigate these challenges. Isolation of wetlands is occurring or will occur from massive cross basin levee projects such as *Morganza to the Gulf* in the Terrebonne Basin now under construction and with some of the proposed alignments of *Donaldsonville to the Gulf* in the Barataria Basin. A system to close the entire Pontchartrain-Maurepas Basin, nearly 1,000 square miles of embayment and wetlands, has been debated for decades. A proposed levee bordering the north side of I-10 between the Bonnet Carré Spillway to Ascension Parish in the Pontchartrain Basin would isolate large areas of wetland south of the levee and prevent effective diversions to wetlands north of the levee. Most of these wetlands are in a highly degraded state and declining rapidly; levees will make restoration much more difficult.

The placement of levees is critical both for flood protection and for wetland health. Wetlands behind levees are threatened. Wetlands not only require interchange of water and nutrients, they need sedimentary inputs (McKee and Cherry 2009; Turner et al. 2007). Cutting wetlands off from the riverine inputs with levees is an extremely destructive but routine case, but storm related deposition is also critical for longer term sustainability of estuarine wetlands located far from riverine input (Freeman 2010). Levees can reduce or eliminate deposition of resuspended sediments during high tides and storm surges. Relatively low levees can result in significant reduction of sediment input as evidenced by the LaBranche wetlands where a railroad embankment of about 6 ft has led to serious marsh break up (Day et al. In Review). The wetlands inside the hurricane levee system in Bayou Sauvage NWR in New Orleans, and the Central Wetlands of St. Bernard and Orleans parishes have shown steady decline since enclosure behind leaky levees. And both areas suffered catastrophic declines among freshwater dependent plants as a result of levee overtopping during Hurricane Katrina, and subsequent semi-impoundment of salty anaerobic waters for weeks after the storms.

In terms of sedimentary input it is not the height or breadth of levees, but the first few feet of levee that deprives the marsh. But it is the last few feet of elevation that determines whether flood protection succeeds or not. Ironically, then, a levee that fails to provide adequate flood protection during more catastrophic storm events may still cause marsh deterioration.

The evolution of these issues converges with the growing recognition that levees ultimately put areas at more risk to dramatic events in exchange for protection from more frequent and moderate events. Levees built to lower elevations, which are more affordable and can be constructed more quickly and maintained with locally funded assets, can reduce risk from routine tidal flooding. But the trade-off is that they increase the severity of flooding during less frequent but more catastrophic events. This is because the levees themselves trap water, isolate those who remain, complicate return after the storm, and have to be repaired before pumps can be employed to drain the basin. Levees also induce development and encourage structures that are less flood resistant. This was seen most dramatically in metropolitan New Orleans during Hurricane Katrina, but it has happened on a smaller scale on numerous occasions in coastal Louisiana. Where levees serve as the containment perimeter for forced drainage systems, as they do in metropolitan New Orleans, lower Plaquemines and Lafourche parishes, and elsewhere, they induce sub-surface lowering of the water table and subsidence (Yuill et al. 2009). In coastal Louisiana this has led to sections of communities as much as 10 ft below sea level. Such subsided communities are of course even more susceptible to catastrophic flooding if the protection system fails.

Leaky levees (of any height) that allow tidal interchange will not induce significant subsidence. However, in an era of rising relative sea level, there is another cost. One of the central purposes of leaky levees is to allow coastal communities to maintain navigable connections to the Gulf. But as sea level rises, the frequency of closures will increase. A time will come when floodgates will need to be closed continuously, cutting communities off from the very reason they exist in the first place—their connection to coastal resources (USACE 2013). Elevation and flood-proofing of structures, roads, utilities and infrastructure will be required in order to be able to keep the gates open. This will, of course, beg the question as to why this was not simply done in the first place, rather than going through the costly and futile interim step of levee and floodgate building.

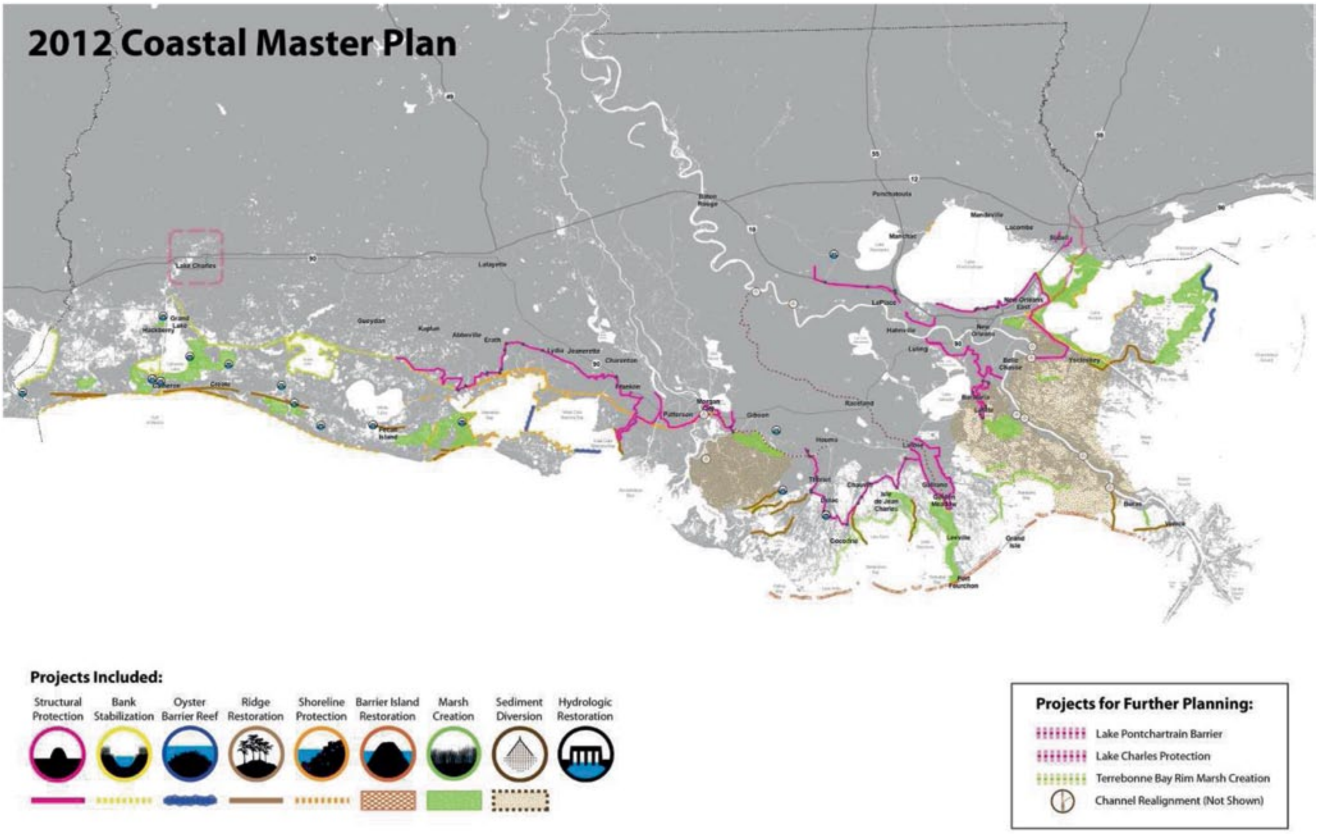

Fig. 5 Louisiana's 2012 Comprehensive Master Plan for a Sustainable Coast has identified 109 projects to facilitate sustainable, long term, large-scale restoration of Louisiana's coastal wetlands. Courtesy Louisiana Coastal Protection and Restoration Authority

Coastal communities face bleak choices. This is as true of New Orleans as it is of the smallest bayou town. Their continued viability is contingent. The future rate of sea level rise, the frequency and intensity of future hurricanes, the availability of public funding, the speed with which it is obtained so that risk reduction measures can be taken, the potential cost escalation in an energy constrained future, the cost of insurance, and the national response to future disasters, are all unknowns. And yet each of these variables could be the one to tip them from viability to decline or destruction.

Growth patterns in Louisiana's coastal zone over the last 50 years have been complex. While population has increased in larger metropolitan areas, it has tended to sprawl, following the suburban pattern seen nationwide. But compared to other southeastern states, Louisiana's growth has been anything but robust—it has lost two seats in the U.S. House of Representatives. Even this anemic growth somewhat masks in-state migration from parts of the coastal zone, driven by the relentless reoccupation of the delta by the sea. This migration from the coast is occasionally punctuated by mass relocations or dislocations after hurricanes, as especially after Hurricane Katrina in 2005. Historically, whole communities have migrated inland, as after the storms that wrecked Isle Derniere in 1856 and Chenier Caminada in 1893. Shrinking communities, or communities that grow more slowly than their counterparts, face increased competition for the very support needed to keep them viable.

As with navigation or fisheries, the choice for communities is either to adapt to living in a functional delta with all of its uncertainties or to abandon it and head to *terra firme*. Our uncertainties are compounded because we live during a period of rapid and accelerating sea level rise. But if we cling to the illusion that a delta can be frozen in time if only we spend enough money on dredges and levees, we will be overwhelmed. We could be overwhelmed anyway if we are unlucky with the timing of hurricanes and the rate of sea level rise, but at the very least we can leave behind a re-invigorated delta that provides at least some small measure of the ecosystem services that drew us here in the first place (Fig. 5).

We are on the cusp of returning to that delta. Louisiana's 2012 *Comprehensive Master Plan for a Sustainable Coast* lays out an achievable set of actions that will return about one half the peak flow of the Mississippi River to areas of the delta now in a free fall collapse, restoring deltaic function. It proposes a plausible set of aggressive, costly and energy intensive projects that could, with luck, good timing, and money, stave off destruction of coastal communities until the delta begins to show signs of recovery through natural land building. It lays out a path forward for capturing *more* than 50 % of the river in the future. It creates a process for remaining flexible as a state to respond to changing variables like sea level rise rates, costs, new science or lessons learned through adaptive management. There is broad political, economic, and social support for the plan, at least conceptually. And real dollars, enough to make a down payment on the plan, are in the pipeline from a number of sources. Fines and penalties available for restoration in Louisiana already exceed $ 1.2 billion from the Macondo oil spill. Billions more are possible. In addition, beginning in 2017, Louisiana's share of Federal Outer Continental Shelf revenues will increase substantially.

But resistance and magical thinking still remain.

A Narrative of Denial

We shouldn't do diversions because:

There is Not Enough Sediment

An argument that has become commonplace is that because of changes to the river, or because of the time requirement to build a delta, diversions will not work as a solution to coastal land loss. Arguments include the claim that "there is not enough sediment", or "the excess nutrients from farm run-off in the water will harm remaining marshes", or "it will take too long".

The proposed antidote is pipeline sediment delivery from dredges in the river, coastal bays, or offshore, mining the bed load of the river, or deepening the bays, or mining the shoals. This has been done successfully, and has resulted in new marsh platform and barrier island nourishment. "Creating" marsh is technically trivial. Dredge sediment and transport it to an area of open water. Fill the area to within a suitable range of elevations, and marsh or ridge or dune vegetation will colonize the sediment platform.

To extend the medical metaphor, this is the "treating the symptom" approach. Wetlands, ridges and barrier islands have disappeared, so put them back. This approach has a lot of appeal. It can be done relatively quickly—at least on a small scale and where a sediment source is available. It does not change salinity—fresh marsh can be built in freshwater areas, brackish marsh in brackish areas, and so on.

Despite the clear usefulness of this band-aid approach as a means of treating specific injury, it is not a substitute for the cure. Dredging bay bottoms to build adjacent marsh robs Peter to pay Paul, or to use another apt *cliché*, it is simply re-arranging the deck chairs on a sinking ship. Moving sediment from a bay bottom to build adjacent marsh results in no net gain to the system. Like a hole on a beach, the system immediately seeks equilibrium and the hole fills up, eroding adjacent shoreline.

Even when borrow is obtained from a distance, "outside" the system, from the river's bedload or from shoals far offshore, artificially created marsh still needs continuous riverine input in order to sustain itself. Otherwise it will begin to deteriorate under the same inexorable forces that destroyed the natural marshes in the first place. Additionally, energy costs will continue to rise, making the cost of pumping sediment eventually prohibitive. While diversions have higher upfront capital costs, the cost of operation and maintenance is relatively trivial (CPRA 2012).

Offshore shoals are finite resources, and their removal has ecological costs, as well as rising economic costs that track fuel prices and increase as transport distances increase. The river's bedload of sandy sediments is replenished relatively slowly. And even if *all* of the bedload sediment of the river could be harvested by dredge, that would still leave about 80 % of the river's annual available sediment unutilized. Dredges can capture the bedload, but the fine material that remains in suspension, the mud in the "Big Muddy," would be missed by the dredges. Without wholesale diversion of the river back into its delta, most of this 80 % would continue to be lost to the Gulf each year. The marsh creation band-aid is an important tool, but it has critical limitations. And it is simply incomprehensible to propose using only 20 % of the available sediment resource to rebuild the delta, especially considering that perhaps only 50 % of the peak nineteenth century sediment load is still carried by the river today.

There is Not Enough Time

Another argument touted in favor of mechanical marsh creation is that natural delta building is too slow a process. But this observation is another example of drawing conclusions from a shifted baseline. Proponents of this argument point to the relatively small scale land building going on in the Bird's Foot, and to the alleged slow pace of accretion in the Atchafalaya and Wax Lake deltas. However, both within the Bird's Foot and now at the Atchafalaya River Delta and Wax Lake Outlet Delta, successful land building is taking place despite the less than ideal depositional environment into which the river must discharge sediment.

The Bird's Foot was a natural anomaly—at the time of European discovery the river had forged a route far out onto the shelf. It had by whatever means largely confined itself between natural levees that pinned the channel seaward of flanking marshes.[3] It was truly shaped like a bird's foot—

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[3] The strangeness of the Bird's Foot receives little attention. But its position far out onto the shelf, having outrun, so to speak, the adjacent coastal marshes, give it a physical shape unlike the other extant Mississippi River delta lobes, and very unlike the classic deltas of the textbooks. There really seems to have been very little flanking marsh in the eighteenth century, and few or no small distributaries. One channel, three forks: today's Pass a Loutre, South Pass and Southwest Pass. Pass a Loutre, the channel with the highest carrying capacity when the French arrived, bifurcated near its mouth, but otherwise it was the river, the three passes, and their natural levees. It was as if the river had already fallen off an edge and was being held in place because subsidence was maintaining a favorable gradient.

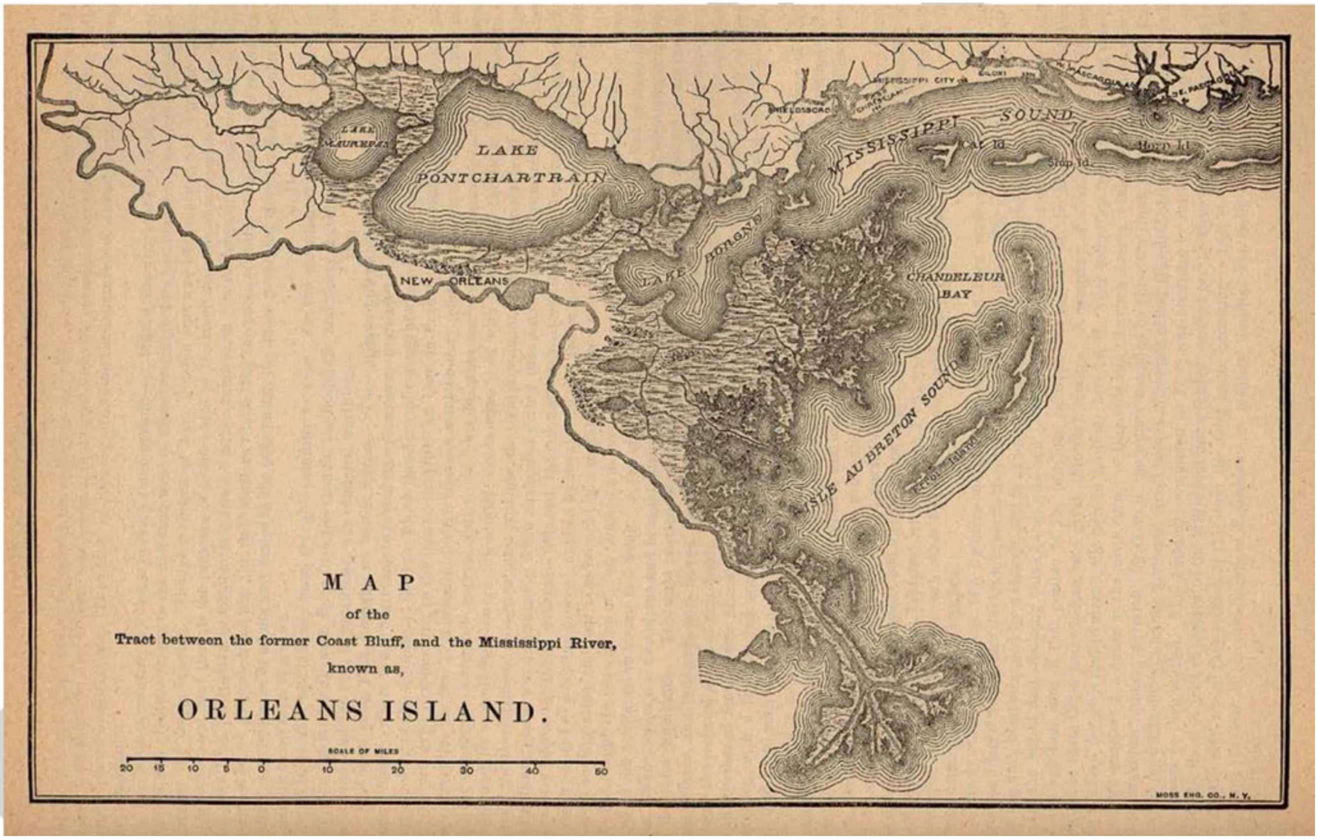

Fig. 6 1880 map of the Mississippi River delta. Note the extension far out onto the shelf, shaped like a classic bird's foot

the tarsus a 15 mile long narrow ribbon, with three narrow 10 mile long toes from Head of Passes. The main channels were so well confined that little sand escaped to the flanks to build fringing marsh. It was like a chicken's foot rather than like the webbed duck's foot we've known for much of the last 100 years—and, of course, it now has more toes, and two of the original three toes are much longer (Fig. 6). Above Head of Passes there were no major outlets—Main Pass, Grand Pass, and Baptiste Colette had not yet formed. In the first upriver European voyage, during the spring flood of 1699, the French Canadian explorer Iberville mentioned no outlets between Head of Passes and Bayou Lafourche, 174 miles upriver, except for Mardi Gras Bayou, on the east bank a day's voyage above Head of Passes.

During the historic period a series of mostly anthropogenic crevasses allowed the river to fill in the webs between the toes and to carve the new toes. These new crevasse splays included: The Jump (Grand Pass, Red Pass, Tiger Pass, etc.); Cubit's Gap (Main Pass, which created today's Delta National Wildlife Refuge); Baptiste Collette; West Bay off Southwest Pass; and the various splays off Pass a Loutre (which created today's Pass a Loutre Wildlife Management Area) (Coleman 1988; Roberts 1997). Throughout the last 200 years land has built, been cut off from flow either by natural levee buildup or channel work by the Corps, deteriorated, and then in some cases been rebuilt by re-opening to river flow. The net acreage has been large, but the gross acreage much larger. The principle difference between gross and net area gained is that the Bird's Foot experiences subsidence rates that average 2 m per century, caused by compaction and fault slippage (Figs. 7 and 8) (Dokka 2006; Gagliano et al. 2003; Kuecher et al. 2001).

It should also be understood that very little of the sediment reaching the lower river is accreted there. The Bird's Foot was perched in comparatively deep water when Europeans arrived, and every channel project undertaken for the last 300 years has pushed the river's mouth into deeper water. Deposition into deeper water requires more sediment on the vertical axis. But it also means that less can be captured, because finer sediments, the clays that built most of the delta, are transported far from the depositional environment (Roberts et al. 2012). Fine grains take a long time to settle even in a stilling basin—they can be carried for tens of miles by currents, such as those encountered in the gulf at the mouths of the passes, and even tidal fluctuations and wave energy prevent them from settling to the bottom. Capture of fine grains is best facilitated in shallow, low energy environments, where numerous impediments interrupt flow. In other words—marshes build more marsh.

So while net acreage at the Bird's Foot may seem to indicate insufficient sediment in the river to meaningfully offset our historic rates of land loss, this is only because where the

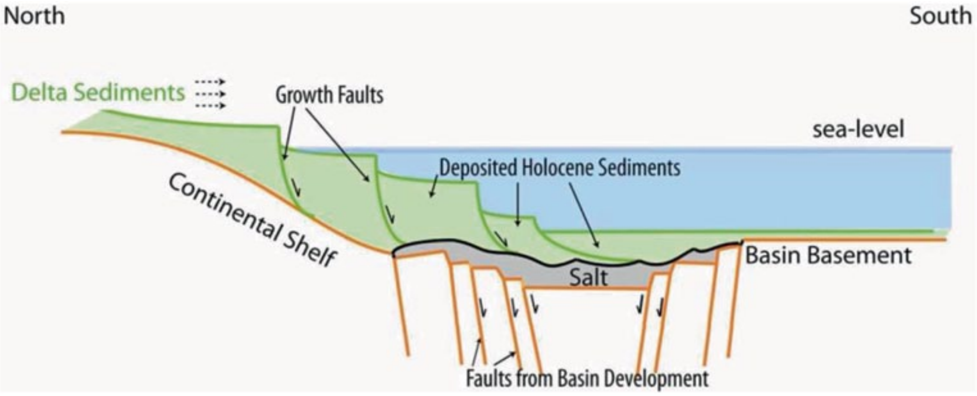

Fig. 7 Generalized faulting along coastal Louisiana and the Gulf of Mexico. One of the consequences of this geological substructure, is differential rates of subsidence. (From Yuill et al. (2009))

deposition is taking place today gives us a false impression. Diverting sediment laden river waters into shallower areas, with lower subsidence rates, lower hydraulic energies and more existing vegetated platform will result in concomitantly higher rates of sediment capture and deposition.

The Atchafalaya and Wax Lake deltas are accreting, building land into Atchafalaya Bay (Roberts et al. 2003). But compared to the magnitude of loss elsewhere, the gains appear modest. After all, 30 % of the total flow in the system eventually makes its way to these two sub-deltas. If that is all 30 % can give us, will the remaining 70 % added on be enough? Again, the Atchafalaya deltas are the wrong analogy. They are being built out into a large estuarine bay—a high energy environment where little of the fine material is trapped but is instead carried away and distributed far and wide. In addition, the Atchafalaya still has a floodplain that averages 15 miles wide and extends for more than 60 miles, about 600,000 acres in which the floodwaters can spread and sediment be trapped before it reaches the delta (Atchafalaya Trace Commission 2011).

Thirty per cent of the flow diverted into the existing delta platform, into broken marsh and very shallow interior ponds, would result in significantly higher rates of capture than now takes place in Atchafalaya Bay (Kim et al. 2009). Modeling for the 2012 Master Plan suggests that even against a sea level rise of 0.45 m in 50 years, diverting between 35 and 45 % (50 % of the river below Old River and 150,000 cfs from the lower Atchafalaya) of the total flow at peak flood into existing broken marsh would build or maintain about 300 square miles of marsh platform over 50 years.

Having lost 1,900 square miles in the last 100 years, 300 square miles seems inadequate. But it has to be measured against continued and accelerating future loss. Either the river builds land, or the sea takes it. By confining the river over the last 300 years, we gave up most of the delta landscape to the sea. We can't get that back. By expending extraordinary amounts of money we can move sediment around with dredges to temporarily fill holes. The 2012 State Master Plan proposes almost $ 20 billion to build less than 200 square miles over 50 years. But we'd all but literally be building sand castles in the face of a raging sea. On the other hand, for a modest investment, we can allow the river to resume the process of building land. The 2012 Master Plan models show costs of just under $ 4 billion to get those 300 square miles, against a moderate sea level rise scenario. But even if that estimate turns out to be half of what it actually costs, and even if sea level rise confines the net land gain to half the estimate, the investment is trivial compared to the benefit. The alternative is no delta at all. And the plan, in this iteration, leaves 50 % of the river's peak flood untapped for delta building. Creative re-engineering of the navigation channel would allow us to tap much of the remaining delta building potential, and increase the area of new delta we could build against the rising sea.

Conclusion: The Very Ground We Stand On

The real world teaches us one thing: the Mississippi River can build deltas. It is somewhat surreal to listen to my fellow citizens, opponents of river re-introduction, stand up in meetings held in New Orleans, Chalmette, Belle Chasse, Lafitte, Thibodaux, Houma, or any other southeastern Louisiana community, and insist that the river, re-directed by diversions into the collapsing delta, will not build land. The very ground beneath our feet belies these statements. Equally surreal are researchers and bureaucrats who continue to urge caution and delay on river reintroduction in the face of the overwhelming certainty of the disaster we face if we don't allow the one known delta building force to operate. It is a peculiar delusion—to grasp that one lives on and in a delta, but to somehow believe that the untapped river that courses through it without outlet can't do again what it so manifestly has already done. We are unconnected to the past and to the physical realities of our home. We fear changing what we know, even if what we know is a declining, indeed a collapsing, system. We are beset by magical thinking, confusing the efficacy of dredging and rock barriers on the small

Fig. 8 1874 U.S. coast survey map of the Mississippi delta

scale, with the reality of loss on the delta-wide scale. We fear the change that massive riverine re-introduction will inevitably bring. Resisting change and clinging to magical thinking are traits that have served individuals and our species well. It is the right evolutionary strategy most of the time. But not when the very geology is against us.

Our fear of change is rooted in the false impression created by the shifted biophysical baseline that is our sole experiential reference point. We as humans did not evolve the innate capacity to comprehend physical changes taking place on a geological time scale—changes that take eons. But just as importantly, we have no innate capacity to internalize gradual change, such as happens in the natural cycle of delta building and decay. From a geological perspective, delta geology is instantaneous, but it is not so for us. We are comfortable with stasis. Incredibly, during the last century in south Louisiana we managed to speed up the delta cycle to a pace that became noticeable even to us. Our reaction was to clamor for stability, for a return to a delta we remembered. But deltas don't work that way. Delta lobes grow, or delta lobes shrink. It is the delta process that gives stability, with offsetting growth and decay. None of us alive in south Louisiana has lived in such a deltaic environment. But we could. And if we allowed the river to rebuild such a delta, our grandchildren might even get a glimpse of the abundance of wildlife and fish among which American Indians once lived and which stunned the first visitors from the biologically depauperate old world upon their arrival 300 years ago.

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How Deltas Work: A Brief Look at the Mississippi River Delta in a Global Context

Liviu Giosan and Angelina M. Freeman

Abstract

River deltas have been a preferred human habitat due to their high productivity, rich biodiversity, and easy transport along abundant waterways. It has been argued that deltas fostered the development of civilizations. However, deltas are fragile geomorphic features that can change dramatically with modest modifications in environmental conditions. Intensive human development, population growth, and recent global changes are transforming deltas into one of the most endangered coasts. Future preservation of deltas will become increasingly difficult and require developing complex management strategies based on a profound understanding of delta dynamics and history.

Keywords

River diversion · Sediment budget · Sediment retention · Delta cycle · Land building

A Primer on Deltas

Formation and maintenance of deltaic plains is the direct result of water, sediment and nutrient delivery from drainage basins that are several orders of magnitude larger than the deltas themselves. Soil generation in wetlands is also a fundamental component in the emergence and persistence of deltaic plains above sea level. Deltas develop despite massive sediment loss at the coast through changes in relative sea level changes, wave attack, currents, and tides.

Construction of a delta is accomplished by coastal progradation and aggradation of the delta plain. In a simplified manner, this can be described by the lateral and upward translation of a deltaic shoreface or delta front. River mouth processes dominate frontal progradation, whereas channel processes control the aggradation of the delta plain. However, channel processes may also be responsible for large scale avulsions of the entire delta to new coastal locations.

As termini of large drainage basins, deltas act as filters, repositories, and reactors for a suite of continental materials on their way to the ocean, including freshwater, sediments, carbon, nutrients, and pollutants, significantly affecting both the regional environment at the land-ocean boundary and global biogeochemical cycles. High river flows supply materials that stimulate high biologic production and control a series of high diversity deltaic habitats. Wetlands create organic soil and process pollutants contributing to maintaining water quality in coastal regions. A large part of the organic carbon reaching or being produced in deltas is buried with their sediments. Deltaic wetlands and forests also act as natural buffers to reduce the impact of storms.

Delta Dynamics: Natural vs. Engineered

Deltas are ineficient traps for fluvial sediment and because a majority of sediments is involved in progradation or is lost offshore, a common morphological trait of deltas is their low relief, with gradients smaller than decimeters per

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km. In natural conditions, deltas freely adapt to changes in boundary conditions by advancing, retreating, switching, or aggrading. Virtually all major deltas are now becoming unstable under growing sediment deficits, historical engineering infrastructure, subsidence and accelerated sea level rise. However, early anthropogenic effects linked to extensive land use changes may have already bequeathed us overexpanded and vulnerable deltas.

Without human intervention, in response to rising sea levels and/or diminishing fluvial sediment discharge, most deltas would reduce their size under wave and current attack and migrate to shallow parts of the basin by switching and/or inundation. Negative feedbacks may delay the destruction of a delta. For example, on the delta plain, soil formation may switch to fast organic deposition, crevassing and sheet flooding may intensify to increase accretion of the delta plain, or the whole delta may avulse to a position more advantageous for sediment retention. Similarly, the deltaic fringe (i.e., subaerial and subaqueous parts of the deltaic coast interacting with and being modified by waves, tides, and currents) could respond by barrier and dune buildup and sediment redistribution to counteract sediment loss.

Modern deltas developed during the Holocene, in dynamic, but relatively limited ranges of sea level, freshwater and sediment input regimes, and other environmental characteristics. Human modification of this dynamic balance begins with far-field upstream production or retention of freshwater and sediments, but many deltas have also been modified by human occupation; around half a billion people now live on or near deltaic coasts and wetlands. Population centers, including rapidly growing megacities, are often located on deltas. Anthropogenic near-field stressors such as accelerated subsidence following groundwater and petroleum extraction, relief stabilization and changes in the distribution of water and sediment within the delta through channelization and flood protection structures, ecosystem changes, and infrastructure development linked to direct human occupation and urbanization have also impacted delta dynamics. Unfortunately, Mississippi delta makes no exception in this multitude of negative impacts; indeed, it has become a paradigmatic case for endangered landscapes and ecosystems.

History of Development of the Mississippi River Delta

The modern Mississippi River Delta formed over the past approximately 7000 years as the Mississippi River deposited sand, clay, and organic material at its receiving basin, the Gulf of Mexico. The Mississippi Delta is a river dominated delta. The architecture of the delta reflects the prevailing processes of the Mississippi River system taking precedence over the physical processes of the Gulf of Mexico receiving basin (Galloway 1975). The dominance of the Mississippi River system results in a complex branching networks and a small width to length ratio of the delta plain (Galloway 1975; Roberts et al. 2012).

As North America's largest river, the Mississippi drains approximately 40 % of the United States (3.4×10^6 km^2) from six major drainage basins, and has a present annual 15,360 m^3/sec discharge of fresh water. The current annual sediment discharge of 145 million metric tons marks a substantial reduction from the 400 million metric tons per year of material that built most of the delta before large-scale human activities modified the river basin was modified by dams, locks, meander cutoffs, and other engineering structures (Meade and Moody 2010). The delta plain has a variety of habitats including cypress swamps and marshes, reflecting the transition from freshwater habitats in the upper delta plain, to brackish to saline habitats in the lower delta plain due to tidal inundation (Roberts et al. 2012).

Delta building in the Mississippi River Delta occurred in six episodes of land construction that resulted in six distinct delta complexes (Frazier 1967; Kolb and van Lopik 1958; Roberts 1997) (Fig. 1). Before recent artificial levee construction, channel avulsions created a new course for the Mississippi River every 1000–2000 years, changing the locus of sediment deposition. Each time this happened a new delta complex was initiated and the older abandoned deltas slowly deteriorated and experienced land loss by the combined processes of subsidence and sea level rise (Roberts 1997; Roberts et al. 2012). The Mississippi River built the 30,000 km^2 delta plain (Roberts 1997), depositing sediment from upstream and changing river course periodically looking for a shorter route to the Gulf of Mexico. Once the sediment deposited by the river fills the accommodation space, a subaerial delta complex plain forms, with wetland plants taking root and contributing to organic deposition. When the river relocates, input of clastic sediments in the abandoned delta lobe is reduced to occasional inputs during flood events through distributary channels (Blum and Roberts 2012) or sediment deposition during storm events (Turner et al. 2006). Local organic accumulation processes dominate until the lobe erodes and subsides (Blum and Roberts 2012).

The geologic history of the lower Mississippi valley and delta region influences land surface dynamics of the modern delta plain. During the Plio-Pleistocene (<5 million years ago), the region experienced tremendous sediment loading. At the latitude of New Orleans, sediments deposited during this period are > 500 m in thickness, with increasing thickness to > 4,000 m at the shelf margin (Blum and Roberts 2012; Woodbury et al. 1974). This rapid sedimentation created instabilities made more variable through movement of underlying mobile prodelta clays and salt deformation (Woodbury et al. 1974). Due to this massive sedimentation, the modern delta region is inherently unstable, and experiences subsidence due to sediment loading (Galloway 2008).

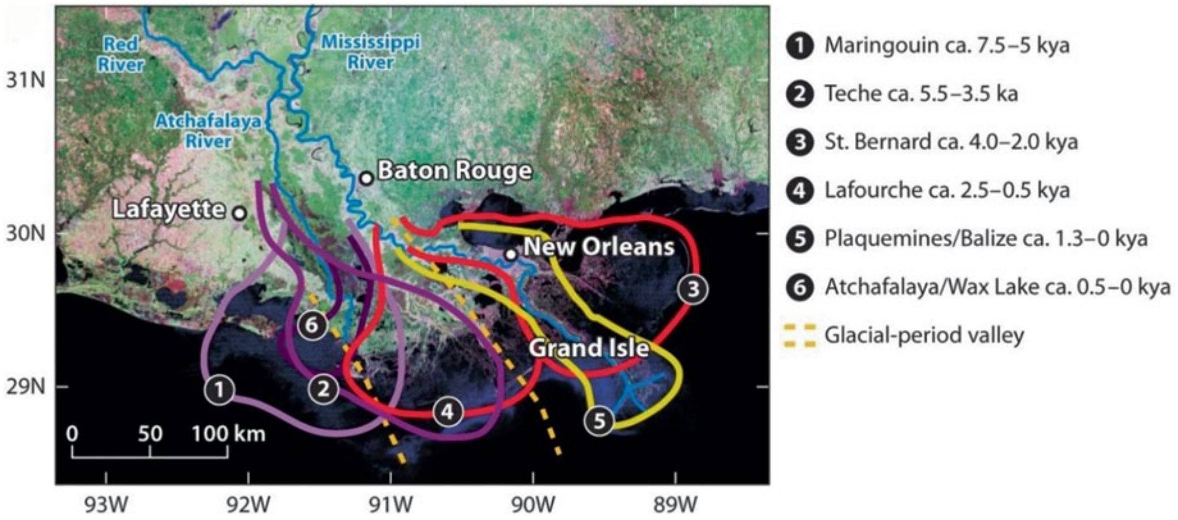

Fig. 1 Location of prehistoric and historic lobes of the Mississippi Delta, adapted from Blum and Roberts 2012. Reproduced, with permission, from the Annual Review of Earth and Planetary Science, Volume 40 © 2012 by Annual Reviews www.annualreviews.com.

The first Mississippi River delta complex, the Maringouin, formed between 7000–8000 years ago when the rate of sea level rise slowed markedly following the latest Pleistocene glacial maximum (Fig. 1) (Frazier 1967). At this time, all the world's great rivers started building deltas into the marine environment resulting in a seaward advance of Holocene shorelines (Stanley and Warne 1994). Submergence of the Teche delta and over 75 km of landward transgression occurred after the river switched to the east and started building the St. Bernard delta (Blum and Roberts 2012). The switching of constructive and destructive cycles is also present on smaller spatial and temporal scales within each delta lobe in the construction and destruction of subdeltas and bayfills (Coleman and Gagliano 1964; Roberts 1997). Penland et al. (1988) illustrated that through time, an abandoned delta complex would be eroded along its seaward perimeter and the coarsest sediments concentrated into beaches and spits, then barrier islands separated from the eroding delta, and finally submerged shoals. Large basins such as the Atchafalaya, Terrebonne, and Barataria Basins were formed between current and old Mississippi River channels and their natural levees. Both the St. Bernard and Lafourche deltas are currently in the destructive phase of the delta cycle, with barrier island arcs that are rapidly disappearing (Miner et al. 2009). Today's Terrebonne, Lafourche, and St. Bernard marshlands represent the surfaces of once active delta complexes that are in various stages of deterioration resulting in land loss. Local processes of erosion in addition to subsidence result in the expansion and merging of open water areas within the marshlands resulting in lakes that enlarge with time (Day et al. 2009).

Sediment deposition at the mouth of the Mississippi River is characterized by buoyant spreading of the less dense fresh water over the denser salt water of the Gulf of Mexico (Bates 1953). Fine grained sediments are broadly distributed with expansion of the sediment-rich plume. Coarser sediments from the river are deposited close to the river mouth (Bates 1953). The fine-grained sediments are deposited over a wider area, and as the delta progrades, coarser-grained sediments are deposited over top of these finer-grained sediments resulting in a coarsening upward geological structure (Roberts et al. 2012; Tye and Coleman 1989).

The latest delta complex is the embryonic Atchafalaya-Wax Lake delta complex (Roberts 1998) (Fig. 1). Progressive capture of flow from the Mississippi River by the Atchafalaya River has been occurring since at least the 1500s (Fisk 1952). The Atchafalaya River provides a much more efficient route (220 km) for water and sediment to reach the Gulf of Mexico than the current Mississippi River course (520 km). Renewed progradation of the eastern Chenier Plain has been documented as fine-grained sediments from the Atchafalaya are transported westward (Roberts et al. 1989; Wells and Kemp 1981). The Atchafalaya Basin contains one of the few remaining largely natural deltaic ecosystems in the world.

Coastal Louisiana experiences some of the highest subsidence rates worldwide, making the Mississippi River Delta one of the first areas to experience the effects of global sea-level rise. Subsidence is a problem in many deltas, where rapidly deposited sediments compact and dewater causing subsidence and adding to relative sea level rise. The long-term sustainability of the world's deltas is at risk due to projected acceleration in sea-level rise and changes in hurricane intensity and frequency (Bindoff et al. 2007; Hoyos et al. 2006; Webster et al. 2005)

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The Last Naturally Active Delta Complexes of the Mississippi River (LNDM): Discovery and Implications

Richard E. Condrey, Paul E. Hoffman and D. Elaine Evers

Abstract

The most ambitious ecological restoration project yet attempted is just getting started to re-naturalize the Mississippi River Deltaic Plain. All the channeling, leveeing, lumbering, damming, dredging, and polluting of this system over the past 300+ years make it difficult to envision today how a more natural ecosystem might look and function. Our hope is that an awareness of the protohistoric deltaic plain may help guide the modern restoration program. To accomplish this, we explore the historic record for a description of the last naturally active delta complexes of the Mississippi River (LNDM) as the most appropriate restoration model for Louisiana's coast. The LNDM is our reconstruction of this system as it was encountered by the first Europeans to navigate it. To accomplish this, we focus on Alonso de Chaves' ca. 1537 manuscript. We find Chaves' latitude estimates accurate ($R^2 = 0.99$), his league to equal 6.3 km, and his location of the LNDM consistent with the most authoritative first-hand accounts of the protohistoric and colonial period (Barroto, Iberville, Evía, and Dumain). We find the LNDM was a vast seaward-advancing arc that occupied, through four distributaries, all of the five most recent delta complexes of the Mississippi River and extended across all of coastal Louisiana east of the Chenier Plain. It was characterized by plumes of freshwater that extended for more than 10 km into the Gulf of Mexico (GoM) during the spring flood of the Mississippi River and by a vast offshore oyster reef covering >2,000 km^2, impeding navigation, and functioning as an offshore harbor near the reef's western end. Our findings support "reconnecting the river to the deltaic plain via … the reopening of old distributaries" (Day et al., Science 315:1679–1684, 2007) and the desirability of "a fully revised delta-lobe-scale chronostratigraphy" (Kulp et al., Soc Sediment Geol Special Publ, 83:279–293, 2005). Implications of our findings are discussed in light of what we view as fundamental errors in Louisiana's coastal restoration plan and the "Berms to Barriers"/post Deepwater Horizon oil spill efforts. Here we find that many of Louisiana's coastal restoration benchmarks—diversions restricted to the lower regions of coastal Louisiana (i.e., the Birdsfoot and the Atchafalaya delta complex); oyster reefs confined to estuarine environments; brackish-water

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dominated estuaries in the spring; deepwater shipping channel inlets; and artificial levees—are incompatible with a sustainable coast and that recent data are consist with a constant rate of land loss in coastal Louisiana of 69.1 km^2/yr (1.47 football fields/hr) for 1932 through 2010. We also find that the "Berms to Barriers" concept is necessarily going to fail unless the natural flows of the Mississippi through and across the LNDM are sufficiently restored so as support Louisiana's barrier islands and coastline against the forces of the GoM. Our findings support Lamb's (Separata du Revista da Universidale de Coimbra 24:9, 1969) argument that Chaves (ca. 1537) provides our earliest comprehensive view of the coasts of the Americas and Ovieda's (1851) argument that De Soto's men sailed out the mouth of *Río del Espíritu Santo* (River of the Holy Spirit)—which we conclude flowed through the Atchafalaya/Vermilion Bay complex and not the Birdsfoot.

Keywords

Forensic ecology · Protohistoric and colonial delta record · Diversion positioning · Coastal restoration · Oyster reefs

Introduction

Our paper is an exercise in forensic ecology in which we use navigation records from the sixteenth century to reconstruct the lay-out of and extract clues about the ecological functioning of the LNDM. This is done not merely to establish a starting point for the largely man-made destruction of this critically important ecosystem, but to provide insights for current efforts to restore at least a portion of the Mississippi River Deltaic Plain (defined in Fig. 1) to a sustainable condition.

Our use of the terms 'Mississippi River Deltaic Plain', 'delta complex', and 'delta lobe' is based on Frazier (1967), who discusses the theoretical "development of a typical delta complex" (p. 288–291), river shifting between delta complexes, and simultaneously prograding delta lobes (p. 306). We define the LNDM as all emergent delta complexes in which at least one delta lobe was occupied by a Mississippi River distributary delivering a ≥ 1 km plume of fresh water into the Gulf of Mexico (GoM) during the protohistoric and colonial period.

In this paper, history is understood to be the preserved, human-recorded record (written or illustrated) of human-observed events; the protohistoric period begins with the earliest preserved written record of coastal Louisiana (ca. 1519) and ends with its first continuous occupation by European settlers (1699); the colonial period immediately follows the protohistoric period and ends with the advent of Louisiana statehood (1812); and the historic period begins ca. 1519 and extends to the present.

The Critical Discrepancy in Louisiana's Coastal Restoration Plan

Louisiana's Comprehensive Master Plan for a Sustainable Coast (Plan) seeks to reverse Louisiana's catastrophic rates of wetland loss in the Mississippi River Deltaic Plain and Louisiana's Chenier Plain (CPRA 2007, 2012). The Plan is an evolving document (e.g., CPRA 2011, 2012) which builds on the analyses found in the Coast 2050 Plan, hereafter 'Blueprint' (LCWCRTF and WCRA 1998) (e.g., CPRA 2007, p. 36).

Engineered diversions of the Mississippi River are a critical component of the Plan's efforts to restore the Mississippi River Deltaic Plain (e.g., Blum and Roberts 2009). The question is: Where should they be placed?

The Mississippi River Deltaic Plain is composed of a series of overlapping delta complexes formed over thousands of years in response to changes in the River and sea level. Each delta complex is the result of a series of somewhat consecutive delta lobes (Fig. 1). A delta lobe advances seaward when it is active and "dominated by fresh, turbid water" from the Mississippi River. The cycle

> begins when an upstream diversion directs a distributary… toward some low lying area of the coast… Sediment is deposited to form bars and shoals… [which] gradually emerge as land…[that] becomes colonized by wetland vegetation [which] captures sediment to accelerate… build up… [T]he shore advances seaward and the delta [lobe] builds coastal wetlands… [W]ith natural [or anthropogenic] closure of distributary feeder channels at their heads… [t]he supply of fresh water and transported sediments is cut off… The newly deposited deltaic sediments subside rapidly and marine processes become dominant. (LCWCRTF and WCRA 1998, p. 19–22)

Given expected rates of sea level rise and anthropogenic reductions in Mississippi River sediment supply, Blum and Roberts caution that "significant drowning [of coastal Louisiana] is inevitable… [and that] even the most prudent selection of diversion sites can only slow the overall rate of submergence" (Blum and Roberts 2009, p. 488–490). They advocate upstream over downstream diversions, as the former "have the virtue of mirroring geological processes that build deltas [i.e., delta complexes] from the top down" and should "build or sustain more land-surface area with the available sediment supply" (Blum and Roberts 2009, p. 490).

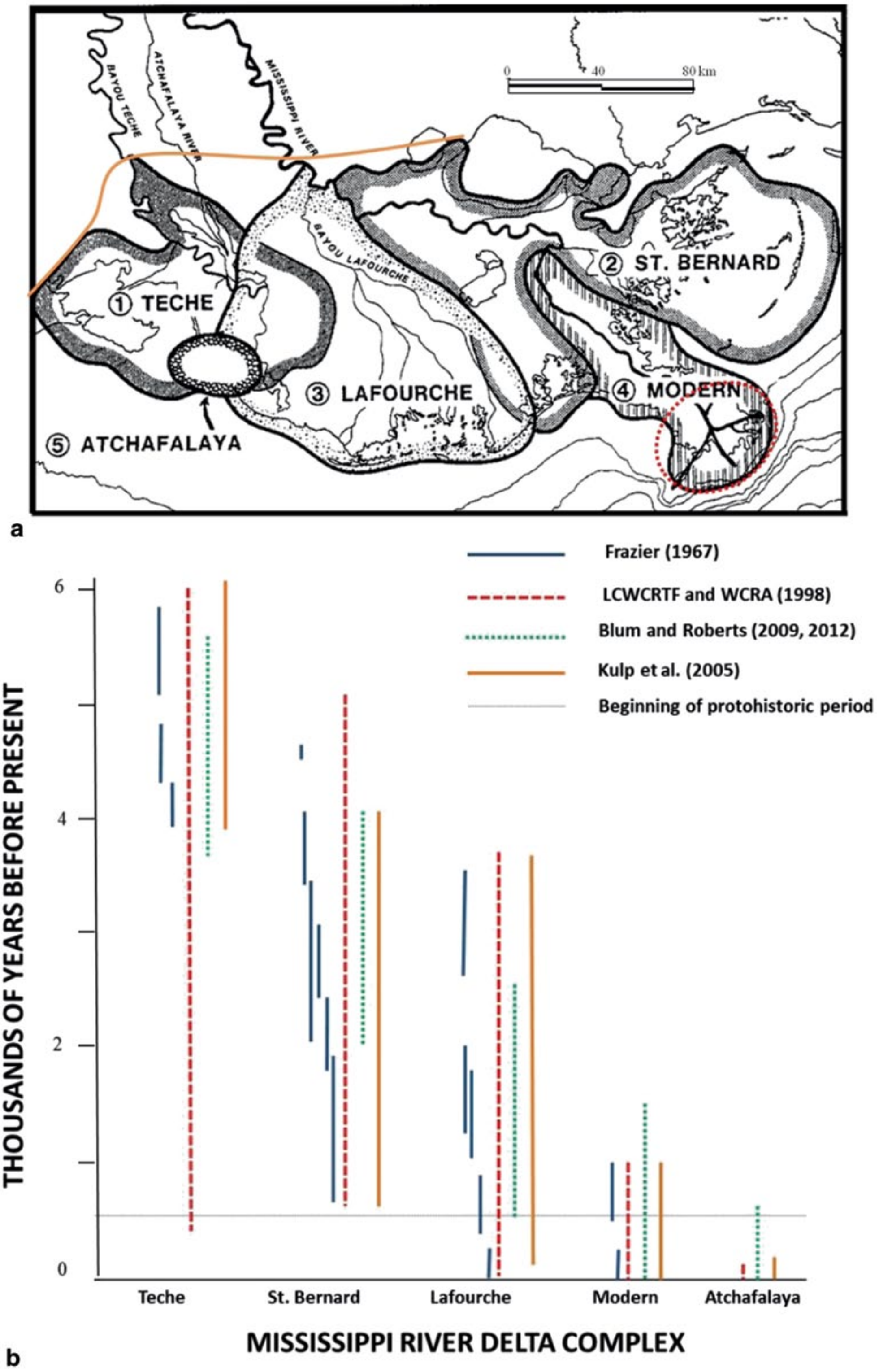

Fig. 1 Comparison of the five most recent delta complexes that built the Mississippi River Deltaic Plain. **a** Areal extents (modified from LCWCRTF and WCRA 1998 [Fig. 2] by georectifying; to approximate the Birdsfoot [Fig. 1; *dotted red line*];and to indicate that Frazier does not delineate the northern extent of the Teche, Lafourche, or St. Bernard delta complexes or the western extent of the Teche [*orange line*]). **b** Estimated active ages (Frazier, Fig. 1 and Append. A; LCWCRFT and WCRA, Fig. 2; Blum and Roberts 1998-Fig. 1, 2012-Fig. 7a; and Kulp et al., Fig. 2). Frazier's ages are for individual delta lobes within a delta complex. The older Maringouin delta complex is not shown. Frazier refers to the Modern as the Plaquemines-Modern and does not denote the Atchafalaya in his Fig. 1. Blum and Roberts and Kulp et al. refer to the Modern as the Plaquemines-Balize. Blum and Roberts refer to the Atchafalaya as the Atchafalaya-Wax Lake. Blum and Roberts (2009, p. 2 supplementary information) use the term "deltas" as synonymous with "delta complexes"

Diversions currently operated under the Plan are located well downstream from the headwaters of Bayou Lafourche. These locations could be favored by Blum and Robert's considerations if the Blueprint is correct in its conclusion that

> during historic times, delta building has occurred in only a few [two] areas along the Louisiana coast… the active Mississippi delta [Birdsfoot] … [and] the Atchafalaya Delta [our Fig. 1]

(hereafter, Conclusion) (LCWCRTF and WCRA 1998, p. 19) since the Plan's operating diversions begin upstream from or in these two areas.

However, the Blueprint's Conclusion is contradicted by both the data and references the Blueprint used to derive its Conclusion. Specifically:

1. The Blueprint's Fig. 2 and Frazier (1967) present data that suggest more than two delta complexes may have been active during historic times. The Blueprint's Fig. 2 suggests four—the Teche, Atchafalaya, Lafourche, and Modern—while Frazier (who does not consider the Atchafalaya in his Fig. 1) suggests the possibility of three—the Lafourche, Modern, and St. Bernard (Fig. 1b).
2. Russell (1936) observed that active delta building was occurring during historic times in St. Bernard Parish as a result of the overflow of the Mississippi River into the St. Bernard delta complex (Fig. 1a). Delta building ceased with the construction of artificial levees, which were apparently destructive to that landscape. He notes:

> Most of St. Bernard Parish is a subdelta of the first order. It is inactive at present but has functioned within rather recent times …. Since the building of the artificial levees … there has been practically no sediment carried into St. Bernard Parish by streams. With the cessation of land extension and upbuilding, the forces of destruction have had full sway. Few regions are undergoing more rapid topographical change than this flat territory. (Russell 1936, p. 12, 49)

The Blueprint's Fig. 2, Frazier's data in our Fig. 1b, and Russell's observations all suggest that the Plan's diversions should have begun above the headwaters of Bayou Lafourche if they are to mirror "geological processes that build deltas [delta complexes] from the top down" and "build or sustain more land-surface area with the available sediment supply" (Blum and Roberts 2009, p. 490).

Our Objectives and Hypotheses

Given the questionable basis for the Blueprint's Conclusion, our objectives are to locate a candidate LNDM based on the earliest written authority (which we assume is Chaves ca. 1537) and to test our candidate LNDM for consistency with the most authoritative first-hand accounts of the protohistoric and colonial periods. Our hypotheses are:

1. Chaves' estimates of latitude reflect reality.
2. The definition of Chaves' "league" can be derived from his data.
3. Chaves' descriptions are sufficient to suggest the most likely locations of coastal areas associated with an active delta complex (or complexes) of the Mississippi River (Candidates).
4. Chaves' Candidate-associated vectors can be used to locate the LNDM.
5. Chaves' LNDM is consistent with the most authoritative first-hand accounts of the protohistoric and colonial periods (Barroto, Iberville, Evía, and Dumain).
6. Our view of the LNDM is consistent with the most authoritative chronostratigraphic model of the evolution of late Holocene (~7 kyBP) Mississippi River delta lobes and complexes into the current Mississippi River Deltaic Plain

Chaves' Authority

In 1503 Queen Isabella established the *Casa de la Contratación* (House of Trade) at Seville to run a navigation school, collect and synthesize data on new nautical discoveries, and (beginning in 1508) produce and update its secret *Padrón Real* (Master Map) from the logs and sworn testimony of the pilots and masters of ships returning from the Americas. In 1528, Charles V appointed Alonso de Chaves to the *Casa* and in 1552 Chaves became its *Piloto Mayor* (Chief Pilot; Lamb 1969).

Though no Padrón Real by Chaves is known to exist, his "*Cosmografía práctica y moderna llamado Espejo de Navegantes*" (*Practical and Modern Cosmography called the Mariners' Mirror*, hereafter Cosmografía) (Chaves ca. 1537) is an undated manuscript in the *Real Academia de La Historia* (Royal Academy of History) in Madrid. A "rutter" or coastal pilot forms "Book Four" of the Cosmografía. A transcription of Book Four was first published as Chaves (1977), the Cosmografía as Chaves (1983). Book Four treats "The Indies of the Ocean Sea, their parts and both their individual and general navigations" in 25 chapters. Chapter 1 describes the Atlantic crossing. Each of the remaining chapters begins with a summary which lists major coastal features (such as harbors and capes) and the compass directions and distances between them. Each of these chapters then continues with a geographically organized, more detailed coastal pilot subdivided by sequentially numbered place names where each place (herein designated by its book, chapter and entry number in Chaves' Cosmografía) is normally referenced to other named places by distance-direction vectors. A note describing relevant sailing-related features of each named place usually completes each numbered entry. Lamb (1969, p. 3–4) suggests that the Cosmografía

> was the depository of the material taught in Seville, especially to the pilots of the *Carrera de Indias* (Indies Trade) and … contains the earliest preserved example of part of a Padrón Real… the Casa's most important scientific enterprise.

Chaves' authority during the 1500s is reflected in Gonzalo Fernández de Oviedo's rendition of Rodrigo Rangel's account of the De Soto's expedition:

> When that river [of their escape] comes forth to the sea, the navigation chart states and indicates that it is the Río del Espíritu Santo; which, according to the charts of the cosmographer Alonso de Chaves, enters in a great bay, and the mouth of this river, in the salt water, is at 31° on this side of the equator. (Oviedo y Valdés 1851 1:562; Rangel 1993 1:281)

Frazier's Authority and Deficiencies

Though Frazier's (1967) chronostratigraphic model of the evolution of late Holocene (~7 kyBP) delta complexes into the current Mississippi River Deltaic Plain is considered the most comprehensive study currently available (i.e., H. Roberts, personal communication 2012; Kulp et al. 2005, p. 282), it contains deficiencies in experimental design, aging techniques, and data reporting (i.e. Kidder 1996; Törnqvist et al. 1996). Additional deficiencies which we find are a failure to consider the possibility that Bayou Plaquemine had been a naturally active Mississippi distributary supporting its own delta lobe(s) (Frazier 1967, Fig. 5) and to test Frazier's assumption that the Atchafalaya River had never been more than "a modern, man-induced distributary of the Mississippi River" (Frazier 1967, p. 296). Combined, these deficiencies underscore the desirability of "a fully revised delta-lobe-scale chronostratigraphy" (Kulp et al. 2005) based on current radiocarbon aging techniques, a more holistic approach, and improved experimental design which includes testing the LDMR model.

Even as our most comprehensive model, Frazier's (1967) estimates of the ages of delta lobes within a delta complex often result in periods of inactivity within the relevant delta complex (e.g., our Fig. 1). However, authors who rely on Frazier normally discuss their estimates of delta complex ages as if each complex was continuously active before becoming permanently inactive. An understanding of how these transformations occur is almost always difficult especially as the transformations often result in a precision which does not accurately reflect Frazier's data (Box 1).

Box 1 Aging Delta Complexes: Do Precise Patterns in Longevity Accurately Reflect the Temporal Data?

As an example of the difficulty in understanding how some authors transform Frazier's often discontinuous delta complexes of varying lifespans into continuous complexes with similar delta-complex lifespans, contrast Frazier's (1967, Appendix A) delta lobe ages with Blum and Roberts's (2009, 2012) delta complex ages, both summarized in our Fig. 1. Despite Blum and Roberts's partial dependence on Frazier's Appendix A data, their estimates of the onset of delta complex activity, B (in kyBP), conform to a quadratic of the form:

$$B = 9.66\ \text{kyBP} - 2.30 * N + 0.013 * N^2 \qquad (1)$$

($R^2 = 0.999$) where N = number of the delta complex (from oldest [1 = Maringouin] to youngest [6 = Atchafalaya]). In a similar fashion, their estimates of the end of delta complex activity, E, (where N is confined to the pre-colonial period and excludes the Modern and Atchafalaya) conform to a linear relationship of the form:

$$E = 6.5\ \text{kyBP} - 1.5 * N \qquad (2)$$

($R^2 = 1.000$). As a result, in Blum and Roberts (2009, 2012) the Maringouin delta complex is predicted to have had an active life of 2,500 y, while the Teche, St. Bernard, and Lafourche each had an active life of 2,000 y. These remarkably precise predictions of the longevities of Mississippi River delta complexes which were not theoretically affected by colonial and post-colonial modifications (in the Blum and Roberts treatment) do not accurately reflect Frazier's data (e.g., our Fig. 1). The unexplained differences call into question the usefulness of Blum and Roberts pattern as hind- and forecasters of delta complex lifespans.

This is not the case with Kulp et al. (2005, their Fig. 2). Here it appears that these authors used three modifications to Frazier's data. First, they apparently portioned Frazier's discontinuity in activity between the Maringouin and Teche by assuming the transition in activity between the two deltas complexes occurred at 6 kyBP. Next, they apparently disregarded (as an active delta lobe) Frazier's short lived lobe 3 within the St. Bernard delta complex. And, finally, they apparently disregarded all other periods of inactivity between active delta lobes within a delta complex, thus making each complex continuous between the remaining lobes.

In the resulting Kulp et al. pattern, the Teche was naturally active for ~2.1 ky (~3.9 to ~6 kyBP) and the St. Bernard, ~3.4 ky (~0.6 to ~4 kyBP), while the Lafourche and Modern became active ~3.6 and ~1.0 kyBP (respectively) and remained naturally active until they came under human control. The Kulp et al. pattern is visibly compatible with Frazier's data and suggests that, barring human control, a delta complex may have been naturally active >3.5 ky; two delta complexes may be contemporaneously active from ~0 to ~3 ky; while three may be contemporaneously active from ~0 to ~0.5 ky.

Materials and Methods

Translation and Examination of Chaves

We used a digital image of Chaves ca. 1537 to check for and correct transcription errors in Chaves (1977). We used all site-specific, GoM-associated vectors and latitude estimates in Book 4. Where the manuscript contained an imprecise, but directional, deviation from the compass rose such as "just N of NW", we somewhat arbitrarily adjusted the compass reading by 1.15° in the direction indicated. Though we could not correct non-directional deviations such as “almost NW”, we did not exclude these from our analyses.

Statistical Test of Hypothesis 1 (Chaves’ Latitudes)

We used Analysis of Covariance (ANCOVA) to test the relationship between Chaves’ estimates of latitudes versus those determined using Google Earth 5.1 for two types of geographical positions: certain and likely (our class variables in the ANCOVA). Positions which had been continuously known since Chaves’ time were considered “certain”. Other positions which we felt reasonably confident in identifying were considered “likely”. All statistical analyses were conducted using Proc GLM and Proc REG in SAS 9.1©.

Statistical Test of Hypothesis 2 (Chaves’ League)

To estimate Chaves’ definition of league, we used plane geometry to compute the north to south (NS) distance (b) implicit in his geographical vectors. To accomplish this, we used all of his geographical vectors between points for which he also provided estimates of latitude (L_c) and calculated b using the cosine function,

$$b = \cos(\theta) * c \tag{3}$$

where $\theta =$ the acute angle which describes the NS component of Chaves’ compass heading and $c =$ Chaves’ estimate of sailing distance in leagues. Here our assumptions were that Chaves was using a standard league and data generated with plane rather than spherical geometry, though both were known in Spain at the time.

We then regressed b against the latitudinal difference, d (where $d = L_{c1} - L_{c2}$),

$$b = i + r * d \tag{4}$$

where i is the intercept and r is the slope. We chose to use parametric rather than nonparametric regression procedures under the assumption that the errors associated with latitude were much less than those associated with sailing distances.

Test of Hypothesis 3 (Chaves’ LNDM Candidates)

We examined Book 4 for areas associated with major riverine outflows (e.g., substantial discharges of fresh water, sediment, and/or drift trees; extensive offshore shoals; etc.) into the GoM under the assumption that these would indicate possible Candidates.

Test of Hypothesis 4 (Locating Chaves’ LNDM)

We converted Chaves’ leagues to km using Eq. 4 (Results) and then used two related procedures to locate the position of our Candidates.

In the first, we took all of Chaves’ vectors associated with our Candidates and created an array of vectors radiating from these Candidates (Array). Within the Array, we created an axis (Axis) by fixing the relative positions of the Candidates to each other using the appropriate vectors. We transposed the Array onto a current map of the GoM and adjusted its fit by eye to the current GoM coastline.

In the second, we took the subset of Candidate vectors that were associated with at least one of several continuously known positions. We independently projected each of these vectors from its known position towards that of its Candidate.

Test of Hypothesis 5 (Conformity of Record)

For the post Chaves’ protohistoric-colonial period, we consider Barroto (Weddle 1987; Condrey in prep.), Iberville (McWilliams 1981; Condrey in prep), Evía (Hackett 1931; Condrey in prep), and Dumain (1807; Condrey in prep) as the most authoritative first-hand accounts. Chavez’ descriptions of Candidates and their locations were compared with information in these later accounts about these locations.

Test of Hypothesis 6 (Conformity to Chronostratigraphic Model)

With one exception, we accept Frazier (1967) as the current authority for comparing ages of the Mississippi River delta lobes and Kulp et al.’s (2005) treatment of Frazier as the authority for comparing ages of its delta complexes. As previously discussed, that exception occurs with Bayou Plaquemine and the Atchafalaya River. Here, Frazier fails to explore the role of Bayou Plaquemine as a naturally active distributary of the Mississippi River (i.e., his Fig. 5) and considers the Atchafalaya River as “a modern, man-induced distributary of the Mississippi River” (his p. 296). Neither assumption is supported by the pre-1900 post-colonial record.

Results

Within Book Four, we found 57 named places which are associated with the GoM and for which Chaves gives estimates of latitude. Of these 57, 10 have been continuously known since Chaves’ time: (from S to N) *Río Grijalva*, *Río de San Pablo* (currently *Río San Pedro y San Pablo*), Veracruz, *Río Tuxpan* (*Río Tuspan*), *Cabo Rojo*, *Río Pánuco*, *Cabo de San Antonio*, Havana, Tortugas, and *Bahía de Miruelo* (Apalachee Bay). We felt comfortable in linking five others to current locations: (following the coast from Yucatan to Florida) *La Desconocida* (Celestún, Yucatan), Villa Rica (*Río de la Antigua*), *Río de las Palmas* (*Río Soto la Marina*), *Cabo Bajo* (Cape San Blas) and the southern point of La Florida (Cape Sable). These 15 positions are located between 17.75 °N and 30.67 °N.

We found 148 sailing-direction vectors linking these 57 named places to each other. Thirty-eight of these 148 vectors were associated with the three positions we identified as Candidates—*Río de Flores* (River of Flowers), Río del Espíritu Santo, and *Cabo de Cruz* (Cape of the Cross)—(Results, Hypothesis 3). Seven of the Candidate-associated vectors were associated with any one of several continuously known positions. One of the Candidates (Río de Flores) did not have a vector linking it to a known position.

Hypothesis 1 (Chaves' Latitudes)

There was no class effect of certain or likely positions in the ANCOVA run to test Hypothesis 1. The resulting regression,

$$L_c = -2.35 + 1.11(L), \tag{5}$$

reveals a remarkably close agreement ($R^2=0.99$) and a random scatter of the residuals (Fig. 2). As such we accept Hypothesis 1 and conclude that Chaves' provides a reasonably accurate and precise estimate of latitude, although errors on the order of a degree (111 km) are not uncommon.

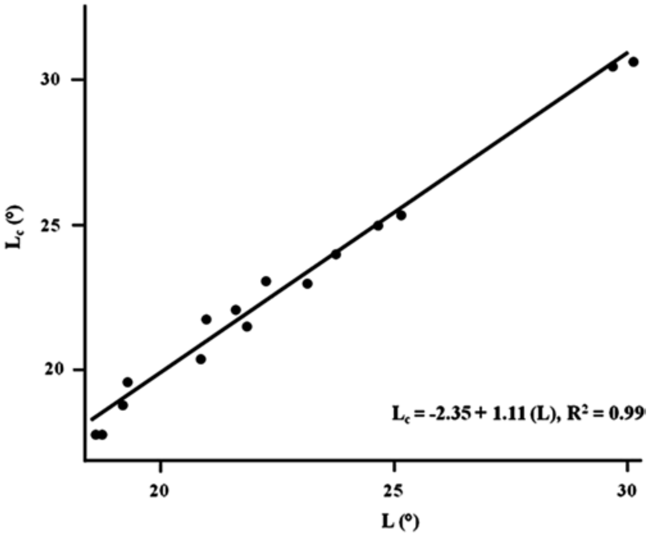

Fig. 2 Comparing Chaves' (ca. 1537) estimates of latitude (L_c) to current values (L)

Hypothesis 2 (Chaves' League)

We found a remarkably close agreement ($R^2=0.98$) between the NS distance implied in Chaves' sailing directions and the latitudinal distances Chaves provides for these linked positions,

$$b = -0.4 + 17.5(d) \tag{6}$$

(Fig. 3). Our examination of the residuals revealed no pattern that would negate our assumptions. As such we accept Hypothesis 2 and conclude that Chaves was using the then current Spanish standard of 17.5 leagues to a degree of latitude (García de Palacio 1587, pp. 63–64 in the 1994 facsimile) and Chardon (1980, pp. 140–142, 151). Such a league is equivalent to 6.3 km.

On the other hand, we do note that the scatter of the residuals seems to be inversely related to latitudinal distance. This implies that the precision associated with Chaves' vectors may be inversely related to latitudinal difference, an observation which is consistent with variations Chaves gives in multiple observations of closely related points. For example, when latitude differences are less than 3° (333 km), residuals greater than 60 km are not uncommon (Fig. 3).

Hypothesis 3 (Chaves' LNDM Candidates)

Chaves divided the northern GoM's continental shoreline into two provinces: *Nueva España* to the west (Book Four, Chap. 12) and *La Florida* to the east (Book Four, Chap. 13). The Río del Espíritu Santo is the largest river on the coast of Nueva España and the dividing line between Nueva España and La Florida. Río de Flores is the largest river on the coast of La Florida. According to Chaves these two rivers are relatively close to each other and are separated by two noteworthy geographic features. In addition, Chaves describes a prominent cape south of Río del Espíritu Santo.

Chaves' Río del Espíritu Santo is

> at 30° … 6 leagues wide at the mouth. In the middle of the entrance is a small island. Then, entering the river there is a great embayment that runs NE, and is called the *Mar Pequeña* (Small Sea). It is 20 leagues deep by 10 leagues wide. Three rivers enter this bay, not counting the larger one and another comes from the W side. In this bay one may anchor. There are many fish. From the mouth of this river to the E [as far as] *Bahía de Miruelo*, the whole coast is full of shallows and reefs. It is very dangerous. (Chaves ca. 1537, Book Four, Chap. 12, number 39; Chaves 1977, p. 119)

A cape called Cabo de Cruz lies approximately 10 leagues S of the mouth of Río del Espíritu Santo. According to Chaves, this cape

> is the most notable that there is in all this coast. This cape is high (*alto*) and shaved (*tajado*) toward the sea and round with

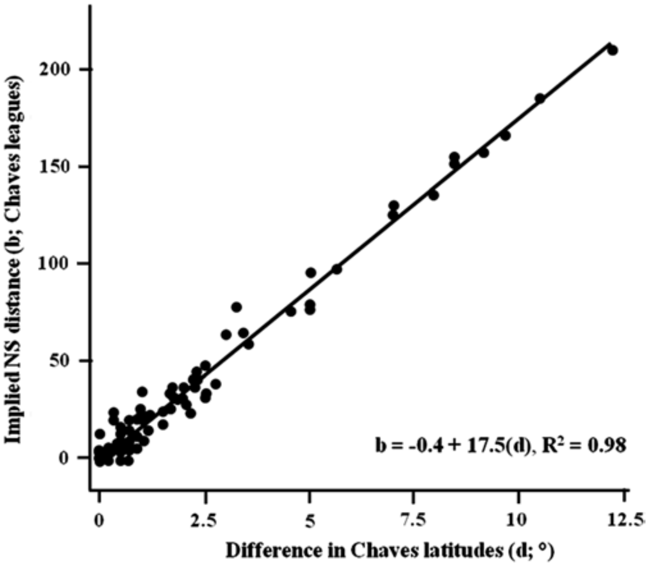

Fig. 3 Testing the hypothesis that Chaves (ca. 1537) was using a standard league in describing his GoM sailing directions

> some bluffs (*barrancos* (sic))…. On the S side it has a good port in which large ships can anchor. Some great bluffs (*barrancas grandes*) there give them shelter. On the sea side this port has a reef that goes more than a league into the sea. (Chaves ca. 1537, Book Four, Chap. 12, number 38; Chaves 1977, p. 119)

Chaves' Río de Flores is

> at 30°…. 68 leagues E of Río del Espíritu Santo…. On the W side it has a cape that goes further to sea than the one on the E. In the mouth of this river are three small islands in a line N-S. All of the coast is full of reefs … and … shallows [shoals]. (Chaves ca. 1537, Book Four, Chap. 13, number 4 (main description) and number 1 (shallows); Chaves 1977, p. 121, 120 respectively)

The two coastal features lying between the Río del Espíritu Santo and the Río de Flores are:

> *Matas del Salvador* (Rods (?) of the Savior) is at 30°…30 leagues E of Río del Espíritu Santo… 30 leagues W of Río de Flores. These are some inlets (*ancones*) in the manner of bays and all the coast to Río del Espíritu Santo is full of shallows [shoals]. (Chaves ca. 1537, Book Four, Chap. 13, number 2; Chaves 1977, p. 120)

and

> *Río de Cañaveral* (River of True Canes), is at 30°… 46 leagues E of Río del Espíritu Santo…. 18 leagues W of Río de Flores. This river has some three small uninhabited islands (*islotes*) from E– W (*en rencle de este [a] oeste*) and the coast and other shallows [shoals] [sic.]. (Chaves ca. 1537, Book Four, Chap. 12, number 3; Chaves 1977, p. 121)

Based on Chaves' identification of river outflows, we chose Río de Flores and Río del Espíritu Santo as active delta complex Candidates. Based on its proximity to the Río del Espíritu Santo, comparatively large number of vectors, and striking description, we also chose Cabo de Cruz as a Candidate. As a result of these choices, we accept Hypothesis 3.

Hypothesis 4 (Locating Chaves' LNMD)

The fit of the Array corresponds fairly well to the general outline of the GoM (Fig. 4). The fit is poorest for the coasts of Texas and southern Florida which had no permanent Spanish settlements and best along the Spanish-occupied, southern GoM coast (i.e., from Villa Rica to Havana)—likely reflecting a link between settlement patterns and the reliability of nautical data.

The fit of the Axis by the Array places the Río del Espíritu Santo N and slightly W of Vermilion Bay, Cabo de Cruz at the eastern-most portion of Louisiana's Chenier Plain, and Río de Flores N and E of the present mouth of the Mississippi River. This fit suggests that the LNDM probably extended across much of coastal Louisiana in the 1500s and contained at least two active delta complexes.

The fit of the vectors projected from known positions to Candidate positions suggests a similar (but not independent) location of the western edge of LNDM in the 1500s (Fig. 5). Six of these vectors intersect the GoM coastline between the western end of Vermilion Bay and the east-central portion of Louisiana's Chenier Plain. The other vector approaches the Texas coastline east of Galveston Bay.

The location of the Candidates suggested by the two methods used to generate Figs. 4 and 5 is generally consistent with their written descriptions in Chaves (Results, Test of Hypothesis 3**)**, the E-W alignment of positions Chaves describes as existing between the Río del Espíritu Santo and Bahía de Miruelo (Apalachee Bay) and known geomorphic features visible along the northern GoM (Fig. 6). Chaves' description of Cabo de Cruz is generally consistent with the current morphology of Chenier au Tigre, the eastern-most chenier in the Chenier Plain. The comparatively high relief (elevation of the land and its live oaks above the surrounding marsh) and coastal location of Chenier au Tigre conforms to Chaves' description of Cabo de Cruz, although Chenier au Tigre currently lacks an association with an offshore reef that would create a natural offshore harbor (i.e., USGS 1983). In addition, Paul Kemp (personal communication 2012) notes that Chenier au Tigre's " ridge is composed entirely of oyster shell".

Chaves' description of a 37.8 km-wide mouth to Río del Espíritu Santo is consistent with the current configuration of the Louisiana coast from Vermilion Bay's Southwest Pass, the southern shore of Marsh Island, and the shell reefs which line the current entrance into Atchafalaya Bay (USGS 1979). Chaves' description of the Mar Pequeña (Small Sea) within the Río del Espíritu Santo is consistent with the size and general orientation of the current Vermilion/Atchafalaya Bay Complex.

Chaves' description of Río de Flores is generally consistent with the Birdsfoot. Matas del Salvador generally coincides with the Last/Timbalier Island chain; Río de Cañaveral with Bayou Lafourche; *Río Nieves* with Pensacola Bay;

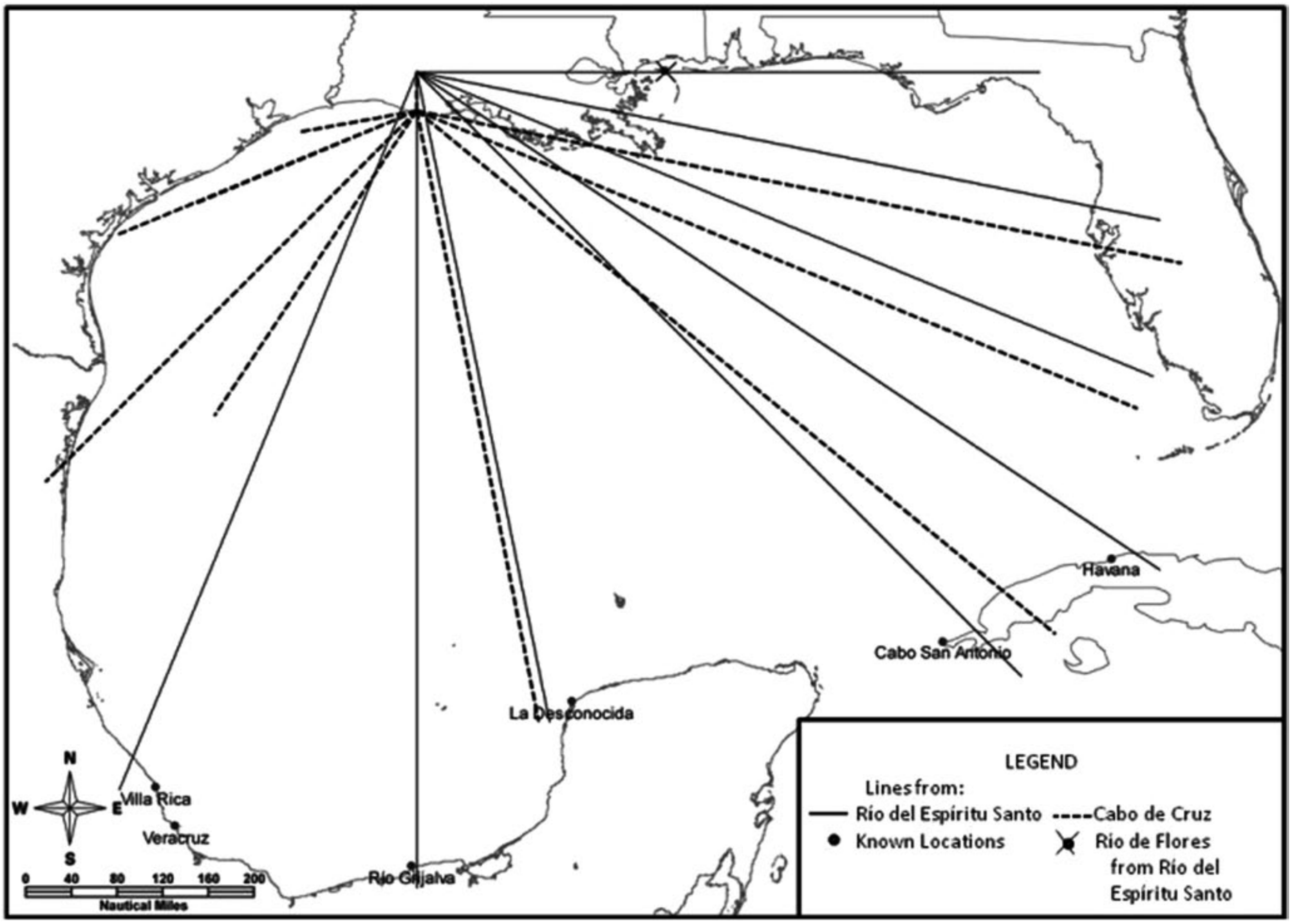

Fig. 4 Comparing the GoM coastline with all Chaves' (ca. 1537) sailing vectors (Array) associated with the Río del Espíritu Santo, Río de Flores, and/or Cabo de Cruz (Candidates). The Array's vectors are projected from a central axis (Axis) formed by linking the Candidates' shared vectors

Cabo Bajo with Cape San Blas; and Bahía de Miruelo with Apalachee Bay. The pattern shown in Fig. 6 suggests that three delta complexes were active during the 1500s. Based on these similarities, we tentatively accept Hypothesis 4, reserving an understanding of how an offshore port would have naturally occurred off the Louisiana coast in the 1500s.

Hypothesis 5 (Conformity of Record)

Barroto 1686

In 1686, Juan Enríquez Barroto sailed east along the northern Gulf coast under orders to chart the coast for Spain. Near Chenier au Tigre he encountered a shallow reef that provided protection from the sea. Near Point au Fer he noted large quantities of driftwood for "more than a league (~6 km) … upon the oyster banks" and "the sea covered with countless logs brought by the wind and current". Near Last Island he noted a break in the nearly continuous coast line of "marsh', mud, sand, woods, and driftwood". As he approached Bayou Lafourche he was forced to sail his shallow-draft vessels out of the sight of land by a shoal which extended ~22 km into the GoM. And near Grand Isle, he was able to fill his water vessels while anchored in the mouth of a fresh water river (*Río de la Aguada*) (Hackett 1931; Condrey in prep.).

Barroto's description of the Louisiana coast between Chenier au Tigre and Grand Isle parallels that of Chaves (Fig. 6). His protective reef near Chenier au Tigre corresponds with—and begins to explain—Chaves' port at the Cabo de Cruz. His Río de la Aguada corresponds to Chaves' Río de Cañaveral. His description of the coast reflects Chaves' dangerous coast full of shallows and reefs. Moreover, the proximity of an extensive shoal and the Río de la Aguada to Bayou Lafourche (Chaves' Río de Cañaveral in Fig. 6) indicates that the Lafourche was an active distributary of the Mississippi River in 1686.

Iberville, 1699

In February-April, 1699, Pierre Le Moyne d'Iberville explored the St. Bernard and Modern delta complexes from Ship Island, Mississippi, upriver to the Tunica Hills north of Baton Rouge. Iberville's description suggests that both the St. Bernard and Modern delta complexes received the over-

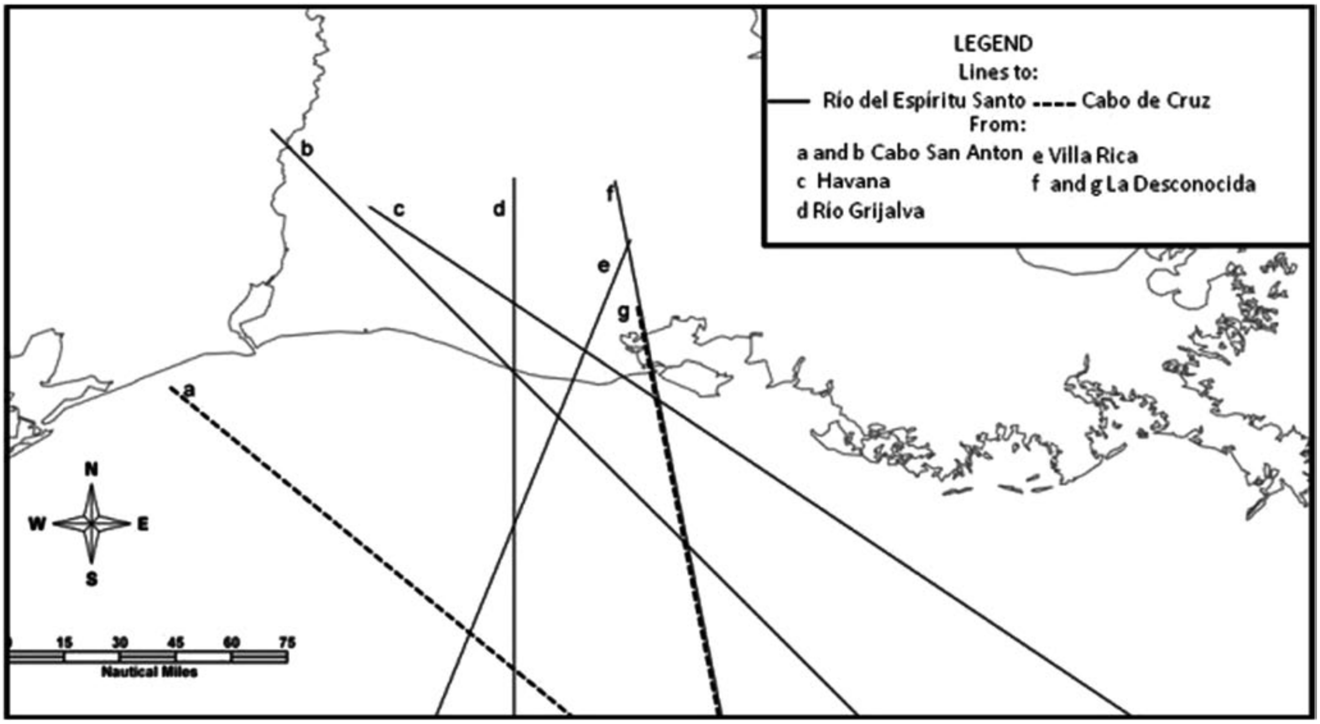

Fig. 5 Coastal trajectories of Chaves' (ca. 1537) sailing directions from continuously known positions to Río del Espíritu Santo or Cabo de Cruz

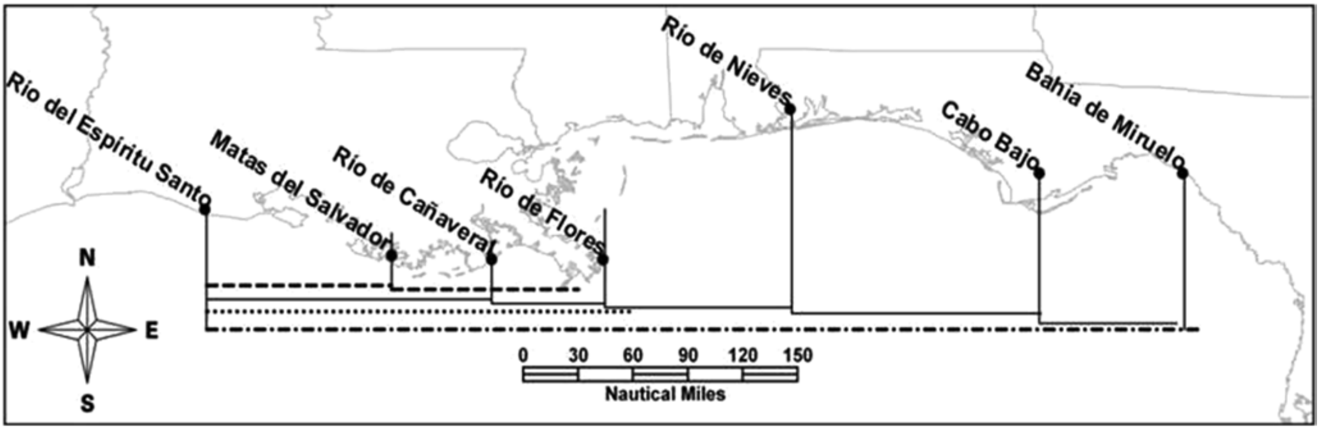

Fig. 6 E-W alignment of geographical features Chaves (ca. 1537) identifies between the Río del Espíritu Santo and Bahía de Miruelo when our fit of the Axis is accepted. Each *horizontal line* style represents one of the four logical linkings of Chaves' directions. (For example, the *dashed line* represents Chaves' linking of the Río del Espíritu Santo to Matas del Salvador to Río de Flores.) Each *vertical line* represents the relationship between the predicted position (or its average) and the GoM coast

flow of the Mississippi River and had a nearly continuous eastern coast which was generally adjacent to shallow and narrow bays fringed by extensive barrier islands [now the comparatively wider and deeper Chandeleur and Breton Sounds and the fragmented and disappearing Chandeleur and Breton Islands]. In addition, he noted that: the freshwater outflow of the pre-flood Mississippi extended into the GoM for 3.6 km; drift trees were important in forming the coast; all the entrances into the Birdsfoot were shallow (≤4.6 m [15 ft]).; the annual inundation of the Mississippi over its natural levees generally diminished in a rectilinear fashion from the Birdsfoot to Bayou Baton Rouge with an inflection slightly below New Orleans; and the pre-flood Mississippi flowed into Bayous Lafourche, Plaquemine, Manchac, and Baton Rouge (McWilliams 1981; Condrey in prep).

Iberville's description of this portion of the Louisiana coast is compatible with Chaves' description of a coast full of shallows and reefs and with the association in Fig. 6 of Chaves' Río de Flores with the Birdsfoot.

Evía and Dumain, 1785–1807

In 1785, the Spanish surveyor José Antonio de Evía was charged with charting the shoals that lined the Louisiana coast. Sailing west from the Birdsfoot, he described the coast to Last Island as flat, subject to overflow, full of drift logs from the Mississippi, and containing passes that could only be entered by pirogues. Once he reached Last Island, he anchored on an extensive set of offshore oyster reefs which were generally under 0.9–1.2 m of water and provided coastal protection from southerly and southwesterly winds The reefs extend laterally along the coast from Last Island to Chenier au Tigre and into the GoM for 18.5 km (at their eastern edge) to 9.3 km (at their western edge). Near Chenier au Tigre, he observed the coastal protection provided by the reefs from land-ward advancing squalls and that fresh water extended > 11.1 km into the GoM. He noted that the spring flood of the Mississippi through the Atchafalaya River, Bayou Lafourche, and Barataria Pass sent plumes of fresh water 16.7 km into the GoM where they joined the downstream current carrying the discharge of the Birdsfoot (Hackett 1931; Condrey in prep).

In 1806 Louis Dumain surveyed a portion of the Louisiana coast for the United States. His report parallels Evía's description of an extensive offshore oyster reef and the Atchafalaya as a distributary of the Mississippi River. Specifically Dumain reports that oyster reefs extended ~27–33 km into the GoM from the mouth of the Atchafalaya and that the annual flood of the Mississippi did not cause the lower Atchafalaya River to rise more than 0.9 m (Dumain 1807; Condrey in prep.).

Evía mirrors Chaves' and Barroto's description of the Louisiana coast between Chaves' Cabo de Cruz (Evía's Chenier au Tigre) and Río de Flores (Birdsfoot), Barroto's description of the offshore oyster reef, and our interpretation of Chaves (Fig. 6). Dumain mirrors Evía's estimate of the seaward extent of the offshore oyster reef south of the Atchafalaya Bay. The westward limit of the Evía/Dumain oyster reef is consistent with the necessity to enter Chaves' Río del Espíritu Santo from the west and explains why Cabo de Cruz (Evía's Chenier au Tigre), in conjunction with the reef's westward end, functioned as an offshore port. Evía's measurements of the freshwater discharge of the Atchafalaya River/Bayou Plaquemine and Bayou Lafourche/Barataria Pass qualify these streams as active distributaries of the Mississippi River by our definition. Moreover, Evía's descriptions of the Mississippi's vast freshwater outflows begin to suggest how the LNDM nurtured an extensive offshore oyster reef.

General Consistency of the Protohistoric and Colonial Record

There is a remarkable consistency in the protohistoric and colonial record and our interpretation of Chaves (Figs. 4, 5, and 6).

Chenier au Tigre is an ideal candidate for Chaves' Cabo de Cruz. There is no other elevated area on the Louisiana or Texas coast that approaches its proximity to our location of Chaves' Cabo de Cruz; a river containing a mouth greater than 2 km in width; and extensive, historic offshore oyster reefs. In the early 1500s the comparatively high relief and coastal proximity of Chenier au Tigre would have provided some protection to ships at anchor from northerly and westerly winds, while the vast oyster reefs would have provided similar protection from southerly and easterly winds (as Evía noted).

Vermilion Bay's Southwest Pass and the Vermilion/Atchafalaya Bay complex is the most logical candidate for Chaves' Río del Espíritu Santo and its Mar Pequeña. Its dimensions conform to Chaves' description of a river having a 38 km wide mouth and a 63 by 127 km, NE-oriented embayment. The vast offshore oyster reef described by Evía would have impeded entrance into the Vermilion/Atchafalaya Bay complex from the S and E, while encouraging a western entrance through Vermilion Bay's Southwest Pass. As a prominent oak covered chenier, Chenier au Tigre (our estimation of Cabo de Cruz) would serve as a visual guide to vessels approaching from the sea. Once into the system, Marsh Island would serve as a southern land border until one reached the mouth of present day Atchafalaya Bay, where the oyster reef would continue as an impediment to a southerly exit and provide protection from storms from the S and E.

The current mouth of the Mississippi River is the most logical candidate for Chaves' Río de Flores. Its present and historic descriptions closely mirror that given in Chaves, especially when viewed in light of Figs. 4, 5, and 6.

Given these considerations, we accept Hypothesis 5.

Hypothesis 6 (Conformity to Chronostratigraphic Model)

There is general consistency of our view of the LNDM with Frazier's (1967) for the beginning of the protohistoric period. The Modern and Lafourche delta complexes were both active. There was no unobstructed free flow of water between the Atchafalaya and Mississippi Rivers. The St. Bernard delta complex had recently become inactive: Frazier finds the St. Bernard's Bayou Sauvage delta lobe became inactive ~200 years before the advent of the protohistoric period; while Iberville's 1699 observations suggest that the St. Bernard delta complex continued to receive the annual overflow of the Mississippi, though the complex had no

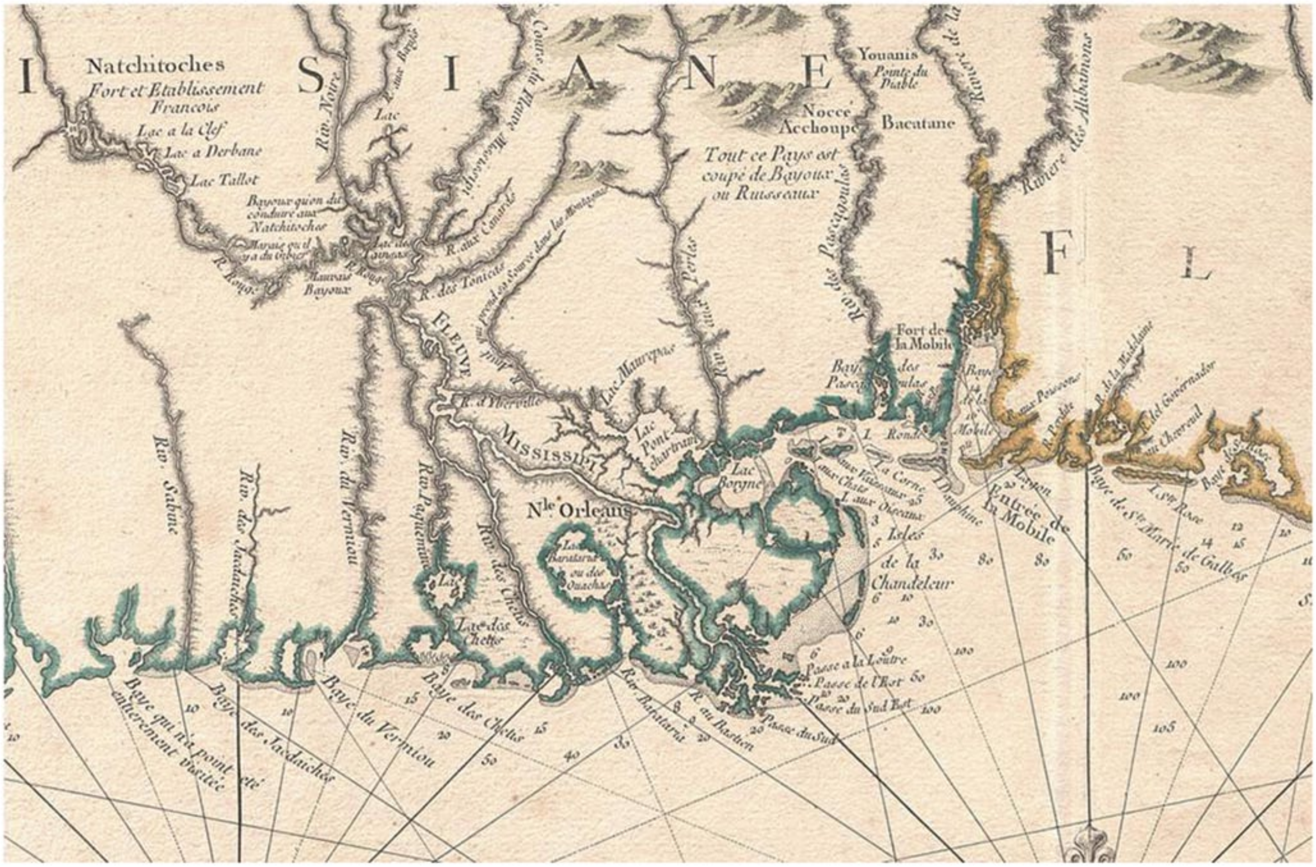

Fig. 7 Detail from Bellin (1764) showing the position of the LNDM within coastal la Louisiane. Proceeding counterclockwise from the Atchafalaya Bay (*Baye du Vermiou*), major features of the LNDM include Bayou Lafourche (Riv. Chetis), Chandeleur Sound (to the west of Isles de la Chandeleur), and the headwaters of the Atchafalaya River (Riv. du Vermiou) located near the convergence of the Red River (*R. Rouge*) and the Mississippi (*Fleuve Mississippi*). (Courtesy Special Collections, Louisiana State University Libraries)

active delta lobe. Additional studies which expand Frazier's approach to include Bayou Plaquemine and a humanly unaltered Atchafalaya's River are required before a comparison of our view of the LNDM with the Deltaic Plain chronology of these streams can be accomplished.

Given these considerations, we accept Hypothesis 6.

Viewing the LNDM

We can begin to see the LNDM in the authoritative maps of cartographers who had access to living witnesses (and/or their accounts) like Barroto, Iberville, Evía, and Dumain. Examples are Juan Bisente's (1696) *Carte du Golfe du Mexique*, de l'Isle's Guillaume (1703) *Carte du Mexique et de la Floride des Terres Angloisers et des Isles Antilles au cours des evirons de la rivere de Mississipi*, and Jacques Bellin's (1764) *Carte reduite des costes de la Louisiane et de la Floride* (Condrey et al. 2008).

In the detail of Bellin (1764; from Natchitoches, Louisiana in the NW to the entrance to Mobile Bay in the SE, Fig. 7) we see the interconnectivity of the Atchafalaya River (*Riv. du Vermiou*), Bayou Plaquemine (*Riv Plaquemine*), and Bayou Lafourche (*Riv. Chetis*); the all season connections of the Mississippi to Bayous Manchac (*R. de Iberville*), Plaquemines, and Lafourche; Chaves' nearly continuous coast full of reefs and narrow inlets; Barroto's Río de la Aguada (*Riv. Barataria*, now Barataria Pass); Iberville's narrow and shallow Chandeleur Sound and extensive *Isles de la Chandeleur*; and we begin to understand why Evía and Dumain were sent to map the LNDM's extensive offshore oyster reef.

Implications

Sustainable Benchmarks for Restoring Coastal Louisiana

The historic record describes the LNDM as a vast seaward-advancing arc which occupied, through four distributaries, all of the five most recent delta complexes of the Mississippi River: the Teche, St. Bernard, Lafourche, Modern, and Atchafalaya

(Figs. 1, 4, 5 and 6). During the annual spring flood, much of the LNDM carried plumes of freshwater out into the GoM for >10 km. Overbank flooding of the Mississippi's natural levees in the Modern and St. Bernard delta complexes began as far north as Bayou Baton Rouge. The eastern shore of the St. Bernard and Modern delta complexes was low and subject to overflow; occupied much of what is now open water in Chandeleur and Breton Sounds; and abutted shallow bays filled with islands. The portion of the LNDM west of the Birdsfoot received the outflows and overflows of the Mississippi's four distributaries. This coast was also low and subject to overflow; nearly continuous; and characterized by reefs, shoals, drift trees, and shallow inlets. The network of distributaries associated with the western portion of the LNDM nurtured a network of offshore oyster reefs which covered ~2,000 km^2 of the US GoM and extended along the US coast for >150 km (Condrey in prep). From 1500–1800, this offshore oyster reef restricted safe access to the Mississippi's western-most distributary (Chaves' Río del Espíritu Santo). Here, in combination with Louisiana's eastern-most coastal cheniers (Chaves' Cabo de Cruz), the reef produced a natural harbor that was evidently of great importance to Spanish sailors caught in storms along the northern GoM during the 1500s and 1600s. Given Oviedo's interpretation of Rangel (Introduction), Chaves' descriptions (Results, Hypothesis 3), and the desire of De Soto's men to reach Mexico, it is more reasonable to conclude that De Soto's men rode the spring flood out of the Vermilion/Atchafalaya Bay complex than the Birdsfoot.

Louisiana's Blueprint for coastal restoration is based upon its Conclusion that the LNDM was restricted to the Birdsfoot and the Atchafalaya delta complex (Fig. 1). The Blueprint then continues with a statement that "massive coastal erosion… began around 1890 and peaked during the 1950s and 1960s" (LCWCRF and WCRA 1998, p. 31). It then targets estuarine conditions generally encountered in the 1950s–1980s as benchmarks for coastal restoration.

Our analysis finds that the Blueprint's Conclusion is based upon an incomplete and incorrect consideration of the historic record. Because of this, the Blueprint underestimates both the magnitude of the LNDM and the magnitude and onset of anthropogenically induced land loss in coastal Louisiana. Our analysis suggests that much of Louisiana's coast was advancing into the sea at the onset of European colonization, that colonial and post-colonial modification of the Mississippi resulted in a cumulating loss of much of this potential, and that Louisiana's total land loss (measured not just in loss of existing land but also in potential land gains) peaked long before the Blueprint's 1950s−1960s estimate. In partial support of this argument we offer Iberville/Russell's Chandeleur Sound, Barroto/Evía/Dumain's vast offshore oyster reef, and Chaves' coast, all of which suggest the potential, as well as the actual, land that has been lost.

As a consequence, many of the Blueprint's coastal restoration benchmarks are incompatible with a sustainable coast. Among these benchmarks are: diversions (similar to the Birdsfoot and the Atchafalaya delta complex) restricted to the lowest regions of coastal Louisiana; oyster reefs confined to estuarine environments; brackish-water dominated estuaries in the spring; deepwater shipping channel inlets; and artificial levees.

Benchmarks which describe the vibrant and sustainable coast the early Europeans encountered include: four active distributaries; freshwater-dominated estuaries in the spring; and a nearly continuous, seaward-advancing coastline characterized by shallow inlets, a vast offshore oyster reef, and overland flow of floodwaters throughout most, if not all, of Louisiana's coast east of the Chenier Plain. The historic record strongly suggests that these benchmarks will only be obtained with multiple, large-scale diversions of freshwater and sediment which begin at or above the headwaters of the Atchafalaya River, Bayou Plaquemines, and Bayou Lafourche and reconnect the Mississippi River to its Deltaic Plain in a manner which reflects the connectivity of the river and its LNDM. As such, our analysis supports Day et al.'s (2007, p. 1681) recommendation for "reconnecting the river to the deltaic plain via … the reopening of old distributaries", as well as the desirability of "a fully revised delta-lobe-scale chronostratigraphy" (Kulp et al. 2005, p. 282).

Given the Plan's limited consideration of the historic record and the incompatibility of many of its benchmarks with a sustainable coast, it is not surprising that the most comprehensive recent estimates of "land area change in coastal Louisiana" (Couvillion et al. 2011) are consistent with a constant rate of land loss of 69.1 km^2/yr (Fig. 8; 1.47 football fields/hr; NFL 2011, p. 1) for the period 1932 through 2010.

For some of Louisiana's renewable resources that thrive under the current and naturally unsustainable conditions, a replacement of the Blueprint's unsupported benchmarks with those supported by the historic record may result in a decline in their current and unsustainable productivity. In other cases, they may not. For example the Blueprint advocates the position that the fragmented coastline of a brackish, decaying estuary supports the greatest fishery productivity. This is not true for one of Louisiana's two most valuable historic fisheries—that on white shrimp which peaked in the 1940s (LDWF 1992, p. 50; Condrey and Fuller 2005)—and may not be true for the other—that on oysters (i.e., Evía). The historic record suggests that coastal restoration efforts that restore the fresh-water conditions of Louisiana's estuaries shown by the LNDM should eventually enhance the productivity of Louisiana's white shrimp and oyster resources.

Fishery considerations pale, however, when one considers the catastrophic consequences of the Blueprint's failure to explore the historic record and restore Louisiana's coast in

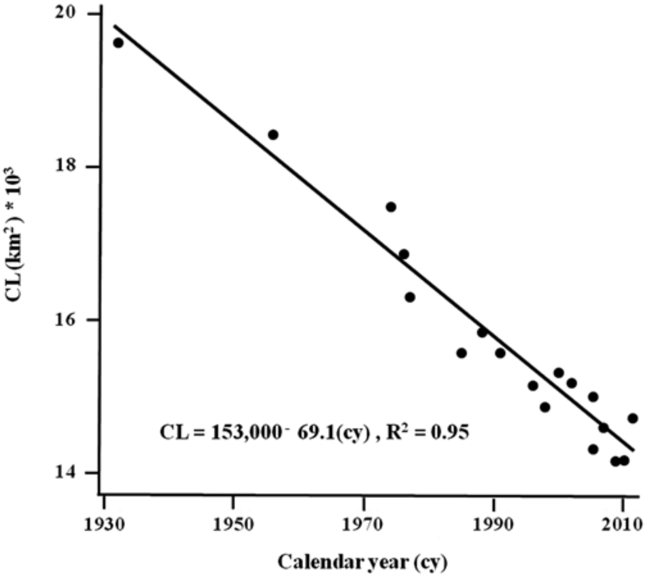

Fig. 8 Land loss in coastal Louisiana, 1932–2010.8. The regression is fitted to the coastwide land area (*CL*) data reported in Couvillion et al. (2011, Table 1). The linear regression is not consistent with the assumptions that coastal Louisiana land loss over this period peaked in the 1950s–1960s and/or that there has been a positive impact of the Plan on Louisiana's net loss of coastal land

a meaningful and timely fashion. Even with moderate rates of sea level rise, Blum and Roberts (2009)'s model predicts that—without effective restoration efforts—most of the emergent Holocene deposits of the Mississippi River Deltaic Plain below Butte la Rose will be converted to open water or brackish/saline marsh in 90 years. This area (Area; their Fig. 3b) currently contains >1 million people (USCB 2014), covers ≥10,000 km^2, and affects at least 10 parishes: Jefferson, Lafourche, Orleans, Plaquemines, St. Bernard, St. Charles, St. James, St. Martin, St. Mary, and Terrebonne. Freshwater diversions restricted to the Birdsfoot and the Atchafalaya delta complex (Fig. 1) will not build or maintain land in most of the Area because such structures are not located far enough upstream to mimic the natural processes which operated in the LNDM.

Ironically, the same Area of south Louisiana that may be under salt/brackish water in 2100 was subject to fresh water flooding in the spring of 1880. Tower et al. (1880) reported to Congress that if and when the spring floods of the Mississippi reached Butte la Rose through the Atchafalaya River, they would spread out over the face of the land. In the 1850–1880s, however, the flood consisted of sediment-rich fresh water, occurred in the spring/summer, enriched the land, advanced the coast, and encountered comparatively little human settlement. In 2100, the inundation predicted in Blum and Robert's model will not be confined to the spring, enrich the land, or advance the coast. Moreover it will adversely affect major human population centers and millions of lives.

The Deepwater Horizon Oil Spill and Temporary Sand Berms

With the advent of the Deepwater Horizon oil spill (DHOS), the consequences of the Blueprint's failure to adequately explore the historic record took a new twist.

In May, 2010, Louisiana requested permission from the U. S. Army Corps of Engineers

> to construct a sand berm [Berms] approximately 300-foot [91 m] at the base, approximately 25-foot [7.6 m] at the crown and approximately 6-foot [1.8 m] above the mean high water line… [from] the seaward side of the Chandeleur Island… [to] Timbalier Island… [with] gaps…for tidal exchange

and the Mississippi River (USACE 2010, unnumbered p 4). The Berms were intended to protect the Louisiana coastline from DHOS oil and were to be constructed either directly in front of existing coastlines or in open waters (USACE 2010, unnumbered p 4).

It is instructive to view the Berms in light of the historic record of the LNDM. On one hand, if the LNDM had been functional when the DHOS occurred, the State of Louisiana might not have even considered Berms, as the coastline would have been nearly continuous with shallow passages and the spring flood of the Mississippi would have driven the surface oil away from the coast.

On the other, if the Plan's view of the LNDM had been historically correct, it seems unlikely that Louisiana would have proposed the Berms as there is nothing in the historic record to suggest the long-term stability of 1.8 m berms of sand in open waters along the Louisiana coast. For example, Humphreys and Abbott's (1861; Condrey in prep) landscape measurements reveal that the natural levees of the Mississippi only reached an average height of 1.8 m when the River was 148 km (in river distance) from the coast, surrounded by wetlands with an average elevation greater than 0.6 m above GoM sea level, and covered in mature communities of saltwater-intolerant vegetation. More recently, Sallenger et al. (2009, p. 27) observed that

> Hurricane Katrina… removed 86 % of the [pre-Katrina] surface area of Louisiana's Chandeleur Islands… During the storm, the Chandeleurs were completely submerged by storm surge… the (GoM) shores were eroded landward an average of 268 m… Peak elevations on the islands decreased from more than 6 m to less than 3 m, and all of the sand visible from the air was stripped from the islands… These islands are conditioned for extreme erosion and ultimate disappearance because of small [natural] sand supply and rapid sea level rise induced on the Mississippi River Delta by subsidence.

Berms to Barriers

On May 27, 2010, the US Army Corps of Engineers offered an emergency permit to Louisiana for the construction of 72.4 km of Berms (USACE 2010). The permit reminded the

State that permission would be required before federal sands on Ship and St. Bernard Shoals could be mined for sand. Though not mentioned in the permit, pre-DHOS Ship Shoal had recently been found to be a biodiversity hotspot (Dubois et al. 2009) and nationally important blue crab (*Callinectes sapidus*) spawning ground (Gelpi et al. 2009)—characteristics hypothesized to be shared by the biologically unstudied St. Bernard Shoals (Condrey et. al. 2010). Nothing in the permit referenced concerns that these shoals might support endangered sea turtles such as loggerheads (*Caretta caretta*; i.e., Stone et al. 2009, p. 242) seeking blue crab (e.g. Seney and Musick 2007) or that the DHOS might be impacting the ecology of the shoals and threatening the blue crab fishery (Condrey et al. 2010; Leibach 2010; Box 2).

Box 2 Berms, Sand Mining, and Sea Turtle Mortality

The 2010 sand mining efforts for the Chandeleur Islands Berm produced two “very alarming observations”: extremely high catch rates and unprecedented mortalities of loggerheads (Bernhart 2010, p. 3). Creef (2010, p. 12; consistent with Bernhart 2010, p. 3) suggested that these sea turtles may have been

> adversely affected by [DHOS] oil and dispersants… [leaving them] less able to avoid entrainment by hopper dredges and… less able to physically tolerate the stresses of capture by trawling efforts.

If sand mining on Ship and/or St. Bernard Shoals results in a precipitous decline in blue crab abundance, the decline may cause “loggerheads to forage in nets or on discarded fishery bycatch” (Seney and Musick 2007, p. 478). If diet-displaced loggerheads are less able to “tolerate the stress of capture by trawling” (Creef, above), their mortality in the US GoM shrimp fishery should increase. This could reignite the 1989 conflicts between shrimpers and regulators (e.g. Condrey and Fuller 2005, p. 110–111) though the underlying problems arose from a combination of sand mining and the lingering impacts of the DHOS.

In November, 2010, the Office of the Louisiana Governor reported

> plans to fortify the temporary sand [B]erms for oil protection so that they become barrier islands [Barriers] that both block oil and help to restore and protect Louisiana's coast….against the threat of submerged oil before the next hurricane season…. [making this] the largest barrier island restoration project in Louisiana history. (OG 2010).

On the surface, this seems like a wise decision as “Louisiana’s barrier shoreline is one of the fastest eroding shorelines in the world” (CPRA 2011, unnumbered p. 24 of Appendix C).

On closer inspection it is not clear how the effort, which will cost ~9% of the $ 1.1 billion 2012–2014 budget (CPRA 2011; Table ES-2, p. x), will lead to sustainability as previous restoration projects have only increased barrier island life spans by ~10 to 16 years:

> The good news is that restoration efforts … have shown benefits. Timbalier Island … restoration… added approximately 10 years of life to the island. [Restoration projects on] the Isles Dernieres … have increased their life span by approximately 16 years….
>
> the State plans to utilize the [B]erm material and approximately $ 100 million… to convert the temporary [B]erm features into the more resilient barrier island features that were designed as CWPPRA projects. CPRA 2011, unnumbered p. 24 of Appendix C)

A recent USGS study of the Berm constructed along the Chandeleur Islands suggests that it may not remain long enough to allow for its conversion to a Barrier. One year after its construction, Flocks et al. (2012, pp. 5–6) report that

> erosion of the [Chandeleur B]erm is being influenced by the island chain. The northernmost segment of the [B]erm… has the highest remaining elevation… [T]he central [B]erm is rolling over into the manmade trough … The southernmost segment of the [B]erm exhibits the highest reduction in elevation. Along this reach, islands and dunes are fewer, and overwash splays and inlets are wider. Virtually all of the [B]erm along this reach has been overwashed and eroded and in places has been completely removed.

At best, then, Berms to Barriers may provide some limited and short-lived protection of the Louisiana coast. Toward the worst, it will divert money from more effective coastal restoration projects and prove a negative tipping point for Louisiana’s blue crab fishery.

The Plan is not an Exception

The Plan is not alone in its failure to carefully consider the historic record. For example, Galtsoff (1954a) in the introductory chapter to the first major effort to synthesize our understanding of the ecology of the GoM (Galtsoff 1954b) misleads the casual reader to believe that Alonzo Alvarez de Pineda left a first-hand, written description of the ecology of the Mississippi River and Mississippi Sound. He writes that in 1519 Alvarez de Pineda

> discovered the mouth of the Mississippi River which he called “*Río del Espíritu Santu*” [sic] and described the body of water E of the delta as “*Mar Pequeña*” or a small sea, the name of the present Mississippi Sound which persisted on many charts for nearly two centuries. Pineda noted the physiographical character of the shoreline, recorded the positions of dunes, low-lying sand spits, bays, knolls, marshes, and oyster banks (*ostiales*) which abounded in the Mississippi Sound and in the delta of the Mississippi River. He realized that the majestic freshwater stream that he ascended for several miles must originate on a large land area, and other observations convinced him that he was exploring the coast of a great continent. (Galtsoff 1954a, p. 12)

Galtsoff provides no citation that supports this vivid and incorrect description. Indeed, there is no firsthand account of Alvarez de Pineda's expedition along the northern GoM coast other than what Chaves seems to record and no secondhand account that supports Galtsoff's description. Despite these glaring inadequacies, Galtsoff's unverifiable description of Alvarez de Pineda's findings continue to influence scientific understanding of the GoM (e.g., GulfBase.org. 2010).

Re-evaluating Our Basic Understanding of the Americas

This limited study of Chaves has given us our first view of the last naturally active delta complexes of North America's largest river, a blue print for restoring the Nation's wetlands, and new insight into the exit used by the first Europeans who penetrated North America. Given the discrepancies we have found, we suggest that a careful reappraisal of the protohistoric and colonial record of the Americas is warranted. As the challenge is to separate scientist from charlatan, we suggest Chaves as a starting point. Here we follow Lamb's (1969) insightful argument that "Chaves' undated manuscript… contains the earliest preserved example of part of a Padrón Real", and thus our earliest recorded view of the Americas. Our analyses lead us to suggest that the written coastal descriptions of the early cartographers and surveyors may be far more valuable than even the most authoritative protohistoric or colonial map—especially as we try to build a better tomorrow based upon our understanding of the past.

Epilogue: Barrier Island Restoration: Are the Plan's efforts working?

While this book was in the final stages of preparation, Louisiana issued the 2015 fiscal year Plan update (Update; CPRA 2014). The Update's Section 2, "Progress to Date: Results on all Fronts", is the Plan's "report card on results achieved and in the works" (CPRA 2014 p. 11). The Report Card contains 12 pages of discussion followed by five pages of tables and maps. Approximately 60 % of the Report Card's discussion highlights barrier island/GoM shoreline restoration projects—suggesting in it's before and after pictures that the projects are succeeding.

The scientific basis for the Report Card's evaluation of the Plan's > 20 barrier island projects is contained in Appendix C of the Update.

We used the Appendix-C-associated data to test the assumption that the Plan's barrier island restoration projects were working. As noted in Fig. 9, we found no statistical suggestion that these projects were retarding barrier island land loss. This finding is consistent with our LNDM's concerns for the Berms to Barriers concept (Abstract).

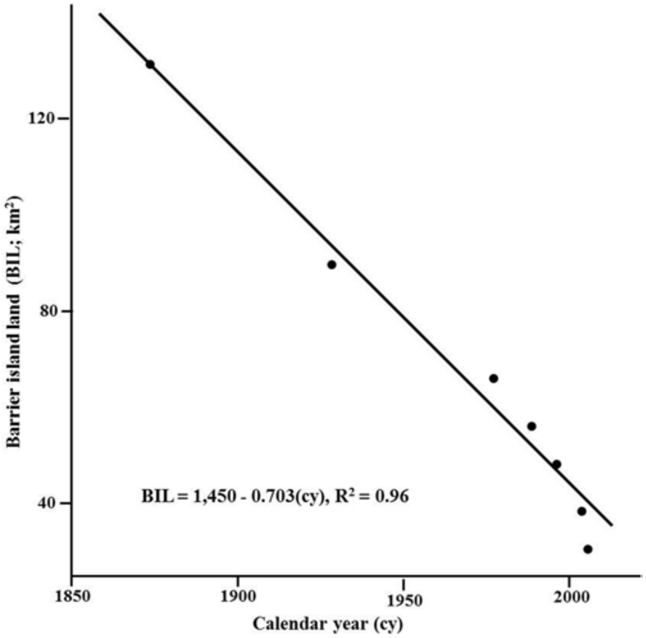

Fig. 9 Barrier Island land loss in coastal Louisiana, ca. 1855 to 2005. The regression is fitted to the coastwide barrier island land data reported in CPRA (2014, Table 2 of Appendix C), Martinez et al. (2009, unnumbered figures 1, 3–7, 9, 11, 13, 15, 17, and 19 of Appendix B), and McBride and Barnes (1977, Tables 1, 3–8). Mean year was used for the 1855–1887, 1922–1934, 1951–1956, 1973–1978, and 1988–1989 surveys. The linear regression is not consistent with the assumption that the rate of barrier island land loss has declined as a result of the Plan's restoration efforts. The linear trend parallels a linear relationship we found in the smaller subset of more recent data reported for Raccoon, Whiskey, Trinity-East, Timbalier, and East Timbalier Islands in CPRA (2014, Fig. 24–26 and 28–29 of Appendix C), reinforcing the argument that barrier island restoration efforts are not working

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Adapting to Change in the Lowermost Mississippi River: Implications for Navigation, Flood Control and Restoration of the Delta Ecosystem

G. Paul Kemp, Clinton S. Willson, J. David Rogers,
Karen A. Westphal and S. Ahmet Binselam

Abstract

The Lowermost Mississippi River (LMMR), from the Gulf of Mexico to 520 km above Head of Passes, remains critical for flood conveyance and transport of agricultural and industrial bulk products from the central United States. The US Army Corps of Engineers (USACE) has managed it with little change for 80 years using the levees and spillways constructed under the Mississippi River and Tributaries project (MR&T). At the same time, public demand for reconnection of the Mississippi to the deteriorating delta ecosystem has grown. Significant sediment diversion projects have been authorized downstream of New Orleans to restart deltaic wetland building to conserve fish and wildlife resources and reduce hurricane flood risk to delta communities. Recent research and observations from the back-to-back record 2011 high-, and 2012 low-discharge events indicate that LMMR hydraulics have changed significantly, and that sea level rise, subsidence and a reduction in sand transport through the Plaquemines-Balize birdsfoot delta (PBD) now favor formation of new, unregulated outlets upstream. During the peak of the 2011 flood, only 27% of the 65,000 m^3-s^{-1} discharge entering the LMMR reached the Gulf via Head of Passes, compared to 36% passing through the two outlets of the shorter Atchafalaya distributary. About 20% of the water lost from the LMMR occurred through unregulated flow overbank and through small, but growing, distributaries between New Orleans and Head of Passes.

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Adding delta restoration to existing USACE missions will require adjusting the MR&T but has potential to lower flood flow lines and reduce navigation dredging costs sufficiently to allow LMMR ports to accommodate larger, Post-Panamax ships.

Keywords

Lower Mississippi River · Mississippi River delta · Coastal restoration · River hydraulics · River engineering · Fluvial sediment transport · Flood control · Panama Canal expansion

Introduction

Our understanding of sediment transport and flow distribution on the Lowermost Mississippi River (LMMR), defined here as the last 520 km above Head of Passes (AHP) and the outlets to the Gulf of Mexico (GOM) (Fig. 1), has been fundamentally transformed by the work of Nittrouer et al. (2011a), Allison and Meselhe (2010), Meade and Moody (2010), Allison et al. (2012a) and (Meselhe et al. 2012) based on extensive field investigations coupled with sediment transport modeling. More particularly, Allison et al. (2012a) demonstrated during the 2008, 2009 and 2010 water years that a surprisingly small percentage of either water or sediment (particularly sand-sized sediment) entering the LMMR is conveyed all the way to Head of Passes, where the main channel branches into three distributaries to form the iconic "birdsfoot," or Plaquemines-Balize delta (PBD).

Observations are now also available from the back-to-back record 2011 Mississippi River flood and near-record low discharge in 2012. This information is relevant to the design of the large, controllable lateral sediment diversions needed to offset or reverse wetland loss in the Mississippi River Delta (MRD) (Nittrouer et al. 2012). The unfolding environmental degradation and loss of ecosystem services provided by deltaic wetlands (Batker et al. 2010; Couvillion et al. 2011; Batker et al. 2014, this volume) has slowed recovery of coastal Louisiana from devastating hurricanes in 2005, 2008 and 2012. Very importantly, the collapse of the wetlands is exposing delta communities to greater long-term risk from hurricane surge and waves (Boesch et al. 1994; Day et al. 2007; Freudenburg et al. 2009; Shaffer et al. 2009; Bailey and al 2012, this volume).

The *2012 Louisiana Comprehensive Master Plan for a Sustainable Coast* (2012 Master Plan) lays out a scientifically informed restoration strategy compatible with recent subsidence and sea level rise scenarios (Louisiana Coastal Protection and Restoration Authority 2012). The 2012 Master Plan identifies a $ 25 to 50 billion investment in LMMR sediment diversions below New Orleans as necessary to reverse deltaic wetland loss. The Nation might choose to forego this expenditure if restarting delta building in the MRD were the only outcome. But the answer might be different if it can be shown that delivering river sediment to disappearing MRD wetlands is also critical to sustaining the $ 37 billion annual international commodities trade that depends on deep-draft access (14+m) to LMMR ports and terminals (LaGrange 2011a, 2012). Draft restrictions were, for the first time, placed on that access for an extended period in 2010 and 2011 because of flood-induced shoaling (LaGrange 2012). The case for restoration becomes even more compelling if new LMMR diversions can extend the utility of the multi-billion dollar federal investment in Mississippi River flood protection levees and floodways undertaken since the 1927 flood (Cowdrey 1977; Barry 1997; Reuss 2004; O'Neill 2006), under the Mississippi River and Tributaries (MR&T) project (Fig. 2).

The 2012 Master Plan calls for maximizing use of river sediments to reverse catastrophic loss of MRD wetlands caused in part by levees that restrict sediment influx to the adjacent wetlands. Accordingly, USACE and the State of Louisiana (State) are jointly funding the Mississippi River Hydrodynamic and Delta Management Study, an MR&T re-evaluation (USACE 2011). At this juncture, we set the stage for this work and provide evidence that building large, controllable, lateral sediment diversions downstream of New Orleans may also prove useful in sustaining traditional MR&T flood control and navigation missions (Louisiana Coastal Protection and Restoration Authority 2012). While river diversions have long been employed in the form of spillways to lower LMMR flood stages (Fig. 2), construction of sediment diversions for land restoration and reduction of navigation dredging runs counter to the predominant "levees only" approach that has characterized USACE Mississippi River engineering tradition for 150 years (Humphreys and Abbot 1867).

Geologic and Historical Setting

Natural processes that have shaped the LMMR and MRD during recent geological time provide a framework over which engineered interventions for flood control and navigation have been superimposed in the past 300 years. Both requirements continue to affect the evolving MRD landscape and the value of the ecosystem services provided to the human economy by the LMMR (Batker et al. 2010). Likewise, both will influence the future, whether under a *status quo* scenario, or one that includes the aggressive

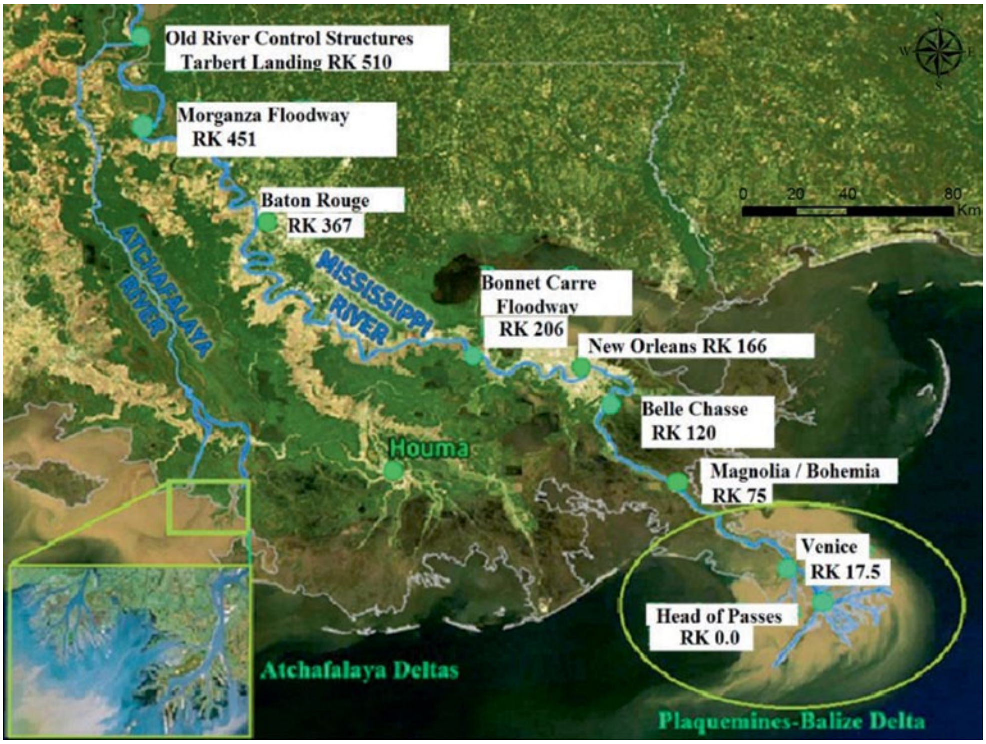


Fig. 1 The Lowermost Mississippi River and Atchafalaya courses are seen in a Landsat image from the 2008 flood showing the Mississippi River Delta with key features and gauging stations noted in river kilometers (RK) above Head of Passes

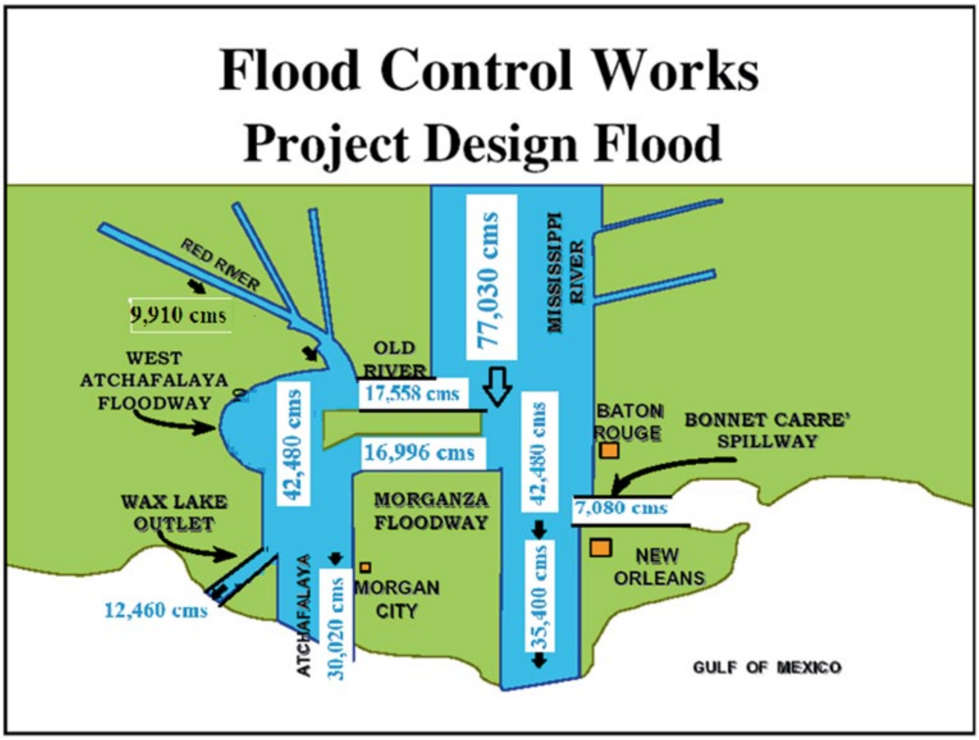


Fig. 2 USACE MR&T post-1956 plan for routing the maximum design flow of 77,000 m^3-s^{-1} from the Mississippi and 9,900 m^3-s^{-1} from the Red River through the Mississippi River Delta. (modified from USACE New Orleans District 2011)

efforts to restore the MRD depicted in the 2012 Master Plan (Louisiana Coastal Protection and Restoration Authority 2012). Engineered restoration projects now being designed will impose a new layer of management on an already extensively modified river that is also following a geological trajectory.

Deltaic Geology

Blum and Roberts (2012) provide an excellent review of LMMR channel switching, the process that built the MRD over the last 7.5 ka. This took place after sea level rise caused by climate warming and de-glaciation slowed and leveled off

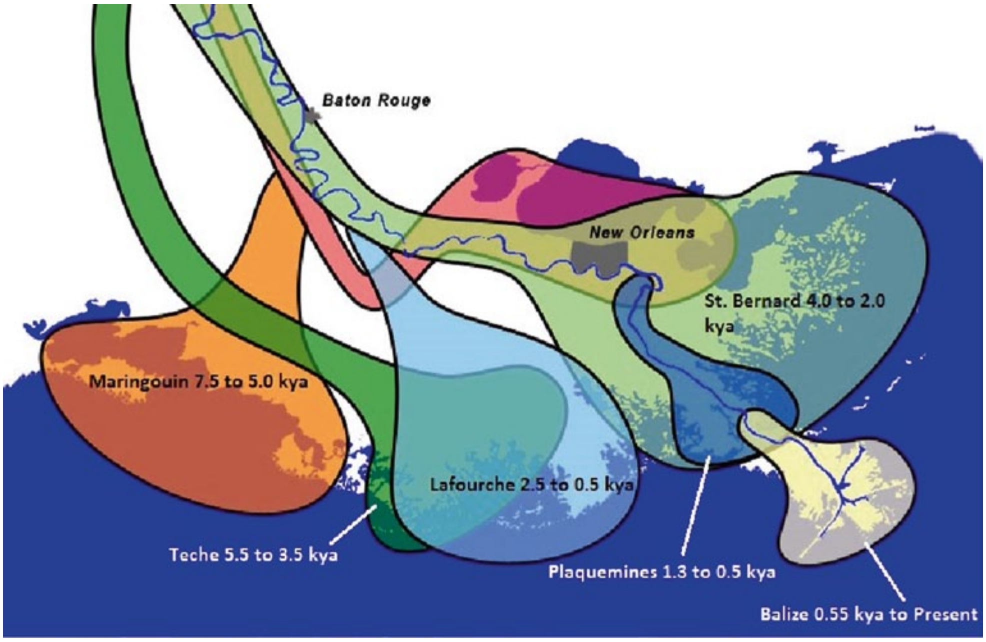


Fig. 3 Location of prehistoric and historic lobes of the Mississippi Delta, adapted from Blum and Roberts (2012)

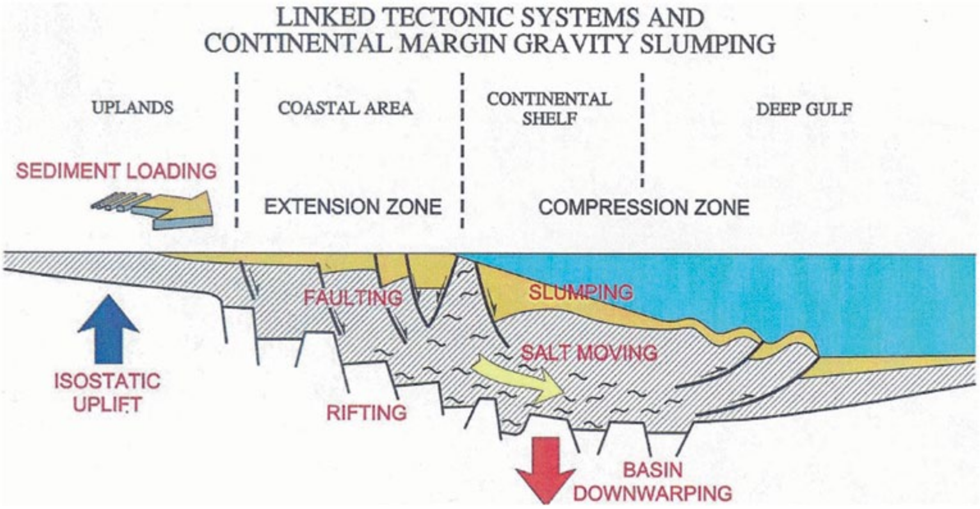


Fig. 4 North-south cross-section through the Gulf Coast Salt Basin showing general stratigraphy, *en echelon* listric, normal growth faults and diapiric salt structures from Gagliano et al. (2003)

(Roberts 1998). Each of the seven natural 1.0 to 1.5 ka delta cycles that have together built the existing MRD complex began with an upstream avulsion or natural diversion that created a shorter, more efficient distributary route to the sea (Fisk and McFarlan 1954; Kolb and van Lopik 1958; Frazier 1967).

Coastal headlands were formed as channels built seaward (Fig. 3). At the same time, bypassed older lobes received diminishing fluvial sediment influx and entered a well-established transgressive (retreat) phase dominated by marine processes. Delta front sands were reworked into barrier beaches while the wetlands behind them gradually degraded and submerged, forming barrier islands and back barrier estuarine bays (Penland et al. 1988; Boyd et al. 1989).

MRD wetland submergence is driven by ongoing loading of the continental margin with sediments delivered by the LMMR (Fig. 4). One effect of this loading is dewatering, compaction and faulting of the more recent Holocene deltaic strata overlying a less compressible Pleistocene surface. This compaction occurred in both abandoned and active delta lobes throughout the Holocene, so wetland loss is not a new phenomenon (Frazier 1967). However, the aggregate land area covered by deltas continued to increase into the historic period.

The difference today is that all parts of the MRD are undergoing more or less rapid conversion to open water, with the exception of two sand-dominated bay-head delta splays fed by the Atchafalaya distributary (van Heerden and Roberts 1980). Adjacent wetlands (Fig. 1) surrounding Atchafalaya Bay have also stabilized as a result of fine-grained sediment introduction from the nearby Atchafalaya (Couvillion et al. 2011). Large areas in the interior of the delta between the

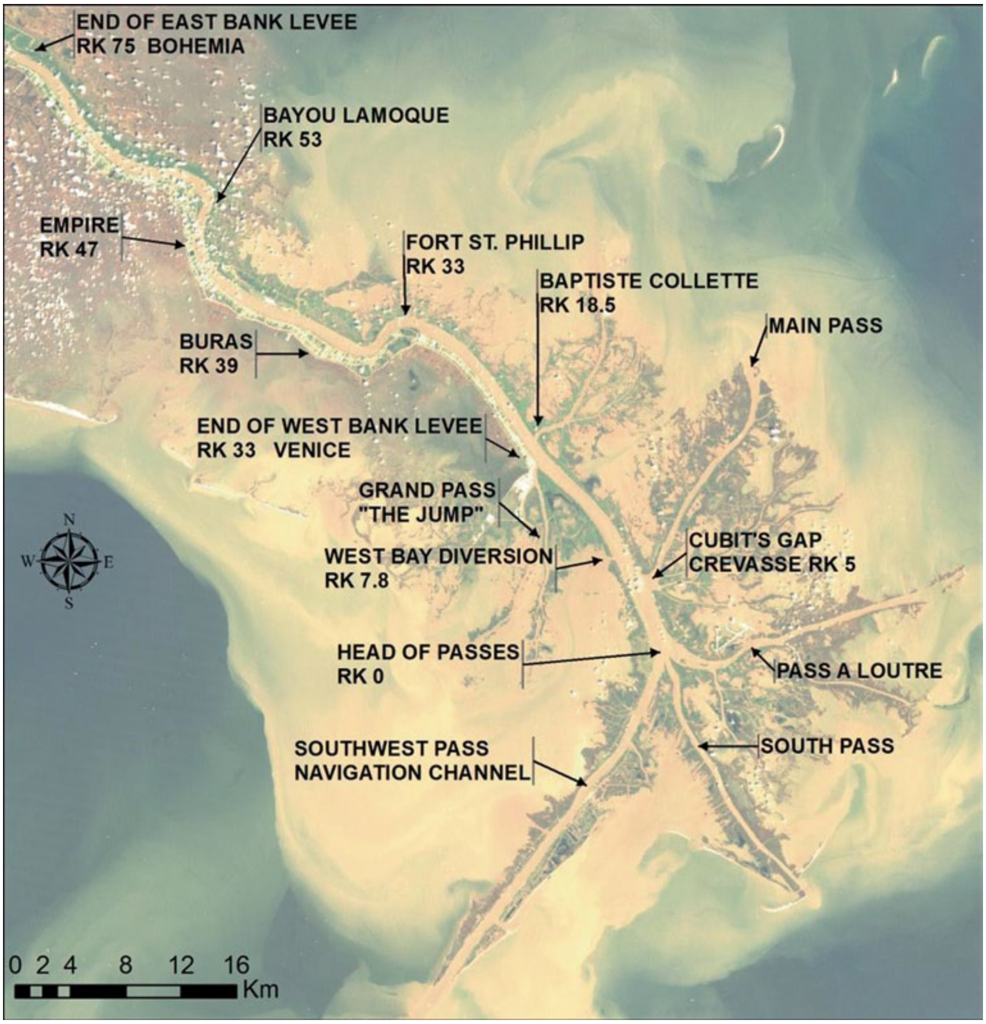


Fig. 5 Landsat Image from April 10, 2011 showing several of the key features in the present Plaquemines-Balize Delta

LMMR and the Atchafalaya, however, are deprived of any direct river sediment input. There, peat-rich fresh and brackish marshes, locally known as *flotants*, detach from the bottom and float all or part of the year, thus masking for a time the true extent and effects of submergence (Kosters 1987, Kosters and Suter 1993).

The Louann Salt, a 1,200 m thick evaporite bed that underlies much of the northern Gulf coast, also contributes to a complex history of geological instability in the MRD generally and the PBD more specifically (Peel et al. 1995). The top of the ancient (mid-Jurassic) salt lies 7 to 10 km deep. Because salt behaves as a fluid under pressure and has a lower density than overlying sedimentary strata, it has flowed upward in hundreds of diapir dome structures that cause or follow fault planes (Fig. 4). A small number jut through the surface where they form densely forested hills up to 100 m high that rise dramatically above the otherwise flat deltaic plain. Most of the crests of these diapirs remain invisible as they occur hundreds to thousands of meters below the surface. Many have been the focus of intensive geophysical study because of their role in trapping hydrocarbons migrating from pierced or contorted sedimentary strata. As the salt flows toward the surface in one place, it is withdrawn from a surrounding source zone, causing differential settlement of overlying strata and displacement along fault planes within the sedimentary package pierced by the diapir.

Ramsey and Moslow (1987) examined displacement of benchmarks discovered during sequential re-leveling campaigns undertaken by the National Geodetic Survey along the banks of the LMMR. They found evidence of differential settlement, some of which has been ascribed to movement along "down to the basin" growth faults that cross the river with east-west (shoreline parallel) axes (Gagliano et al. 2003). More recently, Dokka et al. (2006) reported measurements of subsidence based on episodic Global Positioning System (GPS) observations at stations reoccupied every 1 to 2 years from 1997 to 2005, as well as at continuously observed sites with 2 to 11 years of data. Settlement rates along the LMMR range from 3 to 23 mm-y^{-1} Brown et al. (2009). Rates increase gradually downstream, but become much greater at Empire (RK 47), as will be discussed later (Fig. 5).

Dokka et al. (2006) found that the stations they monitored in the MRD not only experienced vertical displacement, but

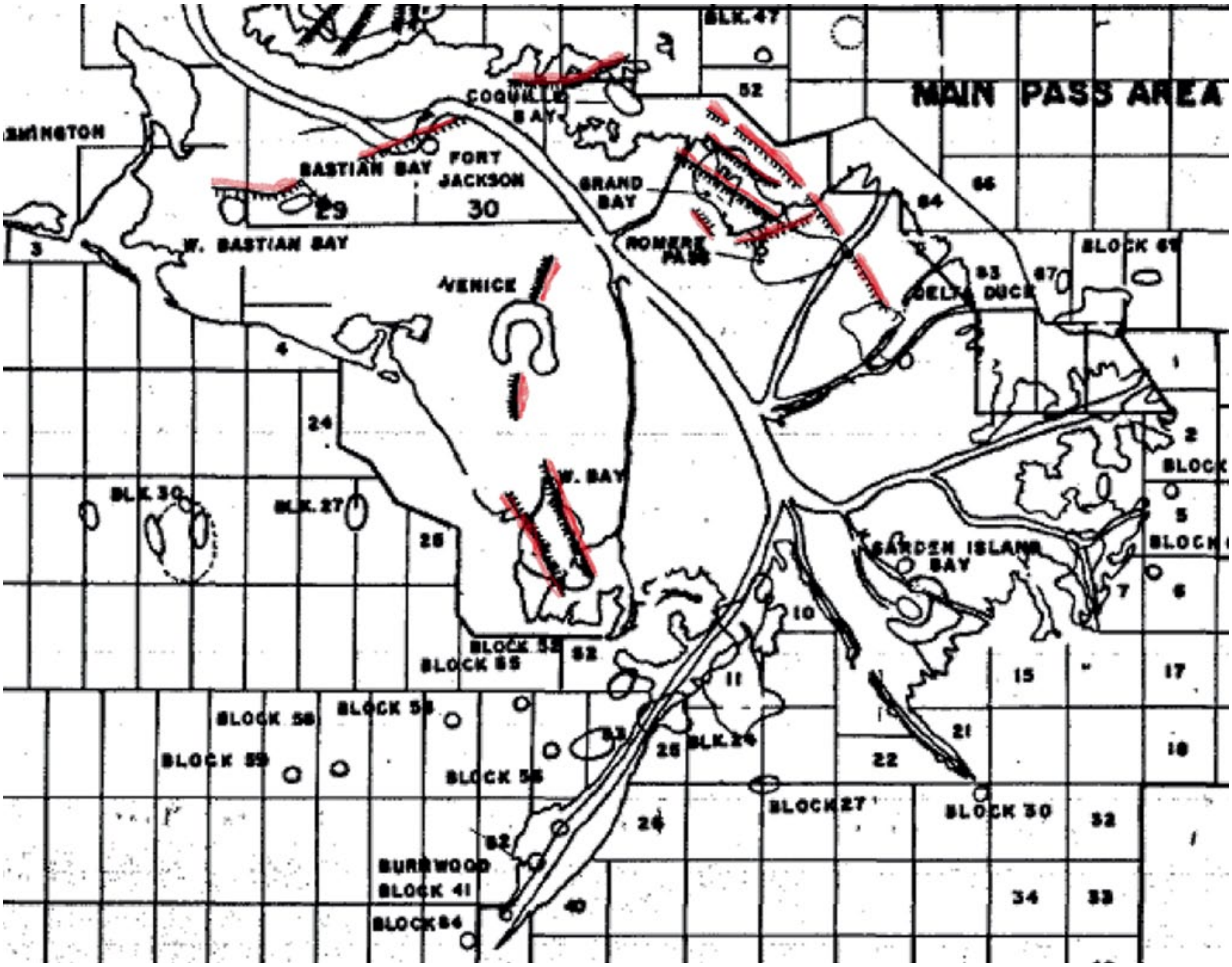


Fig. 6 Portion of Wallace (1966) map showing then known faults, salt domes associated with oil fields relative to oil lease blocks. Map is modified to emphasize stable, up-side of faults. Republished by permission of the Gulf Coast Association of Geological Societies, whose permission is required for further publication use

were also moving in a southerly or seaward direction at up to 6 mm-y^{-1}, a motion that had not been detected previously with standard leveling techniques. They have proposed a regional model for offshore translation of the entire Mississippi River delta sedimentary package, which they call the "South Louisiana Allochthon" (SLA), away from the rest of the stable North American continent. The Louann Salt plays an important role as a ductile lubricant that allows for relatively continuous, aseismic, down-dip movement. On the other hand, they recognized that the SLA is internally fractured by faults that do generate stick-slip seismicity (Fig. 4).

Wallace (1966) produced a "fault and salt" map for the Louisiana coast from geophysical data available at that time. The PBD portion shows an east-west trending growth fault that crosses the LMMR at RK 33 (Fort St. Phillip), and a number of north-south trending fault lineaments within the birdsfoot that run counter to the depositional strike and generally parallel the modern river course (Fig. 6). The dropped side of these faults is on the west of the axis, indicating a potential for displacement toward a salt depletion zone that underlies the western PBD and extends farther to the west (Gagliano et al. 2003).

Gagliano et al. (2003) compiled data from many sources to connect episodic wetland loss since the 1950s to movement along active MRD faults that extend to the ground (Fig. 7). They found low amplitude scarps and cracks in natural levee locations that formed in the 1970s during seismic events. In adjacent marshes, this evidence was complemented by swaths of wetland loss, submergence of natural levees and spoil banks and expansion of marsh lakes. Movement was documented along the Empire and Bastian Bay lineaments of the 150 km long Golden Meadow fault complex. This fault zone crosses the LMMR at Empire (RK 47) and Fort St. Phillip (RK 33), close to the eastern terminus (Fig. 7).

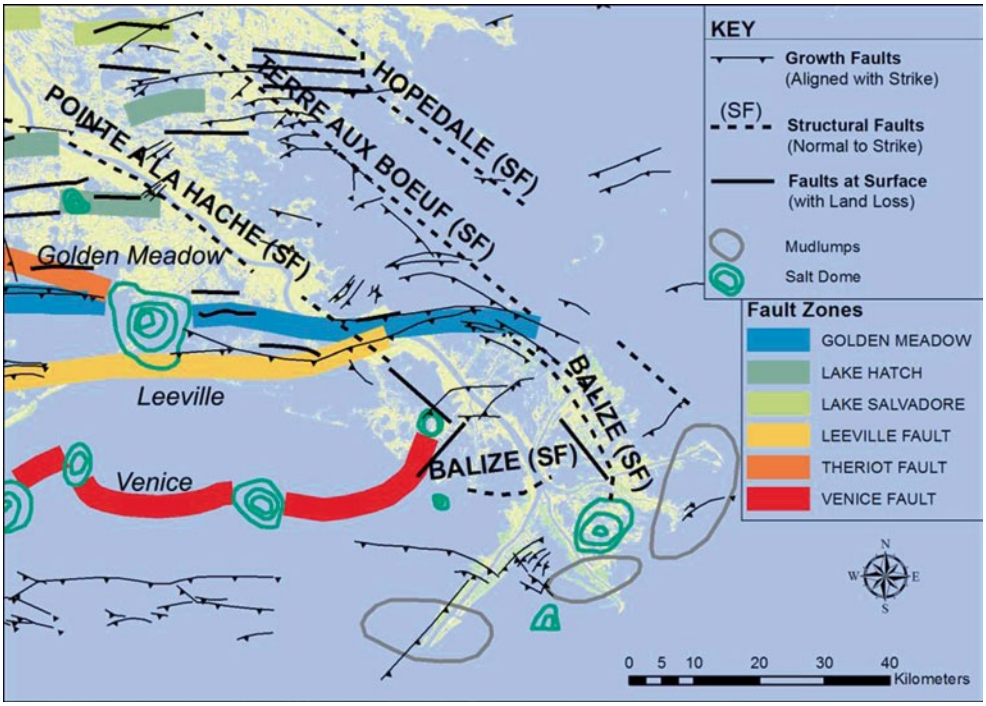


Fig. 7 Portion of map by Gagliano et al. (2003) showing relationship between projections of known faults and evidence of recent surface displacement determined from wetland loss and other indicators of particularly high subsidence on down-dropped rotational blocks

Gagliano et al. (2003) also recognized the importance of "structural" fault alignments oriented parallel to the course of the modern LMMR channel and normal to the sedimentary strike. They interpreted the subsurface data to show that the Golden Meadow growth fault complex joins the Terre Aux Boeuf structural fault on the east side of the river to create the "Balize Loop." The Loop encloses much of the PBD on its eastern and southern sides. Rotational faults in the Balize Loop are associated with significant wetland loss on the western side of the PBD, as will be discussed further.

Like the Holocene sediment package, the thickness of deltaic sediments deposited millions of years earlier increases toward the shelf margin (Blum and Roberts 2012). Sedimentary loading has driven both salt flow at depth and listric normal faulting within the SLA that, in some places, reaches the surface (Fig. 4). Both phenomena are connected, and contribute to geological instability that makes the PBD a particularly difficult place for man to live or work.

Rise and Fall of the Plaquemines-Balize Delta

Land-loss is an expected response of subsiding MRD wetlands to isolation from the LMMR sediment source. But the parallel LMMR federal flood control levees end at Bohemia on the east bank (RK 75) and at Venice (RK 17.5) on the west side (Fig. 5). More natural overbank flooding is possible on the LMMR east bank and in the birdsfoot where the supply of river sediment, it seems, should be greater than in any other part of the delta except Atchafalaya Bay. Yet, approximately 270 km^2, or about 50 % of the land present in 1956 in the PBD, was gone 20 years later in 1977 (Couvillion et al. 2011). Why is the last natural delta built by the Mississippi River dying today (Condrey and Hoffman 2014, this volume)?

When the LMMR began 1.3 ka to abandon the inner-shelf St. Bernard delta, deltaic wetlands and shoals extended north and east of the present Mississippi course (Fig. 4). The LMMR then built two new courses more or less contemporaneously across older delta lobes, feeding the Lafourche and Plaquemines deltas (Törnqvist et al. 1996). The Plaquemines channel elongated rapidly seaward over the westernmost deposits of the St. Bernard delta (Blum and Roberts 2012). It grew quickly without meandering or branching as much as earlier courses, and instead built a narrow peninsula of natural levees fringed by marshes sustained by crevassing and overbank flooding.

Archeological evidence from the most downstream mound sites indicates that the Plaquemines delta, the first phase of the PBD, had reached RK 40 near the present locations of Empire and Buras by about 0.9 ka (McIntire 1958). There, land-building apparently paused for about 400 years while the pro-delta advanced into the deeper waters of the shelf margin (Kolb and van Lopik 1958). The Balize birdsfoot, the final extension of the PBD, reached the shelf edge with much the same configuration it has today by 0.5 ka, becoming subaerial shortly before the first European explorers arrived (McIntire 1954). The Balize fort and pilot station that gives the birdsfoot its name was originally established by the Spanish in the early 1700s adjacent to the Southeast Pass fork of Pass a Loutre (Goodwin et al. 2000), which then served as the main navigation entrance (Fig. 8).

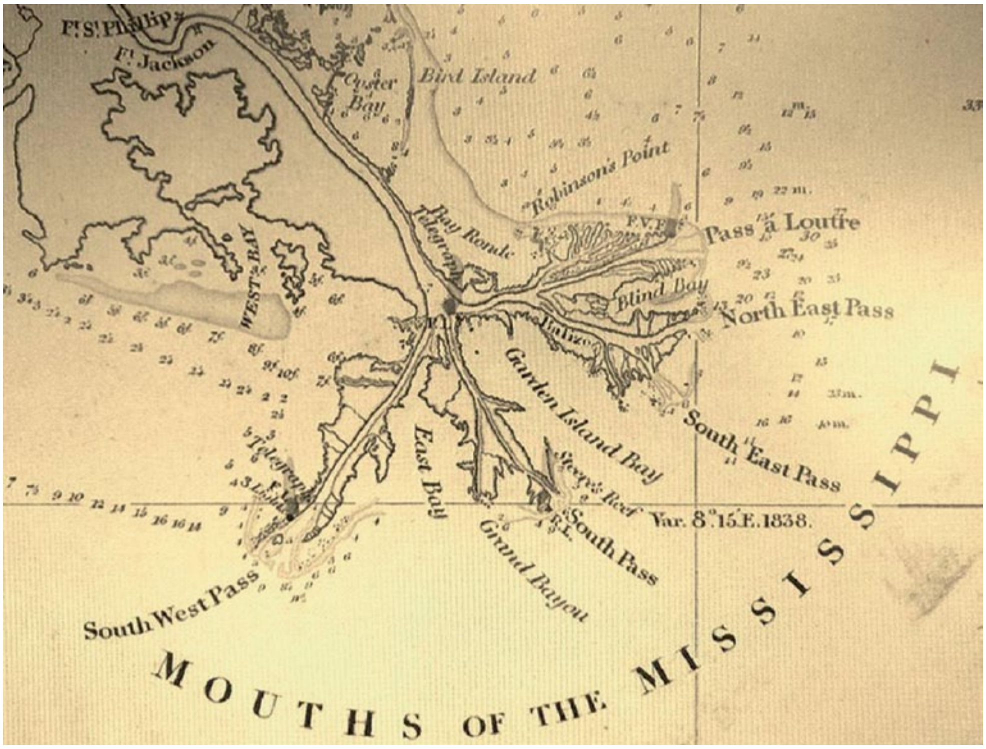


Fig. 8 This portion of 1844 Blunt chart of the PBD shows the location of Balize, as well as limited interdistributary wetlands. Passes are shown with wide openings to the Gulf, extensive mouth bars and subaqueous natural levees. Map courtesy of Dorothy Sloan

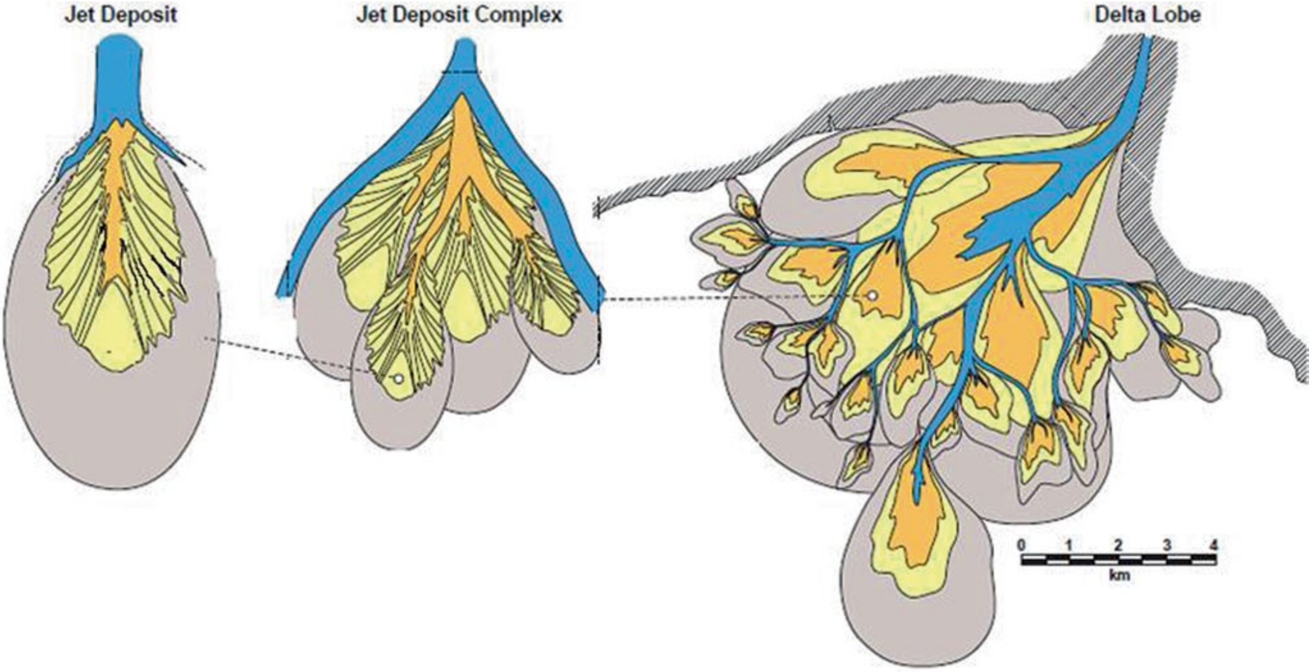


Fig. 9 Wellner et al. (2005) illustration of how deposition of sediment from turbulent jets combined to form the Wax Lake Delta. Republished by permission of the Gulf Coast Association of Geological Societies, whose permission is required for further use

The divergence of the main channel into three distributaries below Head of Passes is not unique to the PBD. The Wax Lake Delta forming at the western outlet of the Atchafalaya (Fig. 1) has a similar trifurcation that has been present since land first emerged above sea level in 1973 (Roberts et al. 1997). Wellner et al. (2005) have described this natural bay head delta as formed by compensational stacking and coalescing of deposits from turbulent jets of many sizes (Fig. 9). Deposition from the first distributary channel jet creates an obstruction that forces bifurcation around it. Welder (1959), Wright (1977) and Wells et al. (1982) earlier invoked similar dynamics for historical sub-delta formation in the PBD. All three channels associated with deposition from a turbulent jet, including the central supply and two bypass channels, may remain active, as below Head of Passes in the PBD, or may fill, as at Wax Lake. The widening at the head of passes in both deltas is a remnant of a more expansive scour apron that predates delta distributary formation. The sequence at Wax Lake—which also applies in the PBD—indicates that this apron is later partially filled by upstream growth of inter-distributary bars and islands (Wellner et al. 2005), as van Heerden and Roberts (1988) documented in the natural portion of the delta forming at the eastern mouth of the Atchafalaya.

Clearly, the head of passes scour feature in both deltas is persistent. It is the only place in the PBD birdsfoot that is deep enough today—outside the navigation channel itself—to allow for dumping of fully loaded hopper dredges. These specialized ships are used almost exclusively to maintain the narrow Southwest Pass navigation channel. While far less efficient than anchored suction dredges in terms of sediment production, they have the great advantage in this instance of being able to maneuver around transiting vessels. During the time that they are on station, they trail dredge heads on each side lowered on arms that carry the sediment slurry from the bottom into the hopper. The dredge gradually settles as it fills, until the deck is awash. Much of the water and fine-grained sediment is lost overboard while the heavier sand is retained in the hopper. When full, the ship moves to the disposal area where hinged hull plates open along either side of the keel to empty the hopper. Sediment dredged from the lower half of Southwest Pass is carried to a disposal area just offshore of the jetties, while that from the upper half is placed in Head of Passes near the entrance to Pass a Loutre (Goodwin et al. 2000).

In less than 100 years, growth of nearly 600 km^2 of wetlands in inter-distributary bays occurred as a number of crevasses added ‘webbing’ to the birdsfoot between 1838 and the 1930s (Fig. 10). This burst of land-building was undoubtedly augmented by increased sediment supply as the Ohio River valley was deforested for agriculture, and the semi-arid grasslands in the Missouri River watershed came under the plough (Kesel et al. 1992, Meade and Moody 2010). Loss of water and sediment to the Atchafalaya distributary during this period was still relatively minor, estimated to have been less than 10 % (Humphreys and Abbot 1867; Fisk 1944; Mossa 1996).

Annual suspended sediment discharge estimated from occasional measurements at the mouths of the passes commonly exceeded 400 MT-y^{-1} through the dust bowl drought of the 1930s into the early 1950s (Holle 1951). The Blunt chart shows the mouths of each of the main passes of the birdsfoot as widening around mid-channel bars (Fig. 8) but does not include the Grand Pass, Main Pass and Baptiste Collette distributaries that developed after that survey from crevasses in 1839, 1862 and 1879, respectively (Fig. 10). These smaller passes became preferred navigation routes prior to the artificial deepening of South and Southwest Passes in the late 1800s because they experienced less shoaling (Goodwin et al. 2000).

Extension of PBD passes seaward across the original 2 to 3 m deep bar shoals accelerated once James B. Eads demonstrated from 1877 to 1879 at the mouth of South Pass that twin jetty systems could be used to narrow the entrance and increase outlet flow velocities to scour the bar to a 10 m depth without dredging (Cowdrey 1977). Since 1908, the USACE has adopted the same approach at Southwest Pass (Holle 1951; Cowdrey 1977) though nearly continuous dredging downstream of Venice has been required to achieve the authorized channel depth, which was increased from 12 to 14 m in 1987 (Goodwin et al. 2000).

Bars at the mouths of South and Southwest Passes advanced 10 km seaward between 1838 and 1973 (Gould 1970; Coleman 1981). Lindsay et al. (1984) determined that about half of the bar sand deposited over this interval was lost to deeper water through submarine slides. A tendency for failure and slumping on the offshore slope in the vicinity of PBD pass mouths results in frequent transfers of sediment offshore via low angle density flows (Coleman et al. 1983). This makes the delta front unstable, and has limited seaward extension of the passes in recent decades. Subaqueous mass movement events are known to be triggered when unconsolidated sediments are weakened by cyclic storm wave loading (Coleman and Prior 1978; Guidroz 2009), by tsunamis (Brink et al. 2009), and by accumulations of methane gas (Grozic 2003).

Seaward movement of the bars at the mouths of passes also loaded pro-delta deposits, 250 m thick in places (Törnqvist et al. 2008), causing dramatic uplift of mud diapirs, analogous to the salt domes, though on a far smaller scale. They were observed to rise quickly during flood events to became ephemeral islands known as “mudlumps” just offshore of the passes (Morgan 1951; Coleman 1981).

Mudlump formation ceased when bar extension slowed, but this dynamic environment has continued to challenge USACE efforts to maintain navigability and to build and repair rock jetties and dikes at the end of South and Southwest Pass for more than a century (Holle 1951; Cowdrey 1977). It has been a Sisyphean task, requiring placement of an average of 20 Kt-y^{-1} of rock to repair jetties and banks and to close crevasses on Southwest Pass alone (Sargent and Bottin 1989). South Pass was abandoned as a major navigation outlet in 1978, and has been infrequently dredged since to maintain a 2 m deep channel for small vessels. Pass a Loutre, once the main outlet, is not maintained at all, and has shoaled to less than 2 m deep in some reaches.

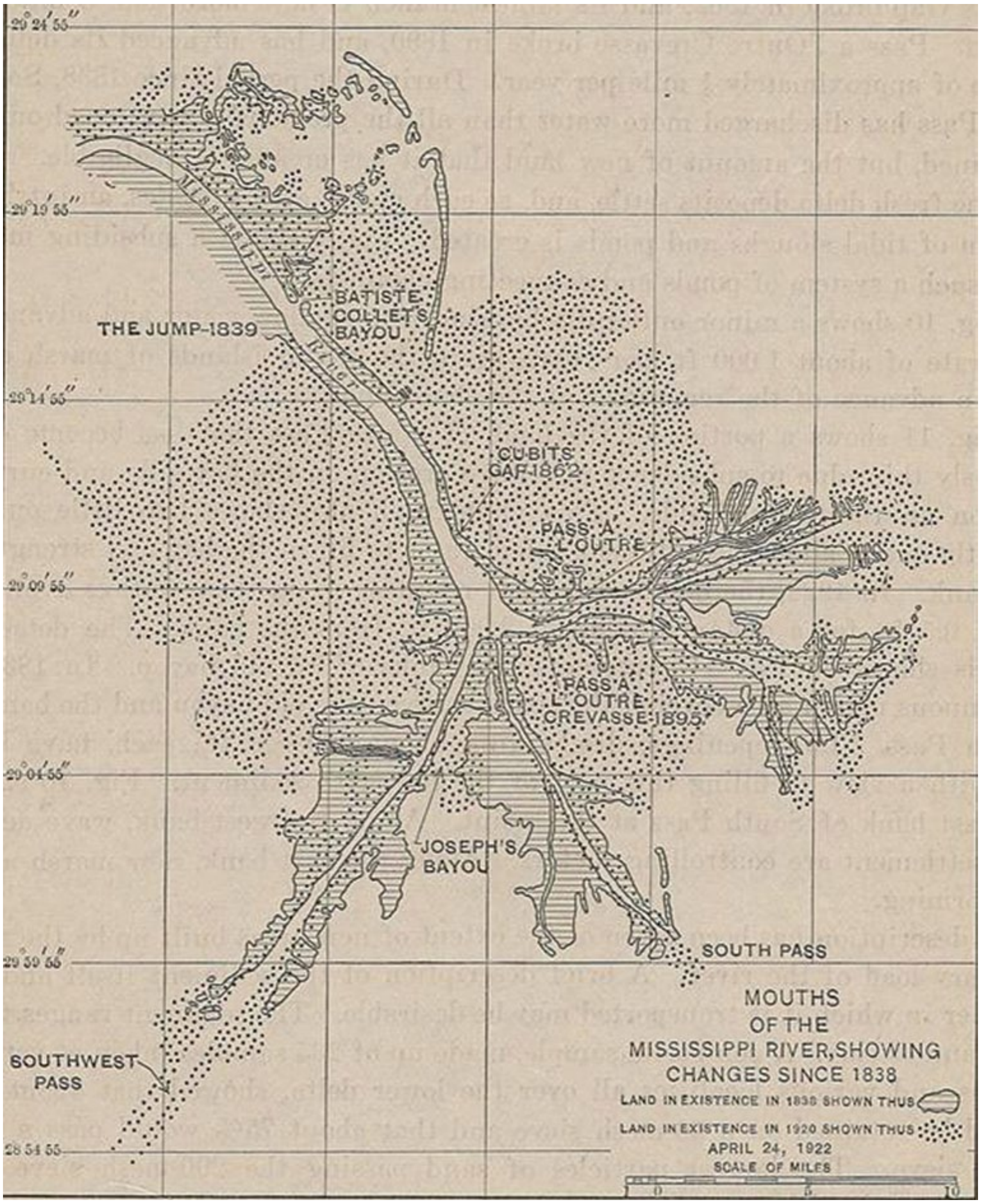


Fig. 10 USACE map of PBD showing land present in 1838 (horizontal lines) and as augmented by land building crevasses and by extension of the passes prior to 1920. (Source: Dent 1924)

Rotational slumping affects not only the inner shelf slope but also occurs within the existing PBD landmass where it helps explain the sudden loss of wetlands between 1956 and 1977 (Fig. 11). The eastern margin of the zone of wetland loss follows a linear contact corresponding to the axis of the Balize Loop (Gagliano et al. 2003). Coleman (1981) produced an isopach map showing the thickness of Recent deposits in the vicinity of the PBD (Fig. 12). It shows an asymmetric elongation of Recent deposition to the west that is associated with a depression in the Pleistocene surface. This is consistent with enhanced downslope sediment translation to the west toward the salt collapse basin at the head of Mississippi Canyon (Lowrie et al. 2004). Coleman (1981) also documents "peripheral faults and slumps" that are not confined to the shelf slope but extend up each of the passes of the birdsfoot to Head of Passes (Fig. 13). Down thrown movement on the seaward side of these faults appears to influence the locations of historic crevasses. On Southwest Pass, for example, preferred crevasse sites occur at Joseph (RK -7.4 BHP), Double (RK -16.1 BHP) and Burrwood (RK -22.7 BHP) Bayous, where the USACE has blocked them several times.

The USACE investigated hydraulics and sediment transport in the PBD as part of an evaluation of the West Bay Diversion project (Brown et al. 2009), an artificial crevasse created in 2003 at RK 7.8 under the Coastal Wetlands Planning, Protection and Restoration (CWPPRA) program. This project and the CWPPRA program will be discussed in more detail later. While the final report has not yet been released, results from the latest draft clearly show that the distribution

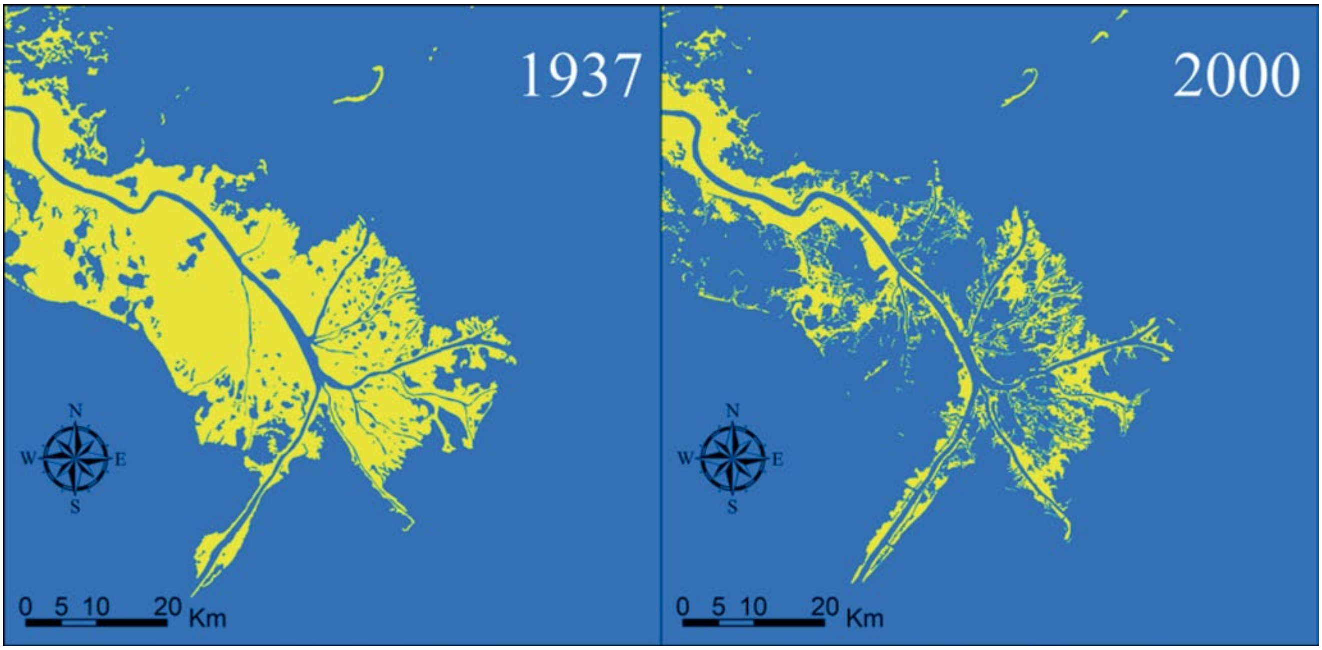
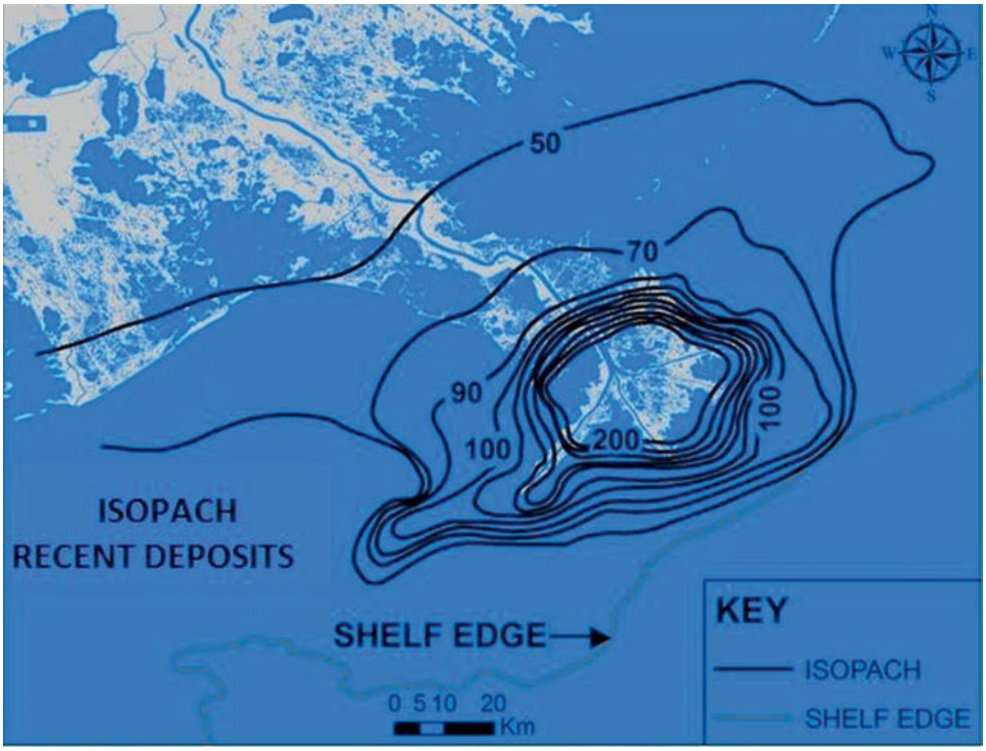


Fig. 11 Land-loss in the PBD since 1937 follows a linear contact east of the main LMMR course corresponding to Balize Loop faulting

Fig. 12 Isopach map showing thickness contours (m) of Recent deposits of the Birdsfoot Delta by Coleman (1981). Head of Mississippi Canyon shown by inland deflection of the shelf edge to the west of the PBD



of flow through the passes of the PBD has changed significantly since the 1960s (Table 1). Discharge through outlets upstream of Head of Passes (AHP) increased from 7 to 24 %, or at an annual rate of 0.35 %, relative to LMMR flow measured at Tarbert Landing (RK 510), while cumulative pass discharge below Head of Passes (BHP) has diminished at a similar fraction. Pass a Loutre has lost the most flow, more than 75 % of its 1960s discharge, while the percentage of flow through the main navigation channel in Southwest Pass has remained steady. In contrast, cumulative discharge through the Baptiste Collette and Grand Pass outlets upstream of the PBD near Venice has increased 250 % over the

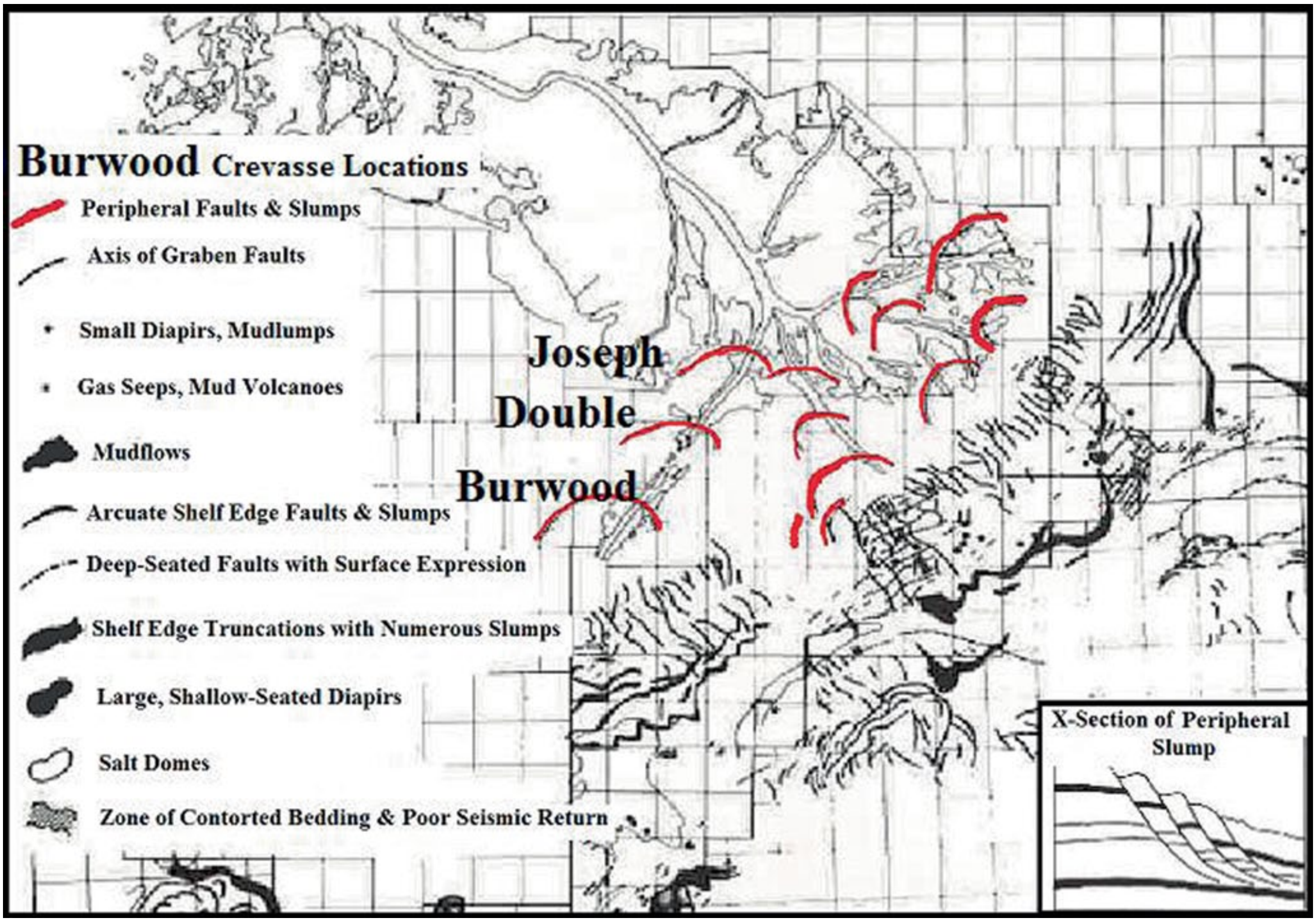


Fig. 13 Occurrence of features caused by sediment loading in the PBD showing peripheral slumping highlighted in red associated with each of the passes of the Birdsfoot. Modified from Coleman (1981)

same 49 year period, and now exceeds that of South Pass and Pass a Loutre combined.

In summary, the PBD is a geologically youthful feature, becoming subaerial only about 0.5 ka. It was just a skeleton of natural levees outlining the three main passes when discovered by European explorers in the 1500s, much as it is today. But the similarity of the current configuration to its earlier appearance belies the dynamism of the intervening years. Wetlands were rapidly built by a number of crevasses into inter-distributary bays over a 100 year period beginning in the early 1800s. About half of this new land was then lost between 1956 and 1977 (Couvillion et al. 2011). This sudden loss, from a geological perspective, is best explained by down thrown movement along active faults, caused by adjustment of underlying strata to continued sedimentary loading. Changes since 1977 have been minor, with loss offset artificially by placement of sediments dredged from the navigation channel (Goodwin et al. 2000). Still, the loss rate over the whole monitoring interval, from 1937 to the present (Fig. 11), is greater on a percentage basis than is found in any of the other MRD sub-deltas (Couvillion et al. 2011).

USACE Management of the LMMR

The foregoing discussion has shown that natural and man-made modifications on the LMMR over the past 300 years are intertwined in a way that is difficult to separate. Relatively low embankments or levees were built on the higher natural banks of the Mississippi River and its distributaries more or less coincident with the arrival of European settlers in the MRD. During the eighteenth and nineteenth centuries, the LMMR would frequently overtop its natural banks, however, and breach the levees built by landowners to flow through as many as 20 *crevasses* in a single year (Kesel 2003). These unplanned diversions carried freshwater and sediments into adjacent swamps and marshes, sometimes for years, before sealing off, with or without human assistance.

Major floods also reactivated senescent distributary channels to spread flood water and sediment well beyond the active PBD depocenter (Humphreys and Abbot 1867). Condrey and Hoffman (2014, this volume) cite reports by sixteenth and seventeenth century Spanish mariners of drink-

Table 1 Discharge through LMMR Outlets (See Fig. 6) as Percent of Tarbert Landing Discharge 1960–2010. (Brown et al. 2009)

Pass or Outlet	Location	1960	1970	1980	1990	2000	2009	%-y^{-1}
Baptiste Collette	RK 18.5	2.8	3.5	4.0	7.3	10.0	12.0	0.19
Grand Pass (Jump)	RK 17.5	3.3	4.5	5.5	7.0	10.0	10.5	0.15
West Bay Diversion	RK 7.8	0.0	0.0	0.0	0.0	0.0	0.7	0.12
Cubits Gap	RK 5	1.0	1.0	1.3	1.3	1.4	1.0	0.00
Southwest Pass	RK 0.0	27.0	32.0	32.0	32.0	35.0	35.0	0.16
South Pass	RK 0.0	14.0	14.0	13.0	13.0	12.0	11.0	−0.06
Pass a Loutre	RK 0.0	32.0	31.0	20.0	11.0	9.0	8.0	−0.50
Total AHP		7.1	9.0	10.8	15.6	21.4	24.2	0.35
Total BHP		73.0	77.0	65.0	56.0	56.0	54.0	−0.39
Total AHP and BHP		80.1	86.0	75.8	71.6	77.4	78.2	−0.04

able freshwater nourishing massive oyster reef complexes 170 km west of the PBD and extending more than 10 km offshore during seasonal LMMR flooding. But this changed quickly once steam powered pumps and earth moving equipment became more widely available to the river engineers.

Twentieth Century River Engineering

Most of the major engineering modifications to the Mississippi River that continue to affect the LMMR today began in the twentieth century. All intermittent outlets except the Atchafalaya River were severed from the main LMMR by plugs and levees before the end of the first decade. In response, the oysters that built the offshore reef complexes died off. The relict reefs left behind have now sunk below the waves. Reef complexes that thrived in most MRD tidal passes were removed to improve navigation and by a shell mining industry that flourished (Bouma 1975) prior to a state ban enacted in 1990 (Francis and Poirrier 1999). Cutting off the distribution of fluvial sediment was certainly a major factor in the 4,600 km^2 of land loss documented in the MRD since the 1930s, though not the only one, that contributed to the most rapid contraction of the deltaic land mass in the past 6 ka (Couvillion et al. 2011).

The USACE focused initially on improving the low discharge navigation channel, leaving flood control to the states (O'Neill 2006). The Corps was tasked by the US Congress after the great flood of 1927, however, to build 3,000 km of continuous, much higher levees along the Mississippi as part of the MR&T project. But many of the earliest interventions under the MR&T remained inland navigation improvements. For example, before the 1950s, the Mississippi was shortened more than 300 km by dredging of meander and chute cut-offs (Kesel 2003). In order to stabilize the new channel, the USACE then lined the banks with nearly 2,000 km of concrete revetments, including about 500 km on the LMMR, that curtailed lateral migration and reduced bank caving, once a major source of sediment carried by the LMMR. Countless dikes were built in the riverbed after 1955 to constrict discharge to the low flow channel. Dike fields have captured vast quantities of sand that would otherwise have reached the LMMR.

The connection to the Atchafalaya distributary at Old River (RK 512) was initially left open, however, while gated, overbank, emergency relief outlets were added first (1931) at the Bonnet Carre crevasse site upstream of New Orleans (RK 207), and 20 years later (1954) at Morganza (RK467), 140 km upriver from Baton Rouge (Fig. 1).

Old River Control Structures and Sediment Transport

Under MR&T, the river was permanently confined to a fraction of its original floodplain by levees and revetments that forestalled meandering (Kesel 2003). In the late 1950s, the USACE began constructing what became the Old River Control Structure complex (ORCS). Its purpose was to prevent the shorter and steeper Atchafalaya River distributary from 'pirating' the flow of the LMMR by limiting flux from the Mississippi to the Atchafalaya River (Fig. 14). ORCS was not part of the MR&T plan until Harold Fisk (1952), a professor at Louisiana State University, convinced the USACE that without ORCS the Atchafalaya was poised to avulsively capture the LMMR.

The first ORCS structure (Low Sill) was completed in 1962. The USACE chose to regulate discharge from the Mississippi to the Atchafalaya in all seasons to 30 % of the combined Red and Mississippi River "latitudinal" discharge. This criterion has not been modified for any significant period since, except briefly during the great floods of 1973 and 2011 to allow additional water into the Atchafalaya. During the three years (2008 to 2010) monitored by Allison et al. (2012a), when the 30 % rule was followed without exception, an average of 24 % of Mississippi River flow at Natchez was permitted into the Atchafalaya, while the remainder (76 %) stayed in the LMMR.

The Low Sill structure partially failed during the 1973 flood, when a large scour hole developed beneath it (McPhee 1987). An overbank structure was rushed into service while

Fig. 14 Current arrangement of channels, levees and water control structures in the Old River Control Structures (ORCS) complex, showing location of Tarbert Landing discharge range downstream of the three inflow channels leading to the Atchafalaya River. (modified from Reuss (2004)

a second massive deep sill structure (Auxiliary Structure) was completed in 1987 (Reuss 2004). Finally, as the head differential between the Mississippi and Atchafalaya increased, a hydroelectric plant was floated in and installed in 1991 (Sidney A. Murray Hydroelectric Station) at the upstream end of the ORCS complex (Fig. 14). This plant also serves as a flood control structure to make more precise flow regulation possible. The power plant passes the majority of flow on most days, while the USACE adjusts gates and sluices on its structures daily to meet the latitudinal objective, in effect freezing the bifurcation between parent and daughter channels.

Allison et al. (2012a) found that for the 2008, 2009 and 2010 water years, managing the ORCS in this way allowed 18 % of the upstream load of suspended sediment to pass from the Mississippi to the Atchafalaya. Suspended sand transfer from the Mississippi to the Atchafalaya was much lower, only 6 %, on average, for the 3 years studied, and 8 % during the major flood year of 2008 (Fig. 15).

Although a connection between the two rivers has existed for about 500 years, the Atchafalaya began to attract significant portions of water and suspended sediment from the Mississippi, as well as an unknown bed load component, little more than a century ago (Humphreys and Abbot 1867). The suspension of avulsive capture at Old River is a perturbation of the natural delta cycle to which the LMMR and Atchafalaya are still adjusting (Aslan et al. 2005; Meade and Moody 2010; Edmonds 2012).

During all but the most recent 50 years of the last 6 ka, the MRD experienced a lower eustatic sea level rise and greater provenance of river sediment than it does today. Blum and Roberts (2009) determined that annual storage of 230 to 290 MT-y^{-1} was required to account for the material found in all Holocene deltas. Since only about 60 % of sediment is trapped in modern deltas, on average, they calculated an actual Holocene delivery rate of 400 to 500 MT per year. Such an estimate matches scattered LMMR suspended sediment discharge estimates made prior to the late 1950s (Humphreys and Abbot 1867; Holle 1951; Thorne et al. 2008).

The Missouri River is the main source of sediment to the Mississippi, while the Ohio provides the majority of the water. Closure of dams on the Missouri between 1937 and 1967, but particularly those built in the early 1950s, along with improvements in soil conservation throughout tributary watersheds, cut the suspended sediment flux reaching Louisiana measured at Tarbert Landing (RK 510) by more than 50 % in a single decade (Kesel et al. 1992; Kesel 2003; Thorne et al. 2008; Meade and Moody 2010; Blum and Roberts 2012). The rate of decrease in total annual suspended sediment slowed after ORCS installation, but has dropped an additional 15 %, from 160 to 135 MT-y^{-1} over the past 60 years (Thorne et al. 2008), without a trend in LMMR discharge (Allison et al. 2012a).

The division of annual suspended sediment load into coarse (medium to fine sand) and mud (silt and clay) fractions has not been reliably established for the LMMR prior to 1959. Thorne et al. (2008) found, however, a statistically significant reduction measured at Tarbert Landing (RK510) between 1959 and 2008 that occurred in the suspended mud rather than the sand fraction. Allison et al. (2012b) have shown that silt and clay still accounts for more than half of the total annual suspended sediment load passing the Atchafalaya take-off, but the mud contribution was far greater before it was trapped in reservoirs upstream. LMMR sus-

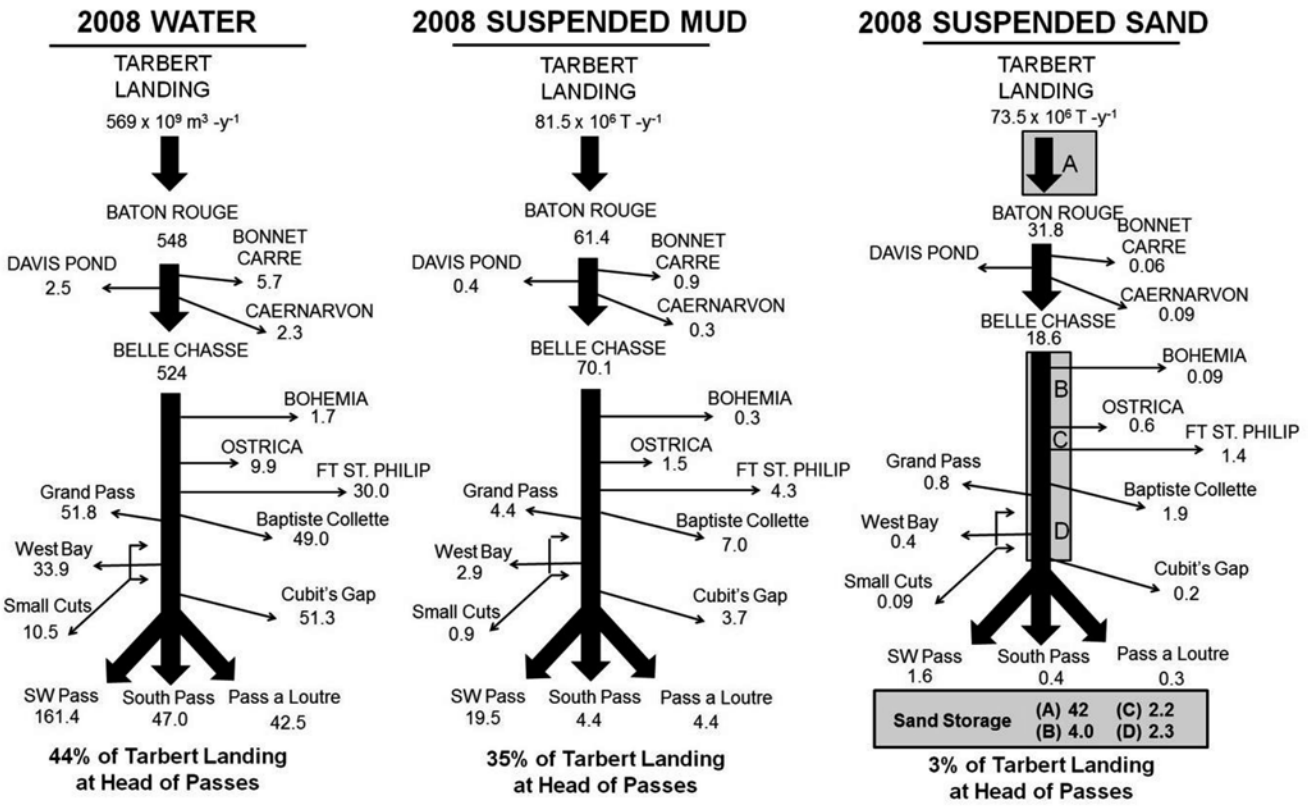


Fig. 15 Cumulative flux of water (Bm^3-y^{-1}), suspended mud (MT-y^{-1}) and sand (MT-y^{-1}) from Tarbert Landing (RK 510) to LMMR mouths during 2008 water year when Bonnet Carre, Davis Pond, Caernarvon and West Bay diversions were operated. (modified from Allison et al. 2012b)

pended sand flux over the ORCS era has varied from near zero to 80 MT-y^{-1} at Tarbert Landing, with an average of 40 MT-y^{-1}. During the significant 2008 flood year, 74 MT of suspended sand bypassed the ORCS to enter the LMMR (Fig. 15). Suspended sand flux into the LMMR, in contrast to the reduction for suspended silt and clay, does not appear to have diminished over the past 60 years (Thorne et al. 2008). This is likely because sand is being eroded out of the Missouri River channel immediately downstream of the dams and continues to be carried into the Mississippi during high flows (Rogers 2011).

Allison et al. (2012b) created a mass-balance budget and estimated that more than 40 % of the suspended sand that bypassed the ORCS to enter the LMMR was deposited across the relatively large floodplain retained between MR&T levees upstream of Baton Rouge (Fig. 15). Another 10 % was stored in the channel between Belle Chasse and the birdsfoot, while only 6 %, on average, of the sand that bypassed the ORCS in 2008, 2009 and 2010 reached the Gulf through the PBD. This is only 66 % of the sand that reached Atchafalaya Bay in those years (Allison et al. 2012b). So the shorter Atchafalaya daughter channel, though carrying less than half the main stem discharge, is today a far more efficient conveyor of sand to the coast than the LMMR.

Navigation Dredging

The controlling depth for the deep-draft navigation channel was increased in the early 1960s from 11 to 12 m in the reach from New Orleans through Baton Rouge (Brown et al. 2009). Similarly, Baptiste Collette and Grand Pass near Venice were dredged to increase the controlling depth to 4.25 m in those channels in the late 1970s (Fig. 5).

Another increase in LMMR navigation depth to its current 14 m from the Gulf to Baton Rouge was authorized in the late 1980s. Material dredged from the channel in the PBD for this deepening was used to restore deteriorated bank lines downstream of Venice, and to fill newly constructed foreshore dikes along Southwest Pass (Goodwin et al. 2000).

Dredging of the naturally deep LMMR is required only near the mouth downstream of Venice, and at 13 “crossings” between New Orleans and Baton Rouge where the channel shifts sides from bend to bend. These shoals become an impediment for deep-draft vessels as the annual floods diminish. Unlike maintenance at the river mouth, sand is not removed from the river at the crossings, but is simply pumped into adjacent deeper bendways where it is swept downstream during the next flood.

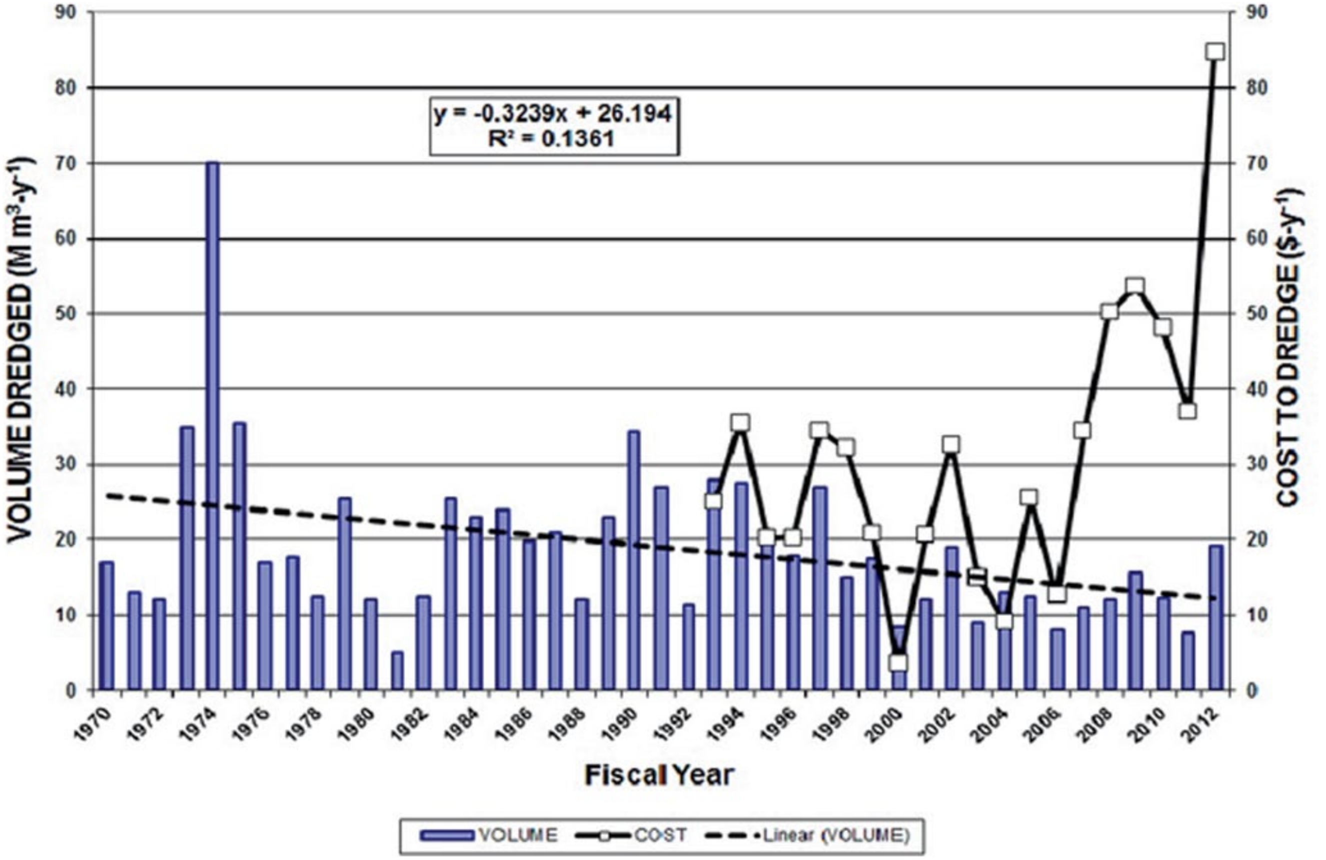


Fig. 16 Annual dredging volume for Southwest Pass 1970 to 2012 (USACE Navigation Data Center website accessed in 2013), with annual cost

Dredging in the PBD has averaged nearly 15 $\mathrm{Mm}^3\text{-y}^{-1}$ since the 1970s (Fig. 16). When combined with the expense of annually clearing the channel crossings, the overall cost of dredging the LMMR has exceeded $ 100 million in four of the past 6 years. The volume of fine sand and silt tabulated by the USACE as dredged each year downstream of Venice is not escalating, rather, it appears to have diminished by half since the 1990s. But the cost to dredge each cubic yard has more than doubled in the past decade with the rising price of diesel fuel (USACE Navigation Data Center website accessed in 2013).

The USACE (2012a) has suggested that the bank nourishment project carried out in the PBD in the early 1990s, the last time the authorized depth was increased, reduced flow escaping laterally from the Southwest Pass navigation channel. This is believed to have increased the velocity enough to account for the recent reduction in the volume dredged. This may not be the whole answer, however, because the noticeable decline in dredging volume did not occur until a decade later (Fig. 16). With recent high discharges in 2008 and 2011, dredging volumes have increased somewhat, but do not rival volumes reported in the early 1970s.

LMMR Channel Response to Engineered Modifications

As part of the West Bay study, the (Brown et al. 2009) conducted a detailed change analysis for the LMMR downstream of Belle Chasse (RK 120 to RK 5), that for the first time put the USACE decadal surveys on a common NAVD88 datum. This 140 km stretch was divided into 15 reaches of varying length (Fig. 17). In reaches 1 through 8, the navigation channel has never required dredging. Reach 9 has been dredged intermittently only in the past decade, while Reaches 10 through 15 have required annual dredging since at least the 1970s. When the change between the 1962 and 2004 surveys was plotted by decade for the upstream 100 km where dredging does not occur (Reaches 1 through 9), it can be seen that the LMMR channel below Belle Chasse has changed from net erosional to aggradational (Fig. 18). While the cause is not known, the deepening trend observed prior to the 1984 to 1992 interval could reflect the intense artificial levee and revetment building that took place during construction of the MR&T improvements. Sand began accumulating on lateral meander bars downstream of New Orleans sometime between 1984 and 1992. This is consis-

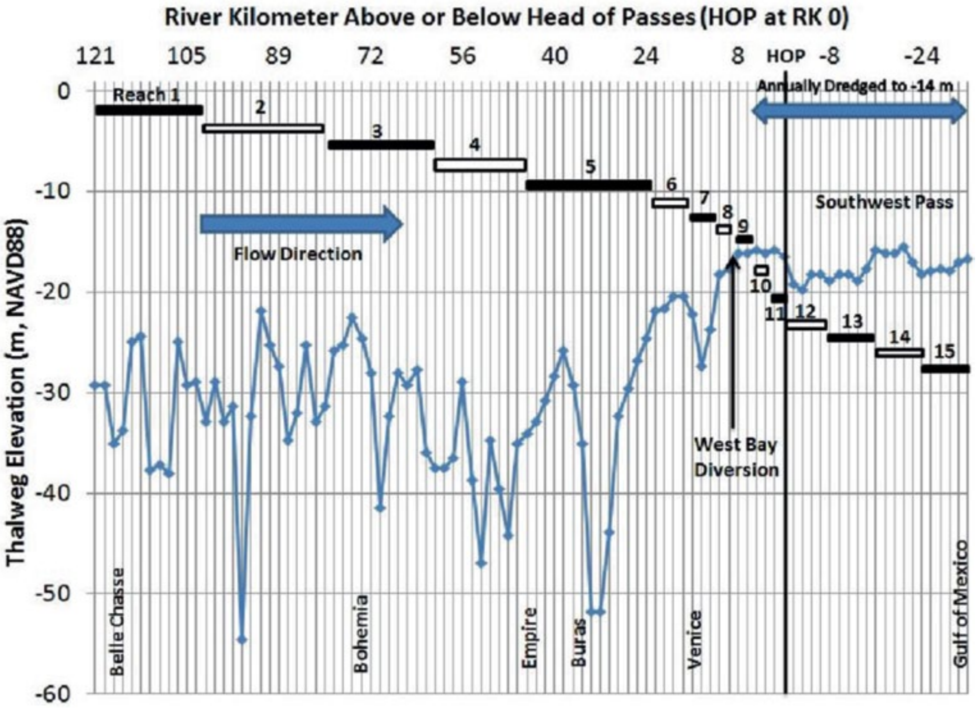


Fig. 17 LMMR 2004 thalweg plot showing USACE numbered study reaches from Belle Chasse to Southwest Pass (Brown et al. 2009). Reaches 10 through 15 are dredged annually

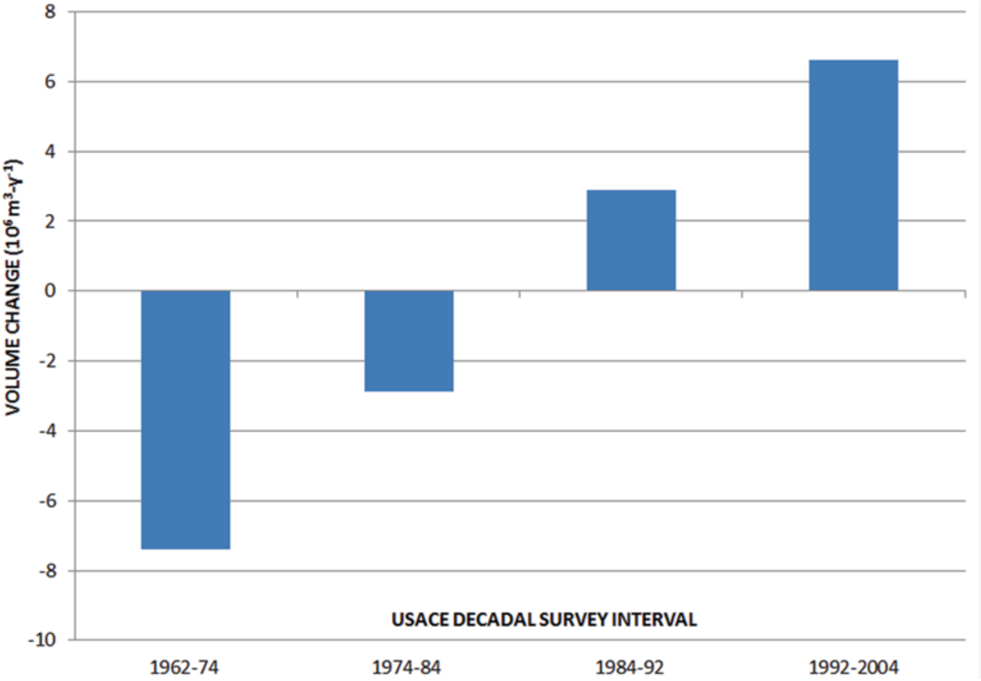
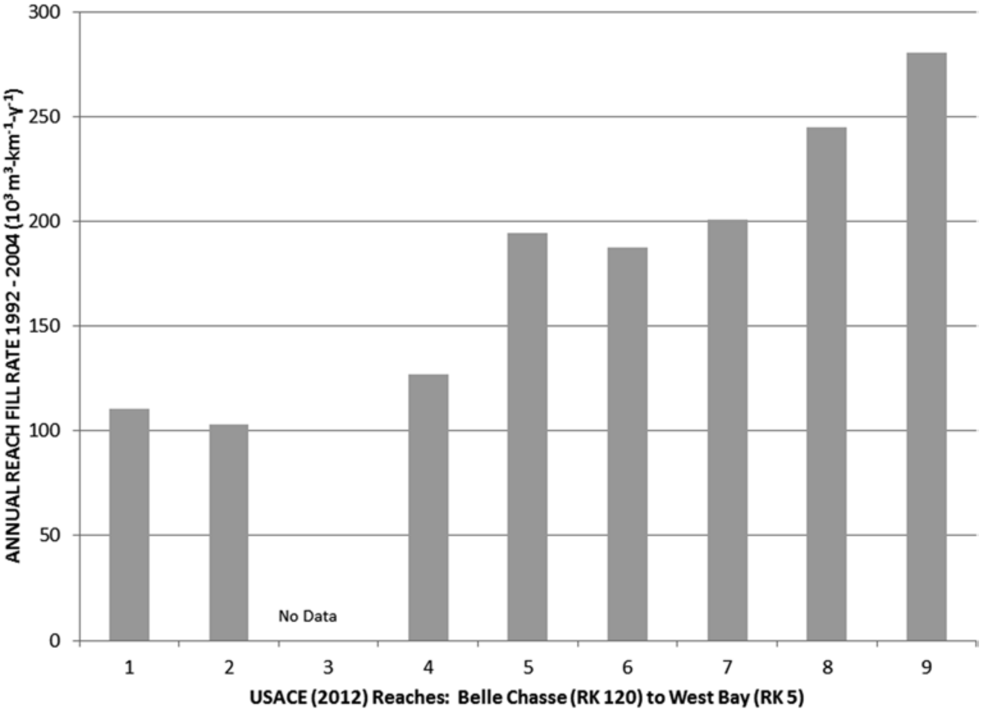


Fig. 18 Change in volume for aggregated undredged study reaches 1 through 9, Belle Chasse (RK 121) to West Bay Diversion (RK 7.6) (indicated in Fig. 17), showing net deposition (+) or erosion (-) in four decadal increments from 1962–2004, normalized by year. (Brown et al. 2009)

tent with observations made by the USACE after the then record 1973 flood (Noble 1976). More detail is available on the annual rate of fill between 1992 and 2004– the last interval for which data is available (Fig. 19). Deposition increased in the downstream direction, so that the volume of annual deposition per kilometer in Reach 9 below Venice is almost 3 times that in Reach 1 at Belle Chasse.

Clearly, the hydraulics of the LMMR has changed. It appears that engineered efforts to stabilize the channel with levees and revetments initially increased velocity during high flow downstream of New Orleans, causing deepening into the birdsfoot. This was a short-term response, however, that has since reversed. For the last decade of the 20th, and the first of the twenty-first century, the zone of net sand

Fig. 19 Rate of fill in USACE (2012) undredged study reaches between Belle Chasse and the West Bay Diversion from 1992 to 2004, normalized by km and year. See Fig. 18 for reach locations



deposition has been moving upstream. Reach 9, which historically was not dredged, will soon require annual maintenance (Fig. 19). A flattening of the LMMR high discharge water surface slope between New Orleans and the Gulf due to relative sea level rise and loss of flow has reduced the competence of the LMMR to convey sand through the PBD. Given that the hopper dredges operating in the PBD navigation channel preferentially collect sand and not the muddy sediments that increasingly make up the bed, the decrease in dredged sediment volume reported for Southwest Pass by the USACE between 1998 and 2008 is consistent with diminished conveyance of sand this far downstream (Fig. 15).

Land-Loss and Restoration in the Mississippi River Delta

Engineering of the LMMR to limit flooding of farms and communities, and to facilitate river navigation, certainly accelerated the deterioration of the MRD in a way that was not widely understood until the advent of aerial mapping and computer-aided change detection technology (Gagliano et al. 1981). But change mapping also brought to public attention the degree of cumulative wetland destruction and hydrologic disruption caused by dredging of an estimated 20,000 km of canals for oil and gas exploration and development in the MRD (Turner 1997). The rate of wetland destruction caused by canal dredging has dropped since adoption of a federally approved Coastal Zone Management program in the 1980s and, importantly, the now routine application of directional drilling technology. But wetland loss attributable to the legacy of earlier hydrologic disruption within the MRD continues, and is an important consideration for restoration.

Morton et al. (2005) showed that subsurface fluid withdrawal and reservoir depressurization associated with oil and gas had also enhanced subsidence and submergence of MRD wetlands, at least on a local scale. Morton and Bernier (2010) and Kolker et al. (2011) have found that this component of MRD subsidence appears to have diminished in recent years as shallow oil and gas fields have been abandoned and regulations were adopted to require reinjection of water and brine.

A rush to develop oil and gas resources on the continental shelf and provide deeper-draft marine access to ports and fabrication yards in the interior of the MRD also led the USACE in the 1960s to build large navigation channels that longitudinally bisect inter-distributary estuaries. The Mississippi River Gulf Outlet (MRGO), Barataria Waterway and the Houma Navigation Channel provide deep, hydraulically efficient pathways for higher salinity waters to move inland from the GOM. Large tracts of interior freshwater swamps and marshes were lost to open water in the vicinity of these canals, while they also increased the threat to delta communities from hurricane surge (Shaffer et al. 2009). The MRGO is the largest and deepest of these channels, connecting New Orleans to the GOM east of the city. It was de-authorized as a federal navigation project in 2007 and plugged in 2009 when it was implicated in the flooding of the city in 2005 during Hurricane Katrina (van Heerden et al. 2007; Freudenburg et al. 2009). The remaining shallower draft federal navigation channels remain in operation and continue to cause wetland degradation and loss.

As scientists studied the pervasive conversion of MRD wetlands to open water, it became apparent that regulatory restrictions alone could not save Louisiana's coastal swamps and marshes or reverse the loss. This led in 1989 and 1990 to coordinated passage of State and federal legislation establishing a cost-sharing partnership for design and construction of projects to rebuild or sustain coastal wetlands (Boesch et al. 1994). The state-federal task force established under the Coastal Wetland Planning, Protection and Restoration Act of 1990 (CWPPRA) has built more than 100 projects over the past two decades that have protected or restored some 440 km^2 of coastal wetlands at a cost of approximately $ 1 billion (Louisiana Coastal Wetlands Conservation and Restoration Task Force 2010). During this same period, however, persistent coastal land loss in Louisiana amounted to 1,355 km^2, indicating that the CWPPRA effort, which did not include large river diversions, was not of sufficient scale to save the MRD (Couvillion et al. 2011).

After the devastation caused by hurricanes Katrina and Rita a month apart in 2005, Louisiana's political leaders joined the science community in recognizing that a better focused and funded campaign was needed to fully employ the untapped land building potential of the Mississippi and Atchafalaya Rivers (Louisiana Coastal Protection and Restoration Authority 2012). Passage of the Water Resources Development Act of 2007, coupled with an augmented financial commitment from the State, initiated a new phase in the fight to protect coastal communities from hurricane surge and restore the MRD. Wetland restoration became popularly regarded as an integral part of a "multiple lines of defense" approach to reducing storm risk that also included better levees and elevating buildings (Lopez and Snider 2008). As an element in this campaign, the state has pressed the US Congress to modify the MR&T project to incorporate LMMR diversions of river water and sediments into the disappearing wetlands (Louisiana Coastal Protection and Restoration Authority 2007; WRDA 2007; Louisiana Coastal Protection and Restoration Authority 2012).

Few CWPPRA restoration projects were constructed in the PBD because the high subsidence rate there was expected to make lasting wetland restoration difficult. Certainly, the PBD history of wetland building and loss over the past century supports this view, and the 2012 State Plan does not propose any restoration work in the PBD other than what the USACE is doing now with a portion of the sand they remove annually from the navigation channel (Louisiana Coastal Protection and Restoration Authority 2012). In 2003, however, the USACE received CWPPRA funding to build an artificial crevasse, the West Bay Sediment Diversion, through the west bank of the Mississippi at RK 7.6 just upstream of the Cubit's Gap crevasse (Fig. 5).

Between 2004 and 2009, no land emerged above the water surface in West Bay as subsidence and loss of material attributed to Hurricane Katrina (August 29, 2005) and other storms offset deposition (Bentley and Andrus, 2007). A cut and fill analysis by Barras et al. (2009) compared bathymetric surveys from 2003 and 2009 and found a net loss of 11.3×10^6 m^3 of sediment volume within the West Bay basin. In contrast, after the record 2011 flood, a similar cut and fill analysis comparing 2009 with a 2011 Mississippi River post-flood survey (Kemp et al. 2012) found a net accretion of 2.3×10^6 m^3 of fine sand over 4 km^2 in the upper part of West Bay (Fig. 20).

Deep- and Shallow-Draft Navigation on the LMMR

At one time, waterborne transport was almost the only way to get raw commodities and manufactured goods in and out of North America. Today, in terms of value, this mode has more competition from land and air transport, but the maritime gateways still accounted for about 50 %, or $ 1 trillion in US imports and exports in 2008 and 2009, despite the global economic slowdown (Bureau of Transportation Statistics 2011).

Terminals and other public and private cargo handling facilities on the LMMR accessible to ocean-going ("blue water") vessels in Louisiana are organized into entities that are separately reported, including the Ports of Plaquemines, South Louisiana, Saint Bernard, New Orleans and Baton Rouge, that are spread out along 378 km above Head of Passes. They are called on by vessels drawing up to, and in some cases slightly more than, the 14 m minimum draft maintained in Southwest Pass. Once a ship passes through the PBD, however, the bottom drops away and the river channel is naturally between 30 and 60 m deep in most locations (Fig. 17). Each port includes terminals specialized for different types of trade, but all ships must enter and leave through the same dredged Southwest Pass channel across the Mississippi River bar, and so, for this analysis, may be considered one gateway that handles more than 400 Mt of cargo annually (Fig. 21). In terms of tonnage, the LMMR eclipses all other US ports, and ranks among the most important harbors in the world, rivaling Rotterdam and Singapore, if not the super ports of China (Geohive 2012).

Any vessel carrying liquid cargos is a tanker, but ships transporting dry goods are divided into 'bulk' and 'break-bulk' ships. Break-bulk items are packaged manufactured goods, while bulk cargoes like grain or coal are typically transported unpackaged in holds within the hull. Since the mid-1960s the practice of transporting break-bulk items in metal containers with standard dimensions and volumes given in 'Twenty-Foot Equivalent Units' (TEUs) has grown exponentially. One TEU is 6 m long, 2.4 m wide and 2.4 m tall. They are made to

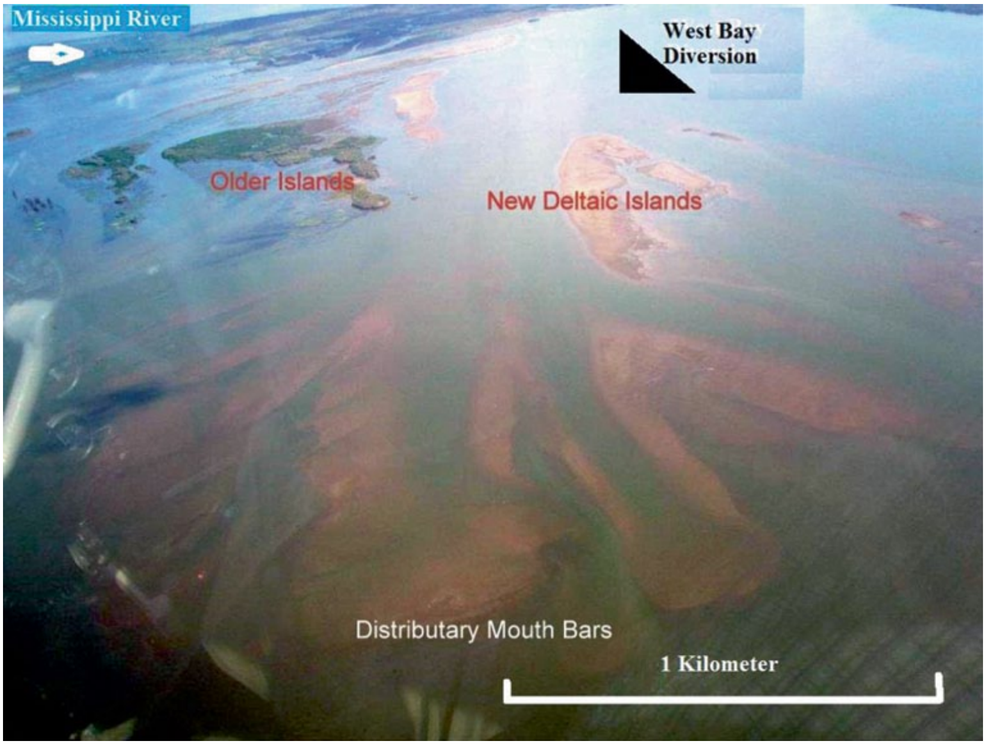


Fig. 20 Oblique aerial view September 14, 2011 from southwest of exposed and submerged deltaic islands in West Bay. Diversion is just out of view on top right. Photo by C. Nelson

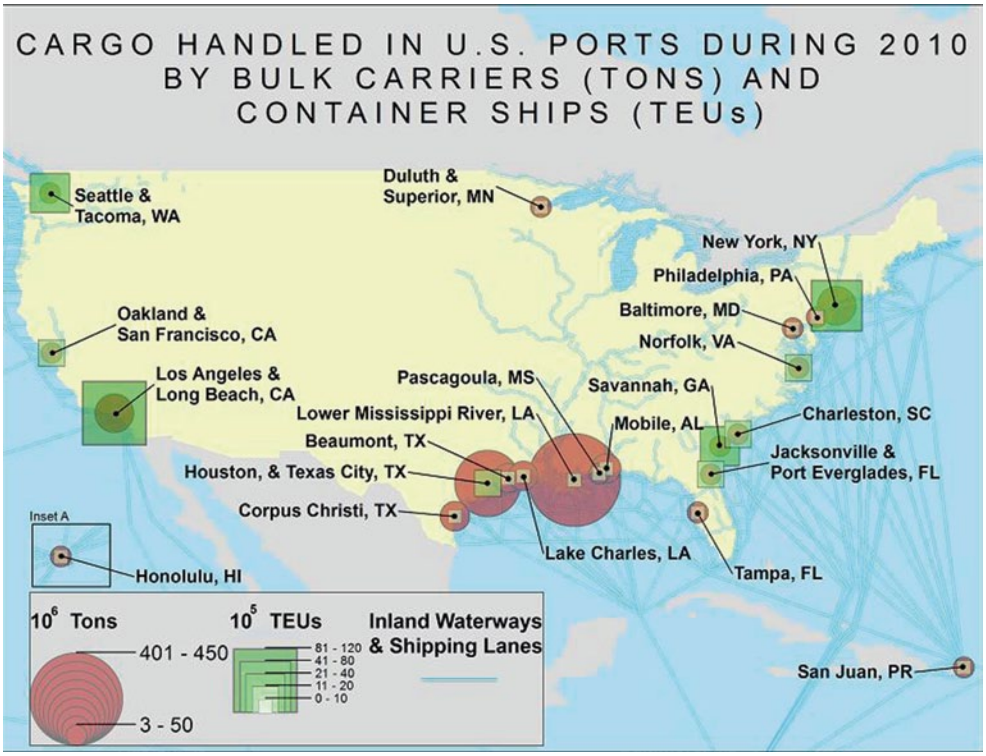


Fig. 21 Primary US ports showing relative importance with respect to bulk tonnage and container traffic with sea lands and inland waterways shown. (Geohive 2012)

be easily stacked and loaded onto trucks or specialized train cars, and purpose-built 'container ships.'

Worldwide, almost 90% of break-bulk cargo is transported today in containers. On a per ton basis, the value of containerized cargoes far exceeds that transported by bulk carriers. As a result, U.S. ports handling high volumes of containerized cargoes, like Los Angeles-Long Beach and Seattle-Tacoma on the Pacific coast, and New York-New

Fig. 22 A 73 barge 'tow' bound upstream near New Orleans.

Jersey and Savannah on the Atlantic seaboard are responsible for higher percentages of the total value of waterborne foreign trade than ports of the Lower Mississippi River or GOM generally (Fig. 21).

The Port of New Orleans, like many others around the U.S., has invested in facilities to handle both containerized and bulk cargoes, but only LMMR ports are uniquely connected to the most extensive inland waterway system in the world. The 15,000 km of navigable channels maintained to a draft of three meters by the USACE in the Mississippi, Ohio, Tennessee, Missouri, Arkansas and Red River valleys are used for barge transport of bulk commodities (Fig. 21). Conversely, the container ports of Los Angeles-Long Beach and Houston do not have inland waterway access, but are connected to transcontinental rail lines and interstate highways and have large, local markets for imported Asian consumer goods. Gulf ports from Mobile west to Corpus Christi are the principal U.S. ports for export of coal, petro-chemicals and agricultural products. They are also gateways for import of steel and raw materials used to manufacture petro-chemicals and fertilizer, commodities critical to the U.S. economy.

Deep-draft ports of the LMMR handle more than 60% of all grain and soybean exports from the Midwest, because massive 'tows' of more than 50 barges, each 61 m long and 11 m wide, can be pushed by a single high-powered 'towboat' round-trip from St. Louis to New Orleans without being broken up for multiple 'trips' through the relatively small lock chambers that interrupt artificial waterways (Fig. 22). Locks along the Gulf Intracoastal Water Way (GIWW), for example, which connects Gulf coast ports from Florida to Texas, cannot accommodate tow packages of more than 8 barges. Because long-distance waterborne transport on the Mississippi River and its tributaries is energy efficient relative to other transport modes, low shipping costs provide a global competitive advantage to Midwest producers of corn, soybeans, and a variety of other cereal grains (Marathon et al. 2006).

During the record low Mississippi discharge in the summer, fall and winter of 2012, barge transport was interrupted for days and light loading was required for months. Some smaller inland Mississippi River ports and terminals became inaccessible. In November, a consortium of organizations representing the shallow-draft ('brown water') Mississippi River operators called on the U.S. President to issue a federal emergency declaration directing the USACE to release water from Missouri River reservoirs sufficient to sustain commercial navigation, noting that transport of $ 2.3 billion in agricultural products, $ 1.8 billion in chemical products, $ 1.8 billion in crude oil and petroleum products and $ 0.2 billion in coal was in danger of being stranded upstream (American Waterways Operators 2012). It is unlikely, however, that were such a request agreed to, which it was not, that water retained in Missouri River reservoirs as 'discretional storage' would have been sufficient to alleviate the navigation problem on the Mississippi River (Rogers 2011).

One aspect that has received little national attention is the growing likelihood of economic dislocations caused by interruptions of shipping through Southwest Pass in the PBD (Rogers 2011). This is one of the world's busiest shipping channels, transited in 2009 by 2,000 vessels with drafts greater than 11 m, and by another 4,000 ships of lesser draft (USACE Navigation Data Center accessed in 2013).

Uncontrollable shoaling during high discharge at choke points in the PBD could reduce reliability of deep-draft vessel access to LMMR ports, or cause more serious loss of the navigation outlet in a significant crevasse event (Rogers 2011). From September 2010 through June 2011, pilots imposed draft restrictions on vessels transiting the river mouth for the first time (LaGrange 2011a, 2012). This was necessitated by rapidly forming bars that limited the controlling channel depth to 13 m and the width to less than half that authorized between the main navigation entrance at Southwest Pass (RK-22 BHP) and Venice (RK17.5). Due to the skill of the pilots, only the grounding of a single large vessel, a 274 m long tanker, occurred during this period. Fortunately, it was freed two days later without any leakage (Thompson 2011).

Table 2 Dimensions of Locks, Panamax & Post-Panamax Ships. (Source: Canal de Panama 2011)

Dimensions	Existing locks	Existing panamax	New locks	Post panamax
Length (m)	320.0	294.0	427.0	366.0
Beam (m)	33.5	32.3	55.0	49.0
Freshwater draft (m)	12.6	12.0	18.3	15.2
Containers (TEU)		5,000		13,000

Current USACE practice has devolved to require 'emergency' appropriations from the U.S. Congress almost every year to maintain the channel through the PBD. The 2011 fiscal year appropriation of $ 63 million, for example, was known to be inadequate at the time it was made. Annual expenditures in the USACE New Orleans District had been at or above $ 100 million for four of the previous 6 years. In this case, the USACE required an additional $ 100 million to deal with effects of the record 2011 flood. If the navigation channel depth through the PBD becomes less reliable, vessels will light load in the short-term, and bypass the LMMR in the long-term. Alternatively, if the channel cannot be maintained at the authorized width and this leads to more groundings or collisions, then traffic in both directions may be suspended for weeks. Loss of the channel altogether by a crevasse or geologic slumping event in the PBD during high discharge is another possibility that could interrupt vessel operations, perhaps for months (Rogers 2011).

An important reason to acknowledge the inevitable geologic changes at the mouth of the River is to accelerate planning for alternatives to increased dredging. One option is to remove sediment from the main channel by constructing sediment-rich diversions upstream, and to arrange for deposition in shallow wetland building sites beyond the flood control levees and developed LMMR banks. If it can be shown that water passing New Orleans during floods is no longer effective in scouring the navigation entrance, then an opportunity opens up to use the LMMR and the sediment it carries more extensively for delta restoration. It also becomes possible to envision a Mississippi River navigation entrance that could be reliably maintained to −15 or −17 m at the authorized width with less dredging. This will become a critical economic issue when the larger 'New' or 'Post' Panamax container ships and bulk carriers arrive in the Gulf in 2014 (LaGrange 2011b).

A new lane for the Panama Canal is currently being built in a $ 5.25 billion project that is on schedule for completion in 2014. The canal will then be able to handle wider and longer ships that draft more water than Panamax ships of today (Table 2). Global economic forces will continue to drive the maritime industry toward vessels sized to just fit through lock systems on key commercial routes around the world. So, a next generation of Post-Panamax ships just able to pass through the new Panama lane is already under construction or in sea trials. Each of these ships will be capable of carrying almost three times the cargo of current Panamax vessels.

Several east coast U.S. ports, including those in New York/New Jersey, Norfolk/Newport News, Baltimore, Charleston, Savannah and Miami are undergoing major upgrades both to accommodate post-Panamax ships drawing 15 m, and to provide longer berths and new cargo handling equipment able to reach across the wider beams. Currently, no U.S. GOM port will accommodate ships of more than 14 m draft, though Houston expects to have this capacity in 2014. While the Port of New Orleans is creating longer berthing facilities for post-Panamax ships, no funding has been identified to deepen the navigation entrance beyond 14 m, though Congress authorized it to 17 m in 1987 (LaGrange 2011b). Thus, unless a deeper draft entrance becomes feasible without substantially driving up dredging costs, fully loaded post-Panamax ships will be unable to enter the LMMR.

1973 and 2011 Floods and 2012 Low Flow

In 2011, the Mississippi River below Cairo, Illinois (RK 1531), reached a higher discharge than previously recorded before or after the onset of the MR&T project. Peak discharge at Natchez of 63,000 m^3-y^{-1} was 10% greater than that estimated for 1927 (USACE Mississippi River Commission 2011; Barry 1997). Maximum Mississippi discharge entering the LMMR in 2011 was 84% of MR&T design flow (Fig. 2). Flows past Baton Rouge and New Orleans were at 94 and 88%, respectively, of design maxima (Fig. 23). Maximum 2011 discharges at Old River, Morganza and Bonnet Carre diversions were at 108, 35 and 126% of MR&T plan maxima, while peak 2011 discharge through the Atchafalaya River, 23,333 m^3-s^{-1}, was at only 55% of design because the Red River contributed only 2,000 m^3-s^{-1}, just 20% of the discharge allocated in the MR&T plan.

The floods of 1973 and 2011 are the only ones in which both MR&T LMMR floodways at Morganza and Bonnet Carre were operated simultaneously, and so can be directly compared (Fig. 23). The 1973 peak discharge upstream of the LMMR at Natchez (RK 584) was 57,320 m^3-s^{-1} compared to a 2011 maximum of 63,100 m^3-s^{-1} (USACE Mississippi River Commission 2011). Specific gauge stage-discharge curves were developed for the two floods at Red River Landing (RK 486), Baton Rouge (RK 367)

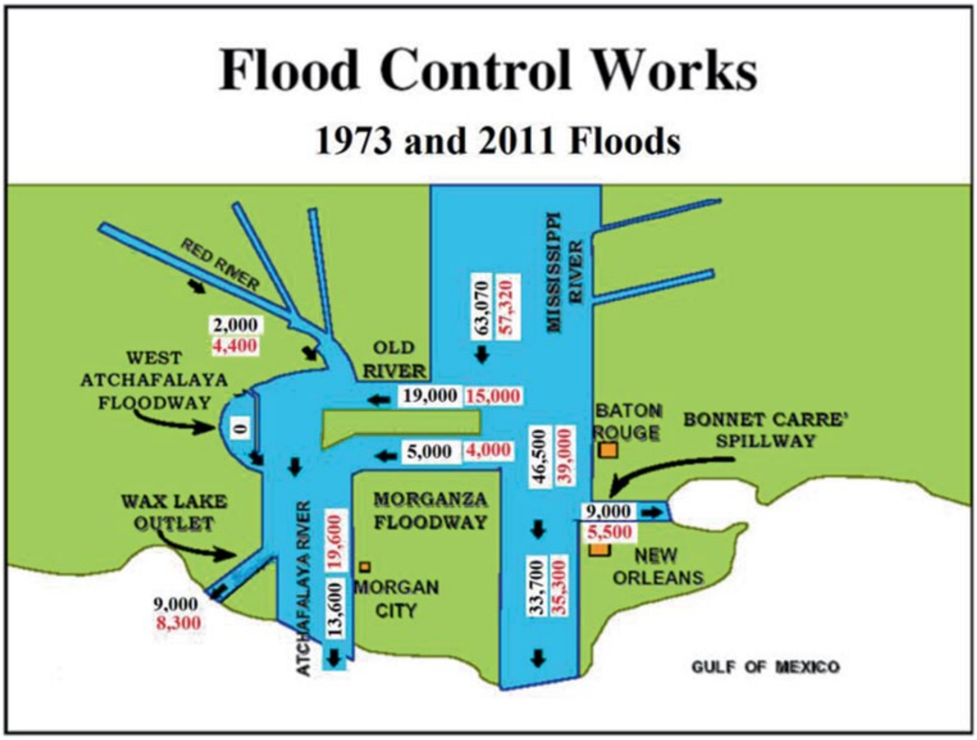


Fig. 23 Comparison of peak discharge (m^3-s^{-1}) at MR&T control points in floods of 1973 (*red*) and 2011 (*black*). (USACE Mississippi River Commission 2011)

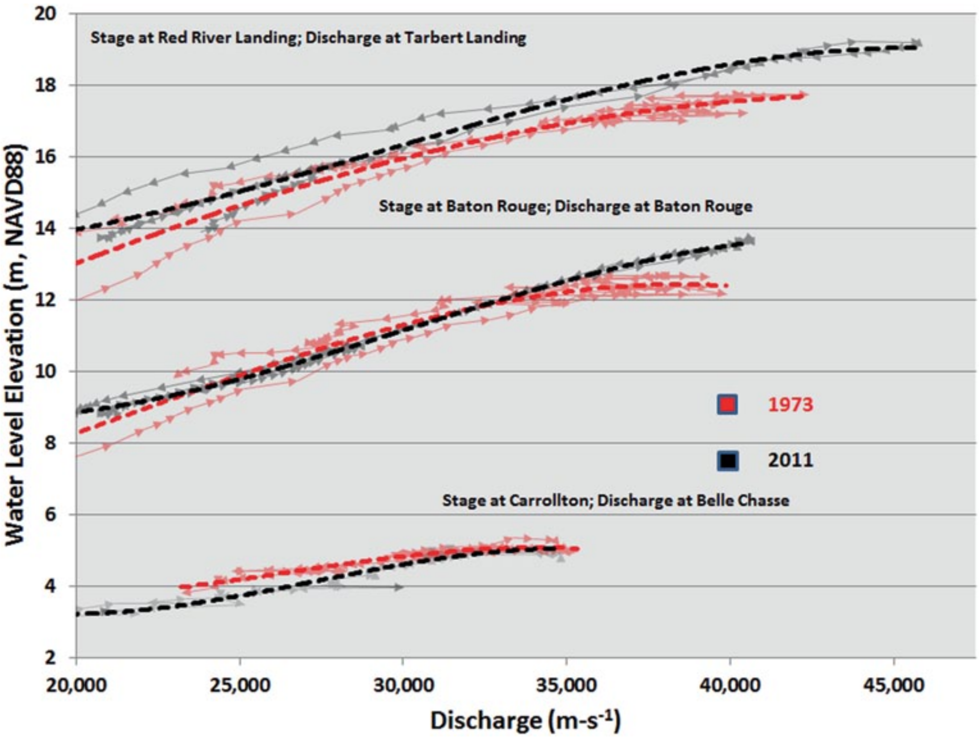


Fig. 24 Stage-Discharge relationships at Tarbert Landing (RK 510), Baton Rouge (RK 367) and Belle Chasse (RK 120) for 1973 (*red*) and 2011 (*black*) floods. Convergence of elevation for both floods around 5 m at Belle Chasse is caused by opening of Bonnet Carre Floodway (RK 206) upstream

and Carrollton (RK166, New Orleans) (Fig. 24). Trendlines were determined for each of the flood years at each gauge location.

The Tarbert discharge range is about 20 km upstream of the Red River Landing gauge and the Belle Chasse (RK 120) range is about 40 km downstream of the Carrollton gauge in New Orleans, but no water enters or leaves the river between associated gauges and discharge ranges. The stage-discharge plots exhibit hysteresis, meaning that the water level during the discharge increase is generally lower than it is for the same discharge on the falling leg of the hydrograph (Fig. 24). This is typical for the Mississippi River in part because the

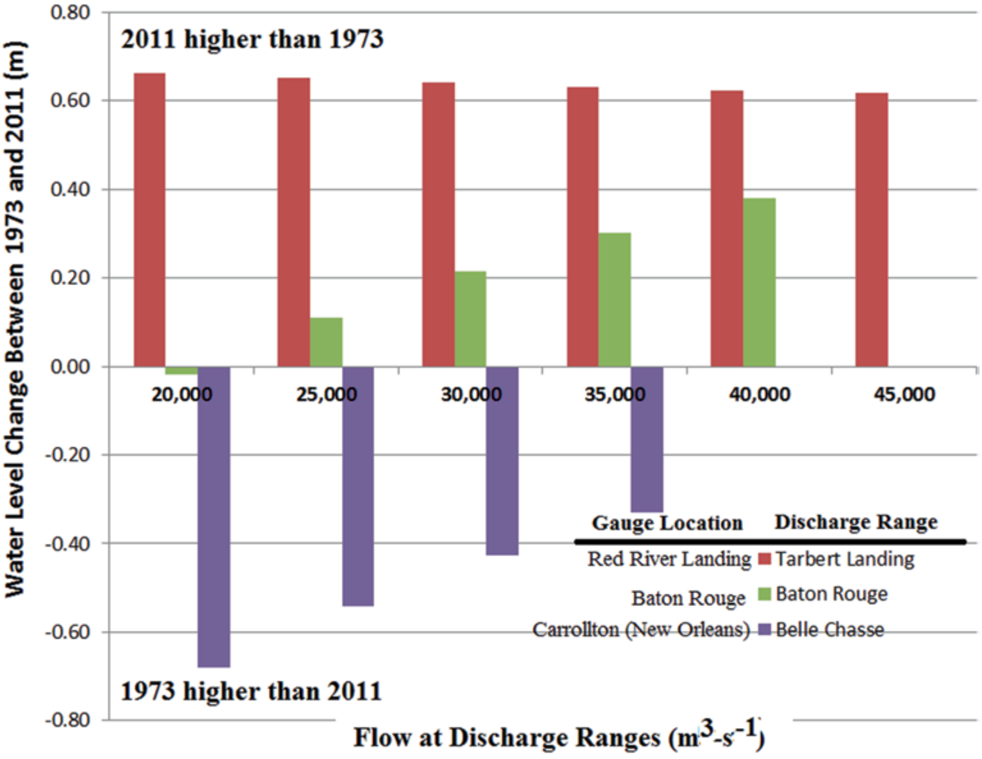


Fig. 25 Increase or decrease in water level between 1973 and 2011 floods at specific gauge locations (Red River Landing RK 486, Baton Rouge RK 367, New Orleans RK 166) for specific discharges

rising flood roughens the bottom of the river, building the size of sand bed forms, which increases frictional resistance to flow (Mossa 1996). These dunes stop moving as flow diminishes but remain frozen in place where, as stationary features, they impart even more resistance.

When logarithmic trend lines for the two flood years were differenced at each location for specific discharges, LMMR water level elevations were higher at Tarbert Landing (RK 510) and Baton Rouge (RK 367) in 2011 than in 1973, but lower from New Orleans downstream in 2011 than in 1973 (Fig. 25). Stage was consistently 0.6 m higher in 2011 than in 1973 for all discharges at Red River Landing. The water elevation at Baton Rouge (RK 367) also was higher in 2011 for discharges greater than 20,000 m^3-s^{-1}, and increased with discharge to almost 0.4 m at 40,000 m^3-s^{-1}. The trend at New Orleans (RK 166) was quite different, however, showing a decrease in stage in 2011 relative to 1973, with the reduction diminishing with rising discharge from −0.7 m at 20,000 m^3-s^{-1} to less than −0.4 m at 35,000 m^3-s^{-1}, the greatest flow experienced there in both years. This represents a shift over 40 years toward an increase in high water slope upstream of New Orleans, and a flattening from there to the Gulf.

The east bank MR&T levee ends at Bohemia (RK 75), while on the west bank it continues to Venice (RK 17.5) (Fig. 26). No cloud-free Landsat images of the PBD from the flood of 1973 were found, but it was possible to compare Landsat images of the PBD during the floods of 2011 and 1983, when discharge in the LMMR through New Orleans was similar in both cases to that in 1973. The sediment plume on the east side of the River in 2011 begins at Bayou Lamoque (RK 53) near Empire for a Tarbert Landing discharge of 25,488 m^3-s^{-1}. The 1983 image shows the sediment plume on the east side of the river extending upstream only to Fort St. Phillip (RK 33) at a time when the discharge at Tarbert Landing was slightly higher at 31,130 m^3-s^{-1}. River water and sediment is clearly flowing over bank to the east in this 22 km reach in 2011 where it was not in 1983.

Allison et al. (2012b) also observed this overflow during the 2008 flood (Fig. 15), when 7 % of the cumulative annual 2008 Tarbert Landing discharge left the LMMR over the unleveed east bank between Bohemia and Fort St. Phillip, carrying 8 % of the suspended sediment load measured at Tarbert Landing, including an estimated 3 % of the fine sand. Information acquired by Kolker and Georgieou (2011) during the 2011 flood suggests that the loss of water over the east bank during high flow amounted to more than 2,000 m^3-s^{-1} (Fig. 27). A portion of this overbank flow became channelized in February 2012 when Lopez (2012) observed head-cutting toward the river in a small channel originally separated from the river by the natural bank. The crevasse connection between the river and the lateral channel formed as the level of the river was falling (Lopez et al. 2013). Because of the date that this crevasse broke through the east bank just downstream of Bohemia at RK 73, it is now named Mardi Gras Pass and has continued to flow even at the lowest river discharges encountered in 2012

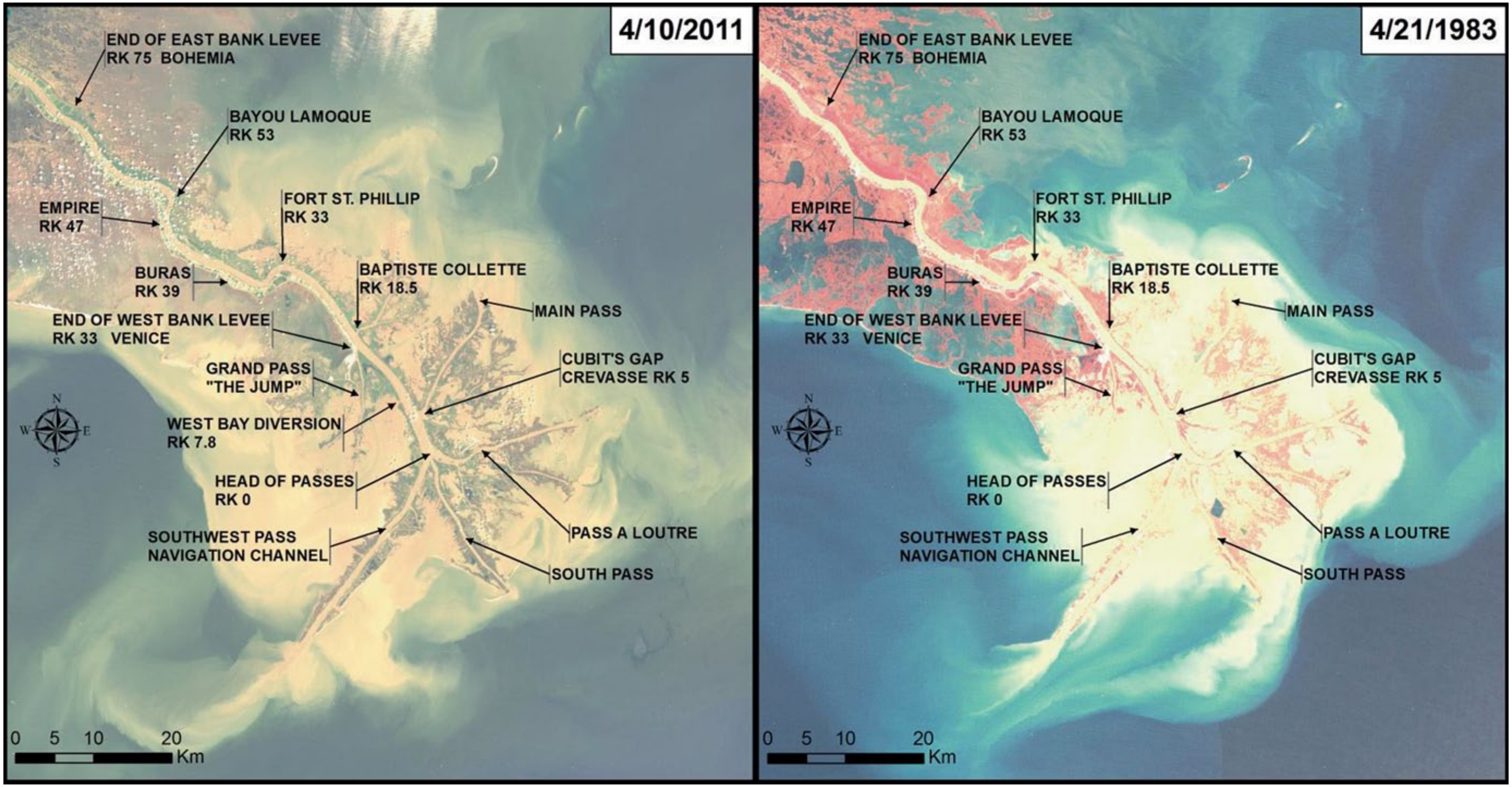


Fig. 26 Landsat Images from 2011 at a Tarbert Landing discharge of 25,488 m3-s^{-1} and from 1983 at a discharge of 31,130 m3-s^{-1} showing sediment plume created by overbank flow beginning in 2011 at the Bayou Lamoque bend (RK 55) halfway between Bohemia and St. Phillip, 22 km upriver of the upstream end of 1983 east bank plume

Fig. 27 Discharge losses through built or natural diversions from peak 2011 LMMR discharge starting upstream of the Old River Control Structures

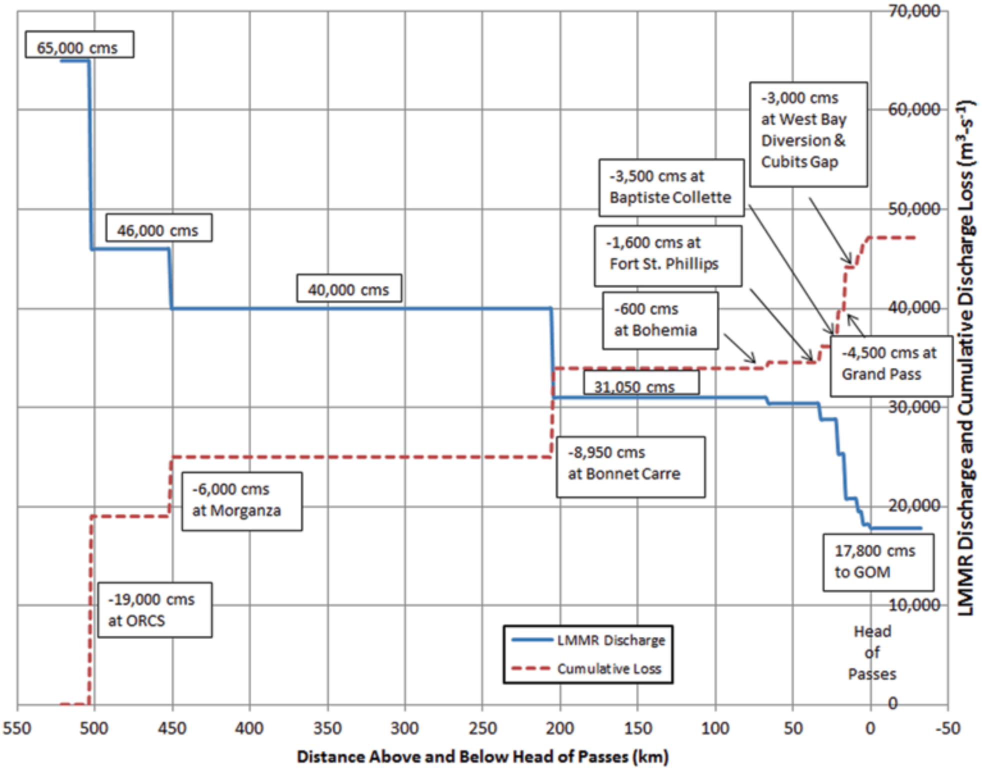
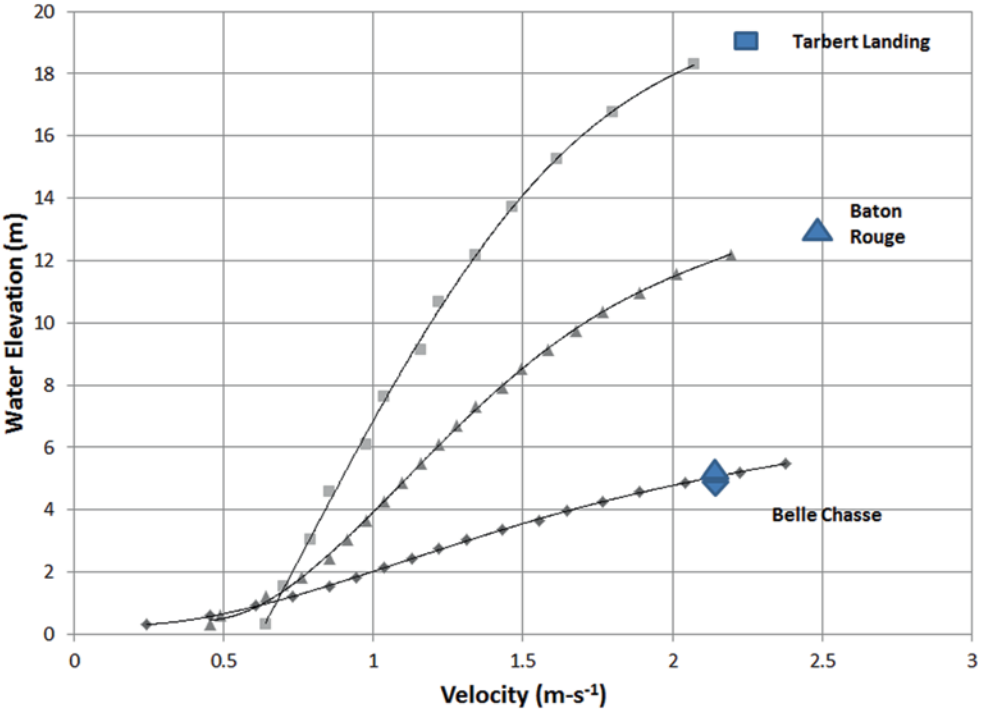


Fig. 28 Mardi Gras Pass crevasse formed on east bank at RK 73 in February 2011 as the river dropped. (Lopez et al. 2013)

(Fig. 28). The new channel is now fully navigable with depths ranging from 2 to 6 m (Boyd et al. 2012).

These recent observations suggest that hydraulic conditions on the LMMR are changing in a way that favors the formation of new outlets upstream of the PBD, whether in the form of controlled diversions or unplanned crevasses. Whether such outlets, if properly designed, have the potential to extract sediment, particularly sand, from the LMMR at a rate proportional to flow, remains controversial. The USACE is skeptical that diversions that take flow laterally can accomplish this, and have warned that increased downstream shoaling will raise navigation dredging costs (Letter et al. 2008). But Nittrouer et al. (2012) has calculated that the Bonnet Carre diversion (RK 207), a 2,500 m wide, overbank MR&T flood relief structure, passed a volume of sand that amounted to as much as 20 % of the measured flux past the spillway entrance

Fig. 29 USACE Stage-Velocity curves at 60% depth at LMMR discharge ranges compiled from data collected 1975 to 1983 showing location of peak water elevation in 2011 at Red River Landing, Baton Rouge and New Orleans gauges (USACE New Orleans District 2009)



during the 2011 flood (Fig. 27). Meselhe et al. (2012) have shown using numerical modeling that the efficiency of sediment conveyance by a lateral diversion is greatly influenced by the location and design of the take-off structure and outlet channel. They have concluded that with proper siting, design and operation of a lateral diversion, it is possible to achieve entrainment of suspended sediment, including sand, at a 1:1 or higher proportion than that found in the parent channel.

LMMR Hydraulics

Schumm and Winkley (1994) defined an alluvial river as one that "has formed its channel in the sediment that is being transported or has been transported." Most of the Mississippi River has this character, but it is not true of the last 165 km studied by Nittrouer et al. (2011a) from New Orleans to Venice, in which significant portions of the bed were devoid of alluvium. Nittrouer et al. (2011a) further suggest, based on less conclusive surveys by others, that this condition may extend as far upriver at Baton Rouge (RK 368). It is interesting that Humphreys and Abbot (1867) also observed the occurrence of a hard, swept bed in the vicinity of the Bonnet Carre crevasse that preceded the built diversion structure. The LMMR downstream of Baton Rouge is incised deeply into stiff Holocene and late Pleistocene clays that Nittrouer et al. (2011b) refer to functionally as "bedrock." Over much of the bed, particularly in the bends, the clay base is swept clean of alluvium. Elsewhere, it serves as an immobile bed across which dunes episodically advance during high flow. Nittrouer et al. (2011b) found flutes and other erosional scour holes on the exposed bed and sidewalls that attest to the presence of high velocities, though the age of the features has not been determined (Fig. 29).

The LMMR as we have defined it differs in another way from the rest of the Mississippi in that it is hydraulically affected by proximity to the GOM and mean sea level, which increases the importance of the pressure gradient at the expense of gravity in driving flow. This is what Nittrouer et al. (2011a) and others before them (Lane 1957; Chow 1959) have called the "backwater effect." Lamb et al. (2012) has recently provided an excellent physical analysis of backwater effects on the LMMR. Because mean sea level is not affected by LMMR discharge, stage in the backwater is constrained to meet sea level at the outlet regardless of discharge. Stages in the river upstream of the backwater, in the zone of normal flow, in contrast, rise to accommodate increased discharge. This is not possible closer to the mouth, where, if discharge remains constant, mean flow velocity must increase in the downstream direction. While the LMMR is today depleted of water during high discharges by MR&T controlled diversion structures, and in the past by overflow of the low natural levees, velocities do generally rise as stage diminishes in the downstream direction (Fig. 29). In an unconstrained alluvial system, this velocity increase toward the mouth leads to channel deepening upstream of the point where distributaries and plume dynamics spread out the flow.

A thalweg elevation plot (NAVD88) was created from USACE New Orleans District (2007) cross-section surveys acquired in 2002 and 2003 from just upstream of the ORCS complex (RK521) to the Gulf (RK-32) (Fig. 30). To this plot were added water elevations for the record high

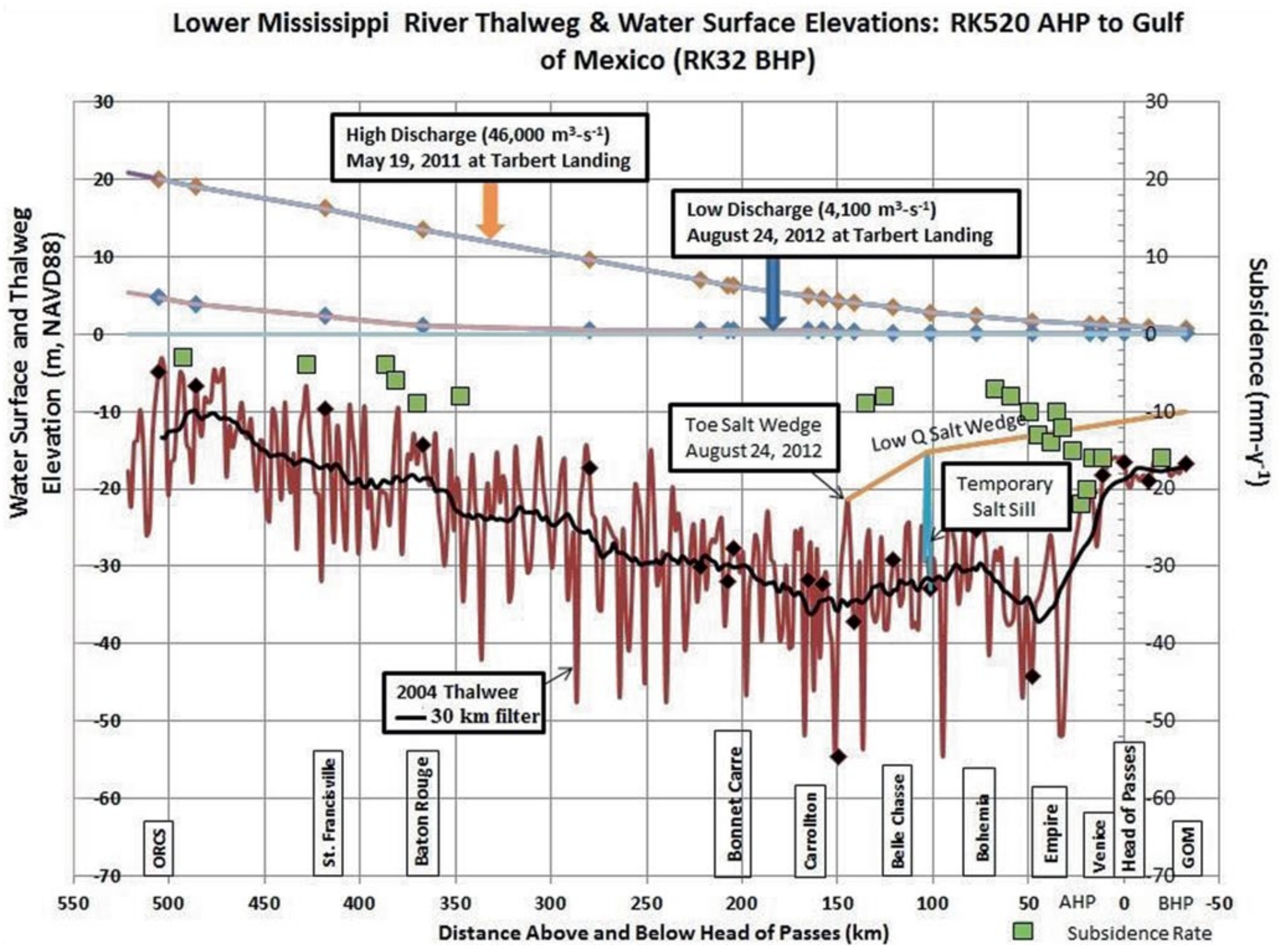


Fig. 30 Longitudinal view of LMMR elevation of the bed (USACE New Orleans (USACE 2007) showing 2011 high and 2012 low-river flow lines from 21 USACE gauges. Also shown is the upstream extent of salt water intrusion during 2012 and temporary salt water barrier sill constructed in August 2012. Subsidence values (mm-y^{-1}) from Dokka et al. (2006)

(46,000 m^3-s^{-1} at Tarbert Landing) flow of May 19, 2011, and the near-record low (4,100 m^3-s^{-1}) discharge of August 24, 2012, based on data from 21 USACE and USGS gauges adjusted where necessary to the NAVD88 datum. This order of magnitude span in discharge over less than a year may reflect a larger climate trend as occurrence of mid-continental intense rainfall events and extended droughts are both among the most robust statistical correlates of global warming (Trenberth 2005).

First, it is apparent that thalweg elevations for the entire LMMR lie below sea level. Second, the depth of the flow does increase toward the mouth as backwater theory predicts. During low flow, when sediment transport diminishes, the backwater zone expands upstream and much of the LMMR is characterized by deceleration. This became very apparent in 2012 when the LMMR became estuarine and water levels were controlled by the 0.3 m GOM tide as far upstream as the Carrollton gauge in New Orleans (RK166). Stratified, two-layer flow occurred then as a salt wedge advanced 150 km upstream of Head of Passes through the dredged navigation channel. This would not have happened under natural conditions because of the shallow depth of the pass mouths, but since the navigation channel entrance through the PBD was deepened to 14 m in the mid-1980s, the USACE has successfully protected New Orleans metro water supply intakes three times, in 1988, 1999 and 2012, by constructing a barrier sill across the bed of the river at RK103 using sand dredged from adjacent lateral bars (Fig. 30). The sill typically erodes away in the next high water providing a good opportunity to measure sand transport rates.

Thalweg elevation can vary more than 40 m in less than a kilometer, reflecting the changing hydraulics associated with the meandering plan form of bars, crossings and bends. When the thalweg elevation is smoothed with a 30 km moving average, eight different bed slope regions are apparent (Fig. 30). Four zones of adverse (negative downstream) bed slopes are interspersed among an equal number of reaches with normal (positive downstream) slopes (Table 3). Three of the adverse bed slope zones are expected. One occurs just downstream of the sand-lean Atchafalaya diversion in a

Table 3 LMMR Bed and Water Slopes for 2011 High and 2012 Low Discharge Measured at Tarbert Landing (RK510). Adverse bed slope reaches highlighted in grey

Reach	Upstream limit	Downstream limit	Bed slope	Low discharge slope (4,100 m3-s^{-1})	High discharge slope (46,000 m3-s^{-1})
Above old river	RK521	RK509	-9.79×10^{-6}	2.45×10^{-5}	8.09×10^{-5}
Old river to baton rouge	RK509	RK366	1.26×10^{-4}	3.73×10^{-5}	7.53×10^{-5}
Baton rouge to reserve	RK366	RK222	5.96×10^{-5}	6.89×10^{-6}	7.19×10^{-5}
Reserve to new Orleans	RK222	RK166	1.49×10^{-4}	2.86×10^{-7}	5.94×10^{-5}
New Orleans to bohemia	RK166	RK77	-8.47×10^{-5}	6.55×10^{-6}	4.76×10^{-5}
Bohemia to empire	RK77	RK48	1.80×10^{-4}	0	3.33×10^{-5}
Empire to head of passes	RK48	RK0	-3.38×10^{-4}	0	2.07×10^{-5}
Head of passes to GOM	RK0	RK-30	-5.11×10^{-5}	0	2.05×10^{-5}

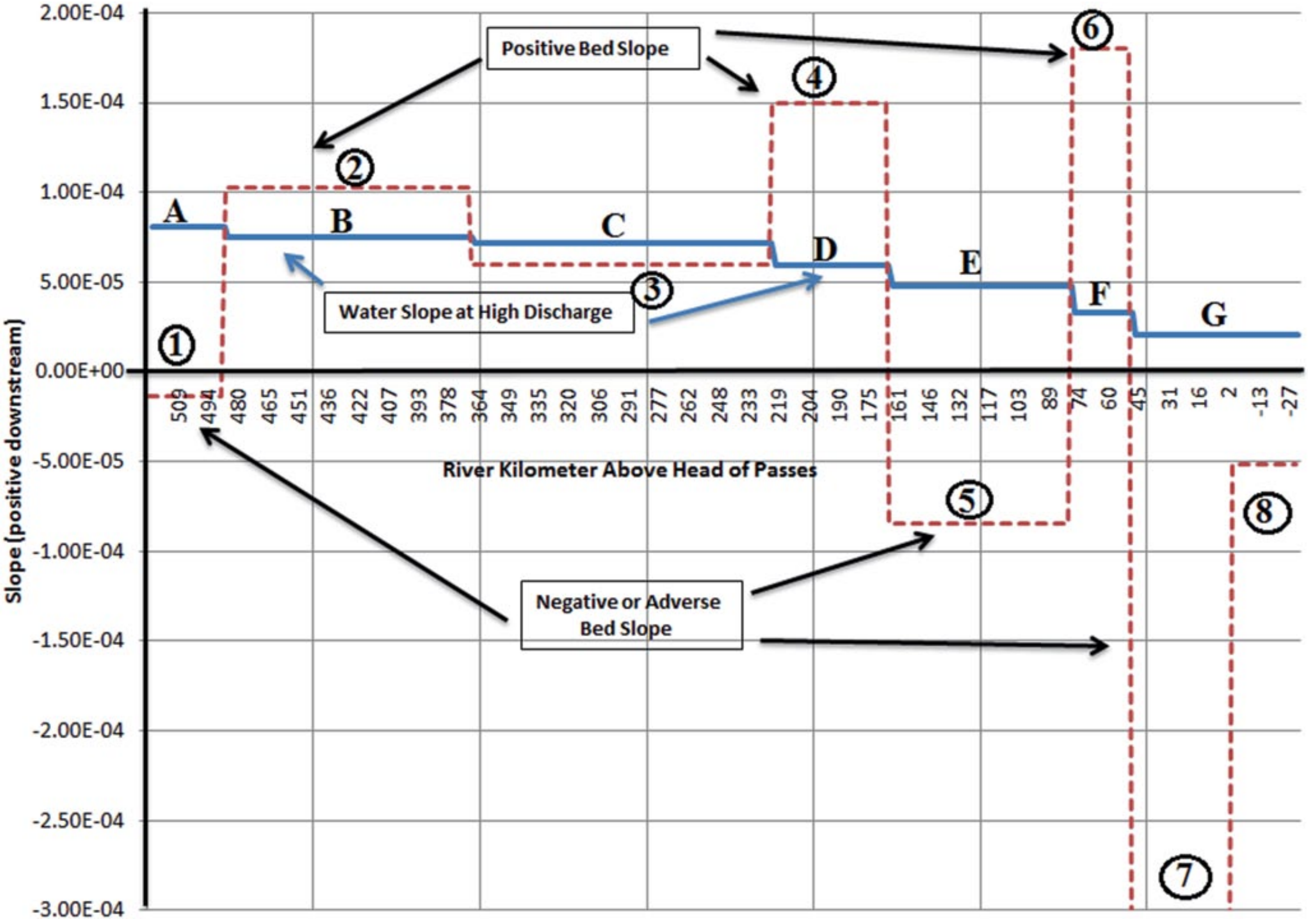


Fig. 31 LMMR bed slopes based on 2004 USACE hydrographic surveys (*numbered*) compared to slopes of May 19, 2011 water surface (*lettered*)

known shoaling area that occasionally requires dredging to maintain the 3 m shallow-draft channel (Mississippi River Commission pers. com.). Another two are in the PBD, and are caused by shoaling upstream of the dredged reaches, as has been discussed. But the adverse slope characterizing a 100 km reach between New Orleans and Bohemia is not as easily explained (Fig. 31). The onset of significant deltaic shoaling occurs at Fort St. Phillip (RK33), which corresponds to Reach 5 in the Brown et al. (2009) USACE study (Fig. 17).

Subsidence estimates made by Dokka et al. (2006) along the LMMR were collected by the USACE as part of a study of the West Bay diversion (Brown et al. 2009) and are the source of values plotted on the LMMR longitudinal section (Fig. 30). Immediately downstream of the rise to Bohemia is a reach that drops 6 m in 30 km giving it the steepest normal bed slope in the LMMR (Table 3). The subsidence rate, which is less than 10 mm-y^{-1} upstream of Bohemia, increases downstream, reaching a maximum near Venice of 23 mm-y^{-1}.

If the drop in the bed downstream of Bohemia is caused by 13 mm-y^{-1} of enhanced subsidence associated with faults crossing the river, a 6 m decline in bed elevation, assuming no erosion or deposition, would require less than 500 years, a value consistent with the age of the Plaquemines phase of the PBD (Fig. 3). Furthermore, if backwater hydraulics have acted since the river occupied the Plaquemines channel 1.3 ka to prevent deposition upstream of the mouth, then the elevation of the bed today probably reflects both hydraulics and tectonics, the results of which have not been obscured by alluvium.

Water level curves for the extreme high and low discharges of 2011 and 2012, respectively, are both concave upward, with what Chow (1959) classified as an M1 configuration. Lamb et al. (2012) modeled a hypothetical LMMR in which no water escaped laterally upstream of Head of Passes and predicted that in high discharge, the concave upward M1 profile would transition to a convex M2 curve with a steep water slope at the entrance to the delta. This might be observed if high levees contained the river to the mouth, but they do not, at least along the east bank. The high discharge flow line roughly follows the mean bed slope from the ORCS to New Orleans (Fig. 30). The flow line slope diminishes from this point downstream where adverse bed slopes predominate (Table 3).

The low discharge flow line (4,100 m^3-s^{-1}) reaches sea level at New Orleans (RK 166), and is less than 2 m higher in Baton Rouge 200 km upstream. The low discharge water slope is less than half as steep as the bed slope between Old River and Baton Rouge, and is an order of magnitude flatter than the bed between Baton Rouge and New Orleans (Table 3).

The LMMR loses discharge through a series of USACE maintained control structures beginning with the ORCS (Fig. 27) just upstream of Tarbert Landing (RK 510). In 2011, the ORCS structures were operated at 108 % of their MR&T rated capacity (USACE Mississippi River Commission 2011). Of the 46,000 m^3-s^{-1} that remained in the LMMR below the ORCS, additional water was shed through MR&T overbank structures, including 5,100 m^3-s^{-1}, or 11 %, at Morganza (RK 467), and almost 8,500 m^3-s^{-1}, or 18 %, at Bonnet Carre (RK 206). There are no more USACE structures downstream of Bonnet Carre, but flow left the LMMR over the natural levees and through a variety of small channels, including an additional 600 m^3-s^{-1} (1 %) between RK75, where the federal levee on the east bank ends, and RK50, an area known as the ‘Bohemia Spillway’ (Georgiou and Troclair 2011). Kolker and Georgiou (2011) estimated that another 4 % or 1,600 m^3-s^{-1} escaped through the eastern bank both as flow overbank and through small channels between Ostrica (RK 40) and Fort St. Phillip (RK33).

Fourteen percent, or 7,500 m^3-s^{-1}, appears to have been lost near Venice (RK19), evenly distributed between the two growing distributaries of Baptiste Collette on the east bank and Grand Pass on the west. This means that 19 % of Tarbert Landing flow was discharged through unregulated outlets between New Orleans and the PBD, leaving only 22,700 m^3-s^{-1} in the river as it entered the birdsfoot (Fig. 27). Finally, an additional 7 %, or 3,000 m^3-s^{-1}, is estimated to have been dispersed between Venice and Head of Passes through the West Bay Diversion, Cubits Gap Crevasse, and other smaller breaks in the artificially reinforced PBD natural levees (Kolker and Georgiou 2011), leaving about 43 % of the peak Tarbert Landing flow, 19,700 m^3-s^{-1}, remaining in the LMMR at Head of Passes. The observed partitioning of flows out of the LMMR above Head of Passes during the 2011 flood peak is similar to that measured by Allison et al. (2012b) during the 2008 high water when the Bonnet Carre spillway was also opened and peak flow past New Orleans was comparable to that in 2011(Fig. 15).

We have suggested that the change in bed slopes observed below New Orleans are linked to subsidence, but have not discussed what should be more obvious, that is, the effect of such movement on elevation of the 75 km of the east bank that is largely unleveed. It is to be expected that this unmaintained bank has also experienced enhanced subsidence. Today, bank elevations there are in many locations little more than a meter above mean sea level (Lopez et al. 2013). Allison et al. (2012a) found in 2008, 2009 and 2010 that this reach acts as a large, unplanned, overbank diversion into Breton Sound. We have confirmed similar performance during the 2011 flood. This is a relatively new development that does not appear to have affected flow significantly before 1983 (Fig. 26). From a flood control standpoint, the growth of this new outlet appears to have lowered flood flow lines—or at least kept them from rising—as far upstream as New Orleans during the flood of 2011. This is a surprisingly large effect, far more than would be expected based on steady-state model results obtained so far (Karadogan and Willson 2010). It is clear that more work is needed. What is not in question is that a change in LMMR hydraulics that began about 1990 has deprived the PBD of sand that is increasingly being stored within the channel upstream of Venice or discharged over the east bank.

Conclusion

We have sought to identify the consequences of changes in the hydraulics and sediment transport dynamics of the LMMR to navigation, flood risk reduction and delta restoration potential since initiation of the MR&T project in the 1930s. The juxtaposition of the record flood of 2011 and record low discharge of 2012 provides a unique frame through which to view the trends, though they are linked to geological processes that have been in progress for a much longer span. Human desires for river management have changed, particularly the need identified in the past 30 years to reconnect the river with its delta. This unique landform is now seen as an ecological and economic asset of impressive scope and value. The fundamental requirements for deep- and shallow-draft navigation on the LMMR and for flood control have also changed. Fear of surges sweeping across the coast from more powerful hurricanes has engendered more upset about the deterioration of coastal wetlands, and a new urgency for rebuilding. An appreciation is growing that all navigation issues cannot be solved by just spending more and more on dredging, whether to get the barges to New Orleans or the ships in and out through Head of Passes.

In a world of changing climate and new economic drivers like the expanded Panama Canal and the end of cheap energy, it is necessary to acknowledge that the LMMR, though one of the most intensely engineered rivers in the world, is also on an unsustainable trajectory that man cannot completely control. Despite USACE intervention in the delta switching process and the expensive battle to 'pin' the sinking PBD to the edge of the continental shelf, and in part, because sea level is rising, the physics that have always governed Mississippi River evolution continue to drive it in a predictable direction, but at rates that are more difficult to ascertain. Currently, all evidence suggests that the river is seeking a shorter path to the sea, in this case by retracing its geological steps, in this case, so that it may not rest until it retreats to the Plaquemines mouth location of 0.9 ka (Fig. 3).

If we can understand the geophysical trajectory of the river, then perhaps those who manage the LMMR will be astute enough to see the opportunities that this presents along with the problems. It is possible that we could use our new knowledge of the river to have it work for us in the future even better than it does today. Experience suggests otherwise, however, that we will wait for disaster, and then spend far greater funds trying to regain a fraction of what is no longer possible. Certainly, we hope this is not the case with the Mississippi River and its delta.

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Using What We Have: Optimizing Sediment Management in Mississippi River Delta Restoration to Improve the Economic Viability of the Nation

Samuel J. Bentley, Angelina M. Freeman, Clinton S. Willson, Jaye E. Cable and Liviu Giosan

Abstract

Management practices on the Mississippi River have reduced the amount of sediment in the river by approximately half. Some have questioned whether the current sediment load in the river is sufficient for restoration of the delta. The Mississippi River does not now, nor has it ever supplied enough sediment to continuously sustain the entire Mississippi Delta coastline. Nevertheless, the available sediment supply is still huge, and so we must use this valuable resource efficiently and effectively.

River diversions are structures designed to mimic the natural pattern of deltaic land formation by reconnecting the river to the coastal system. The suitability of diversions for land building has been the subject of vigorous scientific and policy debate. However, not all diversions are designed to build land. Other uses include salinity control and flood control. The land-building capacity of a diversion is fundamentally dependent on the supply of sediment and retention, versus the "sink" factors of subsidence, sea-level rise, and compaction. If supply exceeds sink factors, then land will build. Sediment diversions, designed to maximize sediment delivery, are being proposed as potentially important tools for land-building in the Mississippi River Deltaic Plain. Several current diversions show that such diversions can build land.

Keywords

River diversion · Sediment budget · Sediment retention · Delta cycle · Land building

Introduction

Sediment diversions are identified as important tools for restoring Louisiana's coast. These man-made channels are proposed for delivering sediment laden river water for land building in the Mississippi River's delta (MRD) plain. *However, water resource management practices on the Mississippi River have reduced the amount of sediment in the river by approximately half over the last century* (Allison et al. 2012; Kemp et al. 2012; Kesel 2003). *As a result, some scientists question whether the current sediment load in the river is sufficient for restoration of the delta* (e.g. (Thome et al. 2008; Turner et al. 2006)). *This point is critical to consider, but it should be considered in the context of delta-building processes overall. The Mississippi River does not now, nor has it ever, supplied enough sediment to continuously sustain the entire Mississippi Delta coastline and delta plain*. The

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Fig. 1 Western Coastal Louisiana. *Light green* areas represent land gained 1937–2000; *Orange* areas represent land lost 1937–2000

delta has always had areas that were building and areas that were eroding. The concomitant reduction in sediment supply due to changes in land use and management practices as well as water infrastructure projects, subsidence rates due to fluid extraction, and projected sea level rise further constrain our ability to build land. *Nevertheless, the available sediment supply is still substantial given that the Mississippi River is the 6th largest river in the world by sediment discharge standards. We must use this valuable resource efficiently and effectively*.

River diversions are structures that may be designed to mimic the natural pattern of deltaic land formation by reconnecting the river to the coastal system. The suitability of diversions for land building remains the subject of vigorous scientific and policy debate. It is important to recognize that some diversions in Louisiana are designed for salinity and flood control, often with controversial consequences for the receiving basins (e.g. (Allison et al. 2012; Kearney et al. 2011; Snedden et al. 2007)). *The land-building capacity of a diversion is fundamentally dependent on sediment supply, limited by the sediment retention rate (that is, how much of sediment delivered remains in place to build land), relative to subsidence, sea level rise, and compaction. If sediment supply amounts exceed these sink processes, then land will be built. Therefore, if diversions are designed to maximize sediment delivery and retention, which is the intent for present designs, they may become important tools for land-building in the Mississippi River Deltaic Plain. Recent studies show that sediment diversions can build land* (Chatanantavet et al. 2012; SEST 2012).

Sediment Availability and the Delta Cycle

To best understand the potential for beneficial use of river sediment for land building, we must take a brief look at the natural sedimentation and erosion cycles of the Mississippi Delta, referred to as the Delta Cycle (Roberts 1997). The modern Mississippi Delta, extending from Vermillion Bay in the west to the Chandeleur Islands in the east, is less than 7,500 years old, and most of that landscape between these areas is even younger (<4,000 years old (Figs. 1 and 2). This landscape was built by cyclic phases of land building (progradation) where the river flowed freely to the sea

Fig. 2 Eastern Coastal Louisiana. *Light green* areas represent land gained 1937–2000; *Orange* areas represent land lost 1937–2000

and coastal retreat in regions distant from the river channel. Rivers deliver sediment to the coast and build land at the mouth (a delta lobe), annually extending the length of the river channel until a major flood or other disturbance causes the river to avulse, or change course, seeking a shorter, more efficient path to the sea. At that point, the abandoned delta lobe begins to undergo coastal retreat, because sediment erosion and subsidence are not offset by new sediment deposition (Fig. 3). These major changes in river course have occurred every 1,000–2,000 years, for the last ~7,500 years, and each growing delta lobe has occupied less than half of the total delta coastline, perhaps 40 % of the coastline, at any one time (e.g., Kolb and van Lopik 1958; Roberts 1997). Consequently, for the last ~7,500 years, most (~60 %) of the coastline was in retreat at any given time, while a smaller, active area was building a new delta lobe. The locations of retreating and building coastal regions have shifted over time with each shift in river course (Fig. 4). In other words, in the last ~7,500 years the overall length of coast in retreat has generally been greater than the length of coast experiencing land building. The net balance of retreat and delta growth in different regions has created the deltaic landscape we see today. Currently, it is estimated the river is maintaining less than 10–15 % of the coast (Barras et al. 2003; Day et al. 2007) with less than half of the historical sediment loads in the Mississippi River now available. This land maintenance mainly occurs in the Atchafalaya region (Fig. 1), where flood control levees are lower and the receiving basin is wide and shallow. Enough sediment is available to maintain limited areas of the Mississippi Delta coastline. A central goal of restoration should be to increase as much as possible the area of the delta maintained by the river.

The sediment supply from the Mississippi River that built most of the delta was approximately 400 million tons per year, before the river basin was modified by the approximately 3500 km of levees and 86 dams, locks, and spillways that capture and control sediment (Kemp et al. 2012; Meade and Moody 2010). Of that total natural sediment supply, about 30–70 % of the sediment was incorporated into the delta landscape, while the remaining 70–30 % was transported into the ocean (Paola et al. 2011). The present sediment supply carried by the river to the delta plain is approximately 200 million tons per year (Kemp et al. 2012), but not all of that sediment reaches the major ocean outlets of the Mississippi River (Allison et al. 2012). Before anthropogenic changes to the river began, each delta lobe occupied

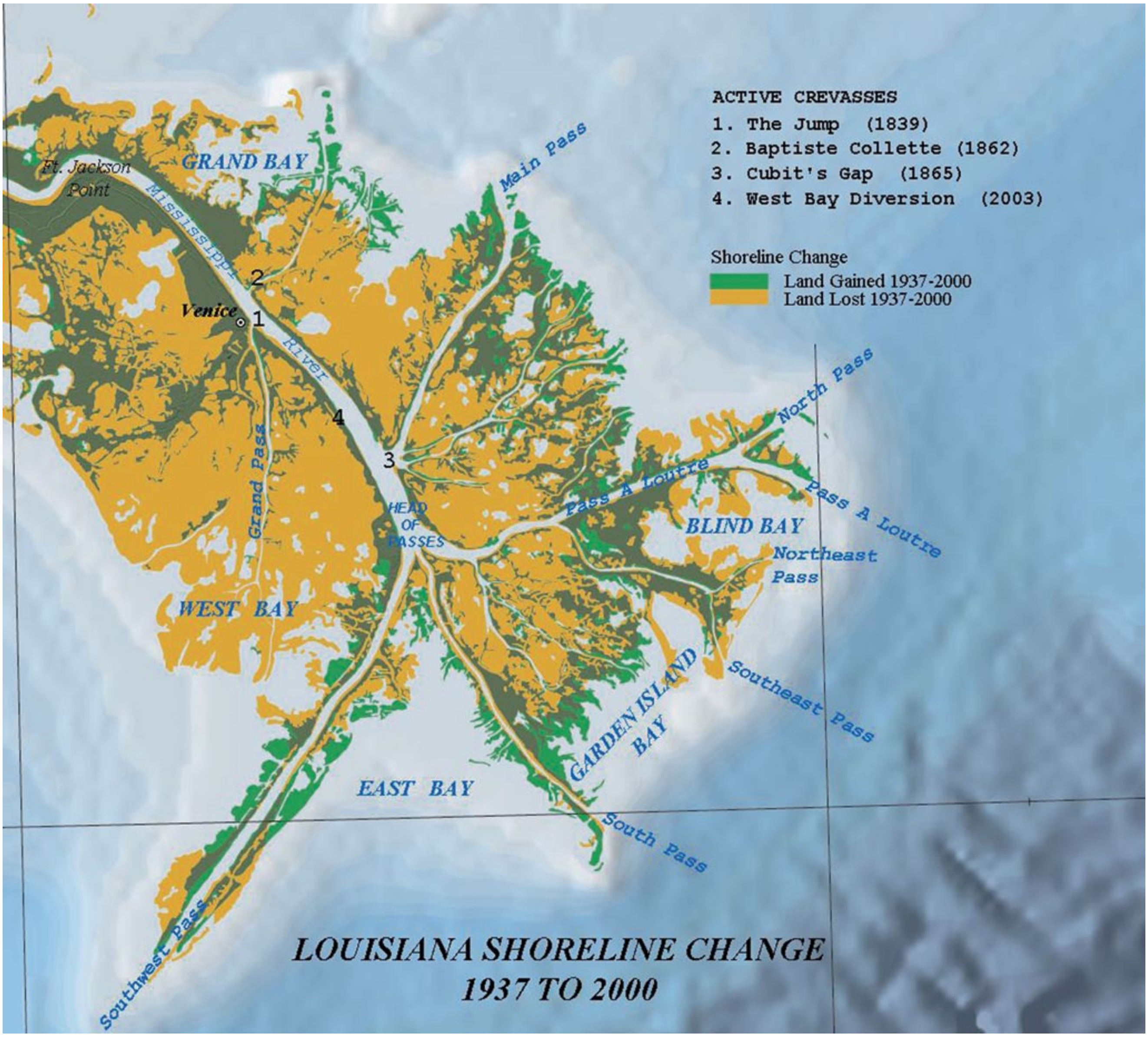

Fig. 3 Louisiana's birdfoot delta. *Light green* areas represent land gained 1937–2000; *Orange* areas represent land lost 1937–2000

about 40 % of the lower delta plain. If the land-building capacity of the river is proportional to the sediment supply, as we ascertain here, then the modern land-building capacity of the river is about half of its pre-dam condition. This scenario suggests the river sediment supply is capable of sustaining about 20 % of the modern deltaic coastline extending from the Chandeleur Islands in the east to Vermillion Bay and Marsh Island in the west.

Modeling by Kim et al. (2009) predicts 700–1,200 km^2 of new land could be added to the delta in 100 years if 45 % of the Mississippi River is diverted. By extending these calculations to include all sediment in the lower Mississippi and Atchafalaya Rivers (~210 MT/yr) and allowing 20 % addition to sediment volume from plant growth and organic production, Kim et al. (2009) suggest that up to 2,740 km^2 of land could be added by 2100. These estimates utilize a "base case" scenario of conservative subsidence at 5 mm/yr and sea-level rise at 2 mm/yr). This best-case prediction represents about 25 % of the additional 10,000–13,500 km^2 land loss by 2100 estimated by Blum and Roberts (2009), and about 50 % of the 5,695 km^2 projected gross land loss (1956–2050) estimated by Barras et al. (2003). The estimates by these scientific studies demonstrate some ranges of solutions required relative to the scale of the land loss problem. Note that these land loss scenarios do not include restoration by directly engineered land building.

Because sediment carried by the river represents a finite resource, two main components of future efforts must be to

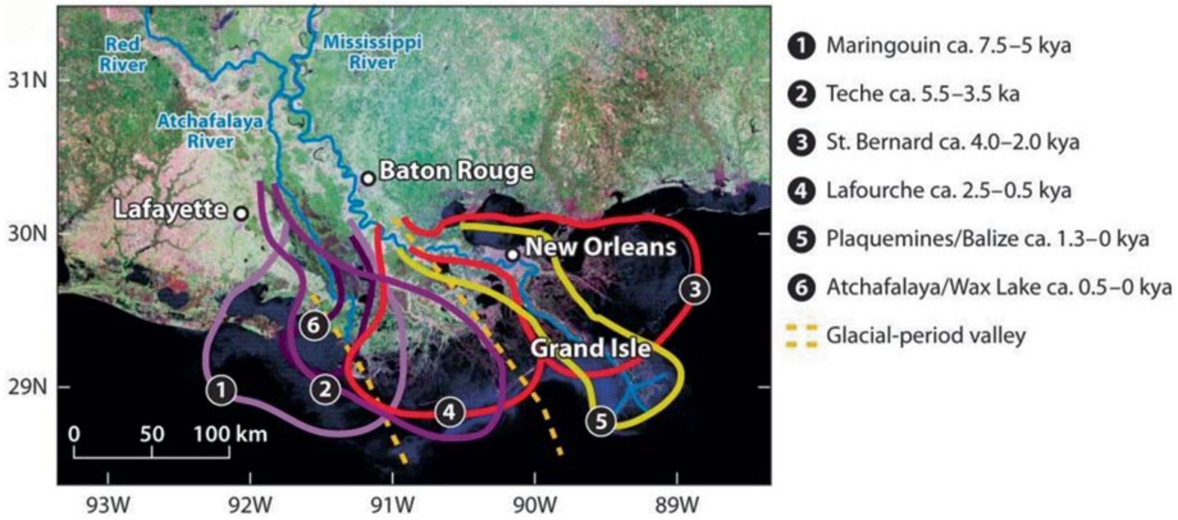

Fig. 4 Location of prehistoric and historic lobes of the Mississippi Delta, adapted from Blum and Roberts 2009. Reproduced, with permission, from the Annual Review of Earth and Planetary Science, Volume 40 © 2012 by Annual Reviews www.annualreviews.com

(A) minimize the loss of sediment to the Gulf of Mexico, and (B) maximize use of sediment transported and stored within river channels (e.g., Allison et al. 2012). If land building by the river can be enhanced by guiding sediment into specific areas where subsidence rates are lower and sediment retention rates are higher, then the area of sustainable coastline will increase. Several studies have suggested that large river diversions should be located as far upstream in the delta as possible to increase the retention of sediment, and take advantage of lower subsidence rates and steeper natural gradients in river elevation (these gradients facilitate sediment extraction from the river) (Blum and Roberts 2009; Condrey 2011; Nittrouer et al. 2012). Observed sediment retention rates in the delta range from 25 % to nearly 100 % (Andrus 2007; Bentley et al. 2012; Blum and Roberts 2009; Fabre 2012; Kolker et al. 2012), depending on the hydrodynamic conditions in the receiving basin. In considering restoration options, optimizing the interactions of sediment supply, sediment retention, and subsidence in will result in a greater area of the delta that can be maintained by the river.

Sediment Deposition

Rivers deliver both coarse sediment (sand) and fine sediment (mud) from their outlets to the coastal ocean, with mud accounting for 75–95 % of total sediment supply in most rivers. Sand generally deposits (at least initially) within several kilometers of river mouths, creating distributary mouth bars and levees that are important components for deltaic land building. Mud is transported farther than sand by currents, and deposits both on the seabed off of river mouths, and in wetlands fringing river outlets. In the Mississippi Delta, sand deposition is largely responsible for land building in the Wax Lake Delta (Fig. 2), whereas mud deposition is probably an important factor in wetland growth visible in Fig. 3 near Main Pass, Garden Island Bay, and Grand Bay. Transport of mud into wetlands is facilitated by wetland flooding with sediment-rich water, resuspended from coastal bays by waves and currents. Along with less energetic winter storms, hurricanes and tropical storms create such flooding through combined wave-current resuspension of sediment coupled with storm surge, and provide an important source of sediment for Louisiana’s wetland ecosystems (Turner et al. 2006; Turner et al. 2007). Such storms stir up sediment from water bottoms and deposit it on the marsh surface.

Fine grained sediment, which represents the majority of current sediment input to the delta, can nourish marshes extending tens of kilometers from river outlets (e.g., Day et al. 2011). Fine sediments delivered by flooding events are particularly effective at maintaining existing marsh, as long as flood frequency and duration do not inhibit plant growth. Day et al. (2011) reported the contrast between salt marshes at Old Oyster Bayou around lower Fourleague Bay (Fig. 1), and Bayou Chitigue (Fig. 2). Old Oyster Bayou is a sediment-rich area near the mouth of the Atchafalaya River, and adjacent marshes are about 10 cm higher, have much higher soil strength in the root zone, and have been stable for over 50 years when compared to salt marshes at Bayou Chitigue that had no direct river input, with most of the marsh deteriorating within a few years early in the study (Day et al. 2011). This contrast was in spite of the fact that the Bayou Chitigue marshes had about twice as much vertical accretion and short-term sediment input, (including storm input) during the study period (1990–2004). The Old Oyster Bayou marshes retained almost all sediment input while Bayou Chitigue retained less than half. Sites at the Old Oyster Bayou marshes flooded 15 % of the time, while sites at the Bayou Chitigue marshes flooded 85 % of the time. Thus, for healthy marshes, a little sediment can go a long way because healthy marshes retain more sediment during storms. These studies highlight the importance of multiple sediment sources for restoration, but also demonstrate that it is imperative to consider flood frequency and duration, along with wetland elevation and drainage, in order to maximize the land-building contribution of wetland vegetation.

River Diversions

Sediment diversions are being planned as a potentially important tool for land-building in the MRD plain. However, the suitability of these diversions to build land has been the subject of vigorous scientific and policy debate (Howes et al. 2010; Kearney et al. 2011). The geologic record of the Mississippi River Delta, and the shape of the MRD landscape demonstrate that natural diversions (or crevasses) in the pre-industrial lower Mississippi River Valley have been powerful agents in building the modern delta. These crevasses deposited sediment from breaks in natural river levees and from overbank flow. With an average size of 1680 km^2, at least 20 crevasses were active in the time period from 1750 to 1927, rapidly building land adjacent to the main distributaries (Davis 2000). Much of the inhabited and agricultural land in the lower delta occurs on natural levee and crevasse-splay deposits. River-sediment diversions are designed to mimic the natural pattern of deltaic land formation.

The land-building capacity of a diversion is fundamentally expressed as the ability of sediment deposited from the flow to cause local increase in the elevation of land or seabed surface. More specifically, the change of local land or seabed elevation is a function of interacting rates of global sea-level rise, local subsidence, local sediment supply, local sediment retention, and local self-weight compaction, combined with the organic contributions of wetland plant growth (Blum and Roberts 2009; Paola et al. 2011). If combined rates of sea-level rise, subsidence, and compaction (or "sink" terms) locally exceed combined sediment source and retention ("supply" terms), then land will not build. If supply terms exceed sink terms, then land will build, and the time required for building land will be controlled by the initial water depth, and the magnitude of the difference between the supply and sink terms.

Types of River Diversions

Constructed river diversions are in widespread use globally, and five major examples exist in the MRD plain alone. However, not all diversions were initially designed for the same purpose. Diversions have been built for flood control, land-building, irrigation, and wetland salinity control, and are operated in many ways (i.e., from uncontrolled flow to carefully constrained flow). To serve these specific purposes, diversions are generally designed to control both water and sediment delivery by taking advantage of characteristics such as location and size of the diversion, type of diversion structure, and scheduling operations with respect to flood stage and sediment concentration.

Examples of major river diversions designed expressly to build land include diversions from the Huang He (China) and Brazos (Texas) rivers (Syvitski and Saito 2007). In the MRD, the West Bay diversion near Head of Passes was also designed to build land. Extensive subaqueous deposits have formed since the diversion was opened in 2004, but new sediments became emergent in West Bay only in 2011 following a historic flood, nearly a decade after construction (Andrus 2007; Andrus and Bentley 2007; Barras and Padgett 2009; Kemp Personal Communication).

Diversions are also constructed for flood control. The Po River (Italy) has been intensely managed for this purpose since the Italian Renaissance (Corregiari 2005), and many other examples exist worldwide (Syvitski and Kettner 2011). In the Mississippi Delta, the Old River Control Structure diverts flood waters from the Mississippi River to decrease downstream flood stages, and consequently this diversion has built land on the Atchafalaya River floodplain and delta. The Wax Lake Outlet of the Atchafalaya River was designed to provide flood control for downstream Morgan City (Louisiana), and has built an extensive shallow-water delta in Atchafalaya Bay (Roberts 1998). The Bonnet Carré Spillway of the Mississippi was designed to ease flood pressure on New Orleans, and has been opened ten times since construction in 1932. Within the spillway itself, up to 2m of new sediment have accumulated since 1932; these new sediments are mined for local construction use (Day et al. 2012). According to Nittrouer et al. (2012), the location of the Bonnet Carre Spillway is exceptionally conducive to capturing sand from the Mississippi River, owing to local hydrodynamic conditions. A short-lived diversion on the Mississippi downstream from New Orleans was created during the Great Flood of 1927, when the Carnarvon levee was breached with dynamite to lower flood levels. Crevasse splay deposits from that event deposited up to 30 cm of mineral sediment (Cable Personal Communication).

Some of the most widely recognized diversions in Louisiana, the Caernarvon and Davis Pond diversions, are called "freshwater diversions" because they are operated to control salinity levels, and their discharge contains relatively

Fig. 5 Caernarvon Diversion showing Big Mar Lake receiving diversion flow, ~4 km^2 of new wetlands have developed in the past decade (Courtesy Lake Pontchartrain Basin Foundation)

little sediment (i.e., the Caernarvon and Davis Pond diversions; Day et al. 2009; DeLaune et al. 2003). These diversions generally flow at less than 10,000 cubic feet per second (<300 m^3/s) (Day et al. 2009). Davis Pond has not yet built extensive sediment deposits, but Caernarvon diversion flow has built about 4 km^2 of new wetlands in the past decade (John Lopez personal communication, Fig. 5). In contrast, the West Bay Diversion flows at >1,000 m^3/s during high river stages (Andrus 2007); the Wax Lake Outlet and Bonnet Carré Spillway each exceeded 5,000 and 8,000 m^3/s respectively for over two months in 2011 (Bentley et al. 2012; Chatanantavet et al. 2012; SEST 2012), while natural historic crevasses had maximum flow rates between 5,000 and 10,000 m^3/s (Fabre 2012; Kolker et al. 2012; Snedden et al. 2007). Each of these larger flow examples has created extensive sediment deposits.

Case Studies

From the above examples, does evidence support a case for river diversions to build land, especially in the MRD plain at present and projected rates of sea-level rise and local subsidence? We propose that the answer is Yes, if diversions are situated where local subsidence is not excessive, and such that sufficient water and sediment can be conveyed by the diversion. Four specific examples and one historical pattern support this: (1) the Wax Lake Outlet of the Atchafalaya River (where a bay-head delta is forming, see Fig. 1); (2) the Bonnet Carré Spillway (where the spillway floor is aggrading due to sediment deposition during spillway operation, see Fig. 2); (3) deposits formed by the 1927 Caernarvon Crevasse (which yielded 17.7×10^9 kg of sediment deposited over a region of approximately 150 km^2 (Kemp Personal Communication; Roberts 1997); (4) the Cubit's Gap subdelta (formed over about 75 years from a man-made breach in the levee near Head of Passes, see Fig. 3 (Roberts 1997); and (5) the existence of an elevated natural levee network in the MRD plain (mostly crevasse-splay deposits from historical and pre-historic levee breaches, (Davis 2000; Roberts 1998). Of these examples, Wax Lake and Cubit's Gap provide the most complete view of fully developed subdeltas built due to human activities. Dent (1924) and later Coleman and Gagliano (1964) mapped sediment deposits in the Bird's Foot Delta using cores and historic coastal charts and documented extensive subdelta growth (land building) in areas that were historically open water, from 1838 to the 1960's.

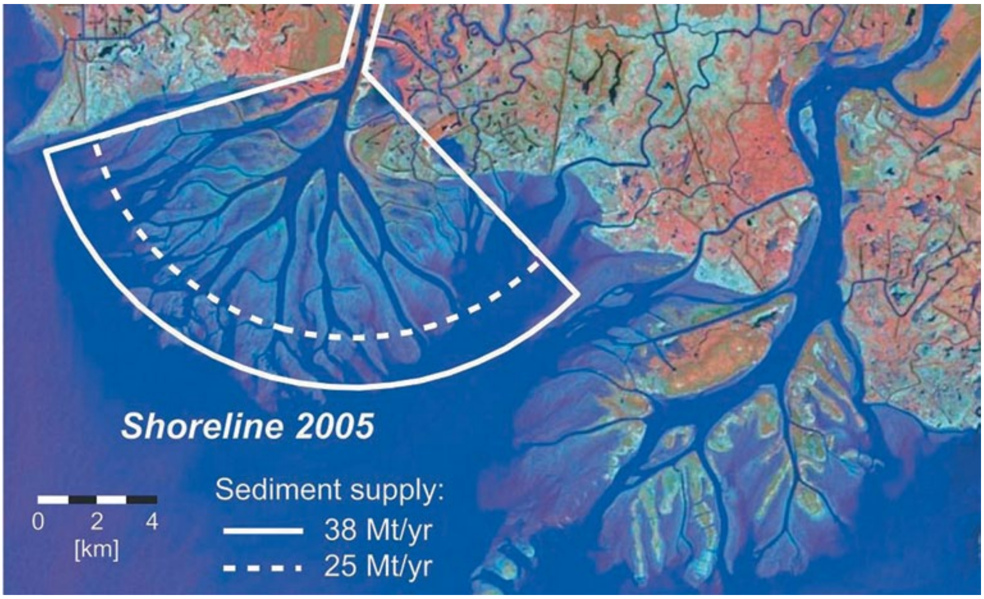

Fig. 6 Wax Lake (*left*) and Atchafalaya River (*right*) deltas, SW Louisiana, showing model hindcast of delta extent. (Kim et al. 2009. Reproduced/modified by permission of American Geophysical Union)

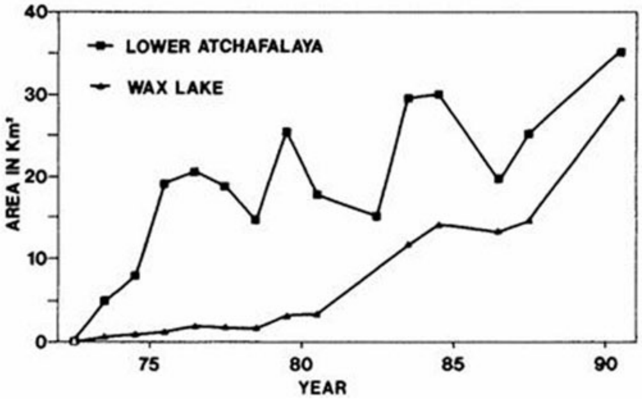

Fig. 7 Growth curve of the Wax Lake and Atchafalaya deltas from Roberts and Van Heerden (1992) cited in Roberts (1997)

Wax Lake Delta

The Wax Lake Outlet of the Atchafalaya River (Figs. 1 and 6) was completed by the United States Army Corps of Engineers (USACE) in 1942 to relieve flood pressure downstream in Morgan City, LA (Roberts 1998). A subaerial delta at the outlet mouth became emergent following the 1973 flood, and has grown rapidly in extent from rates of 2–3 km^2/year to about 100 km^2 in 2005 (Kim et al. 2009; Roberts 1997; Wellner et al. 2005) (Figs. 6 and 7). Measurements and model simulations by Kim et al. (2009) show that this delta growth occurred historically even as local subsidence rates were 5 mm/yr and sea-level rise was 2 mm/yr, and they predict this growth could continue to develop even as the combined rates of subsidence and sea-level rise up to 14 mm/y. This range of net subsidence plus sea-level rise is characteristic of present and projected conditions for much of the MRD plain (Blum and Roberts, 2009; Kim et al., 2009; Tornqvist et al., 2008).

Cubits Gap Subdelta

The Cubits Gap subdelta, upstream from the Head of Passes (Fig. 3, Fig. 8), developed from a manmade cut in the Mississippi River bank in 1862 to allow fishing boats access to Bay Rondo to the east (Welder 1959). By 1868, the gap widened to > 200 m, and over the next two decades an extensive subdelta developed that had remarkable similarities to the Wax Lake delta at the same age (Roberts 1998). The subdelta reached a maximum extent of about 200 km^2 by the 1940s, growing at rates of 2–3 km^2/year, after which the delta extent declined due to declining hydraulic efficiency and local subsidence, characteristic of the Delta Cycle, (Roberts 1997, 1998) (Fig. 8). This subdelta is one of six subdeltas that comprise the Bird's Foot Delta of the Mississippi downstream of the communities of Buras and Empire (Coleman and Gagliano 1964).

Caernarvon Diversion

The Caernarvon diversion is one of the two largest constructed freshwater diversions that are subject to strict flow regulation; the other being Davis Pond (See Day et al. 2009 for a review of studies at Caernarvon prior to Hurricane Katrina). Because it has been well studied, a number of lessons can be learned here. The Caernarvon diversion was designed to supply fresh water and optimize salinities for oyster cultivation; it was not designed to supply sediment and build land. The diversion was initiated in 1992 and has discharged, on average, considerably less water than the maximum rated flow capacity of about 220 m^3/s (Lane et al. 2006; Lane et al. 1999).

Sediment accretion in streamside marshes at Caernarvon, and also the nearby West Pointe a la Hache diversion have been sufficient to keep up with local relative water-level rise (DeLaune et al. 2003; Lane et al. 2006). As indicated earlier,

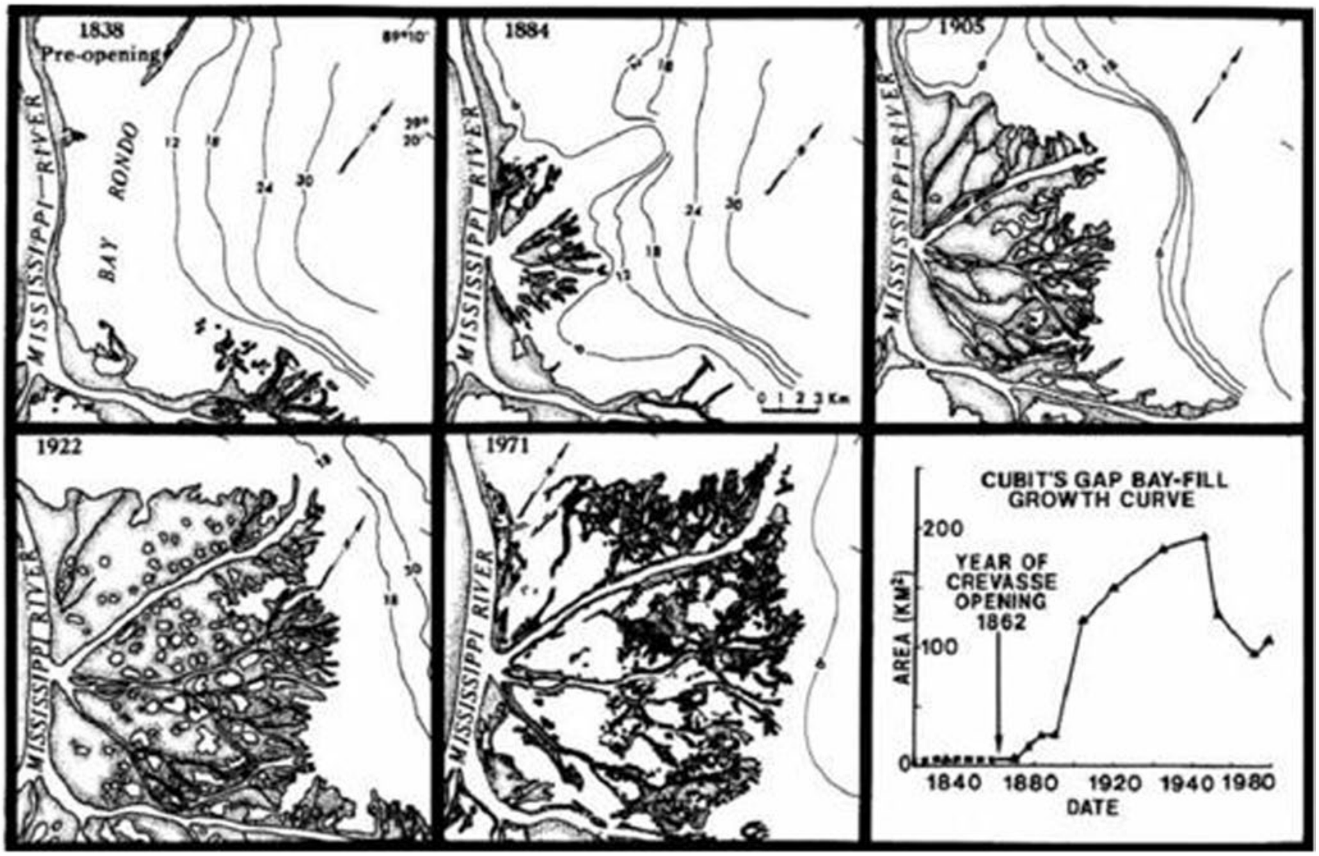

Fig. 8 Historical evolution and growth curve of the Cubits Gap Subdelta, adapted from Wells et al. (1983)

sediment capture is rapidly filling Big Mar Lake, in which about 4 km^2 of new land has emerged in the past five years. More sediment should be passed further downstream as Big Mar is filled. Nutrients introduced in river water are generally rapidly assimilated, especially nitrate and total nitrogen (Hyfield et al. 2008; Lane et al. 2007; Lane et al. 2004; Lane et al. 1999).

Hurricane Katrina caused the loss of about 500 km^2 of marsh out of a total of about 1100 km^2 (Morton and Barras 2011), in the Breton Sound region, encompassing Caernarvon and Big Mar. Much speculation has occurred regarding the cause and possible solution of this hurricane-induced loss. Howes et al. (2010) reported that river input weakened the marsh soil at Caernarvon making it more susceptible to hurricane damage. Kearney et al. (2011) concluded that high nutrient input led to poor rhizome and root growth leading to weak soils. However, Day et al. (2009) reported high belowground biomass in streamside marshes affected by the Caernarvon diversion. Morton and Barras (2011) reported that hurricane surge coupled with significant wave action regularly disrupt low salinity and freshwater marshes whether or not a diversion is present. These marshes tend to recover over time. The marshes near Caernarvon were disturbed during the 1947 hurricane and Hurricane Betsy in 1965. Thus, questions remain about the mechanisms leading to marsh disruption. Excessive nutrients, lack of sediments, and persistent low salinity conditions all may contribute to marsh loss or weakening soil strength. These factors should all be considered in diversion design and operation, with the goal of producing land building and vertical wetland accretion, as evident in the Wax Lake delta and nearby wetlands described above.

Bonnet Carre Spillway

The Bonnet Carre Spillway is a flood control structure built on the Mississippi River north of New Orleans in 1931. The spillway allows flood waters from the Mississippi to enter Lake Pontchartrain and then flow into the Gulf of Mexico. During the 2011 flood when river stages approached and locally exceeded records set by the Great Flood of 1927, large fluxes of water and sediment were delivered to Lake Pontchartrain by the spillway (Pennington et al. 1973). Bentley et al. (1973) and Fabre (2012) found that water discharge reached sustained rates of 8900 m^{3}s^{-1} and sediment discharge reached 77,000 metric tons d^{-1}. The authors estimated 1.1–3.8 million metric tons of fine sediment deposition in the lake. Results indicated that sediment retention in Lake Pontchartrain (with significantly fewer open boundaries to the ocean than Wax Lake or Cubits Gap) was near 100%

following the 2011 flood and operation of the Bonnet Carré spillway.

West Bay Delta

For comparison, the West Bay diversion near Head of Passes serves as an example of a partial success. The West Bay Diversion was designed to build land. Measurements of sediment flux and water depths in the receiving area during the first years of diversion operation show that subaqueous development has been occurring since it was opened with retention rates of 25–50 % (Andrus 2007; Andrus and Bentley 2007). These studies also suggested that West Bay's open connection with the coastal ocean reduced sediment retention, by allowing escape, rather than trapping, of suspended sediment. During the 2011 flood, subaerial deposits of apparently new sediment appeared (Kemp Personal Communication). The combined effects of local subsidence and rising sea-level may be too rapid to permit long-term stability of subaerial deposits in West Bay (e.g., Blum and Roberts 2009; Tornqvist et al. 2008). However, the success of the West Bay diversion in building land despite high subsidence rates and low sediment retention supports the potential of diversions as important tools for delta restoration. These results also suggest that land building would proceed more rapidly for diversions feeding inland basins with lower subsidence rates, and fewer open connections to the ocean (thus increasing sediment retention).

Timescales and Components of Delta/Subdelta Development

From these studies we learn that sediment diversions can build extensive land in open bays and coasts, if sufficient time, water, and sediment are provided and subsidence plus eustatic sea-level rise are not excessive. Natural timescales for development of these subdeltas are on the order of 50–75 years, followed by another 50–75 years of declining land area, if sediment supply is not maintained and/or subsidence and eustatic sea-level rise rates increase. Typical peak extents of these landforms are about 200 km^2. Crevasse splay deposits, which were historically important for forming and maintaining the natural levee of the MRD plain, developed over shorter timescales of 20–30 years and created deposits on the order of 15–20 km^2 in extent.

The rate of growth for these landforms is strongly influenced by the flux of sediment, as well as the retention rate. In Wax Lake, West Bay, and probably Cubit's Gap, sediment retention rates are/were on the order of 25–50 % (Andrus 2007; Andrus and Bentley 2007). For engineered diversions, retention rates and thus land growth could be increased by siting receiving basins in areas with less open water, shallower water (to allow vegetation to establish more rapidly, and contribute to soil volume), probably more vegetation (to slow flow and increase sediment deposition), and fewer direct connections to the ocean. Examples of such locations include wetlands and enclosed basins such as the upper Barataria Basin, or Big Mar farther east. The retention rates influencing crevasse splay deposits are not known with any confidence, but are likely to be of similar order, or higher, if flow entered enclosed swamps or basins, with less potential for re-suspension and transport than exists in more exposed water such as West Bay.

Significance of Events

For both West Bay and Wax Lake, diversions operated for years (West Bay) to decades (Wax Lake) before subaerial deposits emerged, and in each case this emergence was associated with major flood events. Elsewhere, flood events are important as well, as demonstrated by the thick sediment layer deposited in 1927 by Caernarvon crevasse outflow. In each case, however, the ability of a diversion to create new deltaic deposits is controlled by the following same factors: sediment supply rate, sediment retention efficiency, contributions of plant tissue to total sediment volume, and the submarine volume that must be filled to elevate deltaic deposits to a level where wetland plants can grow. In addition, the ability of a diversion to maintain the extent of new land is controlled by these supply factors, plus the rate of local sea-level change, which is controlled by the local subsidence rate plus the rate of global sea-level rise.

Diversion Design and Operation

These observations demonstrate that at least some diversions are capable of building substantial subaerial land from river sediment. With sediment retention rates of 25–50 %, these diversions have required decades to build subaerial land. Historical patterns of land growth and loss (Fig. 7) also suggest that, with continued subsidence and sea-level rise, sediment supply must be maintained.

One approach to shortening the time required for subaerial land development is to optimize sediment concentration in the source, and sediment retention in the sink. Optimizing the diversion design, location, and operation for sediment capture is expected to increase a diversion's land building capacity. One operational regime that is being investigated for both the White Ditch and Upper Barataria Diversions is pulsed operation of the diversion. A pulsed diversion would be operated as a freshwater diversion utilizing zero or low flows most of the year, and an additional pulsing capacity used for the relatively short period (weeks) involving high water events when significantly more sediment, in particular sand, is available in the water column. Data collected in specific reaches of the Mississippi River has shown a 50-fold increase above average in coarser-grained sediment in the river at flows of 2–3 times above average (Allison and Meselhe 2010). On the receiving end of the diversion structure, if sediment retention rates can be increased by careful selection and engineering of the basins into which diversions flow, the time required for building land can be decreased.

The Mississippi River does not now, nor has it ever, supplied enough sediment to continuously sustain the entire Mississippi Delta coastline because there were always some areas that were building and other areas that were eroding. In addition, the river-sediment supply is now at least half of historical levels, reducing our ability to build land. Nevertheless, the available sediment supply is still very large, and so we must learn how to use it efficiently, and decide how to allocate this valuable resource. One approach is to increase sediment flux by bypassing clogged dams, particularly on the Missouri River. A second goal is to better utilize increased sediment if river discharge increases as a result of climate change.

Three major factors will influence how efficiently land can be built with river sediment: (1) how much of the sediment delivered initially is deposited and retained, rather than transported out to sea; (2) how much sediment is eroded and moved away some time after deposition; and (3) how rapidly subsidence and global sea-level rise are raising local sea-level. By choosing to use river diversions that carry large sediment loads to build land, by maximizing the amount of sediment that is deposited, and by minimizing the amount of sediment that erodes, sediment retention can be increased. Good examples of such environments are swamps, marshes, and lakes that do not have extensive open connections to the ocean. In the short term, we cannot control global changes in sea-level, but we can choose to build land where local subsidence rates are relatively low. Because the highest regional subsidence rates are located on the modern Bird's Foot Delta (Fig. 3), and because many locations on the Bird's Foot Delta are also exposed to ocean currents, tides, and waves, this region is not ideal for efficiently building land. In addition, an active program to remobilize sediment captured in reservoirs would make more sediment available for delta restoration.

Climate change projections and increasing cost and scarcity of energy in coming decades make it imperative to take aggressive action soon to combat the effects of climate change while it is still affordable (see Chap. 11). Sea-level rise and more frequent strong hurricanes will lead to the loss of most coastal wetlands (Blum and Roberts 2009). Increases in precipitation, both as rain and snow, have led to increasing discharges by the Mississippi River system (Justić et al. 2003), and it is likely that large floods, such as in 2011, will occur more frequently as climate change intensifies (see Chap. 11). Large floods will likely bring larger volumes of sediments that can be used to offset wetland loss. Making effective use of this sediment for land building will require a commitment to a series of very large diversions strategically positioned to maximize sediment retention in appropriate coastal areas.

Emerging energy scarcity over coming decades will complicate long-term efforts to restore coastal wetlands because expensive, energy intensive actions will likely become much less affordable within a couple of decades. This fact indicates that the most energy-efficient and sustainable restoration tool is using the natural power of the Mississippi River. Although building large diversions is expensive, it will likely become progressively more expensive in coming decades. It seems clear that these forces will require new approaches to river management and flood control that are less reliant on dredging. And as the examples from Caernarvon, West Bay, and the Wax Lake and Atchafalaya deltas show, the benefits will accrue over time but we must be prepared for a relatively long lead time of subaqueous growth before subaerial growth occurs and emergent land appears.

Based on the foregoing information, what can be said about the size and location of diversions? It is clear that they must be much larger than the Caernarvon and Davis Pond diversions and they must be designed and operated to deliver more sediment, both fine and coarse, than these two diversions. Future diversions should approximate the size of the numerous natural diversions that occurred along the distributary channels as well as historic crevasses near the present Bonnet Carré Spillway, which regularly flowed at rates of 5,000–10,000 m^3/s (Davis 2000). The histories of these diversions show that large diversions need not function every year to be effective land builders. Multiple diversions at different locations along the river do not have to be operated simultaneously, so over many years sediment resources can be distributed over a wide area, fed by multiple diversions, minimizing stage reductions to the river. The Bonnet Carré has been opened about once a decade and elevations in the spillway between U.S. 61 and Lake Pontchartrain have risen as high as 2.0 m, far outstripping subsidence and sea-level rise. An aggressive program of very large diversions built in the near future, properly located and operated, will be necessary to offset the projected large-scale loss of wetlands. Both Blum and Roberts (2009) and Condrey et al. (2012) concluded that large diversions should be located as far inland within deltaic basins as possible. This would take advantage of higher upstream river stages that have power to deliver sediment and also control natural river avulsion patterns (Chatanantavet et al. 2012), and lead to a greater capture of sediment and restoration of coastal forested wetlands that are rapidly degrading. Construction of these diversions in the very near future would be a defense against rising energy costs because diversions like the Bonnet Carré Spillway can operate for more than a century using the river's natural energy of flow and with little ongoing human energy investment.

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Fisheries in a Changing Delta

James H. Cowan Jr., Linda A. Deegan and John W. Day

Abstract

Numerous investigations have demonstrated relationships between fisheries yields and the high primary productivities typical of estuaries and estuarine plume ecosystems. Along with the loss of wetlands, presumably so go functions related to them such as commercial harvests of fisheries. However, perhaps the most perplexing aspect of the Mississippi River delta ecosystem is the fact that there is little indication that fisheries productivity has decreased. Why aren't landings decreasing? We favor the explanation that fisheries of today reflect a degraded ecosystem attributable to environmental damages that began in the 1920s or earlier but that accelerated during the twentieth century. There are a few thorough reviews of differential use of habitat by estuarine fishes from other deltaic ecosystems that may allow us to speculate about how the loss of habitat in Louisiana may impact fisheries production. Greater than 75 % of the species that support fisheries in Louisiana are considered to be estuarine-resident or -dependent, and therefore it is likely to end badly for the Sportsman's Paradise if large-scale restoration is not possible, or if possible, not undertaken. Large-scale restoration will cause shifts in the locations of the major fisheries but it may be the only hope of maintaining sustainable fisheries.

Keywords

Fisheries landings · Trophic transfer · Habitat change · Primary productivity · Estuarine ecosystem

Introduction

A number of investigations have demonstrated relationships between fisheries yields and the high nutrient loads, freshwater inputs, shallow depths, large areas of tidal mixing, coastal vegetated area, surface of lagoon-estuarine systems, and resulting high primary productivities that are typical of estuaries, and estuarine plume ecosystems (see Deegan et al. 1986; Nixon 1988; Iverson 1990; Sanchez-Gil and Yáñez-Arancibia 1997; Yáñez-Arancibia et al. 2004). Thus, despite the small aggregate spatial extent of estuaries (< 1 % of the global marine area), a fraction exceeding 50 % of U.S. marine fishery yields have historically been derived from estuarine or estuarine-dependent species (Gunter 1967; McHugh 1967; Houde and Rutherford 1993; Vidal-Hernandez and Pauly 2004). In the Gulf of Mexico (hereafter Gulf), the fraction is considerably higher (Houde and Rutherford 1993); estuarine-dependent species dominate in large and valuable commercial and recreational catches (e.g., gulf menhaden *Brevoortia patronus* support the second

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largest U.S. fishery by weight, penaeid shrimps support the fifth largest by value, with shrimp landings alone valued at $ 400–500 million per year).

A large fraction of the harvested secondary production in the Gulf's 'fertile crescent' is derived from estuarine ecosystems, including areas on the shallow shelf influenced by estuarine plumes (Darnell 1990; Christensen and Pauly 1993; Chesney and Baltz 2001; Sanchez-Gil and Yáñez-Arancibia 1997; Day et al. 2004). Characteristic of these estuaries are high river discharge rates, large freshwater surpluses, low water residence times, and large wetland areas. This suggests that much of the production and subsequent trophic transfer may occur outside of the physical boundaries of the estuaries, i.e., in association with plumes of freshwater over shallow continental shelves. These contrasting mechanisms of trophic delivery to the fishery forage base, and ultimately to larger consumers (i.e., estuary versus shelf) introduce uncertainty in how we view the functionality of estuaries and the shelf ecosystems they influence.

Disentangling the relative contributions to fisheries production of estuarine vs. estuarine-like inner shelf ecosystems may be key to long-term resource management, especially in light of rapidly changing conditions. For example, the Mississippi River delta is a complex system including vast areas of water bodies and wetlands (~15,000 km^2 of wetlands alone) in which the rate of land loss has reached catastrophic proportions. Within the last 50 years, land loss rates have exceeded 103 km^2 per year, and in the 1990's the rate has been estimated to be between 65 and 90 km^2 per year. This loss represents about 80 % of the coastal wetland loss in the continental United States. The reasons for wetland loss are complex and vary across the state (e.g., Day et al. 2007). Since the scale of the problem was recognized and quantified in the 1970's, much has been learned about the factors that cause marshes to change to open water and that result in barrier island fragmentation and submergence. The effects of natural processes like subsidence and storms have combined with human actions at large and small scales to produce an ecosystem that may be on the verge of collapse. If recent loss rates continue into the future, even taking into account current restoration efforts, then by 2050 coastal Louisiana will lose more than 250,000 additional hectares of coastal marshes, swamps, and islands. The loss could be greater, especially if worst-case scenario projections of sea-level rise and other climate forcings like increased hurricane intensity are realized (e.g., Blum and Roberts 2009), but in some places there is nothing left to lose. Along with the loss of wetlands, presumably so goes the loss of the various functions and values associated with them: commercial harvests of fisheries, furbearers and alligators; recreational fishing and hunting, and ecotourism; habitats for threatened and endangered species; water quality improvement; navigation corridors and port facilities; flood control, including buffering hurricane storm surges; and the intangible value of land settled centuries ago and passed down through generations. The public use value of this loss is estimated to be in excess of $ 37 billion by 2050 (LCWCRTF 1998; NRC 2006a). As such, we may be shooting at a moving target with respect to understanding ecosystem function (including fishery ecosystems), with large scale and rapid changes in fish habitat (much of which is human-induced) occurring against the backcloth of longer time-scale changes attributable to a variety of anthropogenic insults, climate change, and natural delta cycles (Kennedy et al. 2002; NRC 2006a).

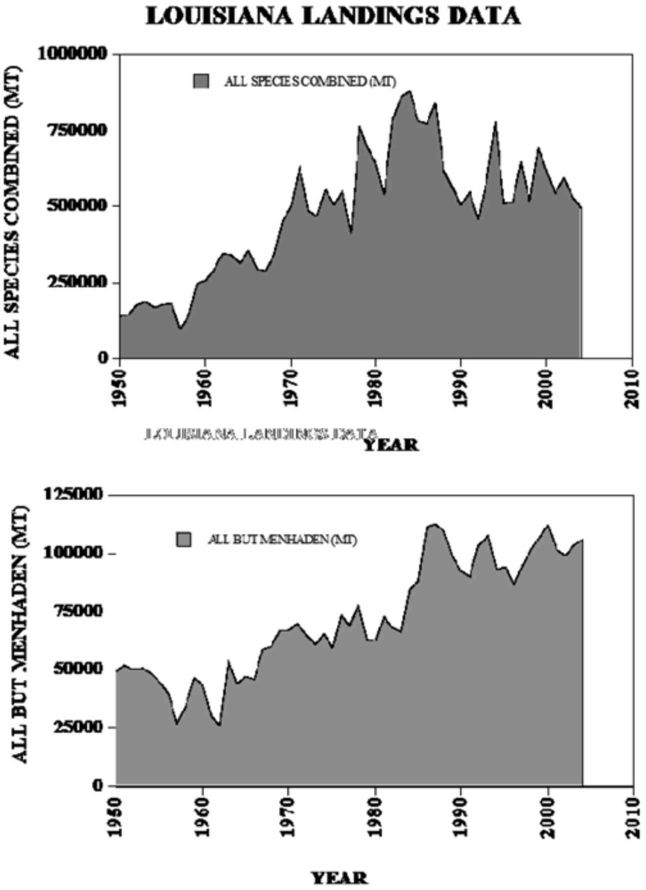


Fig. 1 *Top*. Louisiana commercial landings in metric tons, all species combined. *Bottom*. Louisiana commercial landings excluding gulf menhaden and penaeid shrimp (data from NMFS 2006)

Trends In Louisiana Fisheries

Perhaps the most perplexing aspect of the Mississippi River delta ecosystem, given environmental insults that the system has and continues to endure, is the fact that there is little indication that fisheries productivity has decreased. In fact, the opposite appears to be true if fishery landings (yields) reflect a true measure of productivity, especially if Gulf men-

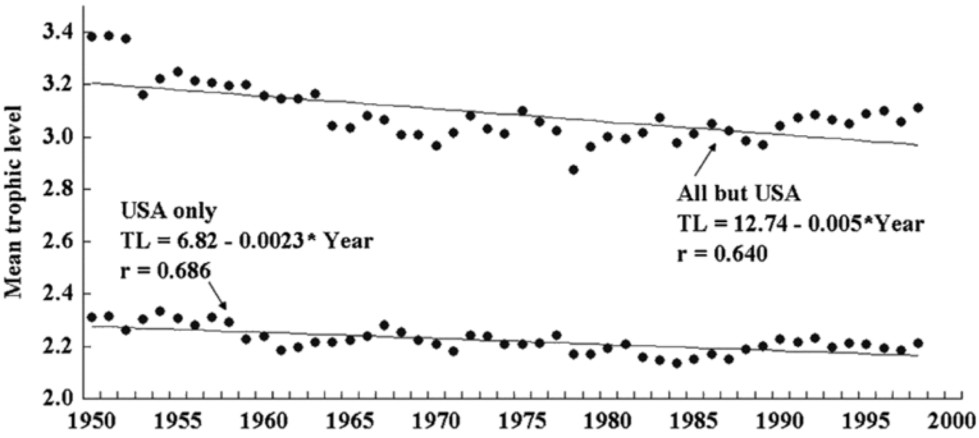


Fig. 2 The mean trophic level index for Caribbean (non-US) and combined Gulf of Mexico and South Atlantic (US only) commercial fisheries. Gulf of Mexico landings dominate the catches in the US region depicted

haden are excluded from catch statistics (Fig. 1). Declines in menhaden catches since the mid-1980s are largely due to changes in fishing regulations. Landings for all other species combined have increased over the period of record. Reasons for this apparent dilemma were discussed by Chesney et al. (2000), and we will not repeat this discussion beyond addressing some new findings that have appeared in the literature since the aforementioned paper was published.

The most significant of the new studies was published by Pauly and Palomares (2005) in which they calculated the Mean Trophic Level Index (Pauly et al. 1998) for Gulf of Mexico commercial fisheries. Briefly, the index is a biomass-weighted estimate of the mean trophic level of all species included in the commercial capture fisheries in a water body, with a declining slope over time in the index purported to indicate serial overfishing. While there has been significant debate over the value of this index as indicator of ecosystem health (NRC 2006b), the Gulf of Mexico index is worthy of discussion (Fig. 2, from Pauly and Palomares 2005).

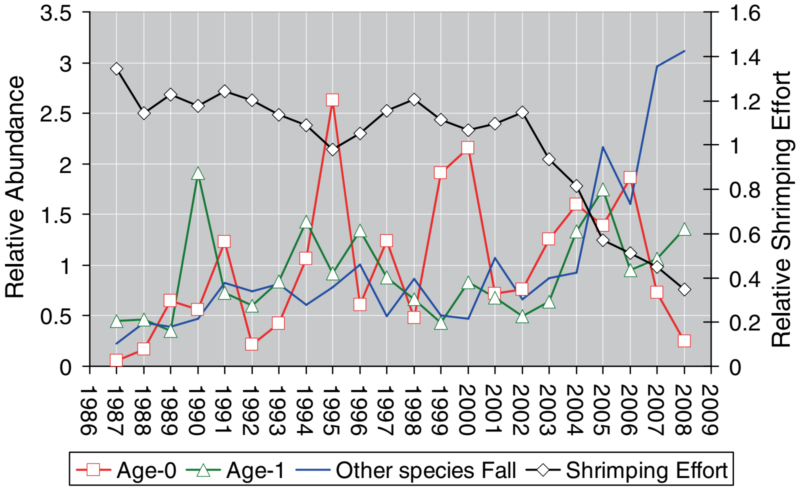
The Gulf situation is not notable because the index declines slowly through time as it does in most locations; rather it is notable because the index begins at a y-intercept (~2.3) that is much lower than for other seas (3–4). Pauly and Palomares (2005) concluded that this difference was attributable to a highly degraded food web in which the largest predators had long since been removed by fishing. One alternative interpretation is that the ecosystem supporting Gulf fisheries is so highly degraded that it can no longer support members of the food web at its apex.

Truthfully, neither of these explanations are easily defended because Gulf fisheries, of which ~75% are landed in Louisiana, have historically been dominated by gulf menhaden, which consume phytoplankton, and by penaeid shrimps, which are primarily detritivores (both of these taxa are assumed to be estuarine dependent). Thus a low mean trophic level index is a foregone conclusion for Gulf commercial fisheries if menhaden and shrimp are included in the calculations (De Mutsert et al. 2008). This interpretation is supported by the findings of Chesney et al. (2000) who detected only minor changes in the relative contribution of the species that make up the commercial landings exclusive of menhaden and shrimp, with only a slight increase in the relative abundance of these species thought to be less dependent on coastal wetlands as nursery habitat. The latter finding may be attributable, in part, to high numbers of demersal fishes (mostly juveniles) that are removed via bycatch in the Gulf shrimp fishery each year (see review by Diamond 2004). However, bycatch now is declining through time, and declines are attributable to improvements in efficiency of the shrimp fleet via technological changes and bycatch reduction measures, and significant declines in shrimp fishing effort due to high fuel prices and the low price of imported shrimp, especially since 2002. As such, groundfish biomass in the shallow Gulf has increased four-fold since 2002 (Blue line in Fig. 3), illustrating how difficult is the task of isolating environmental effects from the effects of fishing even for species that are not targeted.

It should be obvious by now that we do not understand how the Mississippi River plume ecosystem directly affects fisheries productivity, exclusive of habitat links to coastal wetlands that were created by the natural delta cycle (Day et al. 2000; NRC 2006a), beyond speculating that recruitment somehow is enhanced by the estuarine plume, which is a plausible hypothesis given the obvious high numbers of juvenile estuarine-dependent fishes found both on the shelf and in the estuaries. We also note that the life histories of the most important commercial species (menhaden and shrimp) favor resilience in the face of fishing pressure (Rose et al. 2001), and are essentially annual crops.

That said, the current configuration of the Mississippi River is artificial and represents a human-induced interruption of the natural delta cycle that began in a major way after flood control measures and farming practices were altered in response to the 1927 flood (NRC 2006a). These changes have resulted in reduced sediment loads in the river proper, and in a river that now discharges far offshore on the edge

Fig. 3 Relative abundance of age-0 and age-1 red snapper and total biomass of other species captured in the SEAMAP fall ground fish survey. Also shown is relative shrimping effort, which has been declining rapidly since 2002. (W. Ingram, NOAA Fisheries, Mississippi Laboratories, Pascagoula)



of the continental shelf (Day et al. 2000, 2007; NRC 2006a; Blum and Roberts 2009). Both have been linked the high rates of wetland loss attributable to deprivation of nutrients and sediments lost to the offshore environment. These changes, and others, likely also have contributed to hypoxia, and have been punctuated by significant hydrological changes (including saltwater intrusion) that began in earnest with oil and gas exploration in the 1930s and 1940s (LCWCRTF 1998; NRC 2006a) and the impacts of large north-south navigation channels such as the Mississippi River Gulf Outlet and the Calcasieu Ship Channel (Day et al 2000; Shaffer et al. 2009a). Saltwater intrusion has been directly linked to wetland loss (Shaffer et al. 2009b).

So why aren't landings decreasing? One explanation is that Pauly and Palomares (2005) are correct; fisheries productivity, while still high, reflects food web changes that occurred before the period of record. This may be true, but we do not believe that fishing is the likely cause of change. Rather, we favor the alternative explanation mentioned earlier—namely that the fisheries of today reflect a degraded ecosystem attributable to environmental insults that began in the 1920s or earlier but that accelerated during the twentieth century. Recruitment is the most obvious link to biomass and yields, but we have no real evidence that recruitment is limited and/or declining. Table 1 provides a short list of other factors that could be important, some of which have already been discussed.

As can be seen, it is striking that all of the factors listed may have both negative or positive/neutral effects. This may at first seem counterintuitive, but the explanations are quite simple. For example, consider wetland loss. The alteration of flow regimes in large river ecosystems and losses of emergent and submerged aquatic vegetation is a chronic problem worldwide and by no means unique to Louisiana (Nilsson et al. 2005; Syvitski et al. 2009; Voorsmarty et al. 2009). Evidence suggests that fishery landings are correlated with the spatial extent of estuarine vegetation (Doi et al. 1973; Deegan et al. 1986; Pauly and Ingles 1988; Chesney et al. 2000). "Indeed, the role of these nearshore ecosystems as nurseries is an established ecological concept accepted by scientists, conservation groups, managers, and the public and cited as justification for the protection and conservation of these areas…. The ecological processes operating in nursery habitats, as compared with other habitats, must support greater contributions to adult recruitment from any combination of four factors (1) density, (2) growth, (3) survival of juveniles, and (4) movement to adult habitats… " (Beck et al. 2001, pp. 633–635). Interestingly, these criteria established by wetland ecologists and managers clearly echo NOAA's National Marine Fisheries Service (NMFS) criteria for establishing essential fisheries habitat (EFH).

Table 1 Factors that contribute to or obscure the relationship between ecosystem health and changes in fisheries productivity. These factors can have both positive or negative effects depending upon the species in question

Wetland loss and habitat modification
Hypoxia and eutrophication
Fishing impacts/bycatch
Climate change

However, the relationship between fishery production (yields) and the loss of salt marsh habitat, however, is not clear, and we have already shown that Gulf landings appear to be increasing in spite of accumulating habitat losses (Zimmerman et al. 1989, 1991). One potential hypothesis is that marsh edge, i.e., perimeter, is the critical habitat for many species and that the nursery ground function/value will not decline or result in reduced landings until the quantity of marsh-edge perimeter declines. During marsh loss, the amount of marsh edge initially increases and then declines as healthy marsh is converted to broken marsh and then to open water. The transitory increase in marsh-edge perimeter, which occurs in the marsh break-up phase, may mask the immediate impacts of habitat loss on landings (Browder et al. 1985, 1989). Another related hypothesis postulates that marsh edge is not the critical habitat per se, but serves as the essential conduit for critical trophic exchanges with the flooded marsh (Zimmerman and Minello 1984; Hettler 1989; Chesney et al. 1990; Rakocinski et al. 1992; Baltz et al. 1993; Minello et al. 1994). So it is possible that marsh loss is actually having a positive impact, at least for now.

Eutrophication leads to hypoxia, but increased inorganic nutrient inputs have been to shown to increase fisheries yields as primary productivity is stimulated (Nixon 1988; Iverson 1990) from oligotrophy to mesotrophy, but yields can decline under eutrophic and/or dystrophic conditions, often rapidly (Caddy 1993). The latter situation can also result in increases in abundances of trophic dead ends such as gelatinous zooplankton that prey on fish early life history stages (Cowan and Houde 1992; 1993), thus exacerbating the decline. It is interesting to consider that increasing energy cost may increase the cost of fertilizer so much that hypoxia will be reduced because of lower fertilizer use.

Fishing impacts also have been discussed, but groundfish biomass in the Gulf is now increasing. Many of the species taken in the bycatch are estuarine-dependent, illustrating the difficulty of trying to tease an environmental signal from the backcloth of overexploitation.

Climate change too can have both positive and negative impacts. Worldwide, the fisheries for penaeid shrimps are highest nearer the equator than at the latitude of Louisiana (Kennedy et al. 2002), so modest increases in water temperatures may improve yields in this valuable fishery. However, in a study of factors that regulate benthic food webs in the tropical Fly (Papua New Guinea) and Amazon River deltas and adjacent shelf areas, Alongi and Robertson (1995) found that low food abundance can limit secondary production in areas near river mouths that are exposed to high sedimentation rates.

Historically, coastal wetlands in Louisiana have been dominated by *Spartina* sp. (and *Phragmites* sp. in the fresher Mississippi and Atchafalaya River deltas). Recently, however, black mangroves (*Avicennia germinans*) have expanded and proliferated along Louisiana's coastline due to lack of killing freezes, which in the past occurred on average every 4 years, but last occurred in 1989 (i.e., 22 years ago). By the end of the twenty-first century, tidal, saline habitat is likely to be dominated by mangroves rather than salt marsh if, that is, sea-level rise and hurricanes do not completely eliminate intertidal saline vegetation. Fisheries ecologists once widely assumed that both Spartina and black mangroves provided equally valuable nursery habitat (Manson et al. 2005) and that primary production from both habitats was readily transferred to higher trophic levels (Odum and Heald 1975). This paradigm, however, has been seriously challenged, with indications that mangrove detritus may not be contributing significantly to basal resources, and that decapods and finfishes use of all mangrove habitats may not be equally advantageous across habitat types and latitudes (Rodelli et al. 1984; Hatcher et al. 1989; Fleming et al. 1990; Chong et al. 1990; Hoss and Thayer 1993; Lee 1995; McIvor and Smith 1995; Marguillier et al. 1997; Sheridan and Hays 2003). Thus, the continued expansion of black mangroves has unknown consequences concerning nursery ground function and fisheries productivity in Louisiana.

Climate change threatens practically all coastal wetlands of the Mississippi delta due to the combined impacts of rising sea level, by as much as a meter or more, and salinity intrusion. Blum and Roberts (2009) projected loss of essentially all Mississippi delta wetlands by 2100 due to rising sea level and reduction of sediments in the river. This projection used the IPCC projection of eustatic sea-level rise of about 50 cm. This is less than half of more recent estimates (Rahmstorf et al. 2007; Vermeer and Rhamstorf 2009). Thus, practically all intertidal habitat used by fishery species will likely be gone by the end of the century unless there is an aggressive restoration program.

Complicating climate impacts are potentially dramatic increases in the cost and availability of energy. Rising fuel costs are already affecting fishing and continued increases may make fishing as presently carried out unsustainable. It is unclear how the fishing industry can adapt to these challenges. On the other hand, increased energy cost may make the cost of imports more expensive compared to local fisheries. For example, when oil prices reached nearly $ 150 a barrel, the U.S. steel industry became competitive with Chinese imports because of increased shipping costs. It may be that fisheries will have to change to more energy efficient methods

The Future of Louisiana Fisheries—Examples from Other Deltaic Ecosystems

It should be clear from the prevarication in the preceding paragraphs that is very difficult to guess, let alone predict, how fisheries productivity in Louisiana and the northern Gulf will change in response to aforementioned factors. Unfortunately, studies elsewhere provide little insight, as there are few comprehensive studies of secondary and tertiary productivity in deltaic ecosystems worldwide. But where they have been undertaken the most common injuries to fisheries productivity (or changes in species composition) are related to changes in river flow, and do not disentangle the effects of habitat change in the delta proper from changes in adjacent shelf areas (e.g., Leslie and Timmins 1991; Grimes 2001; Cowan et al. 2008). This is true in the Danube, Ebro, Niger, Nile, Po, Rhone and Colorado River Deltas where upstream changes in land use, and the construction of dams have resulted in decreases in fisheries productivity, changes in species composition, and or greater susceptibility to colonization by invasive species (Lumarea et al. 1993; Lae 1994; Lae 1995; Galindo-Bect et al. 2000; Wilson 2002; Elliot and Hemmingway 2002; Salen-Picard et al. 2002; Holcik 2003; Lloret et al. 2004). Few of these studies relate observed changes to loss of vegetated wetlands although Galindo-Bect et al. (2000) implicate habitat loss in the decline of the penaeid shrimp fishery in the Gulf of California.

That said, there are a few thorough reviews of differential use of habitat by estuarine fishes (Wilson 2002; Pihl et al. 2002; Costa et al. 2002; Nordlie 2003) that may allow us to speculate about how the loss of habitat in Louisiana may impact fisheries production. We believe, as do the authors of the aforementioned reviews, that it is not useful to consider the impacts of coastal wetland loss independently from other habitats in the estuarine ecosystem. To illustrate this point, we provide a cogent example found in Pihl et al. (2002). In their comprehensive review of European estuaries, they identify nine distinct habitat types in estuarine ecosystems, and then combine form (habitat type) and function (usage) in a useful semi-quantitative index of habitat utilization that includes habitat use by life history stage (eggs, larvae, juveniles and adults). This takes into account whether the fishes are estuary residents or transients, and also includes diadromous species that often migrate through an estuary to spawn as adults, while both adults and early life history stages can migrate out. The Habitat Utilization Index (HUI) is the sum of life history stages using a single habitat divided by the number of sites for that habitat in all estuaries combined. This index approximates the overlap between fish life history stages and the overall usage of each habitat type and their results are shown in. Table 2.

Table 2 The Habitat Utilization Index (HUI) calculated for European estuaries. The index represents the sum of fish life history stages using a single habitat divided by the number of sites for that habitat in all estuaries combined. (Pihl et al. 2002)

Habitat/Number	HUI
Tidal freshwater	23.1
Reed beds (2)	15.5
Saltmarsh (3)	19.3
Intertidal soft substrate (4)	37.6
Intertidal hard substrate (5)	9.0
Subtidal soft substrate (6)	69.7
Subtidal hard substrate (7)	43.3
Subtidal sea grass beds (8)	46.5
Biogenic reefs (9)	20.7

The HUI evaluates a habitat on the basis of an average number of uses made by all species and all life stages. The results are: subtidal soft > subtidal sea grass > subtidal hard > intertidal soft > tidal fresh > biogenic reefs > saltmarsh > reed beds > intertidal hard. It should be apparent by now that habitat complexity is only one part of the equation that determines the relative value of a particular habitat type to estuarine nekton. The HUI also does not sum to 100 %, stressing the fact that estuaries should be viewed as a matrix of interconnected habitats that can used by many species for the same or different functions, and for any single species, can used be used for different functions depending upon their life history stage.

The habitat attribute that is most important to use by estuarine nekton is the frequency of inundation, i.e., how often the habitat covered by water. Habitats that are always flooded are the habitats that are most well utilized by estuarine fishes and other nekton species Among the habitats that are always flooded, subtidal soft substrate is the largest by areal extent, but also provides excellent feeding and nursery grounds for estuarine nekton. The structural complexity of subtidal sea grasses and subtidal hard substrate also is important both for feeding and refuge, showing that habitat complexity is an important attribute as well. Use by nekton in terms of habitat type and function does not vary significantly with latitude, suggesting that strong local gradients in factors such as temperature and salinity, or high variability among a variety of factors, create conditions to which relatively few species, excepting estuarine residents and dependents, can easily adapt.

While we have not made HUI calculations for Louisiana's deltaic habitats, only intertidal hard substrate among the nine identified by Pihl et al. is mostly lacking in Louisiana, and we believe that if calculations were done here, they would resemble those from Europe. This example, and our own research experience, suggest to us that changes in the coastal landscape that lead to continued wetland loss (or in our case, failure to change) will not act solely on wetlands, but will likely result in simplification of the estuarine habitat matrix, thus reducing the functional integration of habitat uses. Such changes will benefit some species, and greatly reduce the biomass and productivity of others. In Louisiana's case, the losers are likely to be those species that depend most strongly on, and are most tightly constrained to combinations of habitats found in, the habitat matrix unique to Louisiana's coastal deltaic ecosystem. Given that greater than 75 % of the species that support fisheries in Louisiana are considered to be estuarine-resident or -dependent, it is likely to end badly for the Sportman's Paradise if large-scale restoration is not possible, or if possible, not undertaken.

The Way Forward—Ecosystem Restoration and Louisiana Fisheries

While neither exhaustive, nor a thorough review of the issues identified, the list in Table 1 well illustrates that we may be approaching or have reached an important nexus in the history of fisheries productivity in the northern Gulf of Mexico (Fig. 4). Panel A assumes that the fisheries remain

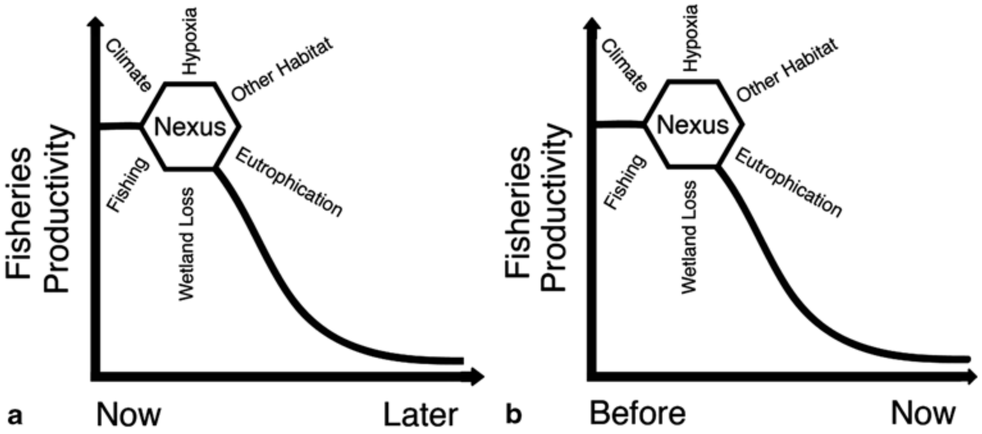


Fig. 4 The history or, perhaps, future of fisheries productivity in Louisiana, and presumed causes for change. Panel A assumes that the fisheries remain intact and near historical highs, but that we may be headed towards a steep decline if cumulative impacts reach a tipping point. Panel B assumes that Louisiana fisheries have already declined below historically higher levels

intact and near historic highs, but that we may be headed towards a steep decline if cumulative impacts reach a tipping point. Panel B assumes that Louisiana fisheries have already declined below some historically higher levels, the cause of which is overfishing, if Pauly and Palomares (2005) are correct. If the latter is true, the path forward may simply be more conservative fishing regulations.

On the other hand, if either Panel A or B is correct, and declines in productivity have been (or will be) attributable to declines in the Mississippi River ecosystem's ability to provide the previously described habitat matrices, the path forward will much more complicated.

Louisiana accounts for 60–80 % of the nation's total annual coastal wetland loss, the causes of which are largely anthropogenic and well documented (Boesch et al. 1994; Day et al. 2000, 2007; NRC 2006a). Continued alteration, degradation, and loss of Louisiana's estuarine and wetland habitats, makes knowledge of the relationship between habitat stability, and its affects on nursery ground function and fishery production critical. To confront this issue in Louisiana and elsewhere, concepts of ecosystem management and sustainable development have become part of state, national and international dialogue about adaptive environmental management, as emphasized in the President's Commission Report on the State of the Ocean, the Pew Ocean's Report, and language in the recent Sustainable Fisheries Act. Formulation and implementation of long-term, sustainable coastal policies and integrated management strategies demand a better understanding of: (1) habitat and ecological stability and associated functional responses to both episodic and chronic insults, especially given the limited vitality of already-stressed coastal ecosystems; and, (2) the compounding and complex effects of multiple impacts superimposed on issues associated with shifting baselines and climate change (Jackson et al. 2001).

Issues facing Mississippi deltaic ecosystems are not unique, but Hurricanes Katrina and Rita in 2005 and Gustav in 2008, as well as the Deepwater Horizon oil spill in 2010, which cumulatively caused loss or degradation of many hundreds of square kilometers of coastal marshes, caused Louisiana to renew its commitment to preserve and restore coastal ecosystems in the region by managing the impacts of human activities through the Coastal Wetlands Planning, Protection and Restoration Act of 1990 (CWPPRA), Coast 2050 and Coastal Louisiana Environmental Assessment and Restoration (CLEAR) programs. These initiatives include large-scale sediment diversions, use of wetlands to provide tertiary assimilation of treated municipal effluent and surface runoff, proactive management of wetland water control structures, as well as creative mitigation banking involving habitat enhancement and creation to offset environmental impacts. But the question remains—can we steer a degraded ecosystem towards some alternate steady state that resembles an historical baseline?

It is possible, we believe, that restoration activities that are being proposed in Louisiana may be able to do just that, based primarily upon the assertion that large-scale re-introduction of Mississippi River sediments can significantly shift the ecological baseline back towards pre-storm conditions in the short-term, and towards less degraded baseline conditions in the longer term. However, we recognize the difficulties embodied by this assertion. While recent research (DeLaune et al. 2003; Day et al. 2003; Mitsch et al. 2005; Day et al. 2009; DeMutsert 2010) has buoyed our confidence in the ability to restore degraded wetlands through large-scale sediment diversions, we understand that there are fundamental differences in opinion in the likelihood of long-term success (Howes et al. 2010) that are dependent upon overall system behavior.

One endpoint of the continuum of possible system responses to restoration efforts infers that the Louisiana coastal ecosystem experienced a regime shift when large-scale leveeing began on the Mississippi River, and oil and gas exploration began in earnest. One important characteristic of regime shifts is that they are usually driven by bottom-up processes, such as climate variability and resulting changes

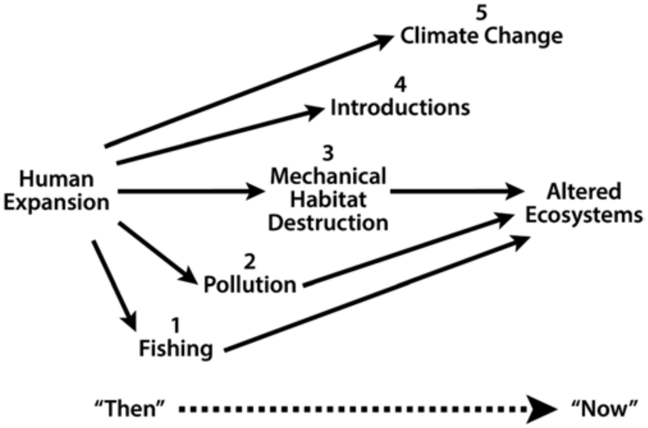


Fig. 5 Examples of top-down controls induced by human expansion resulting in altered ecological baselines. (from Jackson et al. 2001)

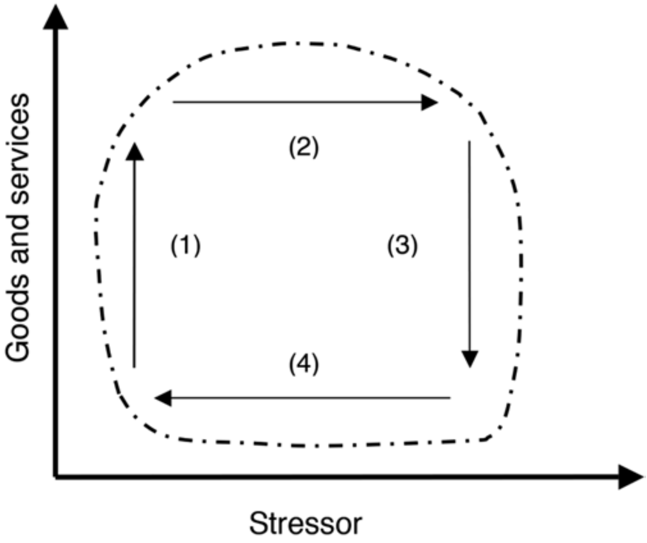


Fig. 6 A hysteresis loop whereby some components of an ecosystem fail to respondthrough time as expected, delaying recovery despite a decrease in stress (Cowan et al. 2008).

in species composition, and in primary and secondary productivity, or by analogy in the case of Louisiana, shifts in the position of the main Mississippi River distributary mouth, and are inherently reversible. Perhaps the most well studied example of regime shifts occur in the eastern Pacific Ocean in response to decadal scale variability in the relative position and strength of atmospheric highs and lows over the north Pacific (i.e., the Pacific Decadal Oscillation). Large-scale climate variability produces bottom-up changes in coastal ecosystems such that during cold regimes, anchovies are favored, and during warmer periods, sardines replace anchovies as the dominant forage species in Pacific Ocean ecosystems (Belda 1999). This type of response is illustrated in a fisheries example by the cycling of anchovy and sardine populations in a variety of locations. It is important to note that after each shift, the ecosystem reverts to an alternate steady state, followed by a recovery of the system to near its previous state prior to the change in climate. If the Louisiana coastal ecosystem responds to restoration as has the north Pacific to climate variability, restoration efforts may produce a nearly linear response in efforts to restore ecosystems goods and services, including fisheries productivity (Walters and Jones 1976).

Another endpoint involves the possibility that the Louisiana coastal zone will respond to restoration efforts in a way that will be more challenging to overcome. In several recent studies it has been shown that human-induced changes in ecosystem function result from top-down effects such as fishing, habitat modifications, pollution, eutrophication, etc., resulting in a shift in the ecological baseline (Jackson et al. 2001, Fig. 5). In such cases, the altered ecosystems are often much less responsive to management actions that attempt to recover ecosystem functionality. This occurs for a variety of reasons ranging from reductions or changes in habitat, to reorganizations of food-webs because of the removal of top predators (NRC 2006b). Regardless of the mechanisms, however, alternate steady states that have been caused by forcing from the top-down may be less likely to return to a state that resembles "pristine", and thus less likely to provide ecological goods and services and fisheries productivity that are similar to pre-disturbed conditions (Jones and Walters 1976).

Perhaps the most notable example of a large-scale shift in the ecological baseline of a fisheries ecosystem occurred on Georges Bank in response to long-term overfishing of ground fish stocks (Rosenberg et al. 2005). In this case, due to extreme top-down forcing attributable both to fishing pressure and habitat alterations from bottom trawling, the Georges Bank food-web reorganized and the more desirable gadoid groundfish complex was replaced by elasmobranches. Despite a tremendous 10-year reduction in fishing pressure, the Georges Bank fishery has failed to recover overall, although the level of recovery is highly species-specific (haddock show recent increases in recruitment while cod remain depressed; Fogarty et al. 2001), illustrating another important aspect of baseline shifts.

In highly degraded systems, species-specific variability in the rate of response to efforts to mitigate and restore man-induced changes in ecosystem function is not uncommon (NRC 2006b). Some species, or even groups of species, exhibit hysteresis and do not respond to management as expected. As illustrated in Fig. 6 (Steele J., personal communication), hysteresis occurs when ecosystem constituents increase rapidly when stress is low (1), reach a stable steady state when available resources are fully utilized or as ecological stressors increase through time (2), and subsequently collapse when stress becomes excessive (3). As suggested by the Georges Bank example, some components of the ecosystem then will fail to recover even (4) as ecological stress is decreases. So the question now becomes—Will the Louisiana coastal ecosystem and its related fisheries productivity respond to restoration efforts as if the region has experienced a regime shift, or a shift in the ecological baseline? Is the distinction important?

We contend that this distinction speaks directly to whether our coastal ecosystems can or cannot be restored, and their fisheries productivity held intact or increased. Moreover, answers to these questions are fundamental to understanding the relationships between fish and marsh habitats, and can only be answered by explicitly linking studies of wetlands functioning to studies of fisheries habitat.

We have reason to be optimistic even though we expect some components of the ecosystem, particularly higher trophic levels, to recover more slowly then others as wetlands are restored (Rozas et al. 2005). Our optimism is based upon the premise that the current degraded condition of Louisiana's coastal wetlands, although driven by human activities from the top down, represents changes that mimic a natural and short, < 100-year interruption in a cycle of delta creation/decay that normally takes hundreds to thousands of years to complete. As such, large-scale restorations efforts to divert Mississippi River sediments back into degraded areas should begin the delta cycle anew and facilitate the "resetting" of prior conditions. This premise also infers that to delay restoration efforts could have important consequences on the likelihood and expected rates of ecosystem recovery.

Projected climate change argues for an aggressive restoration program. If current trends continue, essentially all coastal wetlands will disappear (Blum and Roberts 2009). This outcome would almost certainly lead to significant changes in the nature of fisheries productivity in the Gulf. Kim et al. (2009) report that large-scale sediment diversions on the order of the Wax Lake channel could restore considerable areas of coastal wetlands even with accelerated sea level rise. Large-scale restoration would cause shifts in the locations of the major fisheries but it may be our only hope of maintaining a sustainable fishery.

Increasing energy costs could have both positive and negative benefits for fisheries. Increasing energy costs will likely make imports more expensive and ultimately uncompetitive. This would also make Louisiana fisheries more expensive. But if more energy efficient fishing methods can be used (butterfly nets versus trawling, for example), then a sustainable fishery may be possible. Such a fishery would be different from current fisheries. This is a question that deserves much more thought.

In conclusion, there is much uncertainty how the various factors affecting fisheries interact. Thus far, combined interactions of fishing pressure, habitat loss, and water quality deterioration have not caused a decline in fisheries. It is also uncertain how restoration will impact fisheries.

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The Influence of Nutrients on the Coastal Wetlands of the Mississippi Delta

James T. Morris, J. Andy Nyman and Gary P. Shaffer

Abstract

Among the solutions being proposed for reversing wetland loss in the Mississippi River Delta are the creation of diversions to reintroduce suspended sediment carried in the river. In areas of rapid relative sea-level rise, as in the Mississippi Delta, it is generally accepted that a supply of sediment in flood water and mineral sedimentation are critical to sustaining wetlands. But plans to create diversions have raised questions about the collateral effects of nutrients carried in the Mississippi River, effects that may contravene the benefits of sediment. This review finds the balance of empirical and theoretical evidence supports that nutrients benefit above- and belowground plant production and that fresh water and sediment diversions can be effective and beneficial for restoring wetlands in the Delta, especially if designed to maximize sediment inputs. The input of sediment, nutrients, and fresh water will change the community composition of some wetlands and their biogeochemical processes. Most of the nitrogen input should be assimilated or denitrified. Labile organic matter is likely to degrade more quickly, but labile organic matter does not add 'new' soil volume and its speed of decay is of little consequence. Additional research is needed before we fully understand the consequences of nutrients on the preservation of organic matter in sediment, but building on what is known of the activities of lignin-degrading fungi and their enzymes, it is likely that refractory organic matter should increase and contribute positively to sediment accretion.

Keywords

Nitrogen · Nutrient · Plant development · Mississippi river delta · Sediment organic matter · Decomposition · Diversion · Sedimentation · Marsh restoration · Primary production · Model

Introduction

During the twentieth century a loss was observed of about 25% of coastal wetlands in Louisiana or about 4,800 km^2 (Britsch and Dunbar 1993; Couvillion et al. 2011). A variety of factors led to this including reduction of sediment input from the basin, pervasive alteration of the hydrology of the deltaic plain, enhanced subsidence due to petroleum extraction, and barrier island deterioration. Perhaps most important was the almost complete elimination of river input to the deltaic plain due to flood control levee construction and closure of distributaries which connected the river to the wetlands

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(Day et al. 2007). The overall trend reveals wetland loss is highest in older delta lobes (e.g., Terrebonne basin) and lowest in areas with active river input (e.g., Atchafalaya). Human-induced changes such as these have had important consequences for delta deterioration worldwide (Day et al. 1995, 1997; Syvitski et al. 2009).

The proposed solutions for restoration and stabilization of wetlands in the Mississippi River Delta include the reintroduction of sediment carried in the river by means of a series of river diversions. Diversions from the Mississippi River should generally: (1) affect sediment availability in a relatively small wetland area nearest the inflow site; (2) increase nutrient availability over a larger area; and (3) decrease salinity over an even larger area. Diversions designed to lower salinity over large areas of existing emergent wetlands are called freshwater diversions and are most common from just upstream of New Orleans to Point a la Hache (Boyer et al. 1997; Grossman 2009). The Atchafalaya delta complex can also be considered as a very large diversion. It is not possible to achieve wetland expansion or stabilization through sediment diversions without also introducing fresh water and nutrients, and therein lies the controversy.

One of the concerns is that high nutrient loadings from the Mississippi River, particularly of dissolved nitrogen, will reduce the capacity of highly organic marshes to respond to sea-level rise by increasing the rate of belowground decomposition (Swarzenski et al. 2008). Darby and Turner (2008a) reported that additions of inorganic nutrients reduced belowground biomass in *Spartina alterniflora* marshes in the Mississippi Delta and along the Atlantic coast of the U.S. and Canada. They suggested that this might decrease soil elevation and accelerate the conversion of emergent wetlands to open water. Morris and Bradley (1999) reported that fertilization of a marsh in North Inlet, SC led to an increase in soil respiration rates and a decline in soil organic matter content in the top 5 cm of sediment. Similarly, Wigand et al. (2009) reported a positive relationship between soil respiration rate and nitrogen loading at the watershed scale and an inverse relationship between respiration and soil organic carbon. Deegan et al. (2012) reported that nitrate enrichment of a highly organic New England salt marsh in Plum Island Estuary decreased the biomass of bank-stabilizing roots and increased microbial decomposition of organic matter, leading to a collapse of marsh edges into the creeks. These studies indicate that reduction in belowground biomass and increased soil organic matter mineralization following increased nutrient availability may reduce the capacity of wetlands to keep pace with sea-level rise.

However, other results differ. There are numerous examples in the literature of nutrients increasing root growth and belowground biomass. Anisfeld and Hill (2011) presented results of a 5-year fertilization experiment on a Long Island Sound salt marsh (with phosphorus and ammonium nitrate) that, like earlier studies, showed that fertilization increased aboveground primary production and CO_2 fluxes from the soil. However, fertilization with neither nitrogen nor phosphorus affected marsh elevation (relative to controls), reduced soil carbon, or decreased belowground primary production. Subsequent work by Morris et al. (2002) showed that the decline in surficial soil organic matter reported earlier (Morris and Bradley 1999) was most likely the result of an increase in sedimentation rate and dilution of soil organic matter by an increased mineral input in the fertilized plots.

This review is part of a broader study by an interdisciplinary group, the Science and Engineering Special Team, tasked with synthesizing the complex issues relating to the efficacy of creating sediment and water diversions along the Mississippi River to stabilize its delta. Our goal was to summarize what is known of nutrient effects, especially of nitrogen, on the production and decomposition of soil organic matter, vegetation, and sediment accretion; and, where possible, to resolve some of the inconsistencies in interpretation of data.

The Fate of Nitrogen

Ammonium is the dominant form of nitrogen available to wetland plants, but there are studies that show nitrate also is assimilated by marsh vegetation when available (Stewart et al. 1973; Mendelssohn 1979; Morris 1982). Indeed, nutrients introduced in river water generally are rapidly assimilated or denitrified by the receiving wetlands, especially nitrate (Lane et al. 1999; Mitsch et al. 2001; DeLaune et al. 2005a; Hyfield et al. 2008; Gardner and White 2010; Lane et al. 2010). Nitrogen fixation provides a major source of nitrogen to natural wetlands (Piehler et al. 1998; Nielsen et al. 2001; Tyler et al. 2003), probably in excess of what is derived from flood water (Abd. Aziz and Nedwell 1986; White and Howes 1994; Tyler et al. 2003), and typically there is more ammonium available in marsh pore water than there is nitrate and ammonium in flood water (e.g., Morris 2000).

The biogeochemistry and distribution of inorganic nitrogen in marsh sediments varies with salinity. This is in part due to the cation exchange properties of soil, which change dramatically with salinity (Rysgaard et al. 1999; Gardner et al. 1991). Seawater cations completely occupy the exchange sites on silts and clays at the salt water end of an estuary, effectively outcompeting ammonium. Consequently, ammonium is largely free in solution at the salt water end of an estuary, while at the freshwater end of the estuary ammonium is largely sorbed onto exchange sites (Seitzinger et al. 1991; Rysgaard et al. 1999). Thus, diversions that lower salinity also increase ammonium availability. In addition, seawater cations compete with ammonium for carriers on the root membrane and decrease the efficiency of ammonium uptake, that is, the half-saturation constant for ammonium uptake increases at higher salinities (Morris 1984). This explains why vegetation can be nitrogen-limited in an environment rich in ammonium.

A study of the fate of nitrogen in the Great Sippewissett Marsh in Massachusetts showed that of the $^{15}NH_{4+}$ injected experimentally into vegetated marsh sediment, 25 % was lost rapidly through nitrification-denitrification, 40 % remained even after 7 years, and 54–77 % of the export was accounted for by denitrification (White and Howes 1994). There is evidence that plant biomass is the major sink for free NH_{4+} and that in the absence of plants the balance is shifted in the direction of nitrification-denitrification (Morris 1991). But the study by White and Howes (1994) demonstrated that the bacteria compete effectively with salt marsh plants for NH_{4+}. The stoichiometry of heterotrophic dentrification (Patrick and Reddy 1976): $24NO_3^- + 5C_6H_{12}O_6 + 24H^+ \rightarrow 12N_2 + 30CO_2 + 42H_2O$ can be applied to the nitrogen load to place some limit on organic carbon consumption, but it is complicated by the fact that not all carbon sources support equivalent rates of denitrification (deCatanzaro and Beauchamp 1985).

Kaplan et al. (1979) estimated denitrification in the Great Sippewissett Marsh consumes 0.2–3.5 mg NO_3^-N m^{-2} d^{-1} (0.04–0.7 g $m^{-2}year^{-1}$, assuming a 200 day warm season), fed largely by nitrate in ground water, and accounts for < 0.1 % of belowground production. To put this in the context of the Mississippi River, the diversion at Caenarvon discharges 7.8×10^5 to 1.5×10^6 kg NO_3-N $year^{-1}$ into an 848 km^2 wetland at concentrations ranging from 1.2 to 1.8 mg l^{-1} before entering Breton Sound (Hyfield et al. 2008). This is equivalent to a NO_3-N load per unit marsh area ranging from 1 to 2 g $m^{-2}year^{-1}$ (71 to 142 mmol N m^{-2} $year^{-1}$), which represents only 1.1-2.4 g C m^{-2} $year^{-1}$ of primary production. In contrast, potential rates of denitrification at Caenarvon, measured in wetland sediments spiked with 1,750 and 3,500 mg NO_3-N m^{-2} d^{-1}, were of 57 and 87 mg N m^{-2} d^{-1} (equivalent to 21 and 32 g N $m^{-2}year^{-1}$), respectively (Delaune and Jugsujinda 2003). Van Zomeren et al. (2011) found that within 12 h of spiking a 10 cm water column over sediment with $^{15}NO_3$-N, the 2 mg l^{-1} concentration had dropped below detection, and 64 % of the label was unaccounted for in plant or sediment, and probably was denitrified. The details differ, but in general, nitrification-denitrification is a major sink for NH_{4+} in wetlands and denitification rapidly removes a majority of NO_3- at the expense of carbon roughly in the ratio of 30 moles of carbon to 24 moles of nitrate.

Effects on Productivity and Community

Plant production in coastal wetlands is limited primarily by nitrogen availability as well as by stresses from flooding, salinity, and sulfides (Mendelssohn and Morris 2000). There are important interactions among these factors that affect plant growth and biomass partitioning among roots, rhizomes, and leaves. Nutrient enrichment increases flood tolerance in some wetland species like baldcypress (*Taxodium distichum*) (Effler and Goyer 2006) and bulrush (*Schoenoplectus americanus*) (Langley et al. 2013), and increases salt tolerance in others like *Spartina alterniflora* (Cavalieri and Huang 1979). *Spartina patens*, perhaps the most common plant in coastal Louisiana, is a species whose salt tolerance does not increase with increasing nutrient availability, but it does benefit from reduced salinity (Merino et al. 2010, Fig. 1). There was no growth response to nutrients when the salinity exceeded 35 ppt but nutrients increased growth three-fold when salinity was less than 5 ppt (Fig. 1). The ratio of belowground to aboveground biomass was not affected by either nutrients or salinity and was a constant 0.23:1. Delaune et al. (2005b) reported a doubling of *S. patens* aboveground biomass in greenhouse treatments with additions of 10 g N m^{-2} and, like Merino et al. (2010), found a greater absolute response at 0 than at 8 ppt salinity.

Experience has shown that tree growth is enhanced in forested wetlands used to treat municipal effluent. At the discharge site of the Hammond Assimilation Wetland (HAW), growth of baldcypress was five-fold higher than in reference sites in the Maurepas swamp (Day et al. 2012), and increased primary production and sediment accretion in these sites have been sustained for decades (Day et al. 2004; Hunter et al. 2009). Basal diameter growth of baldcypress seedlings transplanted to treatment subunits ranged from 18.1 (±2.6) mm nearest the outfall to 8.0 (±0.9) mm at a distance 700 m downstream and 6.4 (±0.9) mm in a reference site near the HAW (Lundberg et al. 2011). However, this response is dependent on a favorable hydroperiod; flooding stress can prevent nutrients from enhancing tree growth (Keim et al. 2012).

The input of mineral sediment, fresh water, and nutrients will likely change plant community composition in fresh or brackish, peat-dominated wetlands, resulting in a complex cascade of events. An increased rate of mineral input may result in a marsh community that can vertically accrete faster and is more resilient to disturbance, provided that the soil organic matter is preserved. However, the creation of freshwater wetlands by diversions can result in weaker soils because low salinity marsh soils are generally weaker than higher salinity marsh soils (Howes et al. 2010; Morton and Barras 2011). On the other hand, lower salinity marshes have

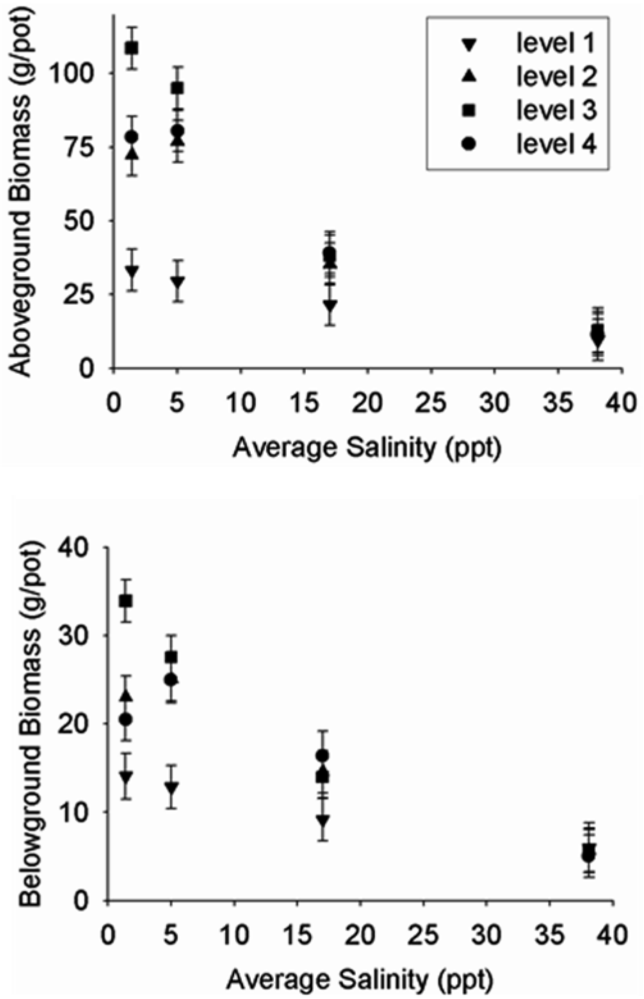

Fig. 1 The *above*- and *belowground* biomass of *Spartina patens* grown at different salinities and at different levels of nutrients, harvested after 144 days of treatment in a greenhouse. Nutrient levels were (1) 0.5 & 0.024, (2) 1.46 & 0.07, (3) 2.43 & 0.12, and (4) 3.89 & 0.19 mg N cm^{-3} & mg P cm^{-3} of soil, respectively. (Modified from data in Merino et al. (2010))

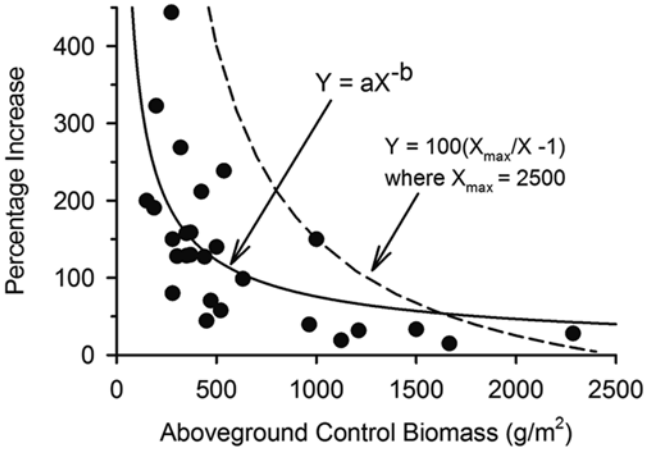

Fig. 2 The relative increase in dry standing biomass of *Spartina alterniflora* after 1 or more years of fertilization with nitrogen or a combination of nitrogen and other nutrients relative to the maximum biomass observed during a growing season on control plots. Also shown are the best fit of a power function (—, a=9,377, b=0.7, r^2=0.41) and a theoretical curve (- - -) generated by assuming each control plot's biomass was increased to a hypothetical maximum of 2,500 g m^{-2}. Updated from Morris (1991). (Sources: Gallagher 1975; Valiela et al. 1975; Patrick and DeLaune 1976; Haines 1979; Mendelssohn 1979; Buresh et al. 1980; Cavalieri and Huang 1981; Silliman and Zieman 2001; Gratton and Denno 2003; Tyler et al. 2003; McFarlin 2004; Olcott 2011; Morris et al. 2013; and Zhang et al. 2013)

the capacity to recover from disturbance via the spread of perennial, rhizomatous plants such as *Typha*, *Panicum*, and *Phragmites* that convert open water to emergent marsh (van der Valk 1981), whereas salt marshes lack such capacity. One solution would be to pulse diversions to allow periodic salt intrusion from late summer through spring.

Plant species do not benefit equally from nutrient enrichment, and it can be anticipated that river diversions will modify plant community composition; this will be most pronounced at the freshwater end of the system. Nitrophilous species such as *Phragmites* and *Typha* could in many cases replace established species (Rickey and Anderson 2004). Moreover, river diversions will reduce salinity, and this too will shift species composition in places away from species typical of salt or brackish water habitats (e.g., *Spartina* spp.) to less salt-tolerant species. Diversions or wastewater inputs can increase flooding, which may stress existing vegetation and select for more flood-tolerant species, confounding nutrient effects**.** Other indirect effects have been observed in treatment wetlands and river diversion sites, including increased herbivory (e.g., nutria "eating out" marshes, Shaffer et al. 1992; 2009).

The growth of vegetation in response to nitrogen fertilization of salt marshes decreases as the *in situ* control biomass increases. The relationship can be described reasonably well with a power function (solid line in Fig. 2). When the control biomass is very high, 2,500 g m^{-2}of dry standing biomass, very little can be gained in the way of added production from fertilization, but at a low control biomass there is a large potential for increasing productivity, provided that salinity and flooding stresses are relatively low. If nitrogen alone were able to raise the biomass to a hypothetical maximum of 2,500 g m^{-2}, the predicted relationship would appear as depicted by the dashed line in Fig. 2.

There is a large gap between the empirical fit of the power function and the hypothetical maximum (Fig. 2). This gap must result because of co-limitation by other factors, and these can be categorized as one or a combination of stresses and limitations, including osmotic stress, hypoxia, herbivory, disease, soil chemistry (toxicity and/or micronutrient deficiencies), and perhaps others. The relative importance of these will depend on the salinity, climate, weather, and elevation relative to the tidal frame. The productivity of roots and rhizomes can be expected to follow a similar trend, that is, their relative responses to nutrients should depend on their status with respect to all of these other limitations and stresses, and this at least partially explains the disparate results from fertilization studies of belowground biomass.

Effects on Belowground Biomass—Empirical Studies

Plant developmental processes and growth are greatly affected by nutrient availability. With few exceptions, the absolute production of roots and shoots increases with nutrient loading. This is supported by numerous experimental studies and field observations (e.g., Stevenson and Day 1996; Shipley and Meziane 2002; Day et al. 2006; Ravit et al. 2007; Hillman 2011). Buresh et al. (1980) reported an increase in belowground macro-organic matter of 5.5 to 6.3 kg m^{-2} 4 months after fertilizing a Louisiana *Spartina alterniflora* marsh with N and P. Haines (1979) reported a trend of increased belowground macro-organic matter in fertilized compared to control plots during the last 6 months of a fertilization study in Georgia salt marsh. Valiela et al. (1976) reported increases of cumulative total belowground biomass from ‘regrowth cores’ in Great Sippewissett marsh high fertilization (HF) sites of 127 % in low marsh and 111 % in high marsh. In plots treated with urea at 20 % the HF rate, cumulative belowground biomass increased 177 % in low marsh and 32 % in high marsh. Of the total belowground biomass, the greatest response was seen in rhizomes. Haines and Dunn (1976) also reported an increase in rhizome biomass following nutrient treatment. Zhang et al. (2013) reported a 33 % increase in belowground biomass of *Spartina alterniflora* in fertilized mesocosms in Jiangsu province, China.

The nutrient effect on roots, however, is not universally the same. Tyler et al. (2007) reported that the effect of fertilization on belowground biomass differed between San Francisco and Willapa Bay estuaries: there was no effect in San Francisco Bay in either edge or meadow plots, but a 108 % increase in fertilized Willapa Bay meadow plots relative to controls. Boyer et al. (2000) reported no significant change in belowground biomass of fertilized *S. foliosa* in a constructed marsh in the Tijuana Estuary. Darby and Turner (2008a) reported decreases in live root and rhizome biomass on field sites fertilized with nitrogen and phosphorus, with the greatest decreases associated with reference sites supporting the greatest belowground biomass. In a Louisiana marsh fertilized monthly from April through August, Darby and Turner (2008b) found no change in total belowground *S. alterniflora* biomass, but a 40 to 60 % reduction in live biomass. Nyman (2014) reviewed the literature concerning river diversions within the context of the delta lobe cycle and concluded that nutrients were not the cause of wetland loss at the Caernarvon river diversion. Langley et al. (2013) found that the response of *Spartina patens* belowground biomass was dependent upon relative elevation: at elevations 5–15 cm below mean sea level, biomass was about 100 % greater in fertilized treatments, but the response declined with increasing relative elevation. Likewise, Priest (2011) found that nutrient additions increased belowground biomass of *S. alterniflora* in a North Carolina mesocosm study at all elevations from -20 to 53 cm NAVD88, but the response was greatest (+ 115 %) at the lowest elevation.

Biomass Partitioning—The Theory

Plant root:shoot ratios decline as nutrient loading increases (Morris 1982; Ågren and Ingestad 1987; Hilbert 1990; Ericsson 1995; Ågren and Franklin 2003, Darby and Turner 2008a, b; Hillmann 2011). This has led to some confusion about the effect of nutrients on belowground organic matter production. If added nutrients decrease belowground production, as some studies show, then soil strength will decrease with the loss of root structure, and the additive effect of roots on soil volume would be diminished (Darby and Turner 2008a; Turner 2010).

The observation that root:shoot ratios are variable and subject to control by nutrient availability inspired a well-known theory in the plant literature known as the functional balance model. The theory is based on the concept that there exists a functional balance between roots and shoots. This is an idea that can be traced to a paper by Brenchley (1916), who stated ‘the plant makes every endeavor to supply itself with adequate nutrient, and as if, when the food supply is low, it strives to make as much root growth as possible’. Much later, Davidson (1969) stated that the root mass multiplied by the rate of absorption is proportional to leaf mass multiplied by the rate of photosynthesis. These models are discussed in an excellent review by Bastow Wilson (1988). Thus, if nutrient uptake and carbon fixation are balanced, then $\alpha\rho W_L(t) = \mu W_R(t)$ (1).

Where W_L and W_R are the weights of leaves and roots at time t, respectively, α is the optimal concentration of tissue-nitrogen, ρ is the specific rate of primary production, and μ is the specific nitrogen uptake rate. From Eqn. 1 the root:shoot ratio is simply $W_R / W_L = \alpha\rho/\mu$ (2).

For *Spartina alterniflora*, the value of the specific-production term (ρ) is about 0.16 d^{-1} at 20 °C (Morris 1982), net of respiration, though we will use half that value because we will lump leaves and rhizomes and assume that these organs have a constant weight ratio of 1:1. The maximum uptake term (μ) or V_{max} for specific ammonium uptake has a value of 3.26×10^{-3} d^{-1} at 20 °C (Morris 1980). If the ideal nitrogen concentration in tissue is 2 %, then the root:shoot ratio should be, from Eqn. 2, about $(0.02 \times 0.08)/\ 3.26 \times 10^{-3} \approx 0.49{:}1$. This is the theoretical minimum root:shoot ratio, where shoots are defined as leaves plus rhizomes. If leaf weight and rhizome weight are equal, then the ratio of root:leaf would be about 1:1.

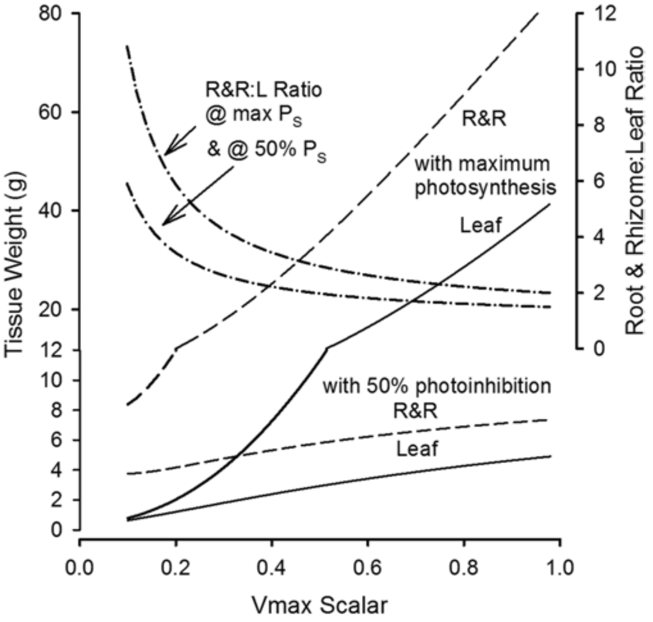

Fig. 3 Simulation of leaf and root + rhizome (R&R) growth (Eqns. 7 and 8) when the specific nitrogen uptake rate was scaled from 0.1 to 1.0 of Vmax. The resultant leaf (——), root + rhizome (- - - R&R) weights and ratios of root + rhizome to leaf weight are shown after 100 days of simulated growth under conditions of either maximum photosynthesis ($\rho = 0.16\ d^{-1}$ of leaf weight) or photoinhibition ($\rho = 0.08\ d^{-1}$)

The total rate of production (dW_T / dt) is $dW_T / dt = dW_L / dt + dW_R / dt = \rho W_L$ (3)

Substituting for W_R from Eq 2 and rearranging gives $\rho W_L = (1 + \alpha\rho / \mu)\, dW_L / dt$ (4)

Solving the integral of Eq. 4 $\left(\int dW_L / W_L = \frac{\rho}{(1+\alpha\rho/\mu)} \int dt \right)$ (5)

gives the leaf weight at time t $W_L(t) = W_L(0)e^{\frac{t\rho}{(1+\alpha\rho/\mu)}}$ (6)

and from Eqn. 1 the root weight at time t is $W_R(t) = (\alpha\rho / \mu) W_L(t)$ (7)

The specific rate of nitrogen uptake (μ) is variable, depending on the concentration of available nitrogen, oxygen, salinity, and other variables, and follows Michaelis-Menten kinetics (Morris 1980; Bradley and Morris 1990, 1991): $\mu = V_{max} N / (N + k_m)$ (8)

Parameter V_{max} in Eqn. 8 is the maximum specific uptake rate; N represents the concentration of available nitrogen, and k_m is the half-saturation constant. The term $N/(N+k_m)$ can vary between 0, when $N=0$, and 1 when the nitrogen concentration is high. Thus, $\mu = V_{max}$ when the nitrogen concentration is non-limiting. In what follows, we will explore the effect of changes in N by using a single scalar as a substitute for $N/(N+k_m)$.

The effect of nitrogen limitation on the growth of roots and leaves can be illustrated by scaling nitrogen uptake from 0 to 100 % of V_{max} (Fig. 3). For example, the solutions of Eqns. 6 and 7 when applying a scalar of 1.0, simulating high nitrogen availability, resulted in a constant (over time) ratio of roots + rhizomes:leaves of 2:1 at maximum photosynthesis. Total plant weight increased to 124 g and root weight (exclusive of rhizomes) to 41 g in 100 days. Scaling the uptake parameter to 50 % of its maximum value (Fig. 3), simulating nutrient-limited growth, resulted in a ratio of roots + rhizomes:leaves of about 3:1, final plant weight of 45 g, and final root weight of 22 g. Thus, the roots + rhizomes:leaves quotient decreased from 3 to 2 when we simulated a high level of nitrogen availability, but the increase in aboveground production was so great (41 vs 11 g) that, even with a lower root:shoot ratio, the absolute production of roots was almost 2x greater. Conversely, nutrient limitation results in an increase in the partitioning of photosynthate into root growth, which reduces leaf growth and, ultimately, total plant and root growth.

Scaling back the rate of photosynthesis (D) by 50 % greatly reduced the nitrogen effect. (Fig. 3). Total plant weight was reduced to 12 and 9 g at full and half V_{max}, respectively. Interestingly, root weight was marginally greater at half V_{max}, 2.9 vs 2.5 g, than at full V_{max}, though total belowground biomass (roots plus rhizomes) was 5.8 and 7.4 g at full and half V_{max}, respectively. This reduced rate of photosynthesis also lowered the ratio of roots + rhizomes:leaves, especially at low V_{max}. These results illustrate the complexity of environmental interactions that are possible and their control of plant development.

Plant growth data published by Shipley and Meziane (2002) provide another good example. Experimental results from more than 20 plant species showed that the mean ratio of root:total plant weight decreased, total plant weight increased, and root weight increased 70 % with increasing nutrient supply when plants were grown in high light. In low light, root weight was independent of nutrient supply, which is consistent with the model's predictions.

The effects of a step change in nutrient status show that a reduction in root biomass is possible theoretically after raising nutrient levels from a limitation to a surplus, but the reduction is fleeting and is not necessarily seen in rhizomes (Fig. 4). The theoretical results (Fig. 3) and the type of long-term growth studies discussed by Shipley and Meziane (2002) are equilibrium studies. Plantings were raised from start to harvest in the greenhouse or *in silico* in differing, but constant nutrient environments. We simulated what could happen when a plant, growing at a nitrogen-limited rate (at 40 % of V_{max}) experiences a step increase in nitrogen availability (Fig. 4). The plant growing in equilibrium at a low nitrogen supply developed a root biomass of 3 g by day 50.

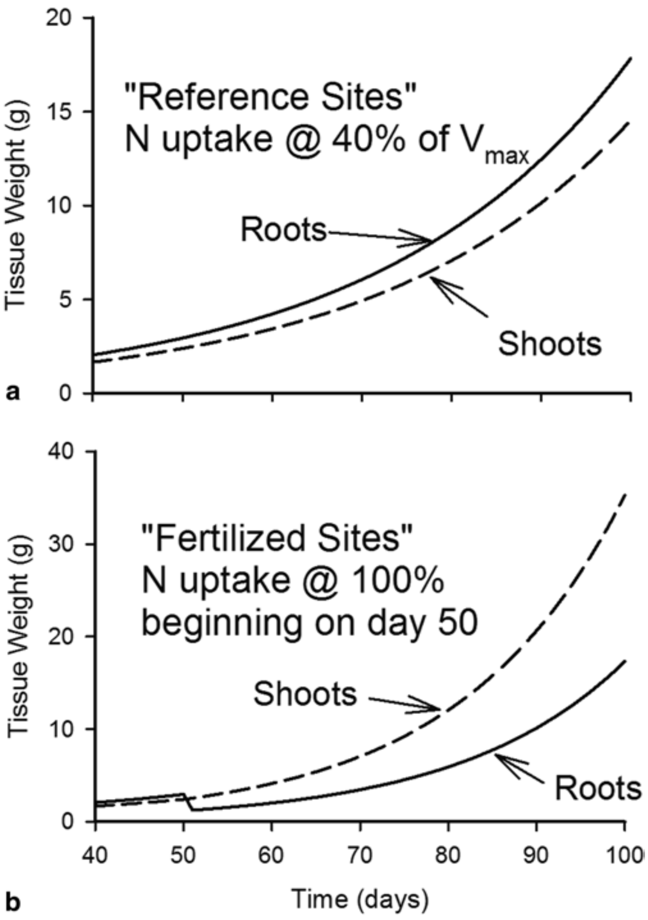

Fig. 4 Simulated time series of (**a**) nitrogen-limited growth with Vmax (see text) scaled back 40% and (**b**) when Vmax was scaled up from 40 to 100% on day 50 and beyond. Shoots are the sum of leaves plus rhizomes

Following the step up to high nitrogen supply, root biomass dropped to 1.25 g as the plant adjusted to a higher μ (Fig. 4b). By day 100 the root biomass of the nitrogen-limited plants increased to 17.8 g, leaves + rhizomes (shoots) increased to 14.5 g (Fig. 4a), and those of the 'fertilized' plants to 17.3 g and 35.3 g, respectively, (Fig. 4b).

A change in equilibrium following a step increase in nutrient supply (Fig. 4b) could explain discrepancies in short-term field fertilization experiments, but we emphasize that the resulting decrease in simulated root biomass extends only to roots. There is no reason to believe that rhizome biomass should decline. Rhizomes are the anatomical equivalents of the branches on a tree; they are horizontally growing, subterranean stems; they give rise to and support the leaves, and they probably respond to nutrients much like the branches of a tree. This was the rationale for aggregating leaves and rhizomes in the root-equilibrium model described above.

Effects on Sediment Organic Matter

The capacity of highly organic marshes to respond to sea-level rise would be compromised if the rate of belowground decomposition were to increase (Swarzenski et al. 2008) or, more specifically, if nutrient enrichment were to decrease the stability of the extant inventory of refractory organic matter. The long-term accretion of organic matter will decrease if the decay of refractory carbon increases or its production decreases. It is possible that nutrients, particularly the electron acceptor nitrate, may destabilize the extant inventory of soil organic matter. However, there are two sides to the equation. Organic matter accumulation and the volume of soil that it generates are primarily functions of the production of refractory organic matter and its stability. They are equivalent to primary production plus net import-export and minus the decomposition of the labile portion or organic production. The labile fraction of primary production does not increase sediment volume.

Nitrate is an energetically favorable electron acceptor, close to O_2 in energy yield (Fenchel and Blackburn 1979), and river diversions that are rich in NO_3 could actually stimulate the decay of organic matter that typically would resist decay under anaerobic conditions. However, this should only be a significant factor in peat marshes where organic matter makes up the majority of soil volume. Furthermore, these highly organic marshes represent a mature stage of the deltaic cycle (Gosselink 1984) that are likely unsustainable without significant mineral input. Wetland loss is a natural part of the growth and decay of a delta lobe, where losses from an old lobe eventually are balanced by accretion of land in a new lobe (Coleman 1988).

The production of refractory organic matter, as opposed to labile organic matter, is a question of litter quality, and litter quality is a function of species and nutrition. Decomposition is primarily a function of the quantity and quality of organic matter, and factors such as the availability of electron acceptors, temperature, and nutrients that affect the rate of decomposition. Where freshwater diversions reduce salinity, the dominant electron acceptor may change, altering the balance between sulfate reduction and methanogenesis (Kelley et al. 1990). The intrusion of salt water into freshwater wetlands or, conversely, the conversion of brackish to freshwater marsh will determine the availability of sulfate, the dominant terminal electron acceptor in anaerobic marine systems (Howarth and Teal 1979; King 1988), potentially altering the rate of decomposition of soil organic matter (Reddy and DeLaune 2008). However, the greater efficiency of sulfate reduction over methanogenesis is not enough to offset the greater quality of organic matter in fresh marshes over that in saline marshes (Kelly et al. 1990; Nyman and DeLaune 1991).

Another factor that may impact soil organic matter is the significant difference in the composition and decomposition of plants typical of tidal freshwater marshes and salt marshes (Odum and Heywood 1978). This difference affects both litter quality and the fraction of organic matter that is refractory. *Spartina alterniflora*, for example, has a relatively high lignin content and low nitrogen:lignin ratio (Marinucci et al. 1983; Valiela et al. 1984) and therefore decays more slowly and produces a higher fraction of refractory organic matter than a typical freshwater plant. Of the dominant plants in coastal Louisiana, *Spartina patens* produces the most refractory organic matter (Nyman and DeLaune 1991). Thus, river diversions that convert *S. alterniflora* marshes into *S. patens* marshes should increase refractory organic matter whereas diversions that convert *S. patens* marshes into fresher marshes should decrease refractory organic matter.

Morris and Bradley (1999) found that rates of CO_2 flux from the marsh sediment surface increased with nutrient enrichment (N and P), but it is not clear if this was from increased respiration of living roots and rhizomes, higher respiration from the decay of increased production and turnover of belowground biomass, or higher respiration from the decay of extant refractory soil organic matter. Field studies of decomposition often confuse these effects. Bragazza et al. (2006) found that the decomposition rate of recently formed litter from peat bogs increased along a gradient of atmospheric nitrogen (as nitrate) deposition, but in a peatland where plant growth was N-limited, increased N-supply led to an increase in the net accumulation of soil carbon (Aerts et al. 1995).

The focus in much of the decomposition literature has been on the effect of litter quality in terrestrial systems. Melillo et al. (1982) found that the initial lignin:nitrogen ratio was negatively correlated with the initial decomposition rate of leaf litter from six hardwood species. Other studies supported the result that lignin content of litter has a negative effect on the initial decomposition rate (Osono and Takeda 2004; Zhang et al. 2008). Talbot and Treseder (2012) found that litter nitrogen content in the model plant *Arabidopsis thaliana* had a positive effect on total mass loss because it increased the loss of lignin, nitrogen, and soluble organic carbon. Lignin content had a negative effect. However, another study found elevated litter and soil nitrogen had a minor, if any, effect on decomposition, and nutrient limitation of decomposition was not predictable from nutrient limitation of primary production (Hobbie and Vitousek 2000). Gentile et al. (2011) concluded that, while litter quality controls the short-term dynamics of decomposition and soil organic matter accumulation, long-term soil organic carbon storage cannot be predicted based on initial litter quality or, by extrapolation, nutrient supply. They concluded that the formation and stabilization of soil organic matter is controlled more by the quantity of litter input and its interaction with the soil matrix than by litter quality.

Aerts and de Caluwe (1997) manipulated the leaf litter chemistry of four *Carex* species by nitrogen fertilization and found that increased tissue nitrogen did not necessarily lead to higher litter decomposition rates. They speculated that high atmospheric nitrogen deposition may lead to a shortage of phosphorus in the organic substrates available to bacteria and fungi. Indeed, there is evidence that phosphorus limits microbial activity in some marshes (Sundareshwar et al. 2003), but this is not universal and its significance for overall decomposition and carbon sequestration is uncertain. Aerts and de Caluwe (1997) observed that increased nutrient supply led to faster release of N and P from litter in most species and a higher rate of nutrient cycling. This positive feedback between nutrient supply rate and the rate of nutrient cycling was reinforced by an increase in litter production in response to increased nutrient supply.

The evidence from terrestrial systems suggests that the addition of nutrients increases soil organic matter (Prescott 2010). After a decade of experimental NO_3 deposition, organic matter and N increased, 12 and 9% respectively, in forest floor and mineral soil. Apparently NO_3 deposition exerts a negative effect on microbial activity in this forest ecosystem by depressing the lignolytic activity by microbial communities and leading to the accumulation of forest floor and soil organic matter (Zak et al. 2008). A factorial experiment involving eight temperate sites, seven substrates, and nitrogen fertilization showed that nitrogen had neutral or negative effects on decomposition rate and that the nitrogen effect was independent of initial lignin concentration (Hobbie 2008).

Fungi, especially the white-rot fungi, are the primary degraders of lignin in terrestrial systems (Martínez et al. 2005; Sinsabaugh and Follstad Shah 2012), while bacteria dominate in anaerobic aquatic systems (Benner et al. 1986). Most fungi are obligate aerobes capable of degrading lignin to CO_2, but are incapable of growing on lignin as a sole carbon and energy source (Griffin 1994). Their dependence on oxygen partially explains the high accumulation rate of soil organic matter that we observe in anaerobic soils. Enzymes such as phenol oxidase require molecular oxygen for their activity and, therefore, are rarely active in anaerobic environments. Freeman et al. (2004) showed that the activities of hydrolase enzymes that have no oxygen requirement are also extremely limited in peatlands as a consequence of the inhibition of these enzymes by phenolic compounds and oxygen constraints on phenol oxidase. Thus, limitations on phenol oxidase activity promote conditions that inhibit decomposition (Freeman et al. 2004).

Nitrogen addition increases the incorporation and stabilization of organic matter into humus through a combination of chemical reactions and enzyme inhibition (Prescott 2010). High levels of inorganic N suppress lignin oxidation by white rot basidiomycetes and generally enhance cellulose hydrolysis (Waldrop et al. 2004). Frey et al. (2004) found that active fungal biomass was lower in fertilized compared to control hardwood and pine stands, while active bacterial biomass was not greatly affected by N additions. This shift in microbial community composition was accompanied by a significant reduction in the activity of phenol oxidase, a lignin-degrading enzyme produced by white-rot fungi. Similarly, a basidiomycetous fungus isolated from decaying sea grass had no lignin peroxidase activity when grown in high-nitrogen medium (Raghukumar et al. 1999).

Although lignocelluloses are recalcitrant to anaerobic biodegradation, they will slowly degrade, presumably by bacteria, but there appear to be differences among plant species. After 294 days in the laboratory under anaerobic conditions, 16.9% of the lignin and 30.0% of the polysaccharide components of lignocellulose derived from *Spartina alterniflora* were degraded, but only 1.5% of the lignin and 4.1% of the polysaccharide components of lignocellulose derived from *Rhizophora mangle* were degraded (Benner et al. 1984). Benner et al. (1991) also reported differential decomposition of the submolecular components of lignin. Kirk and Farrell (1987) attributed the very limited anaerobic metabolism of lignin during extensive incubations to nonlignin components or metabolism of abiotically derived subcomponents. Prescott (2010) questioned the selective preservation model, and argued that microbial and biochemical transformations of plant compounds into novel recalcitrant compounds, rather than selective preservation, lead to the creation of stable organic matter. Soil organic matter is a complex chemical buffet of products and byproducts, and the bacterial and fungal consumers are finicky diners.

Effects on Marsh Elevation

Coastal wetlands maintain equilibrium with sea level, within limits, by inputs of mineral sediments and in situ organic soil formation (Reed 1995; 2002; Morris et al. 2002). Critical variables that determine accretion rate and elevation are the concentration of suspended sediment in flood water over the marsh surface, primary productivity, decomposition of sediment organic matter, relative elevation or flood duration, and kinetic energy. In estuaries where relative sea-level rise is high, as in the subsiding Mississippi Delta, the concentration of suspended sediment in flood water and mineral sedimentation are critical to sustaining healthy marshes. When flooding with sediment laden water is low, relative marsh elevation declines. Evidence from empirical studies shows that vegetation typical of coastal wetlands thrive when sedimentation rates are raised experimentally (Croft et al. 2006; Fragoso and Spencer 2008). Wetlands downstream of diversions at Caernarvon, West Pointe a la Hache, and Bonnet Carré (Lane et al. 2006; Day et al. 2009; Day et al. 2013) and marshes affected by Atchafalaya River discharge (Day et al. 2011) all have higher vertical accretion rates, high belowground biomass, and/or greater aboveground growth. The effectiveness of sediment diversions for marsh restoration in the Delta will depend on the concentration of sediment, the volume of discharge, and the manner and effectiveness of sediment distribution. Impounded wetlands are isolated from surface flow and will not benefit from diversions unless they are hydrologically reconnected.

Summary

Among the proposed solutions for reversing wetland loss in the Mississippi River Delta is the creation of water diversions or utilization of siphons to reintroduce suspended sediment carried in the River. However, diversions will introduce significant quantities of nutrients as well as sediment, and this has raised concerns about the effect of nutrients on the wetlands, particularly on the production and stability of sediment organic matter. Contradictory results from experimental field studies have fueled these concerns. The effects of nutrients are complex. They influence plant community composition, herbivory, biogeochemistry, and plant growth and development. Sediment and freshwater diversions will change some wetland plant communities, and highly organic wetland soils will transition to minerogenic sediments.

To understand the effect of nitrogen on soil organic matter, it is useful to consider its fate as well as its effects on both decomposition of organic matter and primary production. The majority of nitrate added to a wetland will be denitrified at the expense of a fraction of the labile organic carbon. The balance between organic production and decomposition will determine the change in volume of soil organic matter, and the aboveground plant production will affect sedimentation. The net effect of the organic matter balance and the mineral input determines wetland soil accretion.

With respect to plant development, increasing nutrient availability is associated with a decrease in the root:shoot ratio, though numerous studies document that the absolute production of roots and rhizomes increases with nutrient enrichment (Haines and Dunn 1976; Stevenson and Day 1996; Shipley and Meziane 2002; Ravit et al. 2007; Hillmann 2011). This also is supported by the functional balance theory of plant development (Davidson 1969; Bastow Wilson 1988; Fig. 3). It was shown theoretically that a step increase in nitrogen availability can temporarily decrease the standing stock of roots as a new equilibrium is established, but there is no reason to think that rhizomes should be similarly affected.

The consequences and stability of the extant inventory of refractory organic matter (e.g., lignin) are entirely different from the consequences of the decomposition of labile organic matter. Labile organic matter does not add new volume to soil; it decomposes relatively quickly and the speed of its decay matters little. However, the production of refractory organic matter and its stability do matter. In terrestrial soils where fungi are the dominant degraders of lignin (Martínez et al. 2005), it has been shown that nitrate inhibits the activity of the lignin-degrading enzyme phenol oxidase (Raghukumar et al. 1999; Waldrop et al. 2004), leading to an increase in soil organic matter in sites of high nitrate deposition (Zak et al. 2008). The phenol oxidase enzyme is not active in anoxic environments like wetland soils. The activity of hydrolase enzymes, which have no oxygen requirement, is inhibited in wetlands by phenolic compounds that build in concentration as a consequence of the constraints on phenol oxidase (Freeman et al. 2004). Knowledge of the effect of nitrate on anaerobic soils is incomplete, but the balance of evidence supports the efficacy of diverting water and sediment from the Mississippi River to restore and stabilize its wetlands. The need for action to restore the wetlands is urgent, and with a thoughtfully designed monitoring scheme in place, plans to divert sediment laden water into the wetlands should proceed.

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Complexities of Resilience: Adaptation and Change within Human Communities of Coastal Louisiana

Conner Bailey, Robert Gramling and Shirley B. Laska

Abstract

Coastal ecosystems and particularly deltaic coastal ecosystems are among the most productive in the world, and this certainly is true of coastal Louisiana. Residents have a long history of fishing, hunting, cattle raising, and farming, which means that they have drawn on a diversity of natural resources and engaged in a seasonal round of activities that has limited their vulnerability to loss associated with any one activity. Such resilience among residents of coastal Louisiana increasingly is challenged by a number of factors outside their control such as sea-level rise, increased strength of tropical storms, subsidence, and loss of wetlands due to these and other factors. Local residents have a storehouse of ecological knowledge based on generations of living with storms but are increasingly facing the need to make decisions about strategic retreat from the coast. Strong emotional ties link people to the land and water of coastal Louisiana as well as to their cultural communities. We document how residents of coastal Louisiana are in the process of adapting to changing conditions and identify four different approaches that might be taken by coastal residents in the future.

Keywords

Resilience · Coastal communities · Adaptation culture · Population change · Relocation

Introduction

Coastal ecosystems and particularly deltaic coastal ecosystems are among the most productive in the world, and this certainly is true of coastal Louisiana. The high natural productivity and diversity of ecological niches support a wide range of human activities. In coastal Louisiana, residents have a long history of fishing, hunting, cattle raising, and farming in a seasonal round of activities that limits their vulnerability to loss associated with any one activity. In more recent years, the oil industry added to the diversification with important employment and income opportunities for coastal residents. During boom times in the oil patch, farming and fishing declined in relative importance, but these activities continued

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to be practiced and remained as effective safety nets when the oil industry went into periodic decline.

Such resilience among residents of coastal Louisiana is increasingly challenged by a number of factors outside their control. These include eustatic sea level rise and increased strength of tropical storms associated with global climate change, land subsidence caused locally by consolidation of sediments, and loss of wetlands due to these and other factors. The geologic history of delta formation and erosion due to shifts in river course and sediment deposition resulted in a dynamic system. More recently, human efforts to control this system have led to its serious degradation through the loss of sediment with the channelization and containment of the Mississippi River. This process has been exacerbated by the cutting of channels through coastal wetlands for oil and gas exploration and transportation, leading to saline intrusion into freshwater ecosystems. Loss of coastal wetlands has threatened human settlements throughout coastal Louisiana and amplified their vulnerability to damage from tropical storm events. Local residents have a storehouse of knowledge based on generations of living with coastal land loss and the effect the loss has on storm impact, but are increasingly facing the need to make more drastic decisions in response to them, namely strategic retreat from the coast.

Much has been written on the cultural history of coastal Louisiana, and much of this literature describes the intense personal attachment that residents have to this ecosystem as both home and source of sustenance. Strong emotional ties link people to the land and water of coastal Louisiana as well as to their cultural communities. As much as anywhere on earth, the place literally defines the person. Coastal parishes of Louisiana are home to a unique cultural landscape of cuisine, music, and language found nowhere else. People are understandably reluctant to turn their back on this heritage even in the face of impending ecological disaster. Their ancestors are buried there. They own land, homes, businesses and other fixed material assets that they are loath to abandon. More importantly the large extended families and tight social networks living and working supportively constitute a valuable resource. As one young Cajun woman from a large family remarked when leaving the area for a doctoral program in the West, "I don't know if I can function outside of the social network in which I was raised. It is like being one leg of a starfish."

In this chapter we document how residents of coastal Louisiana are in the process of adapting to changing conditions. We argue that humans are by nature a highly adaptive species and that humans living in dynamic ecosystems such as coastal Louisiana are culturally disposed to adaptive behaviors that create personal, community, and social resilience. The concept has particular use in this context because significant changes are underway in the biophysical environment, as documented elsewhere in this book, and these changes are forcing coastal residents of Louisiana to make difficult decisions that affect their lives and livelihoods. We document population mobility over the past 30 years to show that the people of coastal Louisiana already have been making difficult decisions to move, but have done so in a measured manner. We identify four different approaches that might be taken by coastal residents in the future, and argue that the role of science is to help people make the best decisions they can make.

Twenty Years of Population Change

Data on population change in ten coastal Louisiana parishes between 2000 and 2010 is presented in Table 1. Taken as a whole, these ten parishes have lost over 180,000 people during that time period. Most of that population loss occurred after Hurricanes Katrina and Rita in 2005, but evidence of a slow decline in population can be seen before that. A dramatic decline occurred between July 2005 and 2006, with a loss of 332,000 people over that 1 year and relative population stability between 2008 and 2010.

Looking more closely at the data in Table 1, we see variation among parishes with the largest losses in absolute terms occurring in Orleans parish but with proportionately higher losses occurring in St. Bernard Parish and Cameron Parish. Plaquemines Parish also suffered a significant loss of population during the period 2000–2010, with most of this loss occurring after 2005. Some coastal parishes increased in population size during both periods, though growth rates were modest. By way of comparison, the state of Louisiana grew by 1.4 % between 2000 and 2010 (U.S. Census Bureau 2000, 2010).

The U.S. Census Bureau also provides population estimates for "Places," defined as either incorporated communities or census-designated places which, while not incorporated, represent densely settled concentrations of population that are locally identified by name. Table 2 presents data on population change of all census Places in coastal parishes of Louisiana except for the city of New Orleans, which dwarfs in size all other communities shown in Table 2. New Orleans lost more than a quarter of its population between 2000 and 2010, while the remaining Census Places in these ten parishes taken as a whole lost two percent.

Leaving New Orleans city and parish out of the equation, there are nearly 900,000 coastal residents, with roughly 150,000 in Census Places. This means that about 750,000 people living in coastal Louisiana live outside of Census Places as defined by the U.S. Census Bureau. In other words, the majority of the coastal population is very rural. Due to the unique topographical features of the Mississippi Delta, populations tend to follow linear patterns of settlement, with homes following the high ground associated with natural

Table 1 Population change in 10 coastal Louisiana Parishes, 2000–2010. (Sources: U.S. Census Bureau. n.d. American fact finder. Accessed on 18 Aug 2012)

	Cameron Parish, Louisiana	Iberia Parish, Louisiana	Jefferson Parish, Louisiana	Lafourche Parish, Louisiana	Orleans Parish, Louisiana	Plaquemines Parish, Louisiana	St. Bernard Parish, Louisiana	St. Mary Parish, Louisiana	Terrebonne Parish, Louisiana	Vermilion Parish, Louisiana	Totals
2010	6,839	73,240	432,552	96,318	343,829	23,042	35,897	54,650	111,860	57,999	1,236,226
2009	6,584	75,101	443,342	93,682	354,850	20,942	40,655	50,815	109,291	56,141	1,251,403
2008	7,100	75,020	444,655	93,556	336,644	21,138	37,669	51,005	109,161	56,068	1,232,016
2007	7,228	74,810	440,339	92,881	288,113	21,353	33,439	51,163	108,627	55,629	1,173,582
2006	7,457	74,481	420,683	92,780	208,548	21,293	14,493	51,569	108,115	55,313	1,054,732
2005	9,576	73,599	451,652	91,362	455,188	28,549	64,951	50,871	106,192	54,909	1,386,849
2004	9,636	73,399	452,678	91,624	461,915	28,602	65,427	51,541	105,453	54,368	1,394,643
2003	9,688	73,390	451,533	91,236	467,761	27,644	65,727	51,898	105,172	54,161	1,398,210
2002	9,736	73,345	451,453	90,666	472,744	27,119	66,286	52,189	104,923	54,223	1,402,684
2001	9,834	73,277	452,088	90,054	477,932	26,852	66,554	52,528	104,729	53,952	1,407,800
2000	9,949	73,234	454,738	89,974	483,663	26,737	66,988	53,256	104,461	53,966	1,416,966
2010 as % of 2000	0.662	1.025	0.975	1.041	0.734	0.783	0.607	1.026	1.046	1.040	0.872
2010 as % Of 2005	0.688	1.020	0.982	1.025	0.780	0.734	0.626	1.074	1.029	1.022	0.891

Table 2 Population change affecting census places in 10 coastal Parishes in Louisiana, 2000–2010. (Sources: U.S. Census Bureau. n.d. American Fact Finder. Accessed on 18 Aug 2012)

Place	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000	% change
Kenner city, Jefferson Parish	66,702	67,842	68,220	67,774	64,933	69,716	70,105	70,067	70,294	69,902	70,375	0.948
Houma city, Terrebonne Parish	33,727	32,584	32,685	32,679	32,786	32,215	32,201	32,391	32,521	32,678	32,835	1.027
Gretna city, Jefferson Parish	17,736	16,783	16,861	16,751	16,040	17,275	17,306	17,311	17,282	17,399	17,545	1.011
Abbeville city, Vermilion Parish	12,257	12,229	12,088	11,646	11,691	11,606	11,611	11,666	11,791	11,823	11,910	1.029
Kaplan city, Vermilion Parish	4,600	4,997	5,049	5,093	5,141	5,103	5,104	5,130	5,172	5,180	5,215	0.882
Lockport town, Lafourche Parish	2,578	2,691	2,636	2,664	2,596	2,569	2,586	2,600	2,608	2,613	2,621	0.984
Jean Lafitte town, Jefferson Parish	1,903	2,308	2,309	2,284	2,140	2,297	2,281	2,263	2,226	2,180	2,146	0.887
Erath town, Vermilion Parish	2,114	2,156	2,174	2,180	2,181	2,166	2,161	2,171	2,185	2,191	2,192	0.964
Delcambre town Vermilion Parish (part)	1,866	1,522	1,533	1,541	1,551	1,539	1,537	1,547	1,561	1,558	1,566	1.192
Golden Meadow town, Lafourche Parish	2,101	2,096	2,121	2,134	2,149	2,130	2,147	2,158	2,165	2,168	2,188	0.960
Grand Isle town, Jefferson Parish	1,296	1,677	1,650	1,582	1,481	1,590	1,601	1,582	1,568	1,557	1,544	0.839
Gueydan town, Vermilion Parish	1,398	1,591	1,601	1,608	1,614	1,602	1,599	1,602	1,611	1,605	1,607	0.870
Totals	148,278	148,476	148,927	147,936	144,303	149,808	150,239	150,488	150,984	150,854	151,744	0.977

Table 3 Tenure and mobility, United States, Louisiana, and selected coastal Louisiana parishes, 1985–2010. (Sources: Data for 1990 and 2000 are from the US Census Bureau, Censuses of 1990 and 2000. 2010 data for percent of owner occupied homes was from the 2010 Census. Data for population living more than 5 years in the same house are from the American Community Survey 2006–2010 (Selected Housing Characteristics, 2006–2010 American Community Survey 5-year Estimates, Table DP04))

Year	Variable	U.S.	Louisiana	Jefferson	Lafourche	Plaquemines	St. Bernard	Terrebonne	Orleans
1990	Percent homes owner occupied	64.2	65.9	62.9	75.7	75.9	75.8	73.2	43.7
	Percent population more than 5 years in same house	53.3	59.3	59.4	66.3	64.5	65.3	62.7	54.7
2000	Percent homes owner occupied	66.2	67.9	63.9	77.9	78.9	74.7	75.5	46.5
	Percent population more than 5 years in same house	54.1	59.0	61.4	66.9	65.5	65.1	62.4	56.8
2010	Percent homes owner occupied	65.1	67.2	63.7	75.8	74.8	68.8	72.2	47.8
	Percent population more than 5 years in same house	59.2	58.1	64.2	72.7	48.6	38.0	68.1	49.5

Note: for 1990 and 2000, the Census wording was "percent population over 5 years of age living in the same house" in 1985 and 1990, respectively. For 2010 the wording was changed and this new wording is used in this and subsequent tables

levees, cheniers, barrier island beaches and roadways. This presents a number of difficulties in providing social services including water, fire, police, and schools, and also represents a significant challenge to protecting homes and other community structures against damage from storms. Moreover, most Census Places are themselves relatively small. The largest is Kenner, essentially a suburb of New Orleans. Next in size is Houma, with a population of roughly 34,000. There were only two other Census Place over 5,000 in 2009 and only four over 2,500 people, underscoring the essentially rural nature of the coastal population.

Data presented in Tables 1 and 2 indicate that over the past decade some residents of coastal Louisiana have moved away, quite possibly in reaction to perceived risk associated with storms hitting an eroding coastline. This retreat appears to be affecting both Census Places (places with relatively dense populations) and rural residents. The severe damage in Orleans Parish accounts for most of the population decline in terms of sheer numbers. Table 1 also shows that three parishes experienced even more dramatic declines in population as a percent of population. These include Cameron Parish, a largely rural parish in western Louisiana, and both Plaquemines and St. Bernard parishes in the east. All three parishes lost significant population between 2005 and 2010, with St. Bernard Parish experiencing the largest drop (well over one-third of its population). The six other coastal parishes (Vermillion, Iberia, St. Mary, Terrebonne, Lafourche and Jefferson), however, had slight changes, either increasing or decreasing.

In Table 3, parish-level data are presented on the percent of homes which are owner-occupied and the percentage of the population who lived in the same house 5 years prior to the two most recently published census results (i.e., 1985 for the 1990 Census, 1995 for the 2000 census, and 2005 for the 2010 Census). Two metropolitan parishes (Jefferson and Orleans) as well as four coastal parishes from eastern Louisiana (Lafourche, Plaquemines, St. Bernard and Terrebonne) are compared to U.S. and Louisiana figures. From these data, we see that the percent of owner-occupied homes in the U.S. and Louisiana are roughly comparable, but that the four rural coastal parishes have significantly higher percentages of owner-occupied homes. Home ownership is a primary mechanism for building personal and family wealth in the U.S. Home ownership also represents an investment in a specific place and community. Residents of rural coastal parishes in eastern Louisiana are more heavily invested in home ownership and all that entails than are most Americans.

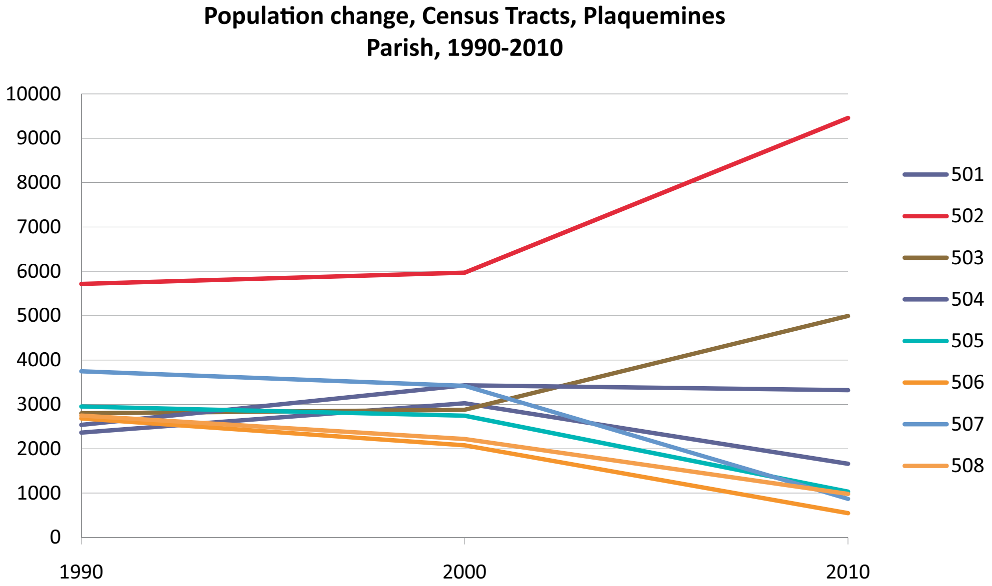
Table 3 also contains data on residential mobility. Louisiana residents in general are somewhat less mobile than the average American, with a higher percentage living in the same house as 5 years previously. The 1990 and 2000 Census data show that residents of the four rural coastal parishes of eastern Louisiana (Lafourche, Plaquemines, St. Bernard and Terrebonne) have been even less mobile than others in the state (including the metro coastal parishes of Jefferson and Orleans) and quite a bit less mobile than the national average. Moreover, there is little variation between the two census periods. The attachment to place continued to that date. Results of the 2010 Census give us a different picture for Plaquemines and St. Bernard Parishes, the two parishes most hard hit by hurricane Katrina. From nearly two-thirds of the population in these two parishes living in the same house as 5 years ago, in St. Bernard Parish that figure dropped to 38 and 49 % in Plaquemines Parish. In contrast, data for Terrebonne and Lafourche Parishes reflect continuity in the form of a relatively stable population of homeowners.

Parish level data are problematic as many parishes contain land that is not immediately subject to storm surge and flooding while other parts of the parishes are vulnerable. In Tables 4 and 5, we present data at the Census Tract level

Table 4 Population, tenure and mobility, Census Tracts of Plaquemines Parish, Louisiana, 1985–2000. (Sources: Data for 1990 and 2000 are from the US Census Bureau, Censuses of 1990 and 2000. 2010 data for population and percent of owner occupied homes was from the 2010 Census. Data for population living more than 5 years in the same house are from the American Community Survey 2006–2010 (Selected Housing Characteristics, 2006–2010 American Community Survey 5-year Estimates, Table DP04))

Year	Variable	Tract number							
		501	502	503	504	505	506	507	508
1990	Population	2,364	5,715	2,797	2,537	2,951	2,681	3,746	2,784
	Percent homes owner occupied	87.6	69.1	47.9	82.5	88.3	79.1	74.7	87.9
	Percent population over 5 years age living in same house as in 1985	74.7	42.9	62.2	22.8	18.6	28.4	45.7	24.7
2000	Population	3,025	5,970	2,878	3,428	2,745	2,075	3,418	2,218
	Percent homes owner occupied	87.3	74.9	49.4	90.2	87.2	82.6	79.2	88.8
	Percent population over 5 years age living in same house as in 1995	73.6	60.0	40.4	66.8	80.8	67.4	70.1	74.7
2010	Population	1,659	9,456	4,992	3,320	1,032	548	868	980
	Percent homes owner occupied	88.5	76.9	38.1	90.7	89.1	88.5	85.0	87.0
	Percent of population more than 5 years in same house	41.8	62.8	37.9	46.3	36.9	31.0	31.0	22.7

Fig. 1 Population change, census tracts, Plaquemines Parish, 1990–2010. For references, see Table 4.



for Plaquemines and St. Bernard Parishes. Census tracts are units of analysis used by the Census Bureau to cover populations of approximately 4,000 people and are designed to be stable between one decennial census period and another.

Population Change in Plaquemines Parish

In Plaquemines Parish, three census tracts (502, 503 and 504) gained population between 1990 and 2010 (Table 4; Figure 1). Most of this growth was in tracts 502 and 503 and was particularly dramatic between 2000 and 2010. Within Plaquemines Parish, these two tracts are the ones furthest from the Gulf of Mexico and population growth in these areas might reflect a gradual retreat of people from tracts closer to the Gulf (the Census data do not allow for direct measure of that question).

The population of Tract 501 grew from 1990 to 2000 but then was cut nearly in half in 2010, almost certainly as a result of hurricane Katrina. Tract 501 essentially covers the entire northeast side of the Mississippi River from the Southwest Pass to St. Bernard Parish. Virtually all of the population in this census tract is to be found in the census blocks in the far north, furthest away from the Gulf of Mexico nestled up next to Tracts 502 and 503. Tract 504 lies southwest along the Mississippi River and, like Tract 501, the population of Tract 504 is concentrated in the furthest reaches north and the furthest from the Gulf of Mexico. The remaining four census tracts lost 14 % of their population between 1990 and 2000, a figure that balloons to over 70 % by 2010. Declines were least in the census tracts of the towns of Port Sulfur and

Table 5 Population, Tenure and mobility, Census Tracts of St. Bernard Parish, Louisiana, 1990–2010. (Sources: Data for 1990 and 2000 are from the US Census Bureau, Censuses of 1990 and 2000. 2010 data for population and percent of owner occupied homes was from the 2010 Census. Data for population living more than 5 years in the same house are from the American Community Survey 2006–2010 (Selected Housing Characteristics, 2006–2010 American Community Survey 5-year Estimates, Table DP04). The symbol "X" indicates where old census tract numbers were discontinued or new census tracts were created)

Variable		Tract Number																			
		301.01	301.02	301.03	301.04	301.05	302.03	302.04	302.05	302.06	302.07	302.08	302.09	303	304	305	306.01	306.02	306.03	307	308
1990	Population	1,613	9,270	X	X	X	4,672	6,634	8,467	3,718	5,995	X	X	2,404	2,814	3,569	3,047	4,194	2,808	2,290	5,136
	Percent homes owner occupied	90.7	84.4	X	X	X	76.8	79.0	85.0	95.8	83.3	X	X	57.2	79.8	91.0	77.6	83.5	9.4	63.9	52.9
	Percent population over 5 years age living in same house as 1985	68.4	61.9	X	X	X	68.5	55.5	63.9	80.8	76.4	X	X	61.9	66.1	78.5	79.9	72.2	14.0	64.0	61.5
2000	Population	1,321	X	6,705	2,693	X	4,292	6,592	X	4,327	5,597	4,892	4,843	2,265	2,731	3,362	2,743	4,112	3,441	2,140	5,173
	Percent homes owner occupied	87.0	X	84.7	85.5	X	74.1	75.2	X	90.2	85.9	96.0	68.7	58.7	78.7	91.8	78.9	82.0	16.6	60.6	51.2
	Percent population over 5 years age living in same house as 1995	77.0	X	66.1	65.3	X	66.0	61.6	X	69.7	75.0	73.8	63.8	61.7	71.0	76.0	64.6	70.0	26.7	67.8	53.3
2010	Population	X	X	4,138	1,780	368	2,612	3,681	X	1,612	2,773	2,541	3,003	1,356	1,282	1,241	925	2,196	1,474	1,517	3,398
	Percent homes owner occupied	X	X	88.5	84.7	85.7	68.1	72.8	X	83.4	72.7	88.8	78.3	56.6	65.3	82.6	51.3	66.9	9.2	55.5	41.6
	Percent of population more than 5 years in same house	X	X	54.3	17.1	50.4	42.5	41.3	X	47.5	41.4	36.0	44.4	32.5	26.9	32.5	19.5	32.1	7.1	49.8	28.4

Buras-Triumph-Venice (505 and 507) and greater in the more rural tracts (506 and 508). The percentages of homes that are owner occupied continued to be exceptionally high by U.S. and state standards in all but one tract (503). The percentage of residents living in the same homes as 5 years previously shows some variability over time, with relatively high levels in 2000 and markedly lower levels in 2010, possibly reflecting the disruptive impacts of Hurricane Katrina. Data from the 2000 Census show that roughly half of all Plaquemines Parish residents who had lived in a different house in 1995 moved within the Parish (U.S. Census Bureau 2000). Due to a change in questions asked during the 2010 Census, data on 5-year mobility were not collected. Such data on mobility in the future will be reported in the American Community Survey (ACS). The ACS (2010) reported that for the period 2006–2010 the majority of residents who had recently moved had moved from one home in Plaquemines Parish to another.

Population Change in St. Bernard Parish

Like Plaquemines Parish, St. Bernard Parish covers an enormous area, much of it submerged. Census tract 301.01 covers the Chandeleur Islands as well as the wetlands area surrounding Lake Borgne. For 2010 the Census Bureau eliminated Census Tract 301.01, an unusual step considering that these units of analysis are designed to be relatively stable over time. Tract 301.02 had been eliminated in the 2000 Census, as had 302.05. Two new census tracts were established for the 2000 Census (302.08 and 302.09) and one new tract was established in 2010 (301.04). These changes complicate population comparisons between the decennial censuses. Table 5 shows that parish-wide data mask important local differences. With the exception of one census tract (306.03), St. Bernard Parish can be characterized as having an extraordinarily high percentage of residents that live in owner-occupied homes. Data from 1990 and 2000 reflect community stability and personal investment in homes.

Census data from 2010 reflect far lower percentages of people living in the same homes as 5 years previously when compared to previous census periods (Table 5; Figure 2). As was the case in Plaquemines Parish, more than half of all St. Bernard Parish residents living in a different house in 2010 than in 2006 had moved from one house to another within the same parish (American Community Survey 2010; Table S0701). A similar pattern is found in the 2000 Census data comparing residence in 2000 and 1995.

The data presented here show that residents of coastal parishes in Louisiana generally, and in both Plaquemines and St. Bernard parishes in particular, have been heavily invested in their communities. The data also show patterns of steady population loss in census tracts that are most vulnerable to storms due to land subsidence, sea level rise and coastal erosion. Where growth has occurred, it has been in those census tracts further from the coast. We believe these data reflect a gradual retreat from the coast with coastal residents moving relatively short distances that provide additional protection from storms but allow for continuation of their traditional coastal occupations and social networks.

Pathways Forward

These census data give us a glimpse of the outcome of decisions made to date by individuals and families about where to live along the Louisiana coast. In this section we delve into the framing of these decisions, both ones already accomplished and those contemplated. These fall into four categories:

Staying in Place but With Major Structural/Spatial/Physical Community Changes

The creation of significantly reconfigured communities surrounded by storm surge barriers has been suggested as a way to retain the current location of threatened communities. An example that is in active discussion is the *localized* structural solution to the threatened community of Jean Lafitte with the surrounding villages of Lafitte, Barataria and Crown Point. Hurricanes Rita (2005), Lee (2011) and Isaac (2012) poured storm surge into this area in amounts and levels of destructiveness not experienced in recent times. Coastal land loss as well as the slow forward speed of these storms are the attributed causes of the destruction they caused. When the prospect of creating a full regional levee was dropped recently by the U.S. Army Corps of Engineers due to the costs of the post-Katrina levee construction standards and the concerns of the negative impact of such construction on the ecosystem, the Corps proposed creating a ring levee system (flood wall) around the most densely inhabited parts of the area. This project may also be threatened by the dropping of the larger project but local and state efforts are going forward in an attempt to save the localized structural solution.

The challenges of a ring levee are enormous. How high must it be to prevent water from surging over the walls and filling the bowl? How large must the pumping system be and how will it be powered to evacuate water that enters via rainfall and possible overtopping? How close will the wall be to existing homes and businesses? Will it act as a barrier to normal community dynamics? How many openings through the ring levee should be constructed to permit the flow of marine activity, especially the fishing boats of local harvesters given the cost of each opening? Post Hurricane Isaac, Mayor Tim

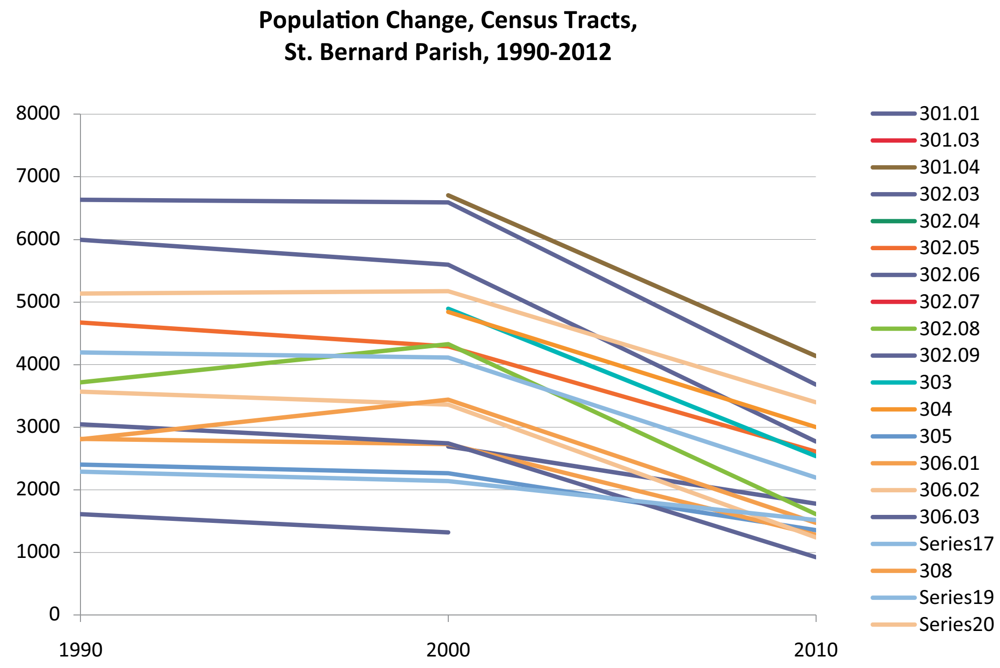


Fig. 2 Population Change, census tracts, St. Bernard Parish, 1990–2012. For references, see Table 5.

Kerner suggested that a 10-ft ring levee would cost about $ 300 million, one third of the proposed higher levee.[1]

In addition, community planning meetings supported by funding from the Louisiana Coastal Protection and Restoration Authority (CPRA) to the Center for Planning Excellence (C-PEX) in Baton Rouge[2] included discussions of ways in which more residences could be constructed *within* the proposed footprint of the ring levee to accommodate some of the residents who live south of the town who have expressed an interest in relocating to the protected area. Since the idea was proposed a couple of years ago, community leaders and residents have regularly articulated concerns for such an adaptation. Can a community function within such 'confinement'? If the 'commons' area in the community is occupied by more housing, will the community lose the opportunity to have the space be used for public and commercial activities?[3] Will residents feel that the original sense of the community is violated by such mixed use of the town's center? Smart growth ideas that combine residential and commercial in close density have been proposed but received mixed responses.

Another community risk reduction idea is taken from the nineteenth century Manila Village Filipino shrimp drying community that lived on platforms nearby.[4] Such elevated walkways might be a very innovative approach that could add historic linkage to the area. These efforts might be combined with the ring levee to provide more risk management. Community and parish leaders drew national attention to the floodwall solution after tropical storm Lee in September 2011 and again after hurricane Isaac in September 2012.

In an effort that also contributes to this discussion of community reconfiguration and encapsulation, coastal ecologist John Day and Jeff Carney, a landscape architect at LSU and Director of the LSU Coastal Sustainability Studio, prepared a white paper demonstrating a plan to encapsulate a small fishing community in T-walls and earthen levees.[5] The difference between the proposal and the Jean Lafitte experience is that the community's existing footprint would be significantly reconfigured, a challenging prospect. There would have to be a community-wide agreement and some land/home owners would have to give up their ownership in exchange for a new location on land currently owned by someone else. Some of these lands have been handed down within families for five generations and contain mineral rights. While it might be possible to accomplish such protection for a small community like Yscloskey in lower St. Bernard, albeit at a very high financial cost, the negotiations necessary to accomplish it for larger communities would be time consuming, and very challenging, thus likely not accomplished within the existing time frame that these communities have left.

In addition, the linear configuration of coastal Louisiana communities along the natural levees of historic Mississippi River paths on the deltaic plain in eastern Louisiana and the cheniers in western Louisiana does not make them "eligible" for such an encapsulating solution. Settlement patterns that

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[1] Channel 8 (Fox) television, Sept 7, 2010.

[2] Project Supervisor, Camille Manning-Broome, Director of Planning, Center for Planning Excellence (CPEX) Baton Rouge, LA.

[3] Personal communication with Ms. Manning-Broome. Concerns of Jean Lafitte Mayor Tim Kerner.

[4] http://philipppines.tripod.com/reggie/manilav.html Accessed 8 July 2012.

[5] Unpublished white paper shared with the chapter authors.

historically followed linear patterns have been reinforced over time as growing populations and infrastructure to support them have developed on this high ground. Despite these challenges, given the risk the communities on the very coastal edge face, it is likely that conversations about these possible local major structural community changes will continue to be broached, refined and promoted for implementation for the small number of settlements for which it might work.

In Place Response of Adaptation/Mitigation/Non-Structural[6]

For coastal Louisiana community residents and leaders, in-place risk reduction is their choice response but with the caveat of not wanting to have government controls placed on private property. Norris-Raynbird (2011) found the least desired method of reducing risk was relocation, but the next least desirable is land use regulations. This is a very serious position the communities are taking because it suggests that the degree of risk seen by the outside advocates of zoning is not perceived by the residents and leaders of the communities as being grave enough that they are willing to compromise land use decisions. "You mean take the property out of commerce?" is one phrase that emerges when land use control is proposed that would prevent development because of flood risk.

Given that the support services and businesses for the offshore oil industry desire to be as close to the Gulf as possible, the location of such businesses in the coastal parts of the parishes may continue despite their risk; Port Fourchon at the tip of Lafourche Parish is certainly such a case. Similar to fishers wanting to remain close to their harvesting grounds, so too oil-production businesses want to locate near the offshore activity they are supporting. Additionally, nationally, little interest has been expressed by businesses to mitigate commercial structures; rather businesses frequently opt to absorb the loss when a flood occurs.[7] Businesses, including in coastal Louisiana, feel that adjustment to the property or building that blocks business conducted the usual way will reduce profits.

It may be also that the community leaders do not believe that asking owners to give up control would be an effective measure of risk reduction even if they agreed to do so, and that the tradeoff might be economic stagnation, a similarly high risk. More research is needed to determine whether risk reduction is negative or positive in its relationship to total community resiliency and specifically to economic activities. That may give homeowners' and officials' needed knowledge to know if their resistance to methods used in larger communities, that are so strongly advocated by planning and mitigation practitioners and their organizations such as the American Planning Association and Association of State Floodplain Managers, to name two nationally important ones, is in their communities', and their businesses' self interest.[8]

The University of Louisiana at Lafayette has studied one very successful case of mitigation—through voluntary home elevation. The town of Delcambre in Iberia/Vermillion Parishes has been very successful in their efforts (Farris et al. 2010). Following Hurricane Rita there initially was little support for elevating homes, but slowly that began to change. After Hurricane Ike, residents began to realize that a 1-in-100 year storm (which is what Rita was called) meant that there was a 1 % chance for such a storm *each year*, not that it would be 100 years before another came along. UL-Lafayette sociologists associated with the Center for Socioeconomic Research conducted a survey of all houses in Delcambre in June of 2009. Over 40 % of the 850 houses were elevated above Hurricane Rita's surge then and they estimate that over 50 % are now elevated. People who have not elevated told the researchers that they "are on the list."

The success of Delcambre's elevation 'movement' began during earlier storms when the community's Economic Development Committee took the lead in promoting elevation and benefitted from the advice of a well-respected mitigation specialist and LSU Sea Grant official. The ensuing storms prompted increasing interest by the residents in what Economic Development officials had promoted. Improvements in efforts to mitigate over multiple flooding events, what is demonstrated in Delcambre, was first observed in the Pearl River subdivisions in Slidell where self-mitigation of homes (no government funding) to increasing protection occurred over several flooding incidents as the earlier efforts showed some success (Laska 1990).

Elevating existing houses in Delcambre cost between $ 10,000 and $ 50,000 apiece. Looking, for example, at Yscloskey in eastern St. Bernard Parish, even starting from scratch and if each new elevated house cost $ 150,000 and if there were 100 of them, that is $ 15,000,000 total, an amount probably less than half the cost of a single floodgate that would be part of the structural strategy (# 1) above. And elevation of commercial and public buildings is of course also possible (see below). Similar rates of home elevation are occurring in southern Terrebonne parish and on Grand Isle. Unfortunately in the latter case the community was refused

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[6] In the jargon of the U.S. Army Corps of Engineers "non-structural" mitigation means any strategy that does not involve large levees, i.e. 'structures'.

[7] Personal communication with Gene Barr, retired U.S. Army Corps of Engineers member of the National Non-Structural Committee. Sept 7, 2012.

[8] Hazards Planning Research Center, Am. Planning Assoc. www.planning.org/nationalcenters/hazards/ and Association of State Floodplain Managers www.floods.org.

funding to repair a breached levee because their elevation efforts had reduced the benefit/cost ratio needed to have the levee supported. Hurricane Isaac targeted Grand Isle and the island was overtopped with 2–5 feet of water. Such an approach toward funding by the Corps—not rewarding elevation but rather considering it contrary to proposals for levee repair—prompts consternation among communities who want to reduce their risk as much as possible: If you elevate effectively behind levees, you might reduce your prospects of retaining federal support to maintain the levees you have.

A more detailed consideration of the combination of multiple methods is warranted. For example, currently no Corps flood protection projects have ever included project 'alternatives' (phrase used to describe various proposed flooding solutions from which the Corps will select one for construction) that combine the two types in one flood risk reduction project.[9] This fact may reduce the willingness of those behind levees, even those behind levees providing less than 1 %/year. protection, to elevate if they fear reduction in levee maintenance if they elevate or do other risk reduction efforts. Erring on the side of redundant risk reduction, as in the "multiple lines of defense" approach is a paradigm shift not yet experienced by government programs and resources, the Community Rating System being an exception. For this program, efforts on multiple measures combine to reduce the cost of flood insurance for an entire participating community. (See below for more details of this program.)

Elevating homes does not, however, protect boats and other community infrastructures. Some community and commercial infrastructure elements can also be elevated. See South Cameron High School, Bridge Side Marina at Grand Isle and Capital One Bank at Cameron for examples. In coastal resource dependent communities boats are the lifeblood of resource harvest and are, thus, a special consideration when mitigation and restoration strategies are considered. It is not uncommon for the boat to be worth more, financially, than the family's home and a common practice is for some family members, usually the men, to evacuate the boat to a more protected anchorage as a hurricane approaches. Wind, rising water, and waves are the threatening forces that tropical storms bring. Boats are usually designed to take a considerable amount of wind and they can float above rising water as long as they can be secured in place and be protected from waves and harm from other boats that have broken loose. Docks that float and thus also rise and fall with the water are common in areas with high tidal ranges and some combination of floating docks, protective anchorages, or systematic, well thought out, evacuation plans for vessels is in some cases as important as a mitigation plan for homes and businesses.

The crossing of the bayous with new bridges, however, prevents the boats from being moved inland as easily as in the past. In addition, surge barriers in bayous or over coastal highways, unless carefully thought out, can also prevent harvesters from securing their boats and equipment. Lafourche Parish built a lock at their surge barrier in Golden Meadow in order to permit boats to enter the safe bayou after the gate is closed behind them. The combination of raised structures and protected havens for boats may offer the best response to both climate and energy challenges. But again, they may be difficult to create with the bayou linear water patterns and extreme loss of land on the coast.

The other means of reducing risk that Norris-Raynbird (2011) studied and that are included in John Lopez's "multiple lines of defense" include: citizen mitigation education, local building code reform for both new and existing construction above the state minimum and wetland restoration projects (Lopez 2006). Several coastal parish leaders (St. Bernard, Terrebonne and Jefferson Parishes are three of them) have acknowledged that higher elevation levels as part of the building codes have mitigated flooding during Hurricane Isaac. These multiple lines of defense were all seen as favorable, i.e. in the middle range of support in Norris-Raynbird's (2011) study. Of course, levees in the locations where they currently exist were also very popular selections.

Our recommendation is that SEST be supportive of communities in determining what they want to do with regard to reducing risk, supporting their knowledge and resources to do so. The 'edge' of this recommendation is that more detailed representations of the worst-case scenarios should be included in the possible models of action. Both the risks and the solutions should be moved from the 'abstract' to the 'real', i.e., best practices. When considering coastal restoration as the prime means of risk reduction we believe that restoration cannot be the focus at the expense of considerations of mitigation. *Restoration and mitigation should be integrated and should not proceed independently nor linearly, i.e. restoration first.* And, we should not minimize the implications of climate and energy threats. These should be clearly presented to coastal residents and others so that fully informed decisions can be made.

FEMA's efforts to be the 'regulator' for risk reduction have achieved mixed results. Mandating elevation in flood zones for example was given a middle approval rating by the interviewed officials in the Norris-Raynbird study, but also resisted—most Louisiana coastal parishes appealed the new National Flood Insurance Program flood maps. Norris-Raynbird found that there was a decline after hurricanes Katrina, Rita Gustav and Ike in willingness to enforce coastal zone requirements already in place and/or being strength-

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[9] Personal communication with Gene Barr. Some efforts have been made to consider non structural alternatives but not in conjunction *with* non structural. Nov 16, 2012.

ened by federal agencies. It might have been expected that stricter regulations would have been received in a positive manner as risk reducing actions. However, the fear that the regulations will increase costs to the extent that they will reduce their communities' ability to continue to exist, turn the regulations into enemies rather than resiliency support. The new regulations changed coastal officials' views from seeing themselves as "regulators" to seeing themselves as being "regulated." This response likely came from the frustration due to limitations placed on the rebuilding process after the storms. Revisions (most often expansion) of the flood maps which determine who must purchase flood insurance and how much it will cost combined with the level to which structures must be elevated in risky areas were major points of concern observed by Norris-Raynbird.

One FEMA National Flood Insurance Program effort–the Community Rating System—is a regulator approach but with a twist. It rewards risk reduction behavior by reducing flood insurance premiums community wide if the community adopts certain risk reduction methods. Several coastal parishes and cities hold the best ratings in the state—Terrebonne, Jefferson, St. James and St. Tammany Parishes and Houma, Kenner and Mandeville (Federal Emergency Management Agency n.d.).[10] Some concern by national officials that the requirements were not strong enough has led to revisions that are requiring parishes to improve their efforts. Terrebonne is trying to anticipate these new requirements so as to retain a good Community Rating System level.[11] Such an approach as the Community Rating System—rewarding good practices—is a possibility for bringing local officials on board. Funded mandates are another possibility of achieving risk reduction activity compliance. It is the unfunded mandates that cause the most resistance.[12]

Long Commutes for Harvesters and Seasonal Use of the Coast

Separating fishers' residences from their boats increases their cost of operation and the greater the separation the greater the cost. Not only are commutes expensive (fuel, vehicle wear, time lost fishing), but also the new cost of renting a berth in a marina is an additional burden.[13] Currently many coastal fishers live on the bayou and literally tie up their boats in their back yards. In addition, the complex networks of exchange and support (see below in #4) would be degraded or lost with this option. Pre-Katrina research funded by the Louisiana Coastal Area program examined the space around ecosystems that was important for harvesters and communities, in other words the ecosystem that must be protected to preserve the existing community and harvesting social structure (Laska et al. 2005). Reviewing what would be lost with continual storm inundation leads to the conclusion that it may be very difficult to relocate harvesters inland very far and still have them continue to harvest (see also Gramling and Hagelman 2005).[14]

As long-time coastal residents have left, new people have come to dominate the coastal landscape in some parts of Louisiana, leading to gentrification of the coast by recreational fishers building new, more storm-resistant camps than the older homes owned by permanent residents. *Gentrification* is a term usually used in reference to patterns of urban development where people purchase inner-city properties that are in decline and develop these into attractive housing and retail destinations displacing the resident population which cannot afford higher rents in the newly desirable locations (Laska and Spain 1980). The same process of displacement is occurring on Louisiana's coast. The new structures, sometimes in "gated" communities tend to be separated from the original residents. While the owners are not included in the population counts, their investment in places like Cocodrie and Bayou Dularge in Terrebonne and Grand Isle in Jefferson Parish are quite evident.

These new investments place new demands on local and state governments, focusing on the needs of weekend and vacation visitors and diminishing the broad community dynamics of local schools, religious organizations, commercial resource extraction activities, and local retailers that supported these activities. Gentrified communities are not a substitute for "comprehensive" small communities that serve permanent residents across a range of economic incomes and occupations. Some would say that no longer are they communities but rather have become 'locations' for temporary activities. Original residents must shift their economic activities to serve the vacationers' interests and worry about how they will satisfy their other needs such as schools for their children as the permanent resident population declines.

An example of such coastal development is the recent creation of the Queen Bess gated community on Grand Isle that was carved out of the marsh on the bay side of the island contiguous to the tract preserved by the Nature Conser-

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[10] East Baton Rouge and Shreveport are the inland exceptions.

[11] Personal communication, Chris Pulaski, Senior Planner, Terrebonne Parish Government. Sept 7, 2012.

[12] Personal communication, Camille Manning-Broome, Director of Planning, Center for Planning Excellence. Sept 6, 2012.

[13] Several shrimp, finfish and crab harvesters participating in the large GoFish anti-BP rally (August 2012, Alario Center, Jefferson Parish) spoke of the exhaustion they experience because they are no longer able to live near where they harvest due to loss of homes from storms or inability to pay house mortgages.

[14] Recent collaborations by UNO-CHART with the Barataria Bay shrimp, oyster, crab and finfish harvesters through CPRA funding (Sci-TEK Project) showed very few of them lived outside of the Barataria area, even though both sides of the Bay were badly damaged during the last seven years. Of the 13 harvesters in the project, only 1/13 keeps their boat at a marina and 3/13 commutes down to their boat from farther inland.

vancy for songbird arrival each spring from across the Gulf of Mexico. Residents express concern that the canals dug for the private boats will act as channels to put more water on the island during storms. There is no doubt that the development reduces the area for songbird usage, with its accompanying economic activity—the Grand Isle Bird Festival—that has brought financial benefits and nationwide kudos for the area's and the state's commitment to the environment.

Relocation

Relocation of populations and communities has many manifestations. The moves documented in the census data in the first section of this chapter are moves of individuals, households of various configurations and perhaps multiple extended family households, close friends or neighbors to the same areas But willingness to move is not common in coastal Louisiana as the Census data in the first section of this chapter demonstrates. Geographic and cultural differences have created more change-resistant and "attached" communities in the wetland and riverine areas of Louisiana than perhaps in the beach communities of say the northern Gulf of Mexico, where many residents have already moved inland after Katrina. To the extent that members of communities on a beach coast already focused on a tourism culture can move inland and still participate in the pre-Katrina tourism economy, the relocation might be less disruptive. While community ties, neighbor and extended family social capital will still be fractured, these tourist-oriented activities are much more focused on the money economy and are not as dependent on complex networks of exchange and support as are the resource dependent communities embedded in the Louisiana coastal wetlands. In addition, because of the population distribution patterns and transportation routes along narrow fingers of remnants of the Mississippi River path created thousands of years ago, relocation involves much longer distances to "safe" areas in Louisiana than inland from the straight Mississippi and Alabama beach-lined coast. No comparison of difficulty is meant here. All relocation is very difficult—disruptive, costly both socially and economically as will be outlined below. But community differences create different challenges for individual and households in their struggle to remain in a risky location or to relocate.

Individual and household relocation has also occurred in coastal Louisiana under dramatically harmful conditions to those who have been 'forced' to relocate, called *involuntary relocation*. One dramatic example is the post Katrina diaspora from New Orleans. The population of New Orleans has been reduced by more than 100,000 since Hurricane Katrina (Table 1), even considering in-migrants to the city after Katrina. Some original residents were evacuated to locations far away and have been unable to return for economic reasons. Related contributing factors are the demolition of most public housing after the storm and housing costs increasing dramatically. It should be emphasized that such relocation is the result of the magnitude of the event and damage but perhaps more so the lack of 'essential resiliency' of the community (Laska 2012). Essential resiliency is the pre-event condition of the entire community and its citizens with regard to available employment appropriate to resident skills/education, social justice commitment (thus trust among groups and of the government), strong social and public service provision and other community characteristics that reflect a community successfully supporting the well being of *all* of its residents prior to a disaster happening. Future major disasters in the region will produce continuing involuntary migration of both urban and rural populations to the extent that essential resiliency is not achieved.

In the case of such involuntary relocation strong tensions exist between working toward removing residents, their homes and belongings from harms' way and supporting a relocation experience that in itself does not harm the migrants. Noted work by Michael Cernea (1997) clearly describes the outcomes of relocation without careful, resourced relocation efforts: landlessness, joblessness, homelessness, marginalization, food insecurity, loss of access to common property resources, increased morbidity and community disarticulation. The latter refers to the fracturing of social networks and social systems critical to individual, household and community resiliency.

Some groups will fare better than others by virtue of their economic resources and involvement in the modern sector of the economy, i.e. more mobile employment skills. One such group comes from suburban communities of middle-income residents, some of whom migrated here from other locations and then will relocate away. Such migrants are more similar to the migrants who might move from one city to another for employment purposes. The move may be less challenging for them because they are less attached to place. The economic contribution such individuals can make to the region is, nonetheless, important and thus a loss if they must migrate. Among such migrants after Katrina are African American professionals from New Orleans East, whose loss to New Orleans is more than just economic.

The third type of relocation of individuals or households is somewhat unusual and includes multiple extended family households, multiple individual close friends or multiple neighbors, either individuals or households. Such group behavior is not common. It is, however, documented in the movement of residents of St. Bernard Parish to St. Tammany Parish after Hurricane Katrina (Lasley 2012). Multiple extended families, close friends or neighbors have moved into the same new residential subdivisions. The linkage is by word of mouth recommendations for particular contractor/developers and for subdivisions of affordable, right-sized homes with desired amenities such as nearby social institutions with linkages to the original parish—churches, schools, butchers, restaurants. The mutual attachment of former St. Bernard residents to one another and their 'migrated' social institutions has played a significant role in this form of relocation. No formal organizations or government activities have caused these relocations to similar destinations. Social networks including social clubs have supported the moves as they have happened.

Another option is to relocate entire community populations (we are coining the term *en group* to describe this form of relocation) to more protected locations, as intact communities. The Louisiana coastal Native American communities at risk to flooding and storm damage have expressed this desire if they have to relocate. Such relocation will permit the continuation of the close social functional ties with other community members and the continuation of cultural practices both of which form the core of the resiliency of such groups.

Our society has little experience with *en group* relocation except as short "up-the-hill" relocations such as the one that occurred with Valmeyer, Illinois moving onto the higher bluffs after the Mississippi River flood of 1993 (Knobloch 2005)[15] and the classic example of the Tug Fork, West Virginia relocation (U.S. Army Corps of Engineers 1984). There appear to be a number of obstacles to achieving such relocation. Not the least of these problems is current land and mineral ownership patterns that in some cases have been established for generations. Cultural and sacred meaning of the current locations of the community places also comes into play. Initiating the complicated process that would be necessary to accomplish such *en group* relocation seems daunting given that few government tools are available and the lack of motivation of state and federal agencies to create such tools. In addition Norris-Raynbird (2011) found little support for this strategy among local officials. Finally, another factor that also enters into the consideration is the resistance by those communities already established farther inland to the increased population density brought on by relocation.[16] There may even be ethnic-group resistance by the receiving communities to such inland migration of some groups such as Native American communities,[17]

Social networks linked to traditional economic activities are fundamental to a way of life in Louisiana coastal communities. Coastal residents engage in a complex set of relationships that combine the social with the economic in webs of support that make many economic activities possible and important. As coastal land loss and repeated storm impacts break up communities and force individuals and families to migrate inland they lose not only the place they were familiar with, but the network of exchange that sustained them, and as a result their new lives, while "safer," are poorer for the loss of place. Their subsistence livelihood fits the "commons" of the marsh, bays and near-edge coastal waters; it cannot function inland.

Additionally, the loss of population in the small communities puts those remaining at risk because of the decrease of people in their social networks.[18] Dennis Mileti's research (1997) on decision-making before a disaster, called researching or 'milling' (in later evolution of the research) finds residents checking facts and beliefs among a family/friends network when deciding whether to evacuate or not. These same dynamics of 'sense making' occur in the recovery phase, according to DeRouen et al. (in press). As community size declines, residents have fewer friends, neighbors and co-workers with whom to interact to make good decisions including those choices of whether to remain or leave.

The state of Louisiana had federal resources after Katrina/Rita that several environmental groups and a university argued could have been used for a relocation of one of the largest most at risk groups, the United Houma Nation, but to no avail. The leaders of another at risk Native American group—the Isle de Jean Charles now hope that they will be able to benefit from the funds resulting from the British Petroleum (BP) oil spill—NRDA or EPA Water Quality fines from BP to accomplish this outcome. The only option currently available for community members is to relocate individually or as households, thus separating them from their resource extraction activities and traditional Native American culture. We know what happened to Native Americans in the twentieth century who were forced from their land into impersonal urban settings. The Cernea work (1997) described above and in multiple other publications, clearly warns of the negative outcomes whether it be for rural Native Americans, for urban African Americans or for those coastal residents in general, regardless of race or ethnicity with limited economic resources and attachment to coastal occupations. To date, the society has declared through the actions of the federal and state bureaucracies that it cannot, will not, use its resources to affect successful community (*en group*) relocation within coastal Louisiana. The future on this option is yet to be written.

Discussion

With some exceptions, coastal restoration efforts will not force people from their communities. Modeling of water levels has shown that Jean Lafitte in Barataria Bay would have problems if the existing diversion from Davis Pond were to fully flow at the same time as the proposed Myrtle Grove diversion, i.e. during the spring high water. Inunda-

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[15] http://freshstart.ncat.org/case/valmeyer.htm.

[16] Personal communication with JoAnne DeRouen, University of Louisiana at Lafayette regarding findings from post Hurricane Rita research.

[17] Personal communication with Albert Naquin, Chief, Isle de Jean Charles Band of Biloxi-Chitimacha-Choctaw Indians.

[18] Personal communication with JoAnne DeRouen, *ibid*.

tion of existing communities' structures was also a concern of the Third Delta Conveyance Channel proposed to deliver fresh water and sediment on either side of Bayou Lafourche (Gramling et al. 2006). (This proposal never moved forward from the study phase.) And in some proposed restoration plans, the shift of salinity that results from introduction of freshwater will affect the location of the harvesting they do, such as oysters, and thus limit the economic usefulness of living at certain sites. For most coastal communities, however, lack of restoration coupled with lack of mitigation of natural and technological hazards will be what forces people away from the coast. Thus, both restoration and mitigation, *which should always be conducted in a coordinated fashion*, are positive activities for coastal communities.

Conclusions

Coastal Louisiana is facing a perfect storm of subsidence, climate change, sea level rise, rising energy prices, and financial constraints on governments. Some areas will be lost. Others may be able to survive, at least for a while. As the most adaptive species on the planet, people and communities will take actions, make choices, and will do so based on knowledge of place and commitment to community. Key national mitigation experts (Natural Hazard Mitigation Association[19]) meeting during the summer of 2012 at the University of Colorado's highly respected Natural Hazards Workshop, affirm the approach developed by James Lee Witt, when he was director of FEMA, entitled "Project Impact"—oriented toward encouraging internal community support for risk awareness and risk reduction response, utilizing the communities' own social capital. The serious question for applied social scientists concerned with coastal Louisiana is this: can the local communities make a commitment to comprehensive non structural adaptive mitigation fast enough to keep up with the increasing risk to which they are subject? And can applied social and physical scientists make a contribution to this achievement? As stated above, scientists should clearly present the full range of challenges facing the coast, including climate and energy scenarios, and best practices for non structural/ mitigation/ adaptation methods so that informed decisions can be made. The 'window' for learning about the threat and for appropriate responses is closing rapidly due to the escalating pace of increased risk.

We need to explain the likely impact of climate change and sea level rise on specific communities. We need to explain the problems with relying exclusively on a structural approach to coastal protection, including high and recurring operation costs that may not be sustainable politically or otherwise. Without a realistic and overarching appreciation of the changes that are occurring to the ecosystem it may be that the protective actions that are taken have the effect of increasing risk. Constructions of elaborate levee systems are likely to encourage further investments behind those levees in homes and businesses that will be at risk *when* the levee systems fail. Coastal policies designed to confront rather than work with natural deltaic forces may send the wrong message to coastal residents, that it is safe to stay rather than continue the process of gradual retreat from the most vulnerable parts of the Louisiana coast.

As scientists concerned with human adaptation to change, we believe it is also necessary to focus attention on issues of public policy including its implementation, and in particular identify those parts of public policy that undermine the ability of coastal communities to have a voice in their futures, or result in investments that favor one set of actors (e.g., recreational or navigation interests) over another (historied communities). Our role as scientists is to clearly and honestly present information on climate, energy, ecosystem dynamics, human social system processes and large economic forces, that may make certain community resiliency options much more difficult, if not impossible, within current planning horizons. Our role should not be to tell communities what they must do, but to help them explore and implement risk-reducing options in as timely a manner as possible.

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The Importance of Mississippi Delta Restoration on the Local and National Economies

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Abstract

Most economic activity in coastal Louisiana depends, either directly or indirectly, on the Mississippi River, its delta and the coastal wetlands of the Chenier plain. Maintaining the economic vitality of the region requires taking action to restore these essential elements of the coastal landscape. The economic value of the jobs and assets that will be lost without restoration can be estimated from standard indices of economic activity in the region such as gross domestic product and jobs, and from the value of ecosystem goods and services.

The economic health of the United States also depends on sustaining the navigation, flood control, energy production, tourism, and seafood and other natural resource production functions of the Mississippi Delta and river system, making Mississippi River Delta restoration critically important. These systems are at risk due to the degradation of coastal wetlands. The Mississippi River Delta ecosystems provide at least $ 12–47 billion in ecosystem goods and services benefits to the people of the United States every year and a natural capital asset value between $ 330 billion and $ 1.3 trillion. Unless the delta is restored and maintained, the entry to the Lower Mississippi navigation system, the lynchpin in the entire Mississippi navigation and freight transportation system, is likely to collapse. The economic value of the MRD is $ 1.3 trillion when the natural capital is included as a valued economic asset. The economics are clear, an investment in costs to modernize the Mississippi River Delta in ways that allow it to gain ground, and to sustain critical infrastructure far into the future is justified and critical to the economic health of both the state and the nation. *Economic collapse on a large scale looms in the near future unless dramatic steps are taken to reverse the deterioration of the Mississippi River Delta*.

Keywords

Mississippi River Delta · Ecosystem services · Ecosystem services valuation · Economic viability

Introduction

When coastal land disappears, the resources, the economic activities, and the communities that depend on it disappear as well. The processes of land loss and environmental deterioration have prevailed in the Mississippi River Delta (MRD) for the past 80 years, and they continue unchecked. However, current management activities in the Mississippi River and the Louisiana coast remain focused on continuing long-standing practices to assure navigation and flood

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control, largely exclusive of other concerns. Based on current trends and projections for future sea-level rise Blum and Roberts (2009) estimate a further loss of 10,000–13,500 km^2 by 2100 unless the focus of management broadens to include restoration of the deteriorating coast. Economic collapse on a scale greater than that wrought by Hurricane Katrina looms in the near future unless dramatic steps are taken now to reverse the deterioration of the MRD.

The ecology and economy of coastal Louisiana are at risk of being lost without changes in the way that the river and coastal wetlands are managed. Continued focus on building levees for protection will do little to avert collapse. Levees protect homes and essential human-built infrastructure against damage and loss from flooding events. They do not address the major processes responsible for the deterioration of the coast: the loss of sediment inputs needed to maintain coastal wetlands in the face of rising sea level and subsidence. In fact, levees will often facilitate the deterioration and loss of the MRD and the associated essential economic goods and services that it provides.

A new emphasis on coastal restoration is required to maintain the economic vitality of this region. Specifically, unless land-building processes are restored in the MRD to offset the effects of sea-level rise and subsidence in the region, jobs will be lost, waterborne commerce will suffer, and petrochemical production will decline. *The cost of flood protection and coastal restoration will be large; estimates range from $ 14–150 billion* (Abramovitz et al. 2002; Coastal Protection and Restoration Authority 2006; CPRA 2012). *Already, repairing damages from hurricanes and floods costs the Gulf Coast region about $ 14 billion annually* (Entergy 2010). *However, the cost of not restoring the coast is even greater.*

The restoration of the Mississippi River Delta is also a pressing national priority. Not only is the future of one of the world's most unique and important ecosystems at stake (along with all the economic and cultural benefits associated with that ecosystem), but the economic health of much of the United States depends on sustaining the navigation, flood control, energy production, and seafood production functions of the Mississippi Delta and river system. Each of those functions is currently at severe risk due to the degradation of the delta and coastal wetlands systems. Consumers throughout the nation will pay the price of further deterioration. Therefore protecting these assets should not fall only on one state or region.

Standard Indices of Economic Activity for Louisiana

We use two methods to evaluate the benefits of restoring the coast: standard indices of economic activity (e.g. GDP, jobs) and the value of ecosystem goods and services. The economy of coastal Louisiana encompasses a diverse range of economic activities including: fisheries and other natural resource-dependent activities, tourism, oil and gas, agriculture, ports and transportation (Table 1). All of these activities are related, directly or indirectly, to coastal ecosystem goods and services. Over 2 million residents live in south Louisiana (about half of total state population), and the bulk of Louisiana's economic activity is generated in the southern part of the state.

By the conventional measures of employment and income, the impact of the Mississippi River Delta is huge. Economic activities related to the river account for nearly 2 million jobs and around $ 20 billion in annual income. Interestingly, this is in the range of the value ecosystem goods and services (see below). Our key assumption is that all of this economic activity is at risk from the effects storm damage and coastal deterioration if we do not begin large-scale restoration activities aimed at reversing land loss and recreating a more resilient coastal ecosystem. We further assumed that the feasibility of restoring Louisiana's coast was not in question, and that options exist for saving this ecosystem.

Fisheries

Fisheries industries provided jobs for more than 40,000 Louisiana citizens. Louisiana commercial landings exceeded 916 million pounds in 2008 with a dockside value of $ 272.9 million, accounting for approximately 24% of the total catch by weight in the lower 48 states (ASPO 2008). Non-commercial fishing in Louisiana employs almost 20,000 people and generates annual expenditures that amount to over $ 1.7 billion (Lagrange 2011). In 2003, what might be considered a typical year, the retail value of commercial and recreational fisheries harvest in Louisiana was $ 2.85 billion (LCWCRTF 2007).

Other Natural Resource-Dependent Activities

Louisiana's coastal wetlands provide habitat for approximately 3.28 million migratory waterfowl each winter (LDWF

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Table 1 Louisiana's principal economic activities

Category	Index and source	Dollar impact	State jobs
Commercial and Recreational Fishing Industries	Yearly impact 2003 (LDWF 2011)	$ 1.15 billion	20,000
Recreational Fisheries	Yearly impact 2003 (LDWF 2008)	$ 1.7 billion	20,000
Other natural resource-dependent activities	Hunting related expenditures (CWPRA 2007)	$ 975 million annually	
	Wildlife watching (Doi et al. 1973)	$ 517 million annually	
	Fur harvest 2007–2008 (NOAA 2011; USACE 2011)	$ 1.75 million	
	Alligator and egg Harvest (Doi et al. 1973)	$ 109.2 million	
Tourism	Lodging and food services in Louisiana (Times-Picayune 2011)	$ 9.7 million	180,289
	Statewide value of tourism before Hurricane Katrina, most in south Louisiana (Poor et al. 2007)	$ 10 billion	165,000
Oil and gas	Economic impact for TX, LA, MS, and AL (America's Wetland Foundation 2010)	$ 1.1 billion to state and local taxes	Direct employment of 131, 500
	Job related benefits	$ 2.7 billion to state and local taxes from payroll	More than 50,500 Louisiana residents
Agriculture (sugar production)	Crop Value in Louisiana Economic (Rose et al. 2001)	$ 809 million	
Ports	Direct economic impact of south LA ports (Ryan 2001)	In 1999, $ 10.3 billion	250,000
Transportation	Economic impact for TX, LA, MS, and AL (America's Wetland Foundation 2010)	$ 3.7 billion to state and local taxes from payroll	1.1 million

2011) that contribute to hunting-related expenditures amounting to $ 975 million annually (CWPRA 2007; USDOC 2009). Expenditures related to wildlife watching in Louisiana amount to $ 517 million annually (Doi et al. 1973; USDOC 2009). Fur harvest in 2007–2008 in Louisiana's coastal wetlands generated approximately $ 1.75 million (NOAA 2011) while Louisiana's alligator and egg harvest was valued at approximately $ 109.2 million (USDOC 2009).

Tourism

Lodging and food services industries employed about 180,000 persons in coastal Louisiana (Times-Picayune 2011). This industry is especially sensitive to environmental disruption. Employment in the leisure and entertainment industry in the New Orleans metropolitan area was 84,300 in 2004 and fell to 57,200 following Hurricanes Katrina and Rita (Howes et al. 2010). Similarly, the economic value of tourism to Louisiana was nearly $ 10 Billion in 2004, and it fell to $ 8.08 Billion following the storms.

Oil and Gas

The state of Louisiana ranks number one in the US in terms of crude oil production, number two in total energy production, number two in petrochemical production, number two in natural gas production, and second in refining capacity (LCWCRTF 2007). Oil and gas extraction industry directly employs 50,500 in Louisiana; more than half of these are from coastal parishes. The industry pays $ 2.7 billion annually in wages. The refining and petrochemical industries account for many of the 134,000 jobs in the manufacturing sector (US Census Bureau 2013).

Agriculture

Sugar cane is a major crop in the coastal zone. The sugar industry has an economic value of $ 809 million (Rose et al. 2001) (Table 1).

Ports

Five of the top fifteen largest ports in the United States are located in Louisiana (LDWF 2011). The port of South Louisiana ships more than 200 million tons of cargo annually and is the largest port in the U.S. in terms of tons shipped. The ports of Lake Charles, New Orleans, Baton Rouge, and Plaquemines each ship less than 100 million tons of cargo. In 2005, Louisiana ports carried 457 million tons of waterborne commerce, accounting for 18 % of all waterborne commerce in the United States (Bradley and Morris 1992). The direct economic impact of port-related activity in 1997 and 1999 was $ 9.7 billion and $ 10.3 billion, respectively, and the total economic impact was between $ 28 and $ 34 billion. Port-related employment added up to 250,000 jobs (Ryan 2001).

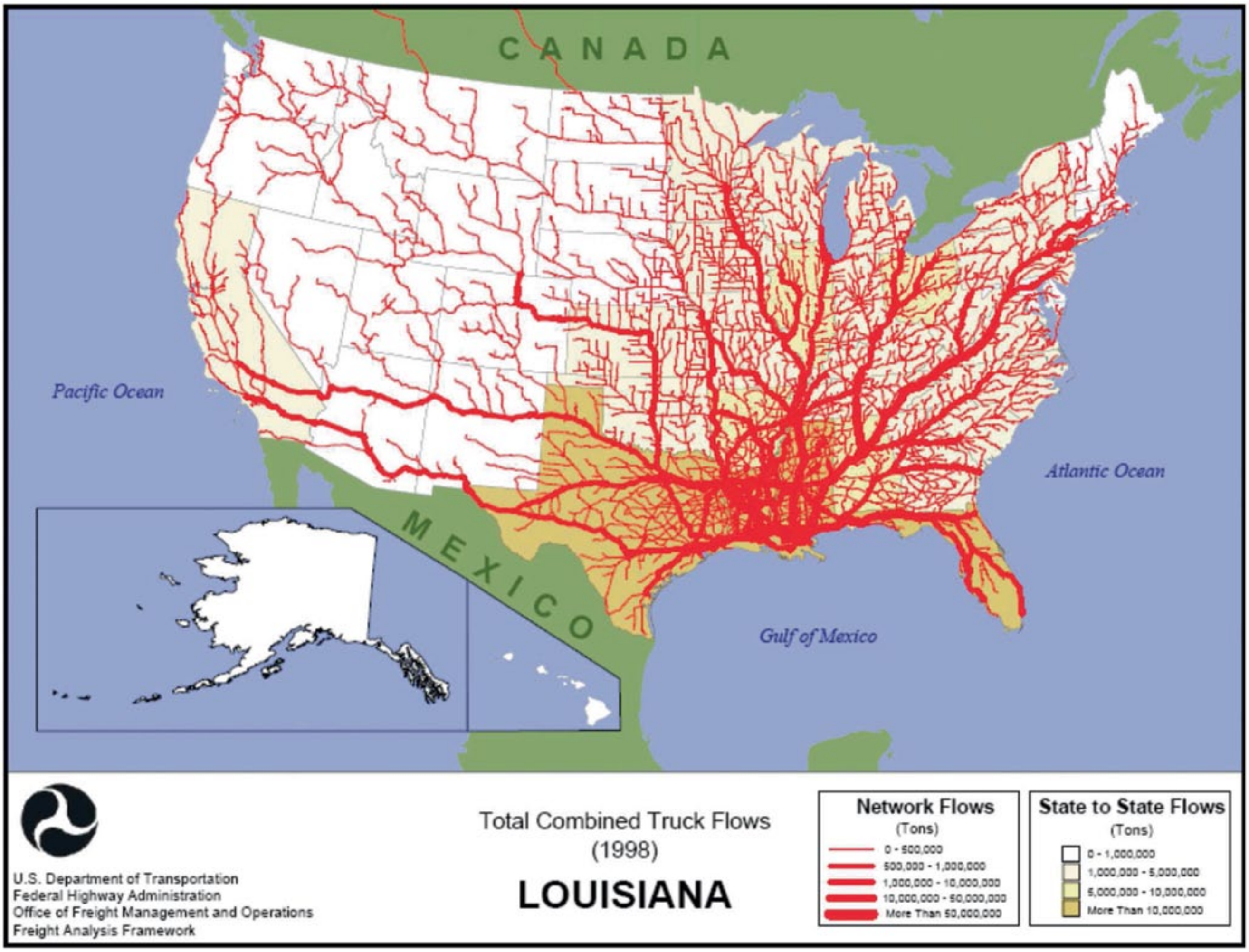


Fig. 1 Louisiana's Mississippi River ports-inland movement of maritime cargo by truck. Courtesy FHWA 1998

Transportation

The Louisiana ports feed a transportation network that serves the entire contiguous United States (Fig. 1). The transportation and material moving industry, including the port systems, directly employs approximately 1.1 million people with $ 3.7 billion contributing to state and local tax revenues from this payroll (America's Wetland Foundation 2010). In 2009, 67,900 people in Louisiana worked in the transportation and warehousing industry. The magnitude of these financial flows does measure the full economic value of the transportation network centered on Louisiana's ports. Imagine the cost to mid-west farmers of lost access to overseas markets and the financial premium that shippers would have to pay to find alternative means of moving goods in the event that navigation through the mouth of the Mississippi River is closed.

Value of Ecosystem Services

The river and the wetland ecosystems of Mississippi River Delta provide a vast amount of goods and services to people in the region. These include supplies of freshwater, regulating nutrients, fisheries and other harvested natural resources, carbon sequestration, recreation, protection from coastal storms and river floods, and critical habitat for valued animal species. Batker et al. (2010) estimate that the benefits provided are worth $ 12–47 billion/year (Table 2). This is on the same order as direct economic benefits. Were the Mississippi River Delta considered to be an economic asset providing this annual flow of benefits, a discounted present value of that flow would yield an estimate of the asset value. Based on this traditional approach for asset valuation, the Mississippi River Delta has an asset value between $ 330 billion and $ 1.3 trillion (assuming a 3.5 % discount rate).

Table 2 Annual value of ecosystem services for the Mississippi delta is $ 12–47 billion per year. (From Batker et al. 2010, Chap. 11). The following ecosystem services were valued

Ecosystem services valued	Valuation method
Water supply	Replacement cost of desalinization
Water quality (nutrient regulation)	Replacement cost of conventional sewage treatment
Fisheries production	Production function
Raw materials (fur and alligator)	Marginal product estimation
Carbon sequestration	Marginal product estimation
Recreation	Travel cost, contingent value
Storm protection (wind and coastal storm surge)	Avoided cost
Water flow regulation (river flood)	Avoided cost
Habitat refugium	(Kazmierczak Jr 2001)

Water Supply

The loss of coastal wetlands puts the water supplies of coastal communities at risk of loss due to the intrusion of salt water into surface and groundwater sources. The cost of replacing existing water sources for coastal communities, with freshwater produced by desalinization plants, is used to evaluate the water supply protection provided by existing coastal wetlands.

Water Quality (Nutrient Regulation)

Wetlands assimilate nutrients and remove harmful bacteria from the water. More than 15 communities employ wetlands as part of their municipal wastewater treatment, usually in the tertiary stage of treatment. Use of wetlands in treatment provides savings in energy costs over alternative treatment methods. The value of nutrient regulation by coastal wetlands is based on the cost savings that could be realized in wastewater treatment in communities where the use of wetland treatment is an option.

Fisheries Production

Coastal wetlands serve as nursery grounds for several species that are important in the commercial and sport fisheries. The value of coastal wetlands in supporting fisheries production is estimated from an analysis of data on fishing effort and landings in the Louisiana commercial fishery for a few key species brown and white shrimp, menhaden fish, oyster and blue crab. These figures do not include the value of fish reared in the Mississippi Delta but caught elsewhere in the Gulf of Mexico.

Raw Materials: Wild Fur and Alligator Production

Similar to fisheries, the value of coastal wetlands in supporting the harvest of other natural resources is based on the annual harvest of a few key species: alligator, nutria, and raccoon. This estimate does not include the value of timber harvested.

Carbon Sequestration

Wetland vegetation removes carbon dioxide from the atmosphere, through photosynthesis, and stores it for long periods of time in woody tissues and the soil—a process known as carbon sequestration. The value of this service is estimated based on rates of carbon uptake and storage measured in the plants found in the Mississippi River Delta and reported in the scientific literature. The estimated value, in terms of dollars per ton, of carbon removed from the atmosphere is based on recent prices paid in markets for trading carbon emissions.

Recreation

The value of coastal wetlands in providing opportunities for recreation relates directly to supporting the tourism sector of the traditional economy. Numerous studies have estimated the recreational benefits of coastal Louisiana's wetlands.

Storm Protection

Wetland vegetation absorbs and reduces the destructive power of high winds and storm surge associated with coastal storms and hurricanes. For this reason, coastal wetlands constitute one component of the Multiple Lines of Defense coastal protection strategy. The estimated value of this service is based, in part, on recent analysis of the impacts of hurricanes Katrina and Rita on coastal Louisiana.

Water Flow Regulation

In addition to protection from coastal storms, wetlands of the MRD play an essential role in regulating peak river flows and preventing cities, towns and critical industrial facilities, like oil and gas, from damage when the Mississippi River is in flood. Recent use of the Atchafalaya, Morganza and Bonne Carre spillways during the river flood of 2011 illustrates this function. Estimates reported for the value provided by coastal wetlands through flood protection is based on values estimated for wetlands in other regions rather than an analysis of the recent Mississippi River flood.

Habitat Refugium

Wetlands of the MRD provide essential habitat to a number of threatened and endangered species. Coastal Louisiana is a stopover for resting and feeding by birds that migrate across the Gulf of Mexico between North American and Central America. The existence of this habitat in coastal Louisiana relieves other jurisdictions in the continental US from providing replacement habitat that would be needed to support threatened and endangered species if the wetlands of the MRD are lost.

Low-cost Transportation

The Mississippi River and its tributaries make it possible to move goods between overseas ports and the central midwestern US at lower cost than either road or rail. While not included for evaluation in the study by Batker et al. (2010), navigation between the Gulf of Mexico and the interior of the North American continent constitutes a vital ecosystem service. This service is supported by the physical elements of the coastal ecosystem, i.e. the discharge of water and sediment by the Mississippi River and the landscape built by these processes. Further, the realization of reliable navigation has required the intervention of engineers to mold and direct the natural processes of the river. The fact that maintaining navigation along the river depends on a combination of human-built and natural capital does not diminish this as an important service provided by the ecosystem.

Investment Required for Coastal Restoration

What must be done to sustain the benefits provided by the ecosystems of the Mississippi River Delta that are at risk due to unchecked deterioration of the coast? And how much will it cost? Various efforts have been made to formulate a comprehensive approach to coastal restoration in Louisiana. The actions required are extraordinary, and the estimated financial costs are high, much higher than what governments have been willing to spend on programs focused to restore coastal wetlands. It is becoming increasingly clear, in part by the analyses just outlined, that what is at risk extends far beyond the benefits that coastal wetlands provide in less extraordinary settings. The cost of coastal restoration in Louisiana should be regarded as an investment made for the purpose of securing a reasonable return. The return on the investment consists of the current benefits that are sustained by restoration.

Initially, planning for restoration of the Louisiana coast was in response to concern over the rate of wetland loss. Coastal restoration proposals including federal money started in 1990 with the Coastal Wetlands, Planning, Protection, and Restoration Act (CWPRA) under the Breaux Act. The Coast 2050 request to Congress in 1998 was $ 14.9 billion over 30 years (not including long-term operations and maintenance) and identified the most critical natural and human ecological needs of coastal Louisiana (LCWCRTF 1998). The Bush Administration found the restoration plan too expensive and directed a Louisiana Coastal Area (LCA) study focused on the most urgent problems. This $ 2 billion LCA plan including 12 near-term projects was authorized but is still seeking funding. In June 2007 the Louisiana state legislature unanimously approved a comprehensive Master Plan for a sustainable coast, which was conceptual and estimated by Louisiana officials to cost more than $ 50 billion over several decades (GAO 2007). Louisiana's Master Plan was revised in 2012 and recommends specific groups of restoration and levee protection projects in with the state should invest $ 50 billion over 50 years (Abramovitz et al. 2002).

In the wake of the devastating hurricanes of 2005, the scope of coastal planning broadened to include wetland restoration and flood protection. This Louisiana Coastal Protection & Restoration Authority (LACPRA) plan provides a large range of alternatives for restoration and protection that range in cost between $ 100–150 billion. The high costs of the alternatives often included expensive marsh creation projects and structural measures (levees). LACPR estimates that it would take $ 543,000,000 per year, for a total "life-cycle cost" of $ 10.7 billion, to restore the coast using Mississippi river diversions, marsh restoration using dredged material, and shoreline stabilization in strategic areas, with the proviso that these coastal measures are for hurricane risk reduction only, sustaining existing coastal landscape. The life cycle cost metric represents the total cost of implementing an alternative plan, which includes first costs (engineering and design, facility relocations, real estate, mitigation, and construction) plus operation and maintenance, repair, replacement and rehabilitation costs (USACE 2009). In a recent report, Entergy calculated that $ 44 billion of public funding will be required over the next 20 years to fund key infrastructure projects including wetland and levees in Louisiana (Entergy 2010).

Present Cost of Inaction

The financial cost of damage from storms and floods is easy to count, recurrent, and growing as continued deterioration of coastal wetlands leaves communities and infrastructure more and more vulnerable. Over the last century, hurricanes have caused approximately $ 2,700 billion (2010 dollars) of significant asset damage across Texas, Louisiana, Mississippi, and Alabama (Pielke et al. 2008). The continued loss of protective wetlands will greatly exacerbate these economic impacts. The Gulf Coast is vulnerable to growing environmental risks today with $ 350+ billion of cumulative expected losses by 2030. While the actual losses from extreme storms are uncertain in any given year, on average, the Gulf Coast faces annual losses of approximately $ 14 billion (Entergy 2010). Depending on the scenario, annual losses in 2030 will increase by 30–60 % over current figures. In the 2030 timeframe, Hurricane Katrina/Rita-type years of economic impact may become a once a generation event as opposed to once a century today. The impact of a severe hurricane in the near-term could also have a significant impact on any growth and reinvestment trajectory in the region. Losses represent a significant annual impact of approximately 2–3 % of the region's GDP, which amounts to approximately 7 % of the region's capital investment. This implies that the region spends about 7 % of its invested capital each year on rebuilding infrastructure instead of on more productive capital investments that could be driving future economic development (Entergy 2010).

The full cost of coastal deterioration, which includes loss of ecosystem services, declining wealth, and the displacement and loss of coastal communities, is more difficult to calculate. Consider the case of St. Bernard Parish located adjacent to New Orleans, Hurricane Katrina resulted in 100 % flooding of the parish, a 47 % permanent decrease in population to date, and a fragmented community (Sarah Mack, personal communication). This parish that has been repeatedly flooded demonstrates a non-strategic retreat from the coast with larger implications. The population decrease has caused a loss of tax base and decreased federal funding. Due to this, the parish government has cut back staff up to 50 % in some departments, which makes it difficult to attract new skilled technical staff. The parish now struggles to maintain the same infrastructure, schools, and social programs with a smaller tax base. This indicates that the parish is caught in a cycle that continues making it harder to stimulate private investment and struggles to maintain its infrastructure. This further complicates the situation by creating a disincentive for elected officials to assist in a strategic retreat from the coast in risk prone areas by threatening bankruptcy to these struggling coastal parish governments and municipalities. The decreased financial and human capacity of a Parish makes it difficult for local governments to provide basic services. The result of repeated hurricanes on already struggling parishes is entrenched poverty at the personal and government level.

Coastal Restoration is an Investment in Communities

Restoration of Louisiana's coast is an investment to maintain jobs and billions in state economic value. Without an aggressive restoration program, the economic activity of the coast, worth hundreds of billions of dollars, will be lost with the homes, businesses and communities. According to a report released by Restore America's Estuaries, coastal habitat restoration typically creates seven jobs per million dollars spent. Habitat restoration projects not only create direct local jobs, but they also stimulate indirect jobs in industries that supply project materials such as lumber, concrete, and plant material. Restoration projects can spur job creation in businesses that provide local goods and services to restoration workers. Restoration projects provide strong returns on investment to local and regional economies in the form of new jobs, increased tourism and tourist dollars, hunting and fishing revenues, tax revenues, and property values.

The Ability of Restoration to Improve the Economic Viability of the Nation

Navigation and Mississippi River Commerce

As we have demonstrated in Chapter 5, unless the MRD is restored and maintained, the entry to the Lower Mississippi navigation system, the lynchpin in the entire Mississippi navigation system, is likely to collapse. Even if it could be temporarily repaired—which is doubtful—interim losses and damage to the U.S. economy would be staggering.

The primary commodities of South Louisiana ports (Fig. 2) include food (47 %), petroleum products (23 %), and crude petroleum (9 %); the primary commodities of the New Orleans port include petroleum products (35 %), food (30 %), and crude petroleum (9 %) (Rose et al. 2001). Scenarios involving transportation issues involved with coastal erosion found that a 7-day closure of the lower Mississippi River would raise shipping costs by $ 50 million, a 14-day closure by $ 200 million (as alternative shipping strategies become saturated), and expanded open water in the Gulf Intracoastal Waterway would increase shipping costs by $ 8.4 million per year (Nelson study in Richardson and Scott 2004). The Nelson study also determined $ 323.3 million in lost sales in the Continental U.S. for a 14-day closure, $ 88.6 million in lost earnings, and the loss of 2,653 full-time equivalent (FTE)

Fig. 2 Louisiana's port system. Courtesy of the Port Association of Louisiana

job years. Shipment of agricultural products, coal, and other products to and from the Midwest depends on a functioning MRD navigation system. The Mississippi River is one of the world's most important economic transport corridors, carrying 60 % of all grain exported from the U.S. and making the deepwater ports stretching 54 miles along the Lower Mississippi River from Baton Rouge through New Orleans to the Gulf the largest port by tonnage in the Western Hemisphere (USACE 2010). Waterborne commerce along this corridor amounts to some $ 35 billion annually and provides approximately 300,000 jobs (Doi et al. 1973).

The nation as a whole benefits from the navigation system of the Mississippi River, in particular the agriculture-exporting states of the Missouri, Ohio, and Upper Mississippi River (GCERTF 2011). U.S. Waterborne Foreign Trade along the Mississippi River in 2003, adjusted to 2005 dollars, had an import value of $ 103.8 billion, and an export value of $ 53.5 billion for a total economic value of $ 157.3 billion (Pendleton 2006). All of this commerce is dependent on a functioning entry to the river from the Gulf of Mexico.

There are no alternatives to the Mississippi navigation system that serve the mid-section of the country. Waterborne commerce is far less expensive than any other form of goods transportation (Törnqvist et al. 1996).

Flood Control and Disaster-Response Costs

Hurricane Katrina already demonstrated how the loss of Louisiana's coastal wetlands, a natural barrier to storm surge, can greatly increase storm damage. The Mississippi River Gulf Outlet (MRGO) is an example of this. During the summer 2005 hurricane, levees adjacent to MRGO failed, in part due to the loss of protective wetlands. Levees with extensive wetlands in front of them remained intact (Shaffer et al. 2009; Storesund et al. 2009). Further erosion and loss of these protective buffers could exacerbate damage from future storms.

The cost of these damages is not limited to local populations, as massive amounts of federal disaster aid are often required to address the aftermath of severe storms. The federal budget will be under continuing pressure for many years to come. Thus, reducing the probability of future storm surge damage by beginning now to implement large-scale restoration projects with other sources of funding (e.g., the use of civil penalties from the Deepwater Horizon disaster, as proposed in the recent RESTORE the Gulf Coast Act) is a vital upfront investment in the national interest.

Beyond effects on the federal budget, the economic impacts of disasters include unemployment, loss of investor confidence, increased foreign indebtedness, and depletion

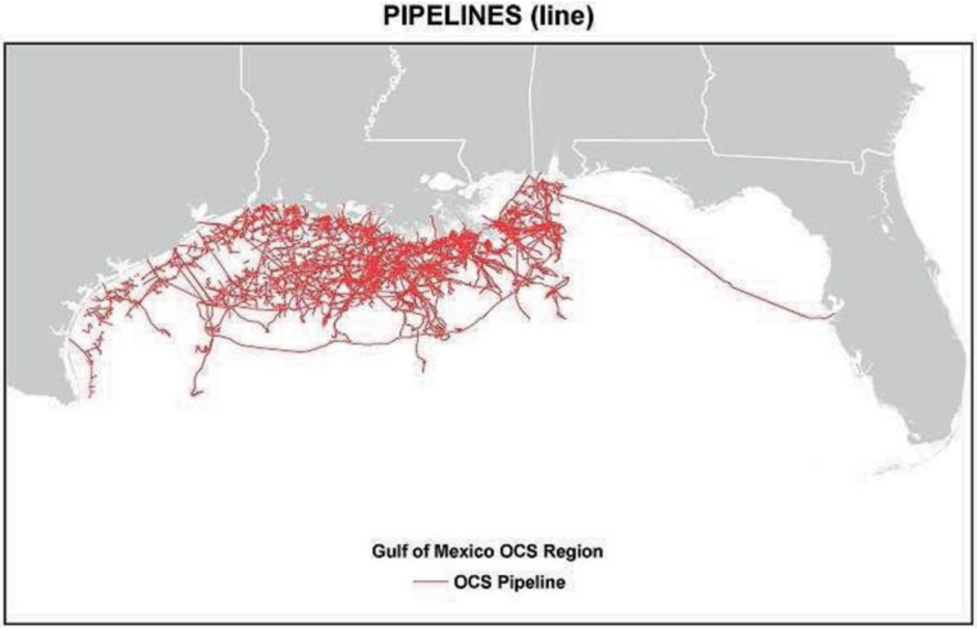


Fig. 3 Oil and gas pipelines in the U.S. portion of the Gulf of Mexico in 2010. Courtesy of the Bureau of Ocean Energy Management

of capital reserves (CWPRA 2007). Natural disasters disproportionately affect the poor both directly at local levels by destroying physical and human capital but also indirectly by destroying national wealth (Meade and Moody 2010).

Energy Production

The second-largest source of federal revenue after income taxes is the Gulf's offshore oil and gas production, which has contributed over $ 165 billion to the federal treasury since 1933 (America's Wetland Foundation 2010). The energy sector is a major economic engine in south Louisiana supporting over 42,000 jobs and contributing $ 2.7 billion in wages. Approximately 30 % of the United States' crude oil production, 20 % of its natural gas production, over 45 % of its petroleum refining capacity, and 43 % of our strategic petroleum reserves lie within the coastal zone of the Gulf of Mexico—most within just a few miles of the coast (Pendleton 2006; RAE 2011). A wide range of potentially at-risk energy infrastructure exists in the coastal areas of the state (see Fig. 1). There are two major refineries in this area, seven major petrochemical facilities, three gas processing facilities and numerous pipeline segments and oil and gas production sites. Many of the potentially at-risk pipelines in the area are responsible for moving a major share of natural gas produced in the Gulf of Mexico to consuming areas in the eastern half of the country including New York, Philadelphia, and Washington, D.C. (Pendleton 2006).

This economic sector is vitally important to the nation as a whole. For example, Louisiana and its Outer Continental Shelf is number one in crude oil production, number two in total energy production, number two in petrochemical production, number two in natural gas production, and number two in refining capacity. In addition, the LOOP (Louisiana Offshore Oil Port) facility is the most important avenue for imported oil for the entire nation (Cieslak 2005).

Any threat to the energy sector in Louisiana is a direct threat to the economy of the U.S. in general. Any disruption in this oil and gas supply impacts prices nationwide, as occurred during Hurricane Katrina. The nation's Strategic Petroleum Reserve (SPR) is located in four 2,000 feet deep salt caverns in Louisiana and Texas that contain approximately 755 million barrels of crude oil. While the salt caverns are virtually invulnerable to meteorological hazards and are located in geologically stable locations—meaning they are relatively immune from earthquakes—the distribution network shares the hazards of the same above-ground distribution infrastructure as the rest of the oil industry in the Gulf Coast. The combined economic impact of a three-week oil production and natural gas outage is over $ 4.5 billion in sales and 45,000 jobs. (Dismukes and Barnett 2006).

Much of the existing and proposed US oil and gas infrastructure on the continental shelf and slope in the Gulf of Mexico—particularly deep and ultra-deep development—is clustered in or just offshore of the Mississippi River Delta (see Fig. 3 and Fig. 4)

Fisheries and Wildlife

Protecting and restoring the Mississippi River Deltaic Plain and its estuaries is vital to sustaining fisheries and endangered species in the Gulf of Mexico. Fish species that depend on the Mississippi River Delta estuaries for at least a portion of their life cycle comprise approximately 80 % of the fish

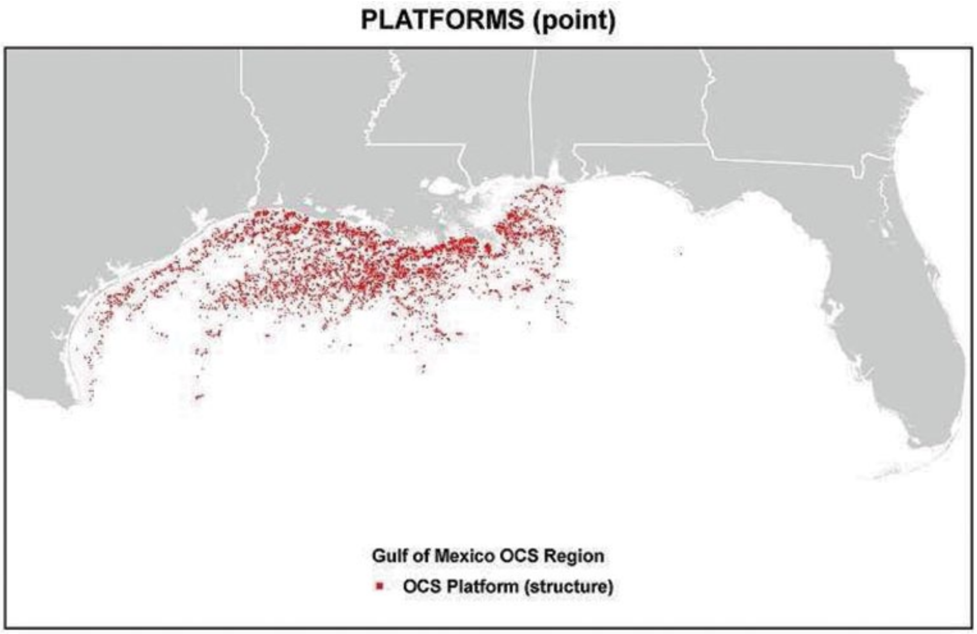


Fig. 4 Active oil and gas platforms in the U.S. portion of the Gulf of Mexico in 2010. Courtesy of the Bureau of Ocean Energy Management

harvested nationwide (Lellis-Dibble et al. 2008). One-third of the nation's oysters derive from the Louisiana, a $ 300 million industry in Louisiana alone (Howes et al. 2010). The Empire-Venice port in Louisiana ranks third-most productive in the U.S. by poundage (Times-Picayune 2011). The Mississippi River Delta ecosystem supports 100 million migratory, nesting, and wintering birds. Richardson and Scott (2004) estimated the annual impact of hunting, fishing, and wildlife viewing on Louisiana's economy in sales (millions of 2003 dollars): Saltwater fishing $ 748.6; migratory bird hunting $ 99.5; wildlife viewing $ 109.5.

Status Quo Costs

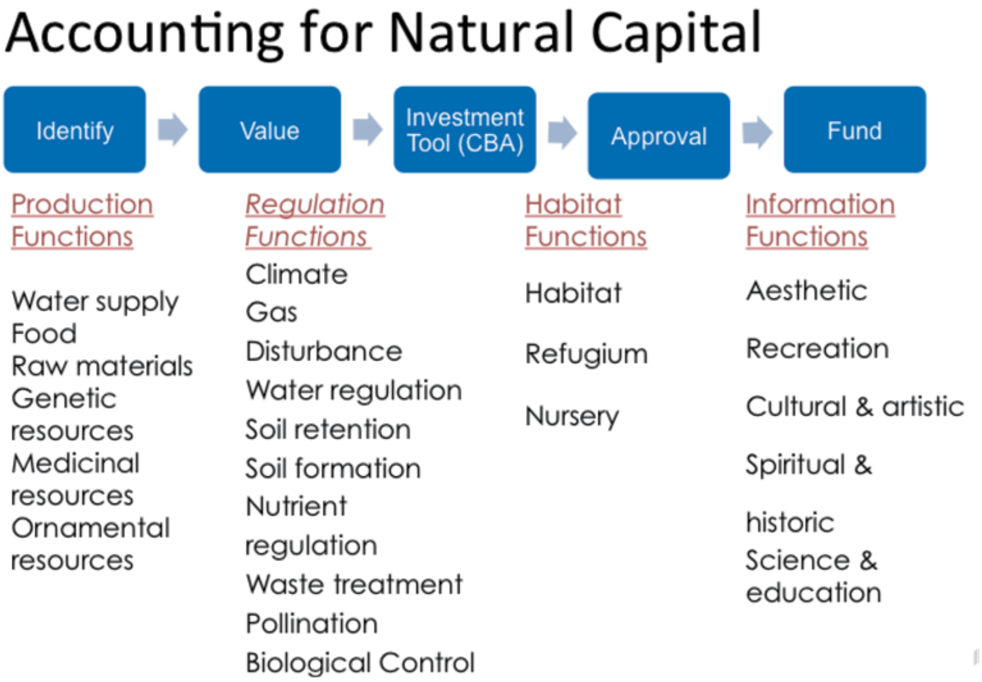
A general agreement exists from the geologic and engineering community that current management of the Mississippi River is short term and extremely costly, and that we are largely unprepared for another costly failure of the engineered (Hansen et al. 2006).

In the high-discharge years like 2008 and throughout much of 2010 and 2011, the Corps of Engineers has had to spend in excess of $ 100 million annually just to keep the navigation entrance at Southwest Pass open to ships up to a draft of 45 feet. Dredging costs rose from an average of $ 85 million/year in 1994 to $110 million in 2010 (USACE, 2013). A significant contributor to the cost run-up has been the rapidly increasing price of the fuel required for this energy-intensive activity. In recent years, it has become impossible at times to maintain the channel to its full width. In the past two years that channel has not been maintained to full depth, causing safety concerns and restrictions on the volume of cargo each ship can carry.

It is now largely understood that an approach that relies solely on dredging to maintain the entrance is not sustainable, and that new approaches, like the use of sediment diversions will be necessary to more economically intercept and extract sediment from the river upstream of the Bird's Foot where it is needed for restoration.

Cumulative economic damages in the Gulf Coast due to growing environmental risk will be greater than $ 350 billion by 2030 (Entergy 2010). Actual losses to specific storm events vary; however, on average, the Gulf Coast faces annual losses of approximately $ 14 billion today (Entergy 2010). Losses are expected to increase in the 2030 timeframe from $ 18 billion to $ 23 billion depending on the climate change scenario. These losses will further increase in the 2050 timeframe from $ 26 billion to $ 40 billion (Entergy 2010). Over the next 20 years hurricane Katrina/Rita-type years of economic impact may change from a once in every 100 years events to once every generation (Entergy 2010). This could severely impact the growth and reinvestment trends in the region. Irrespective of climate change impacts, the Gulf Coast will face increasing loss from subsidence. Depending on climate change scenarios annual losses in 2030 will increase by 30–60 % over current Figs. (Entergy 2010).

These losses also represent a significant annual impact of 2–3 % of the region's GDP. In addition, losses amount to approximately seven percent of the region's capital investment- meaning that the region spends this money on rebuilding infrastructure rather than on capital investments that could be driving future economic growth (Entergy 2010). Approximately half of the increase in loss faced by the Gulf Coast is not related to climate change but due to baseline growth in risky areas and subsidence (Entergy 2010).



Accounting for Natural Capital

Identify → Value → Investment Tool (CBA) → Approval → Fund

Production Functions
Water supply
Food
Raw materials
Genetic resources
Medicinal resources
Ornamental resources

Regulation Functions
Climate
Gas
Disturbance
Water regulation
Soil retention
Soil formation
Nutrient regulation
Waste treatment
Pollination
Biological Control

Habitat Functions
Habitat
Refugium
Nursery

Information Functions
Aesthetic
Recreation
Cultural & artistic
Spiritual & historic
Science & education

Fig. 5 The value of natural systems must be identified, then valued, put into an appropriate investment analysis (this is what a rate of return, benefit/cost analysis, or investment pro forma does. Then there is an approval process, internal to the agency or company and finally the project is funded. Ecosystem Services and goods can be divided into four categories, production functions (goods), regulation, habitat, and information functions (services). (Mccollam 2011)

The Gulf Coast has over $ 2 trillion in asset value today and is expected to increase to over $ 3 trillion in the 2030 timeframe (Entergy 2010). Over the next 20 years, Gulf Coast losses add up to approximately $ 350 billion: the amount to re-build the entire asset base in New Orleans six times over (Entergy 2010).

Accounting for Natural Capital

Wetland restoration has strong co-benefits such as biodiversity protection, ecosystem services or second order economic effects such as risk aversion that encourage economic growth. (Entergy 2010). Methods for measuring the value of these co-benefits have significantly improved over the last decade (Thome et al. 2008). Factoring in a broader range of ecosystem services (Fig. 5) on an asset balance sheet creates the potential governance for a broader range of funding mechanisms such as:

1. Excise Tax
2. Sales, Use Value added Tax
3. Levies and Surcharges
4. Use Fees
5. Mitigation Banks
6. Mitigation Trading
7. Eco-tourism development
8. Traditional bonds

Current accounting of natural capital is about to change at the national level in three very significant ways:

1. Benefit/Cost Analysis—The Council on Environmental Quality has recognized the importance of ecosystem services. The Council has drafted a new Principles and Guidelines document (last changed 1983), in which the value of ecosystem services can be included in all benefit/cost analysis conducted by all Federal Agencies.
2. Discounting—Discounting governs how much weight value-in-the-future has in current decisions. Current discounting, created in the 1940s, for bridges, roads, power plants and other grey infrastructure with a lifespan of little more than a few decades. This does not work for projects with value provided across more than a few decades. Thus, either a lower discount rate should be used for natural capital restoration or another method for treating value over time applied.
3. Changing Accounting Rules—Some of the nation's largest water utilities are requesting a rules change at the General Accounting Standards Board, which governs the accounting rules for government agencies. At present, a filtration plant is an asset that must be included in the utility's accounting and reporting. This "built capital" also has a funding mechanism (a bond, then the utility rates are raised to pay the bond). Yet a watershed, which can filter water better and at less cost than a filtration plant (San Francisco, Seattle, Portland, Tacoma and New York have watershed filtered water). Yet the watershed has only the bare land and timber values on the asset sheet. The watershed has no value for providing and filtering water. Allowing natural assets on the balance sheet would bring traditional funding mechanisms to bear for natural capital assets.

Even if these changes are not implemented in the near future, they demonstrate an awareness of the clear value of improved natural capital. These natural capital values are in-fact easily comparable to more traditional built capital values. For example, using river and sediment diversions to create wetlands at a cost of $ 0.4 billion to manage storm surge can avert losses by 2030 that would require $ 25 billion in total capital investment, non-discounted, across 20 years while levee systems costing $ 0.3 billion averted losses requiring $ 18 billion in total capital investment (Entergy 2010).

The direct impacts of natural capital on the wellbeing of people was analyzed in a recently released report, "Jobs and Dollars" by Restore America's Estuaries. This report estimated that wetland restoration could create as many as 30 jobs for each million dollars invested which is more than twice as many jobs per million as the oil and gas and road construction industries combined (RAE 2011). The key findings were (RAE 2011):

- Coastal habitat restoration—including wetland reconstruction and improvement; rebuilding depleted oyster beds; removal of obsolete dams, culverts, and other obstacles to fish passage; tree planting and floodplain restoration; and invasive species removal—typically creates between 20 and 32 jobs for every $ 1 million invested. In comparison, road infrastructure projects on average create seven jobs per million, oil and gas return just five jobs, and green building retrofits produce 17 jobs per $ 1 million invested.
- Habitat restoration projects not only create direct local jobs, but they also stimulate indirect jobs in industries that supply project materials such as lumber, concrete, and plant materials, and support induced jobs in businesses that provide local goods and services, such as clothing and food, to restoration workers.
- Restoration projects provide strong returns on investment to local and regional economies in the form of new jobs, increased tourism and tourist dollars, hunting and fishing revenues, tax revenues, and property values.

The Mississippi River Delta ecosystems provide at least $ 12–47 billion in benefits to people every year just in ecosystem goods and services. If this natural capital were treated as an economic asset, the delta's minimum natural capital asset value would be $ 330 billion to $ 1.3 trillion (using a 3.5 % discount rate**)**. These values come from a 2010 study by researchers from Earth Economics who calculated the most comprehensive measure of the economic value of Mississippi River Delta natural systems to date (Batker et al. 2010). Marine waters, wetlands, swamps, agricultural lands and forests provide natural goods and services. The goods and ecosystem services valued in the study included hurricane and flood protection, water supply, water quality, recreation and fisheries. Thus, the Mississippi River Delta is a vast natural asset, a basis for national employment and economic productivity. It was built by literally gaining ground: building land with sediment, fresh water and the energy of the Mississippi River. And the values of the natural assets of the delta accrue to the nation as a whole and not just to Louisiana.

Is this national investment worthwhile during a period of financial crisis? The results of the report point to an unequivocal "yes." Seventy years ago, investments in roads yielded high economic returns because the U.S. was transitioning from a horse and wagon, dirt track road system to a motorized and paved system. Today, roads are neither scarce nor a barrier for economic recovery. Hurricane protection is scarce and hurricanes hamper national economic productivity; the disruption of oil and gas supplies alone cost U.S. citizens dearly during Hurricanes Katrina, Rita and Ike. An investment in restoring the Mississippi River Delta is a local, national and international investment that realizes economic benefits at all these levels.

Conclusions

If business as usual continues, Batker et al. (2010) estimate economic losses of $ 41 billion, excluding damages from future hurricanes. By comparison, if a large-scale restoration program is implemented that maintains and expands the delta, an additional annual net benefit of at least $ 62 billion would be realized. This value does not include increased protection for levees, or avoided catastrophic impacts such as levee breaching. It does not include the benefit of reduced displacement of residents, reduced FEMA relief and recovery costs, lower insurance rates, lower national oil and gas prices, less litigation, or the benefits of an expanding coastal economy, greater employment, and stability gained for existing communities and residents.

The economics are clear, whether standard or ecosystem accounting approaches are employed. An investment of up to $ 50 billion in initial costs to modernize the Mississippi River Delta in ways that allow it to gain ground, and to sustain critical transportation infrastructure far into the future is justified, particularly if it is possible to substitute natural renewable energy for fossil energy to transport sediment from the river to coastal wetlands. On the other hand, deltaic loss results in loss of nature's services, causing a hurricane-driven disorderly retreat inland that damages people and businesses at a far greater cost to the nation.

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The Threats to the Value of Ecosystem Goods and Services of the Mississippi Delta

David Batker, Isabel de la Torre, Robert Costanza, John W. Day,
Paula Swedeen, Roelof Boumans and Kenneth Bagstad

Abstract

The Mississippi delta, North America's largest river delta, is also one of the continent's most important coastal ecosystems, both in ecological and economic value. Over the past half century, however, the delta has deteriorated dramatically losing about 1.2 million acres (1900 km^2) or about 25 % of the coastal wetlands that existed in the early twentieth century. Much of this loss is due to how the Mississippi River was transformed and managed in the twentieth century. Major dams, primarily on the Missouri River, trapped sediments and reduced sediment delivery to the Gulf by about 50 %. Flood control levees eliminated almost all riverine input to the deltaic plain. In addition, there was pervasive hydrologic alteration of the deltaic plain including oil and navigation canals, induced subsidence, and impoundment. We carried out an analysis of the valuation of ecosystem goods and services of the delta, including three scenarios for continued degradation, stabilization, and rebuilding of the delta. The goods and ecosystem services valued in this study include hurricane and flood protection, water supply, water quality, recreation and fisheries. Presently, the Mis-

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sissippi River Delta ecosystems provide at least $ 12–47 billion in benefits annually. If this natural capital were treated as an economic asset, the delta's minimum capital asset value would be $ 330 billion to $ 1.3 trillion (3.5 % discount rate). We examined three restoration scenarios. Scenario 1 is a "business as usual" scenario where the delta continues to deteriorate. Estimated losses associated with this option are an additional $ 41 billion not including estimates of damage from major future hurricanes (which could top $ 100 billion in costs for a single event). Scenario 2 is a "hold the line" scenario that with a suite of projects that aim to maintain the current amount of land across the delta and prevent net land loss. This option assumes prevention of further collapse of the delta and the loss of at least $ 41 billion in ecosystem services. Scenario 3 is a "sustainable restoration" scenario, which implements large-scale, controlled diversions of river water and sediment to reconnect the river to the delta and would result in a net increase of wetlands. This scenario will avoid the $ 41 billion in damage under scenario 1 and produce benefits with an estimated present value of at least $ 21 billion, bringing in an annual net increased benefit of $ 62 billion. These values are very conservative figures since they include only partial values of 11 ecosystem services and do not include the value of increased protection for levees, avoided catastrophic impacts such as levee breaching, the benefit of reduced displacement of residents, reduced FEMA relief and recovery costs, lower insurance rates, lower national oil and gas prices, less litigation, or the benefits of an expanding coastal economy, greater employment, and stability gained for existing communities and residents.

Keywords

Ecosystem services · Provisioning services · Ecological valuation · Natural capital · Restoration scenarios

Introduction

The Mississippi Delta is one of the largest and most important coastal ecosystems of the Gulf of Mexico and one of the most important natural habitats in North America (Day et al. 2007, 2013). It is critical, ecologically and economically, to the State of Louisiana and to the nation. The coastal ecosystems of the Delta provide habitat for fish and wildlife, produce food, regulate chemical transformations and nutrient cycles, maintain water quality, store and release water, and buffer storm energy (2000). These processes support a diversity of locally and nationally valuable economic activities. Louisiana has one of the largest fisheries in the nation by volume. Other wetland-related activities include ecotourism, agriculture, hunting, fur and alligator harvest. These natural resource dependent activities generate billions of dollars annually in economic activity when associated goods and services are incorporated (Day et al. 1997). In addition, port activities on the lower Mississippi River are first in the nation by tonnage shipped. About a third of oil and natural gas used in the U.S. is either produced in the north-central Gulf of Mexico or transshipped through the coastal plain and Mississippi River Delta.

The River, its basin, and delta rank among the top 10 rivers in the world: Mean flow of the river is about 18,000 m^3/s. The Mississippi River has a total watershed of 3.2 million km^2, encompassing about 40 % of the area of the lower 48 States, and accounts for about 90 % of the freshwater inflow to the Gulf of Mexico. Major tributaries to the lower Mississippi River include the Ohio, Upper Mississippi, Missouri and Arkansas Rivers. Approximately 60 % of the estuaries and marshes in the Gulf of Mexico are located in coastal Louisiana (Lindstedt et al. 1991).

During the twentieth century there was a massive loss of approximately 25 % of coastal wetlands in the Mississippi Delta. Planning for a large-scale restoration of the delta is underway. The State of Louisiana recently released the 2012 Coastal Master Plan for restoration of the coast (State of Louisiana 2012). An understanding of the causes of this land loss is important not only for a scientific understanding of the mechanisms involved, but also to enable effective management plans and actions to restore the delta (see Boesch et al. 1994, 2006; Day et al. 2000, 2007 for reviews of these issues).

Ecosystem Services

With the loss of wetlands and other habitats in the delta, there is a loss of the ecological functions and the economic processes and activities that depend on the deltaic landscape and ecology. Some of these are clearly accounted for by economic measures such as oil and gas production and shipping. Others are only partially accounted for, such as fisheries. For fisheries, the market value of fish includes the costs to capture and bring fish to market but not the work of the natural system in producing fish. Other economic values of the delta are normally omitted by all economic measures. These include such services such as storm protection, water cleansing, carbon sequestration, and spiritual values. For some of these values, there is no known valuation methodology, for example spiritual value. For others, valuation methodologies are well accepted, as in the case of storm protection value. An important way to include a greater number of these values is by examining ecosystem goods and services. In this paper, our objective is to put a partial dollar value on some of the ecosystem goods and services provided by the Mississippi delta.

"Ecosystem services" (ES) are ecological attributes, functions, and/or processes that directly or indirectly contribute to human well-being—benefits people derive from functioning ecosystems (Costanza et al. 1997a; MEA 2005). Ecosystem processes and functions may contribute to ecosystem services but they are not synonymous. Ecosystem processes and functions describe biophysical relationships and exist regardless of whether or not humans benefit (Boyd and Banzhaf 2007; Granek et al. 2010). An example is soil formation. Ecosystem services, on the other hand, only exist if they contribute to human well-being. They cannot be defined independently of humans. An example is storm protection for human safety or built infrastructure.

The ecosystems that provide the services are sometimes referred to as "natural capital," using the general definition of capital as a stock that yields a flow of services over time (Costanza and Daly 1992). Often for these benefits to be fully realized, natural capital (generally built and maintained without humans) is combined with other forms of capital that do require human agency to build and maintain. These include: (1) built or manufactured capital; (2) human capital; and (3) social or cultural capital (Costanza et al. 1997b).

These four general types of capital are all required in complex combinations to produce any and all human benefits. Ecosystem services thus refer to the relative contribution of natural capital to the production of various human benefits, in combination with the three other forms of capital. These benefits can involve the use, non-use, option to use, or mere appreciation of the existence of natural capital.

The following categorization of ecosystem services has been used by the Millennium Ecosystem Assessment (MEA 2005):

Provisioning services—ecosystem services that combine with built, human, and social capital to produce food, timber, fiber, or other "provisioning" benefits. For example, the production and delivery of fish as food to people from Mississippi delta estuaries require fishing boats (built capital), fisher-folk (human capital), and fishing communities (social capital) to produce.

Regulating services—services that regulate different aspects of the integrated system. These are services that combine with the other three capitals to produce flood control, storm protection, water regulation, human disease regulation, water purification, air quality maintenance, pollination, pest control, and climate control. For example, storm protection by coastal wetlands in the delta requires built infrastructure, people, and communities to be protected. Due to the public good physical nature of these services, they are generally not marketed but have clear value to society.

Cultural services—ecosystem services that combine with built, human, and social capital to produce recreation, aesthetic, scientific, cultural identity, sense of place, or other "cultural" benefits. For example, to produce a recreational benefit requires a beautiful natural asset (a lake or marsh), in combination with built infrastructure (a road, trail, dock, etc.), human capital (people able to appreciate the lake experience), and social capital (family, friends and institutions that make the lake or wetland accessible and safe). Even "existence" and other "non-use" values require people (human capital) and their cultures (social and built capital) to appreciate these values. The rich and complex coastal culture of Louisiana involving food, language, music, and unique ways of life is an example of this.

Supporting "services"—services that maintain basic ecosystem processes and functions such as soil formation, primary productivity, biogeochemistry, and provisioning of habitat. These services affect human well-being indirectly by maintaining processes necessary for provisioning, regulating, and cultural services. They also refer to the ecosystem services that have not yet, or may never be intentionally combined with built, human, and social capital to produce human benefits but that support or underlie these benefits and may sometimes be used as proxies for benefits when the benefits cannot be easily measured directly. For example, net primary production (NPP), which in the Mississippi Delta is among the highest in the world, is an ecosystem function that supports carbon sequestration and removal from the atmosphere, which combines with built, human, and social capital to provide the benefit of climate regulation. Some would argue that these "supporting" services should rightly be defined as ecosystem "functions", since they may not yet have interacted with the other three forms of capital to create benefits. We agree with this in principle, but recognize that supporting services/functions may sometimes be used as proxies for services in the other categories.

This categorization suggests a very broad definition of services, limited only by the requirement of a contribution to human well-being. Even without any subsequent valuation, explicitly listing the services derived from an ecosystem can help provide some recognition of the full range of potential impacts of a given policy option. This can help make the analysis of ecological systems more transparent and can help inform decision makers of the relative merits of different options before them.

Valuation

Many ecosystem services are public goods. This means they are non-excludable and multiple users can simultaneously benefit from using them. Storm protection provided by wetlands for example benefits everyone living behind the wetlands and the coast. Individuals cannot be selected out to exclusively receive the storm protection benefits that wetlands provide. Public goods and services create circumstances where individual choices are not the most appropriate approach to valuation. Instead, some form of community or group choice process is needed. Furthermore, ecosystem services (being public goods) are generally not traded in markets. We therefore need to develop non-market methods to assess their value. This is not a new problem to economics.

There are a number of methods that can be used to estimate or measure benefits from ecosystems. Valuation can be expressed in multiple ways, including monetary units, physical units, or indices. Economists have developed a number of valuation methods that typically use metrics expressed in monetary units (see Freeman 2003) while ecologists and others have developed measures or indices expressed in a variety of non-monetary units such as biophysical trade-offs (cf. Costanza 2004).

A key challenge in any valuation is imperfect information. Individuals might, for example, place no value on an ecosystem service (the ozone layer, for example) if they do not know the role that the service is playing in their well-being (Norton et al. 1998). Here is an analogy. If a tree falls in the forest and there is no one around to hear it, does it still make a sound? The answer to this old question obviously depends on how one defines "sound". If "sound" is defined as the perception of sound waves by people, then the answer is no. If "sound" is defined as the vibratory disturbance in a medium, then the answer is yes. In this second case, choices in both revealed and stated preference models would not reflect the true benefit of ecosystem services. In the Mississippi Delta an analogous question would be "If a fish in the estuary is not caught, does it have value to humans?" Another key challenge is accurately measuring the functioning of the system to correctly quantify the amount of a given service derived from that system (e.g., Barbier et al. 2008; Koch et al. 2009).

But recognizing the importance of information does not obviate the limitations of human perception-centered valuation. As the tree analogy demonstrates, perceived value can be a quite limiting valuation criterion, because natural capital can provide positive contributions to human well-being that are either never (or only vaguely) perceived or may only manifest themselves at a future time. A broader notion of value allows a more comprehensive view of value and benefits, including, for example, valuation relative to alternative goals/ends, like fairness and sustainability, within the broader goal of human well-being (Costanza 2000). Whether these values are perceived or not and how well or accurately they can be measured are separate (and important) questions.

Objectives

This paper presents a partial evaluation of the ecosystem goods and services of the Mississippi delta. We first identify and value individual goods or services. We then sum these to provide an overall range of value for these goods and services, both in terms of annual flows and the value of the natural capital that generates these flows. We then describe how these values will change under three restoration scenarios: continued deterioration of the delta, no further net loss of deltaic wetlands, and aggressive restoration of the delta. This paper is a summary of a much longer technical report by Batker et al. (2010).

Materials and Methods

Study Area

The Mississippi Delta formed over the past 6,000–7,000 years as a series of overlapping delta lobes (Roberts 1997). There was an increase in wetland area in active deltaic lobes and wetland loss in abandoned lobes, but there has been an overall net increase in the area of wetlands over the past several thousand years. Currently, only two of the distributaries of the river are functioning, the lower Mississippi River and the Atchafalaya River, which carries about one third of the total flow of the Mississippi River. When the European occupation began, however, numerous distributaries were still functioning, either year round or during the seasonal spring flood. The delta was sustained by a series of energetic forcings or pulsing events that occurred over different spatial and temporal scales. These pulses include shifting deltaic lobes, crevasses, great river floods, hurricanes, annual river floods, frontal passages, and tides (Day et al. 1997, 2000). The area of the delta is about 25,000 km^2 including wetlands, shallow inshore water bodies, and low elevation uplands (mostly associated with distributary ridges and beach ridges).

The coast has often been described in terms of a series of hydrologic basins that are separated largely by current or abandoned distributary channels (for a summary and references). Coastal wetlands of the Mississippi Delta consist of two physiographic units, the Deltaic Plain to the east and the Chenier Plain to the west (Roberts 1997). Active deltaic lobe formation took place in the deltaic plain, which is divided into six hydrologic units. These are, from east to west, the Pontchartrain, Breton, Birdfoot (Balize), Barataria, Terrebonne, and Atchafalaya basins. The modern mouth of the Mississippi, the Birdfoot delta, although not technically a basin, has been considered a separate hydrologic unit for most analyses of Louisiana coastal wetlands. The Chenier Plain was created by a series of beach ridges and mud flats formed by periods of westward down drift of sediments. It is comprised of two hydrologic units, the Mermentau and Calcasieu/Sabine basins. The coast is also characterized by a series of vegetation zones (saline, brackish and fresh marshes, and freshwater forested wetlands, from the coast inland) that run roughly parallel to the coast and are determined primarily by salinity. Changes in these vegetation zones over the past half century have been described in a series of four vegetation maps (see Day et al. 2000 for references).

There has been an enormous loss of coastal lands in the delta with a total loss of about 4,800 km^2 since the 1930's (Boesch et al. 1994; Britsch and Dunbar 1993; Barras et al. 1994, 2003). Over 95% of this loss was wetland, primarily marsh, conversion to open water. In the 1970s, the loss rate was as high as 100 km^2/yr and the loss rate from 1990 to 2000 was about 60 km^2/yr (Barras et al. 2003). Between 1956 and 2000, the average loss rate of was 88 km^2/yr (Barras et al. 1994, 2003). These high rates of wetland loss are projected to continue for the next half century; from 2000 to 2050, it is estimated there will be an additional net wetland loss of 1,329 km^2 (Barras et al. 2003).

An understanding of the causes of this land loss is important not only for a scientific understanding of the mechanisms involved, but also so that effective management plans and project implementation can be developed to restore the delta (see Boesch et al. 1994; Day et al. 2000, 2007 for a review of these issues). A number of factors led to the massive loss of wetlands. Foremost among these are flood-control levees along the Mississippi River that resulted in the elimination of riverine input to most of the delta (Boesch et al. 1994; Day et al. 2000). In addition to the flood-control levees, most active distributaries were closed, and the river mouth dredged for navigation. This resulted in the conveyance of most river sediments directly to deep waters of the Gulf of Mexico and the loss of sediment supply to the delta. There has also been a reduction of the suspended sediment load in the Mississippi River caused by dam construction in the Upper Mississippi River (Kesel 1988, 1989; Blum and Roberts 2009).

Pervasive altered wetland hydrology, mostly caused by canals, is another important factor contributing to wetland loss. Canals, originally dredged for drainage and navigation, are now overwhelmingly linked to the petroleum industry. Drilling access canals, pipeline canals, and deep-draft navigation channels have left a dense network of about 15,000 km of canals in the coastal wetlands. Although canals are estimated to comprise about 2.5% of the total coastal surface area, their destructive impact has been much greater (Swenson and Turner 1987). Spoil banks, composed of the material dredged from the canals, interrupt sheet flow, impound water, and cause deterioration of marshes. Long, deep navigation canals that connect saline and freshwater areas tend to lessen freshwater retention time, and allow greater inland penetration of saltwater (Shaffer et al. 2009). This saltwater kills intermediate and fresh marshes resulting in the accelerated conversion of marshlands to open water.

In sum, there is a broad consensus that wetland loss is a complex interaction of a number of factors acting at different spatial and temporal scales (e.g., Turner and Cahoon 1987; Day and Templet 1989; Boesch et al. 1994; Day et al. 1995, 1997). However, today, these complex processes are well understood. Day et al. (2000, 2007) reflect the overwhelming scientific consensus that isolation of the delta from the river by levees is the most important factor for wetland loss.

Methods

Mississippi River Delta Ecosystem Services

We considered a subset of ecosystem goods and services for this study. A variety of goods and ecosystem services were valued in this study including hurricane and flood protection, water supply, water quality, recreation and fisheries. All values were converted into 2007 dollars using the Bureau of Labor Statistics' Consumer Price Index. Rather than calculating a single value for specific ecosystem services, we developed high and low values to indicate the range in estimates that can exist. Where values did not exist from studies in Louisiana, we used estimates from other areas.

Water Supply

Most communities in southern Louisiana rely on fresh surface water for water supply and on coastal wetlands for the prevention of saltwater intrusion (Laska et al. (2005). Wetlands protect the water supplies by preventing salt-water intrusion. Farber (1996) used the replacement cost method to estimate the cost for groundwater-dependent communities to develop alternative sources. Values for this service were derived from the replacement cost of desalinization plants for 19 coastal parishes in Louisiana with a population of 2.2 million. Desalinization of brackish water is less expensive than estuarine saltwater. Assuming that the average American uses 90 gal of water per day, this amounts to an annual 72.3 billion gal of water use in the Louisiana coast. Based on a cost of $ 1.50–4.00/1000 gal for low and high scenarios (AWWA 2007), values of $ 46.67 and $ 124.47 per acre-year basis in 2007 dollars were calculated.

Some economists argue that replacement costs provide "upper bound" estimates of ecosystem services values. The replacement cost method is appropriate for valuing the water supply functions of the Mississippi River Delta's wetlands because there are no other alternatives except human-engineered replacements for the provision of freshwater to many communities. In addition, human-built systems, such as a desalinization plant, are less resilient, less reliable and require greater maintenance. Built capital alternatives like a desalinization plant are more vulnerable to hurricane damage, for example. Thus, the replacement costs may be considerable underestimates because a plant may well be destroyed prior to the expected lifetime of the facility. This has been the case for other built capital assets in the Mississippi Delta including roads, railroads, and sewerage treatment plants. Built replacement options, including desalinization plants, are in fact more vulnerable to damage or destruction under the continuing conditions of wetland loss. Thus, replacement cost method for human-engineered systems may greatly underestimate the true costs of supplying drinking water.

Water Quality (Nutrient Regulation)

Excess nitrogen, phosphorous, bacteria, and other pollutants affect water quality. Wetlands have been shown to improve water quality (Day et al. 2004; Kadlec and Knight 1996; Mitsch and Jørgensen 2004). A number of studies in coastal Louisiana have demonstrated that coastal wetlands can improve water quality (Breaux et al. 1995; Cardoch et al. 2000; Kaziemierczak 2001; Day et al. 2004; Ko et al. 2004; Hunter et al. 2008). This approach is more economical and less energy intensive than traditional wastewater treatment (Ko and Day 2004). In addition, wetland waste treatment increases the growth of wetland plants and provides additional ecosystem services including storm protection and an increased rate of carbon sequestration (Millennium Ecosystem Assessment 2005; Hesse et al. 1998; Hunter et al. 2009). We used a number of different studies to derive estimates for the value of water quality improvement by wetlands (Farber 1996; Kazmierczak 2001; Mitsch et al. 2001; Day et al. 2003). The values used here are based on present value. We used $ 281 and $ 1,217/acre as low and high estimates. This analysis uses the median $ 281/acre as a low value and $ 1,217/acre as a high value. These values do not include any increase in fisheries production or recreation due to water quality improvement.

Fisheries Production

Costanza et al. (1989) used a production function developed by Lynne et al. (1981) for fisheries production in Louisiana where catch predictions are based on marsh acreage and catch in the previous year and harvesting effort in the current year. Costanza et al. estimate that the per-acre wetland value for brown and white shrimp, menhaden fish, oyster and blue crab total to $ 25.36/acre/year using 1983 prices ($ 48.10 2004 dollars). Farber (1996) estimated $ 36.93–$ 51.52 per acre in 1990 dollars ($ 58.58 low, $ 81.73 high in 2007 dollars). Since Farber's range of estimates includes those of Costanza et al., we used Farber's low value ($ 58.58) for our low value. These values do not include all species caught and thus do not include the value of the full fish and shellfish catch. The value of subsistence catch is excluded. Some fish and shellfish caught in the Mississippi Delta region but landed elsewhere are not included. Neither is the value of fish dependent upon the Mississippi Delta for spawning or rearing but caught elsewhere in the Gulf of Mexico included. More recent fisheries data (Chesney et al. 2000; Gramling and Hagelman 2005; Lindstedt 2005) corroborated results of Costanza et al. and Farber. A high value of $ 1,233.49/acre in 2007 dollars was used based on a meta analysis for fisheries production value of wetlands derived from an econometric analysis of 39 studies (Woodward and Wui 2001).

Raw Materials: Wild Fur and Alligator Production

Many raw materials produced in the Mississippi Delta, including timber, are not included in the value for this study. Only fur and alligator production are included. We assumed that muskrats come from brackish and intermediate marsh, nutria and raccoons from freshwater marsh, and alligators from fresh, intermediate and brackish marsh. Costanza et al. (1998) used estimates of 0.98 muskrat pelts/ac from brackish and intermediate marsh, and 0.88 nutria pelts/acre from freshwater marsh. They used 1980–1981 values of $ 6 per muskrat pelt and $ 7 per nutria pelt, for a total value per acre of $ 12.04. However, the fur market collapsed in 1987–1988, making these values inappropriate for current use. For this reason, we used 2004–2005 harvests and prices for low values and the 10-year average values from 1995–1996 to 2004–2005 harvests and prices for high values. More recent data show values of over $ 1 million per year for trapping pelts and meat between 1993 and 2002 in Louisiana (Lindstedt 2005). Of this harvest, 71 % of commercial value came from nutria, 18 % from raccoon, and 11 % from other mammals, including muskrat. The low and high values were $ 4.74 and $ 5.38/acre/year, respectively.

Carbon Sequestration

Carbon sequestration as used in this study refers to the ability of vegetation to take up carbon dioxide through photosynthesis and store it for long periods of time in woody tissue and/or the soil. There are two parts to valuing carbon sequestration: establishing how much carbon is sequestered each year and establishing a dollar value for that sequestration service.

Herbaceous wetlands store large amounts of carbon in the soil while forested wetlands store it in both woody tissue and soil. Chmura et al. (2003) reported that the median carbon uptake rates for all wetland types was 186 g C/m^2/year. Trulio (2007) reported higher soil carbon sequestration in salt marsh (2900 g C/m^2) and in brackish to intermediate (1300–1500 g C/m^2) in the Barataria Basin in coastal Louisiana. The net primary productivity (NPP) of these marshes was 1,000–4,000 g C/m^2-year. This is much greater than that of the surrounding upland forests, which are estimated at 200–1,000 g C/m^2-year. Due to sulfate reduction, salt marshes do not generate significant methane. Yu and DeLaune (2006) showed that mature Louisiana swamp forests accumulate carbon, but that atmospheric methane release may offset these gains. Sea level rise may cause upland forests to transition into swamp forests, affecting their greenhouse gas balance. Day et al. (2003) and Hunter et al. (2009) reported increased tree woody growth of 23–80 % under enhanced nutrient conditions in swamp forests. We used various references to obtain estimates of marsh and wetland forest carbon sequestration rates as follows (DeLaune and Pezeshki 2003; Kayranli et al. 2010; Nyman et al. 2006; Smith et al. 1983): degraded marsh 4.5 t CO_2/acre/year, healthy marsh 11 t CO_2/acre/yr, and wetland forests 10 t CO_2/acre/year, with forests enhanced with waste assimilation sequestering up to 25 t CO_2/acre/year including both above and belowground sequestration. For the low value, we used 4.5 t CO_2/acre/year for degraded marshes for all wetlands. We used 11 t CO_2/acre for the marsh high value, which is similar to the findings of Choi et al. We used avalue of 10 t CO_2/acre/year for the high and low of wetland forest carbon sequestration for both above and belowground sequestration.

For the low value per ton of CO_2 sequestered, we used a value that includes both market and social costs from Pearce (2001) who recommend the use of $ 10/t ($ 11.71 in 2007 dollars) of carbon sequestered as a conservative estimate. A compulsory market does not yet exist (but is being initiated in Calfornia), but Zhang (2000) concluded that an ideal global market would be in the range of $ 11.23–14.74/t C. The Stern Report included environmental and social costs not reflected in the market prices providing an estimated value of $ 85/t. This value is used for the high value.

Market prices for a ton of carbon based on voluntary markets fluctuate dramatically, making it difficult to determine a clear market value for CO_2. Being voluntary and without full participation of all CO_2 emitters, the market price of the Chicago and European trading systems do not reflect full market prices. Both markets have fluctuated greatly. Carbon markets are subject to the granting of original rights—in the EU Scheme emitters were granted emissions rights—which lowers prices. In addition, global economic conditions greatly impact fossil fuel usage, carbon emissions and thus, carbon market prices. In addition, no carbon trading scheme is yet all-inclusive of all carbon emitters within the jurisdictions, though there are suggestions for slowly including additional carbon emitting sectors such as commercial aircraft emissions. At the European Union Emissions Trading Scheme, carbon prices rose to $ 36/t early in 2006 and fell to under $ 3/t by spring 2007 (Ecosystem Marketplace 2007). The Chicago Climate Exchange priced voluntarily traded carbon at $ 4/t in 2007 and $ 8/t in 2006 (Chicago Climate Exchange Mar. 2006; Chicago Climate Exchange Sept. 2006). Voluntary carbon markets in the United States have sold carbon offsets at prices ranging from $ 5–25/t with an average of $ 10/t (Clean Air-Cool Planet 2006). The creation of a carbon market in California will help further establish carbon pricing by end of 2012.

Recreation

Numerous studies have estimated the recreational benefits of coastal Louisiana's wetlands as a present value per acre of wetlands or the entire coast. Bergstrom et al. (1990) and Bergstrom and Stahl (1993) reported a value of $ 147.57/acre/year, which we use in our study. Bergstrom et al. similarly used TC and CV across seven parishes. They estimated a value of $ 224.21/ha-yr for marshland only in the study area ($ 147.57/acre/year in 2007 dollars). Bergstrom et al. stratified their sample for sites in fresh and saltwater marsh, at high and low-density recreation sites and across an east-west gradient. Unfortunately, only total values were reported since these would be useful distinctions for recreational valuation across coastal Louisiana. Farber (1996) modeled recreational loss with wetland deterioration as a function of willingness to pay, quality of experience and population, and projected declining values as fishing and hunting quality falls. Bergstrom et al. (2004) reported values for fishing on the lower Atchafalaya almost identical to Bergstrom et al. (1990), supporting the use of a common value for the entire Coast.

Storm Protection (Disturbance Regulation)

Storm protection refers to the function of wetlands in reducing storm energy and storm-generated water surges that cause flooding. This ecosystem service is very important to residents of the Mississippi Delta.

Farber and Costanza (1987) estimated the value of wetlands for hurricane protection from wind damage at $ 63,676/mile of wetlands (1980 dollars), with a present value of $ 23/acre discounted at 3 %. Costanza et al. (1989) provided estimates for both wind and flood damage and Farber (1996) reported estimates for capital, land and maintenance costs associated with levee construction and property loss from wetland disintegration.

Costanza et al. (2008) reported estimates for storm protection values that included Hurricanes Katrina and Rita. They used estimates of spatially explicit GDP (flows of value from built capital at risk) along with storm probabilities to model value per hectare for gulf and Atlantic coast states. Their estimate of the value of wetlands for storm protection in Louisiana was $ 3,446/hectare/year (2007 dollars—$ 1,530.82/acre), which is what we used in this study.

Other Wetland Ecosystem Values

We could not find ecosystem service values from Louisiana on aesthetics, habitat for threatened and endangered species, and cultural values. Therefore, values from other areas were used.

Values for endangered species habitat (Kazmierczak 2001) and aesthetics (Thibodeau and Ostro 1981; Mahan et al. 2000) were adjusted to 2007 dollars per acre per year. Values for gas regulation (distinct from carbon sequestration) and water flow regulation were adjusted to 2007 dollars per acre from 1994 dollars per hectare. Sukhdev and Kumar (2008) in in a study on The Economics of Ecosystems and Biodiversity (TEEB) provide global examples of valuation of biodiversity which were not applied to Louisiana wetlands.

Water Flow Regulation: Flood Protection

Wetlands provide protection against flooding via flood storage, peak flow reduction, landscape for water diversion from the Mississippi River in addition to wind and storm surge of hurricanes. Protection from flooding by the Mississippi is provided both by levees as well as by natural ecosystems in the Mississippi Delta and floodplain. In providing protection, the Corps of Engineers recognize that levees alone are not sufficient contain floods on the river and the importance of natural systems when Mississippi River flood outlets were constructed to divert flow and store water in the floodplain and delta. The Bonnet Carré Spillway and the Atchafalaya floodway are the two most important flood outlets on the lower Mississippi. The flood outlets lower water levels in the river and allow flood storage in wetlands and shallow water bodies. This also reduces damage to levees and flood control structures. This flood protection is especially important for urban areas such as New Orleans, but also far up the Mississippi River Valley. As waters are more efficiently evacuated from the river floodwaters further upstream are also more efficiently reduced.

There are no ecosystem service valuation studies in Louisiana of flood protection benefits of Mississippi Delta or the extensive upstream flood protection benefits. The few studies that do exist primarily examine flood protection benefits provided by wetlands to nearby urban areas. This value of wetlands outside Boston was estimated at $ 6,539 per acre in 2007 dollars (Thibodeau and Ostro 1981). A study in Washington State reported values of $ 8,000–$ 51,000 per acre (Leschine et al. 1997). The full flood protection that the Mississippi Delta provides to public safety and economic assets such as oil and gas infrastructure is perhaps the one that most importantly needs full evaluation.

The flood benefit studies used in this analysis are for wetlands providing flood benefits to urban areas with high value infrastructure. Although freshwater, intermediate and brackish wetlands all provide the function of flood protection, freshwater wetlands are most closely associated with urban areas. They also provide the greatest upstream flood relief, as in the case of the Atchafalaya basin. In this study, the greater values for flood protection are attributed only to freshwater wetlands and not to intermediate, brackish, or salt marshes. For our study we used the value of Woodward and Wui (2001) as the low estimate (Woodward and Wui 2001) and $ 6,539.19/acre as the high estimate (Thibodeau and Ostro 1981).

Habitat Refugium

The Mississippi Delta supports dense populations of aquatic and terrestrial wildlife and is important habitat for migratory birds. It provides valuable habitat for a number of endangered and threatened species. By providing sufficient habitat to keep other species off the threatened and endangered species lists, the delta relieves other areas of costly expenditures that would arise if these species were listed. No full study of the value per acre of provided by the Mississippi Delta exists. However, we use values of Kazmierczack (2001) for the low and high values of $ 203/acre/year and $ 485/acre/year, respectively.

Upland Ecosystems

Less work has been done for the region's upland ecosystems. As an initial effort to assess values for upland areas, we used value coefficients developed for New Jersey (State of New Jersey 2007).

Where there were no values for ecosystem services for the Mississippi delta were available, we used data from other appropriate national and international studies. All values and their sources are explicitly noted. Although these numbers are likely less accurate, we chose to use all available data to get a more complete picture and estimate. The greatest error of most valuation studies has been the omission of values for clearly valuable ecosystem services. This significantly underestimating the value of benefits that ecosystem services provide to people. Further refinement of the value estimates for these upland ecosystems will improve the value estimates for the Mississippi River Delta.

Restoration Scenarios

We analyzed three restoration scenarios over the next 100 years to determine their impact on the value of ecosystem goods and services of the delta: (1) do nothing new or business as usual, (2) hold the line and (3) restore the delta. Each scenario has a set of different possible actions, investments in built and natural infrastructure, and economic and social ramifications. These three scenarios represent a range of realistic possibilities for restoration.

The "do nothing new" scenario assumes the continuation of the past management of the Mississippi River. It includes large investments in levees and reconstruction of hurricane-damaged flood control structures. The Mississippi River remains largely separated from the delta resulting in continued

Table 1 Three scenarios of present value of wetland ecosystem services for 100 years in the future (in billions, 2007 dollars)

Present value of scenario				
Scenario	Discount rate 0 %	Discount rate 2 %	Discount rate 3.5 %	Discount rate 5 %
Do nothing new	−190	−72	−41	−26
No net loss	0	0	0	0
Sustainable restoration	132	41	21	12

Table 2 Total present value for scenario 3, avoided losses and gains realized in $ billions

Major restoration scenario	PV 0 % discount rate	PV 2 % discount rate	PV 3.5 % discount rate	PV 5 % discount rate
Total PV avoided costs and direct gains	322	113	62	38

loss of wetlands and associated ecosystem services, and the increased exposure to hurricanes. This scenario is based on the U.S. Geological Society (2003) estimate of wetlands loss of 328,000 acres in the next 50 years.

The "hold the line" scenario assumes a suite of restoration projects that will result in stabilization of the coast with no additional wetland loss. These projects include smaller diversions and creation of land with dredged sediment. The Mississippi River remains largely disconnected from the delta.

The sustainable restoration scenario involves reconnecting the river to the delta on a large scale and includes large diversions and crevasses. This scenario would deliver large amounts of freshwater and sediments to wetlands and shallow open water areas. It is, in essence, replicating the Atchafalaya and Wax Lake delta building process across the coast as suggested by Kim et al. (2009). This scenario also assumes that sediment trapped by large Missouri River dams will be remobilized and made available for delta building. This scenario will result in multiple beneficial ecosystem services such as storm protection, land building, coastal economic recovery, recreation and carbon sequestration. In combination with projects throughout the Mississippi basin, it would also likely reduce the hypoxic zone in the Gulf of Mexico (Mitsch et al. 2001) but this is not included in our analysis. We assume for this analysis that 500,000 acres of wetlands will be created or restored by 2100.

Under the "no action" scenario, the deterioration of the delta will continue along with the loss of nature's services and increasing damages to communities and economic assets. It will ensure a costly retreat of people and economic productivity. The "hold the line" scenario requires an unspecified set of smaller projects to stop land loss without restoring the functions of the Mississippi River Delta. The third scenario entails large projects that reconnect the sediment, water and energy of the Mississippi River with the delta. All these options entail significant expenditures. Further analysis would refine the costs, benefits and net rate of return on restoration investments. These three scenarios are not actual scenarios but represent a range of continued loss, stabilization, and net wetland gain.

The inland movement of the salt gradient and conversion of wetlands into estuarine open water results in wetland loss. The low value of estuarine wetlands was subtracted from the average low value per acre per year for all wetland types, excluding the highest wetland value for forested wetlands to derive a net loss or gain value of $ 4,515/acre with the conversion of wetlands to open water or open water to wetlands for the three scenarios.

The calculation of net present value of land loss or land gain depends on the discount rate chosen, which reflects how value in the future is counted in the present. A lower discount rate implies giving greater weight to the benefits that storm protection, fisheries and other ecosystem services provide to people in the future. Many benefits from renewable resources are provided in the future. Healthy natural capital does not depreciate. Thus, lower discount rates for natural capital restoration are justified—as opposed to built capital that depreciates. Table 1 shows the Present Value of the conversion of wetlands and open water. It does not include the total cost of implementing each of the scenarios.

Depending on the discount rate chosen, the "no action" scenario will result in losses of $ 26–190 billion in ecosystem services alone depending on the discount rate chosen. This does not include losses such as the costs of future damage by hurricanes, retreat of economic infrastructure, or loss of life. Losing over 500,000 acres of wetlands would leave New Orleans and other coastal cities far more exposed to hurricanes. Hurricane Katrina showed that a single event can cause over $ 200 billion in damage.

The "no change" scenario has no net increase or decrease in values. This scenario would avoid the negative costs associated with the "no action" scenario, but would not increase storm protection or other ecosystem services provided at higher levels in the past.

The "sustainable restoration" scenario will add over 500,000 acres of wetlands in a century and significantly add to the hurricane protection of New Orleans and other cities and communities on the Mississippi River Delta. Because this is a building process, the benefits will increase in the future. The benefits from the net gain in wetland area will be between $ 12–132 billion depending on discount rate. In addition, the costs associated with the "no action" option will be avoided. Table 2 shows the total present value of benefits in scenario 3, the sum of avoided costs associated with the

Table 3 Likely cost or damage and scenario outcomes

Cost/damage	Scenario outcomes		
	"Do nothing new"	Hold the line	Sustainable restoration
Loss of life	Up greatly	Same	Down
Dislocation of people	Up greatly	Same	Down
Loss of infrastructure	UP greatly	Up	Down
Storm associated energy price rises	Up greatly	Up	Down
Insurance costs	Up greatly	Up	Down
FEMA and relief costs	Up greatly	Same	Down
Storm damage costs	Up greatly	Up	Down
Post storm litigation	Up greatly	Up	Down
Loss of coastal economy	Up greatly	Up	Down
Area of dead zone	Up	Same	Down

"do nothing new" option, and the gains from the increase in additional wetlands.

Scenario 3 increases the area of land and avoids the costs associated with the current path of land loss. This provides a net benefit of $ 322 billion with a zero discount rate if future benefits to people are counted equally as benefits to people in the present or $ 38 billion at a 5 % discount rate if renewable benefits provided in the future are rather steeply discounted and deemed as having little value. The US Prime Rate of Interest as of February 1, 2009 was 3.25 %. The figure conservatively adopted here is $ 62 billion at a 3.5 % discount rate. Not included in this analysis, these wetlands would also provide greater protection for built infrastructure, including levees. Adoption of a 2 % discount rate, that is recognizing the greater benefits of restoration in the future, would show over $ 100 billion in benefits.

Restoration of the coastline would reduce levee maintenance and reconstruction costs substantially. A larger area of wetlands around the Mississippi Delta would provide greater hurricane buffering. This alone could reduce future damage to cities like New Orleans by tens or hundreds of billions of dollars.

Even though many of the most important cost and benefit outcomes of these scenarios are beyond the scope of this study or not easily expressed in dollar value (human safety, future FEMA relief costs or community stability), the direction of the outcomes for each scenario is clear. For this reason, we present two tables that examine the likely outcomes of each scenario rated simply "Up, Down, or Same".

Table 3 shows the direction of the cost/damage outcomes for each scenario. The list of costs and damages is not comprehensive. It includes: loss of life, displacement of people, loss of infrastructure, storm-associated national energy price increase, insurance costs, FEMA and other relief costs, storm damage costs, post storm litigation, loss of the coastal economy, and area of the hypoxic dead zone in the Gulf of Mexico.

Table 4 shows the direction of the benefit outcomes for each scenario. The list of costs and damages is not comprehensive. It includes: coastal stability, land building, storm protection, community stability, protection of levees, protection of energy infrastructure, wetland expansion, economic development potential, food, furs and fiber, wildlife habitat, water quality, carbon sequestration, waste treatment, recreation, aesthetic value, people's sense of security and national pride.

Table 3 and Table 4 provide the direction of the impacts of each scenario for each outcome area. The "do nothing new" scenario will increase costs in practically every category over current costs.

The "hold the line" scenario stabilizes some of the outcomes. If the goal of no net land loss is attained, overall coastal stability and land building will not deteriorate further but it will not experience a net advance.

The "sustainable restoration" scenario provides greater benefits and fewer costs by providing a net gain in land and large diversions that enable controlled distribution of sediment and water across the Mississippi Delta. Overall, sediment pumping, barrier island reconstruction and other restoration methods all increase land and the suite of benefits they bring. The dollar calculation of benefits based on a few ecosystem services and an examination of the direction of benefits for the three options clearly show that the "sustainable restoration" option provides the greatest benefits and least costs. Neither the full costs nor full benefits of the projects are included. For example, the "do nothing" option may entail the extremely costly relocation of the people and assets of New Orleans. The sustainable restoration option can ensure the viability of New Orleans and secure vast assets and less disruption for many people.

The many different combinations of delta and levee restoration each produce a different land restoration or deterioration scenario. Human safety, the impact on economic assets and the overall dynamics and sustainability of the Mississippi River Delta are critical to determining which levee/coastal restoration option will provide the greatest public safety, protection of economic assets (including natural assets) and coastal restoration value. The current levee designs are not fully integrated with wetland restoration models. None of the

Table 4 Likely benefit scenario outcomes

Benefit	"Do Nothing New"	Hold the Line	Sustainable Restoration
Coastal Stability	Down	Same	Up
Land building	Down	Same	Up
Storm Protection	Down	Same	Up
Community Stability	Down	Same	Up
Protection of Levees	Down	Same	Up
Protection of Energy Infrastructure	Down	Down	Up
Wetland Expansion	Down	Same	Up
Coastal Economic Development Potential	Down	Same	Up
Food, Furs, Fiber	Down	Same	Up
Wildlife Habitat	Down	Same	Up
Water Quality	Down	Down	Up
Carbon Sequestration	Down	Same	Up
Waste Treatment	Down	Same	Up
Recreation	Down	Down	Up
Aesthetic Value	Down	Same	Up
People's Sense of Security	Down	Down	Up
National Pride	Down	Same	Up

economic analyses fully include the value of ecosystem services. Including ecosystem services and their value would provide a better understanding of the value of public investments in restoration.

The persistent pursuit of restoration projects that are too small compared to the scale of the Mississippi Delta and its land loss is another notable flaw in the current management. The Coastal Protection and Restoration Authority of Louisiana has recognized this and stated that "Creating a sustainable deltaic system requires that we reestablish the processes that originally created the landscape." The plan specifically recommends "building very large diversions that will use majority of the river's sediment and fresh water to both create new delta lobes and nourish existing wetlands." The report does not identify the locations and size of these diversions, but has produced a list of projects that comprise a partial coastal restoration plan. This was an important step forward but it needs the set of projects for moving very large amounts of water and sediment out of the Mississippi River and into the deltaic plain.

Many in the scientific and coastal communities as well as the State of Louisiana are calling for far larger diversion projects that will significantly restore the Mississippi Delta's natural sediment regime and provide a net increase in and more enduring maintenance of existing wetlands. The natural functioning of the delta must be a guide to restoration. Before the levees became widespread, there were many crevasses, often as large as or larger than the Bonnet Carre spillway. This scale of diversion must be considered especially with the increasing sea level rise. Maintaining navigation channels has been a primary concern, but this is relatively easily addressed by constructing locks or using peak flow periods, which provides the greatest potential for natural sediment load land building and where utilization of diversions does not interfere with navigation.

Larger restoration projects may be the only hope for a maintaining a sustainable landscape and economy as well as the long-term sustainability of ports and cities like New Orleans.

Results and Discussion

The ecosystems of the Mississippi Delta provide benefits based on a natural capital asset value ranging from $ 330 billion to $ 1.3 trillion, contributing to the national economy and the quality of life. How much, where, and by whom should investments in restoration and levees be made? What should the balance be? These are critical questions with radically different alternatives.

One thing is certain. The continued degradation of the Mississippi River Delta threatens public safety, economic productivity and ecosystem services. The damage to oil production, pipelines and refineries has national economic implications. Without wetland expansion, hurricane damage will result in higher prices for gasoline, jet fuel, diesel, fuel oil and natural gas for the entire U.S. as it did after Hurricanes Katrina, Rita, Gustav and Ike. Better management of the Mississippi Delta is critical to the U.S.

Part 1 of this study introduced a "new view on value," and the critically important role of natural capital for the economy of the Mississippi River Delta. Part II provided a valuation of 11 ecosystem services and net present value calculations establishing that the delta is an enormously valuable natural capital asset. Part III of this study shows how the dramatic, dynamic physical changes affecting the Mississippi River Delta have profound economic implications. This section examines three scenarios for the Mississippi Delta: continued delta deterioration and land loss, a modest investment in delta restoration, and a more aggressive investment in the restoration of the Mississippi River and the delta.

Land cover types, ecosystem services and dollar value estimates The next three tables provide an overview of results. Table 5 shows values per acre (in 2007 dollars) for all land cover types including wetlands and all ecosystem services for which data is available. It shows the dollar value per acre of each ecosystem service for each land cover type. The highest values per acre are provided by fresh water wetlands and forested wetlands at $ 3,200–12,000. All natural systems provide economic benefits. Some systems have far more available valuation data than for others. Generally, estuarine and open water systems are far less studied than wetlands and forested systems. Water regulation and storm protection benefits have the highest values per acre. Flood prevention and hurricane protection are two of the most important functions of coastal systems in the Mississippi Delta.

Forested wetlands provide significant value for both low and high values in the Mississippi Delta. This is directly tied to the physical functions of these forests. Wetland forests provide strong hurricane protection value by slowing and reducing the storm surge and breaking up hurricane force winds and at the surface where it is most important in reducing waves. Bald Cypress trees, for example, are excellent hurricane buffers because they are well buttressed by an extensive root system that provides tall, sturdy and highly resilient barriers to wind and water. They have evolved to withstand strong wind and water action. All of the marsh types provide hurricane buffering. Salt, brackish and intermediate marshes provide greater buffering value along the coastline. More research is needed to fully understand the mechanics of natural systems in buffering hurricanes.

The color codes in Table 5 correspond to the general source of academic valuation studies. Green indicates numbers derived from local Mississippi Delta data. We used other study references where there was no local data. Purple corresponds to figures used in the 2005 New Jersey study, most of which were derived outside New Jersey. Blue corresponds to the Kazmierczack (2001) wildlife value study. Pink corresponds to Costanza et al. (1997a) and yellow to studies from the Gund Institute for Ecological Economics database. Batker et al. (2010) provides all of the references for the value transfer studies from which each of these figures is derived and a table of the land cover, authors, the type of valuation analysis conducted (one of seven valuation study types, avoided cost, contingent, etc.) and the high and low values in 2004 dollars which correspond to the values in Table 5 (converted to 2007 dollars).

Table 5 Per acre values for land cover types and ecosystem services in the Mississippi River Delta (2004 dollars/acre/year)

Land Cover Type	Acres	Low Value Estimate	High Estimate
Fresh Water Marsh	877,099	$2,833,616,569	$11,077,411,806.55
Intermediate Marsh	660,933	$1,823,993,642	$4,429,535,089.73
Brackish Marsh	547,445	$1,510,797,014	$3,668,942,825.58
Saline Marsh	421,561	$1,098,191,310	$2,760,038,549.65
Shrubscrub wetland	172,106	$393,890,419	$1,531,460,185.19
Forested/Swamp Wetland	1,031,561	$3,335,203,387	$13,258,333,954.99
Open Fresh Water	992127	$428,346,204	$2,959,631,369.64
Open Estuarine Water	3,549,990	$68,661,717	$6,822,566,401.65
Upland Shrub-Scrub	84,799	$9,090,572	$135,305,795.41
Upland Forest	172,106	$78,575,469	$699,135,025.33
Pasture-Agriculture	481,575	$37,997,389	$42,802,567.96
Total	8,940,461	$11,953,060,333	$47,385,163,571

The greatest source of error is introduced by lack of data. Many of the boxes in the table are empty. In many cases, economically valuable services are clearly provided but no valuation studies have been conducted. This is the case for over 50 clearly valuable ecosystem service/land cover type combinations such as the value of wetlands for erosion control. Thus the high and low values are likely underestimates of the true high and low values of these systems. In a few cases, the service may not be provided, for example pollination in marine environments. Because there were no newer and better studies, many of the studies used here are over a decade old. Despite these shortcomings, this table to date gives the most comprehensive accounting of ecosystem services provided by the Mississippi Delta.

Table 6 shows the land cover types, acres of each land cover type, low and high value estimates per acre, and the sum of ranges in value these vegetation types provide on the Mississippi Delta. Thus, this study presents the low and high value estimates of ecosystem services that the Mississippi River Basin provides in one year. The range between the high and low total values—$ 25 billion—is substantial and reflects the uncertainty and differences in valuation studies. Both the low and high values are large and demonstrate that the natural systems in the Mississippi Delta provide valuable economic benefits. These natural systems are also highly efficient at providing this value. It would be far more costly or impossible to replace them with built capital alternatives. In addition, if restored to health, these natural systems are self-maintaining and can, without charge, provide services, such as hurricane buffering.

The large values of wetlands and wetland forests in the Mississippi Delta primarily come from the water regulation and hurricane protection. These areas deserve further study. As is the case with all economic measures, this measure of value is not perfect. Like other aggregate economic measures such as the Gross Domestic Product, or total assessed property values, this analysis takes the marginal value per unit (dollars per acre) multiplied by the total number of units (acres) to estimate a "gross" total value. A better, far more difficult, and not yet developed measure would consider the dynamic nature of the change in value as trade-offs between these land cover types takes place. The Gund Institute for Ecological Economics is developing dynamic tools for this purpose.

The spatial distribution of services is another difficult issue. Not every acre of wetland provides equal amounts of storm protection value, as was assumed here. Because every storm differs in location, intensity, storm surge, wind speed, aspect to the coastline etc., the value of wetlands for storm protection will be different for every storm. Greater Geographic Information System data and better predictive

Table 6 Total value based on acreage for each ecosystem type (2007 dollars)

Land cover type	Acres	Low value estimate	High estimate
Fresh water marsh	877,099	$ 2,833,616,569	$ 11,077,411,806.55
Intermediate marsh	660,933	$ 1,823,993,642	$ 4,429,535,089.73
Brackish marsh	547,445	$ 1,510,797,014	$ 3,668,942,825.58
Saline marsh	421,561	$ 1,098,191,310	$ 2,760,038,549.65
Shrub-scrub wetland	172,106	$ 393,890,419	$ 1,531,460,185.19
Forested/swamp wetland	1,031,561	$ 3,335,203,387	$ 13,258,333,954.99
Open fresh water	992127	$ 428,346,204	$ 2,959,631,369.64
Open estuarine water	3,549,990	$ 68,661,717	$ 6,822,566,401.65
Upland shrub-scrub	84,799	$ 9,090,572	$ 135,305,795.41
Upland forest	172,106	$ 78,575,469	$ 699,135,025.33
Pasture-agriculture	481,575	$ 37,997,389	$ 42,802,567.96
Total	8,940,461	$ 11,953,060,333	$ 47,385,163,571

Table 7 Present value of ecosystem services over 100 years (2007 dollars)

Discount rate	Low estimate	High estimate
0%	1.2 trillion	4.7 trillion
2%	513 billion	2.3 trillion
3.5%	330 billion	1.3 trillion
5%	237 billion	940 billion

data on hurricane strength, location and occurrence as well as land cover types along the expected hurricane route and the lives and value of property protected are the basic information needed to improve this valuation. One advantage to increased coastal wetlands, as opposed to levees, is that a wide skirt of wetlands provides buffering against hurricanes approaching from any angle, speed, or storm surge height. The cumulative nature of wetland protection value is also not measured here.

Every individual acre of wetland provides differential benefits. As better techniques for valuation become available, this differential value will be better measured. However, most economic measures, such as the gross domestic product (GDP), are incapable of accounting for this individual difference in expressed value. For example, every new automobile of an identical make also provides differential benefits. Consider two new trucks of the same model that are sold for the same price, one performs poorly while the lasts for decades. They are valued identically in the GDP. A more useful economic measure of value would be based on the actual economic performance and benefit provided by each truck (analogous to the actual value an acre of wetland provides for hurricane protection). However, this would be impossible to calculate. Imperfect as it is, the GDP is a useful aggregate measure of value. Similarly, this report provides an aggregate value of natural systems in the Mississippi River Delta that can be improved upon. Although the values provided here are underestimates of the true value Mississippi Delta ecosystems provide, they meet the same basic standard of accepted economic measures and are certainly better than nothing.

Based on available data, the value of the services examined here and provided by the Mississippi Delta is estimated to be between $ 12–47 billion annually. Retaining and expanding this annual flow of benefits is good economics. Unfortunately, these benefits have been largely counted as zero for most of the last century.

Table 7 shows the equivalent of an asset value for the economic benefits derived from Mississippi Delta's natural systems. This is the present value of the flow of benefits from these services in a 100-year period, shown for the four discount rates. The asset value of Mississippi Delta ecological systems (a partial value since not all ecosystem services were valued) varies from $ 237 billion at the low end using a 5% discount rate to $ 4.7 trillion if the benefits to people in the future are treated equally to the benefits we receive in the present over a 100-year period. This demonstrates that the natural capital asset value of the Mississippi River Delta is tremendous by any measure.

Since open water provides fewer benefits than land in this area, continued land loss will result in a decline in asset value. In addition, the dead zone reduces the value of estuarine waters within the area of study, thus providing a lower value. The reduced value on account of the dead zone was not included. The reality is that all ecosystems in the Mississippi Delta contribute value to citizens both within the delta and the nation. Local, state and national investment decisions should be informed on the value of natural capital.

The differences between these values depend on the discount rate chosen, as shown by Table 7. This shows how value across time is treated, particularly in respect to renewable resources that provide value across vast amounts of time. A short discussion of how an "asset" value is calculated from the value of annual benefits that the Mississippi Delta provides and some of the implicit issues behind the choice of a discount rate follow.

The difference between an annual flow of benefits and an asset value is often not intuitive to non-economists. Consider first that ecosystems provide an annual flow of benefits, some of which can be expressed in dollar value as shown in Table 5 and Table 6. From this annual flow of value, the value of the asset or the structure that produces that value can be estimated. This is analogous to comparing an annual mortgage payment for a house (the value of living in the house for a year) and the total "asset value" or price of the house.

A natural capital asset value is *analogous* to a built capital asset value because unlike a house or car, ecosystems the size of the Mississippi Delta cannot be bought or sold as a whole asset and because many of the most important benefits are public goods and services which, by their physical nature (like oxygen in the air or hurricane buffering), cannot be bought or sold in markets. However, just as the value of a "built capital" asset can be calculated from the annual flow of net income it produces (annual flow of value) a "natural capital" asset value of the Mississippi Delta can also be calculated from the estimated annual flow of benefits that it provides.

Calculating the present value of an asset requires the use of a discount rate. Discount rates measure the extent to which people value benefits in the present versus benefits at a future date. Current environmental economics literature yields a healthy discussion about whether or not to use discount rates and what rate should be applied to calculate the value of ecological assets over time; there is a variety of alternatives to standard exponential discounting, including using declining rates and "intergenerational" discounting which allows the assignment of different, lower discount rates for future generations versus the current generation.

Renewable resources should be treated with lower discount rates than built capital assets because they provide a rate of return over a far longer period of time (potentially thousands of years or longer, for example, the ozone layer). It would be unwise and a tremendous economic blunder to treat value across time for the ozone layer's protection the same way we treat the useful life of a throwaway coffee cup. The discarded coffee cup provides no value to our grandchildren. Since the value of the ozone layer and a coffee cup are fundamentally different in importance and value to people across time, a coffee cop and the integrity of the ozone layer should be valued differently across time.

Natural capital, when healthy, is an appreciating and self-maintaining asset; built capital depreciates and requires active maintenance, or it falls apart. This has profound implications for defining sustainability and how assets and investments are treated across time. The benefits that a natural asset provides are garnered across time, most in the distant future, whereas the benefits of built capital, such as a car or levee, are largely delivered in the immediate future, depreciating rapidly, with few or no benefits provided in the distant future. Both built and natural assets are necessary to maintain a high quality of life for people. What is more important now than at any time in the past, when natural capital was abundant, is how we balance investments in natural and built assets. In the past, investments in built capital have substituted for and damaged natural capital. In the future, wiser investments in both natural and built capital should be complementary. For example, wetland expansion protects levees and diversion structures enhance wetland restoration.

Discounting tilts valuation and decision making toward choices that pull the benefits into the present and push costs into the discounted future. High discount rates are biased toward investments that have a high and quick pay off, even though their value may quickly disappear and cause large and long lasting costs. Low discount rates give greater value to future benefits.

For simplicity, we use the four discount rates of 0, 2, 3.5 and 5 % to underscore the difference in asset value depending on the value given to future benefits. A zero discount rate implies that we in the present hold future flows of ecosystem services to be just as important to people living in the future as the value of those assets are to us today. We limit the time horizon arbitrarily to 100 years for the zero discount rate. This is short sighted. Without limiting the time period the value of natural assets would be infinite, compared to any built capital asset that depreciates. This reflects the true nature of a potentially sustainable flow of value and an asset that falls apart and can only provide a finite flow of value. However, built capital provides important current benefits. A 2–3.5 % discount rate implies that people today have a positive time preference so that what remains in the future is less important in meeting current needs than what we have today. It gives more value to the future than the 5 % rate or greater, a range that is typically used to value built capital assets or to calculate expected rates of return on monetary investments.

How we treat great amounts of value provided for long periods of time into the future is fundamentally an ethical decision; it cannot simply be left to a mathematical calculation based on today's prime interest rate or any other arbitrarily set discount rate.

To conclude this section, calculations of the present value of the flow of ecosystem services show that intact natural systems provide enormous value to society in the short and long term. While we currently need and enjoy the benefits, such as hurricane protection or the supply of drinking water, most of the benefits that healthy natural capital provides, like all renewable resources, will be retained in the future.

The cumulative economic benefits from healthy, functioning natural capital across time and generations is tremendous.

In the past, we could assume that all natural capital was basically healthy and functioning well. This is no longer the case. For example, cypress trees cannot grow in saltwater. They will die off if saltwater intrudes through canals or coastal land loss in their area. The economic value that cypress trees provide, such as hurricane protection, will also be lost. The same assumption for all natural capital that is under threat can now be applied.

Conclusions

Mississippi River Delta Ecosystems provide economically valuable services, including hurricane storm protection, water supply, climate stability, food, furs, waste treatment, wildlife habitat, recreation and other benefits. These services are valued at $ 12–47 billion/year.

This flow of annual benefits provides a vast amount of value to people across time. A "natural capital asset value" can be established from these annual benefits. The present value of the benefits from these ecosystem goods and services provided by the Mississippi Delta, analogous to an asset value, is worth at least $ 330 billion to $ 1.3 trillion.

Wetlands—a product of Mississippi River deltaic processes including freshwater, saltwater, estuaries/tidal bays and cypress swamps—account for more than 90 % of the Mississippi Delta's estimated total value of ecosystem services.

These benefits are derived from "natural capital" which is self-maintaining and lasts for a long time; it is fundamentally different from "built capital" which depreciates quickly and requires capital and maintenance costs.

In the past, our natural capital was taken for granted. Although natural systems provide economic goods and services such as fish and hurricane protection, they have not been valued as economic assets and were excluded from economic analysis and investment decisions.

Large-scale physical changes are affecting the Mississippi River Delta. In the last 30 years, oil and energy costs have been increasing, hurricanes have become larger and more frequent, sea level has risen, atmospheric temperatures have risen, and the delta has been subsiding. Since 1930, it has lost 1.2 million acres of land. This loss has had tremendous economic implications, including exposing cities like New Orleans to greater threats from hurricanes.

Hurricanes Katrina and Rita triggered a warning that has been sounded several times before. The current management of the Mississippi River, moving the sediment and fresh water of the river off the continental shelf has damaging economic costs in terms of land loss. The river has been walled off from the Mississippi River Delta since the 1930s. The public, academics and the State of Louisiana have sought to reconnect the river to the delta and utilize its sediment, water and energy to renew the processes that added land to the delta for thousands of years.

It is clear that restoration of the deltaic processes and levees are needed to secure public safety, economic assets and valuable ecosystem services.

A "do-nothing" scenario will result in continued land loss costing the U.S. at least $ 41 billion. A "hold the line" scenario could avoid the $ 41 billion, but would provide no additional benefits at a 3.5 % discount rate. A third "sustainable restoration" option would avoid $ 41 billion in losses and secure an additional $ 21 billion in benefits, providing $ 62 billion in net present value benefits.

This analysis does not include many ecosystem services with clear economic value. It is part of a series of efforts to understand the value of the natural capital in the Mississippi Delta. More work is critically needed to understand how and what investments in diversions, levees or other structures can produce the best and most long-lasting benefits.

A major investment to restore the deltaic processes of the Mississippi River Delta is required to maintain or expand the vast value of this natural asset. The movement of water and sediment and the maintenance and expansion of land underlies the production of many economic benefits, including protection against hurricanes. Without this investment, people and economic assets will be forced to retreat from the coastline.

Ecological engineering must form the basis of delta restoration. High and rising energy costs will erode the economics of energy intensive options, such as levees and sediment pumping while water and sediment diversions utilize the Mississippi River's energy and can be easily maintained over many decades.

The overarching solution is well understood: large diversions of water and sediment from the Mississippi River are required to rebuild the Mississippi Delta and to secure the many benefits, including the economic productivity that the river provides. Management of more coarse sediments in the Mississippi Basin, currently trapped behind dams, should also be considered as these sediments will eventually be released in the next 100 years and can contribute substantially to the delta's restoration.

Overall, this study shows that a major investment of $ 15–20 billion for restoring the Mississippi River Delta to significantly increase land building would return at least four to five times that amount. This is in the order of $ 62 billion in net present value at a 3.5 % discount rate.

Once restored in a manner that engenders maintenance of natural processes, these wetlands will continue to support the economic health of the Mississippi River Delta. With the river reconnected to the delta, the system will be closer to self-maintaining at the operating cost of diversion structures.

Without a large investment in restoration, hurricane damage will clearly increase and other ecosystem services will be lost, thereby threatening the economic viability and habitability of the Mississippi River Delta. This could result in vast losses to the country in terms of irreplaceable cultural and natural resources.

Within the context of the current financial crisis, investment in the restoration of the Mississippi River Delta provides high short and long-term returns. The Army Corps of Engineers, Federal, State and local governments should dramatically increase expenditures for the restoration of the Mississippi Delta.

The Mississippi River Delta, the largest delta in North America, is by far the most productive delta in the United States. It comprises 40 % of U.S. coastal wetlands, a crucial flyway for migratory birds, and houses oil and natural gas resources, refineries, fertilizer and chemical facilities and other industries that are vital to the country's economic health.

Economies need nature. This is very evident in the Mississippi River Delta. If the Mississippi River is not reconnected to the delta on a large-scale basis, the land, culture and economy of this vast and productive area will be lost. Effective hurricane defenses require wetland expansion. Reconnecting the river to the delta at the appropriate scale will accomplish restoration that is needed. This is in the best interest of the people of the United States.

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The Impact of Global Climate Change and Energy Scarcity on Mississippi Delta Restoration

John W. Day and Matthew Moerschbaecher

Abstract

Global climate change and increasing energy cost and scarcity pose significant threats to ecological and social systems of the coastal zone and to the restoration of the Mississippi delta. In coming decades, these two factors will affect how much land can be built and maintained and dictate how sediment is delivered to the delta plain. In this chapter we review climate and energy issues and discuss their significance for coastal restoration. Climate change will likely lead to accelerated sea-level rise, more intense hurricanes, highly variable flow of the Mississippi River with both more large floods and very low water years. Increasing energy scarcity will likely make energy intensive activities such as building and maintaining levees, and pumping slurried sediments much more costly. It will be necessary to come up with energy-efficient projects that require less fossil energy for operation and maintenance so that performance is not hampered by energy scarcity or cost in the future. This argues for river diversions because once built, they are very efficient to operate. The more delta restoration and river management can depend on natural processes, the more cost-effective (from both economic and energy perspectives) restoration will be. Because of escalating climate change impacts and increases in the cost of energy, time is of the essence in terms of jumpstarting a large-scale sediment-reintroduction restoration program. This evidence indicates that there will be a window of time in the next one to two decades when climate impacts and energy costs are still moderate. This is the time to put resources into improving existing diversions and building new ones.

Keywords

Climate change · Sea-level rise · Peak oil · Energy scarcity · Ecological engineering

Introduction

In preceding chapters of this book, the major problems of the delta and the challenges of restoration were outlined. Two of the major problems of maintaining wetlands in the delta are increasing water levels and the impact of hurricanes on deltaic wetlands. In addition, earlier chapters point out the importance of the river as a resource for restoration. Thus the challenges of accelerating eustatic sea-level rise and increased frequency of intense hurricanes will make delta restoration more challenging with increasingly severe climate impacts. On the other hand, if there are more high water years, then there will be more resources available in terms of freshwater and sediments. In addition, a number of chapters pointed out that many of the restoration and flood protection tools being proposed are very expensive and energy intensive. These include large river diversions, building and maintain-

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ing flood protection systems, and long distance conveyance of sediments. If liquid fossil fuel energy becomes more expensive and scarce, this may limit options for restoration.

Climate Change

Global climate change has been related to an increasing concentration of greenhouse gases in the atmosphere. This increase comes largely from the burning of fossil fuels. The Intergovernmental Panel on Climate Change (IPCC 2007) predicts that, as atmospheric greenhouse gas concentrations increase, global temperatures will rise from 1 to 5 °C during the twenty-first century. Already, temperature rise is tracking at the upper levels predicted by IPCC models (McCarthy 2009) indicating that temperature rise will not be in the lower end of the predicted range. These predictions compare to approximately a one degree rise in the twentieth century (Fig. 1 and 2). There is high year-to-year variability. Note that in Fig. 1, if an especially warm year were picked as a starting point, a few years would seem to show cooling. The overall trends need to be considered. Overall, temperature data over the last century shows a definite warming of about 1°C. In addition, it is important to consider temperature on a decadal time scale. Together, the mean global temperature increase in the twentieth and twenty-first centuries is predicted to be as high as 6 °C. This rise over two hundred years is similar to what the planet experienced over a 10,000 year period, from the last ice age 15,000 years ago to about 5,000 years ago when the oceans approached their present level.

Temperature rise is related to sea-level rise, and changes in rainfall and tropical storm activity. Temperature also directly controls many vital life processes, and a change in the thermal regime (extreme temperatures, their duration and seasonal rates of temperature change) can directly regulate rates of growth, migration, and reproduction of species. Recently, there has been discussion about the lack of temperature increase from 1998 to 2008. Some even argued that the climate was cooling. A recent study by Kaufmann et al. (2011) reported that release of sulfur particles from dramatically increased coal burning is the likely cause of this lull. The cooling effect of the sulfur particles balanced the warming impact of CO$_2$ release over the past few years, showing how poised the atmospheric envelope is with respect to heat retention and reflection. Most of the increased coal burning occurred in Asia, especially in China, where coal consumption more than doubled between 2002 and 2008 (EIA 2011a). As China has begun requiring stack scrubbers to remove sulfur particles, it is expected that the temperature increase will resume as global temperatures equilibrate to rising CO$_2$ levels.

There has been a consistent long-term rise in sea level since the end of the ninetieth century (FitzGerald et al. 2008; Meehl et al. 2007; Fig. 3). Current eustatic sea level rise (ESLR) is between 3 and 4 mm year^{-1}. Figure 4 shows a record of sea-level rise that illustrates the variability associated with sea-level change. These records are from the mid 1950s to the 2000s. The data in Fig. 4 is for the upper 700–750 m of the ocean associated with thermal expansion indicating that heat is being transferred to deeper layers of the ocean. McCarthy (2009) reported that recent measurements of sea-level rise are in the upper range predicted by IPCC climate models (Fig. 5).

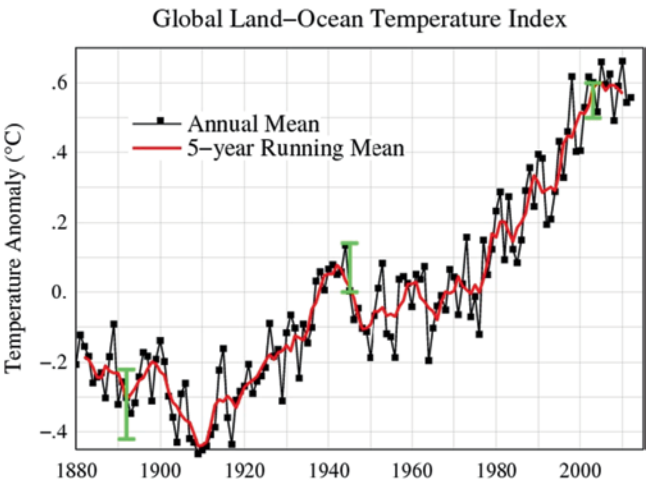


Fig. 1 History of global mean surface air temperature, from the NASA *Goddard Institute for Space Studies*. The scale gives how much warmer or cooler the world was than the average temperature during 1951–1980. Recent warming is clear, but with high year-to-year variability. The *green* vertical lines show data variability for the indicated time periods. Other research groups have produced similar plots. (Modified from Hansen et al. 2006)

There is a strong scientific consensus that the rate of ESLR will accelerate in association with global warming, and the Intergovernmental Panel on Climate Change (IPCC 2007) predicted sea-level rise will be about 40 cm by the end of the twenty-first century, with a range of uncertainty from 10 to 54 cm (IPCC 2007). More recent work suggests that this prediction may be too low, that ESLR may be up to a meter or more (Rahmstorf 2007; Pfeffer et al. 2008; Mitrovica et al. 2009; Vermeer and Rahmstorf 2009; Fig. 6). Increasing eustatic sea-level rise is especially critical in the Misssissippi delta, and other deltas, because it is augmented by high rates of subsidence that have exceeded 1 cm/year. A sensitive, relatively lag-free coupling of temperature to sea level change has been reported by Rahmstorf and colleagues in the papers above. This finding has been corroborated by Kemp et al. (2011) based on analysis of sea-level rise rates over the past 1200 years using cores taken from a North Carolina salt marsh (Fig. 7). During the medieval warm period from about 1000 to 1300, sea level rose at about 0.6 mm year^{-1}. During the little ice age from about 1400 to 1700, the earth cooled and sea level rise stopped and even dropped at about −0.1 mm year^{-1}. From about 1850 to the present,

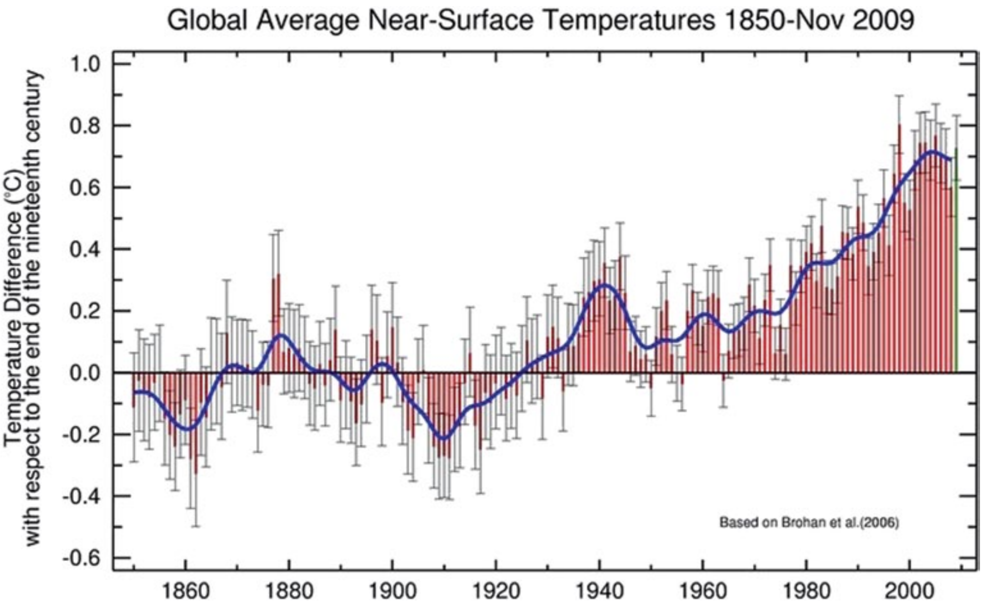


Fig. 2 Variations in global near-surface land temperature in degrees C. (Source: Hadley Climate Center, UK)

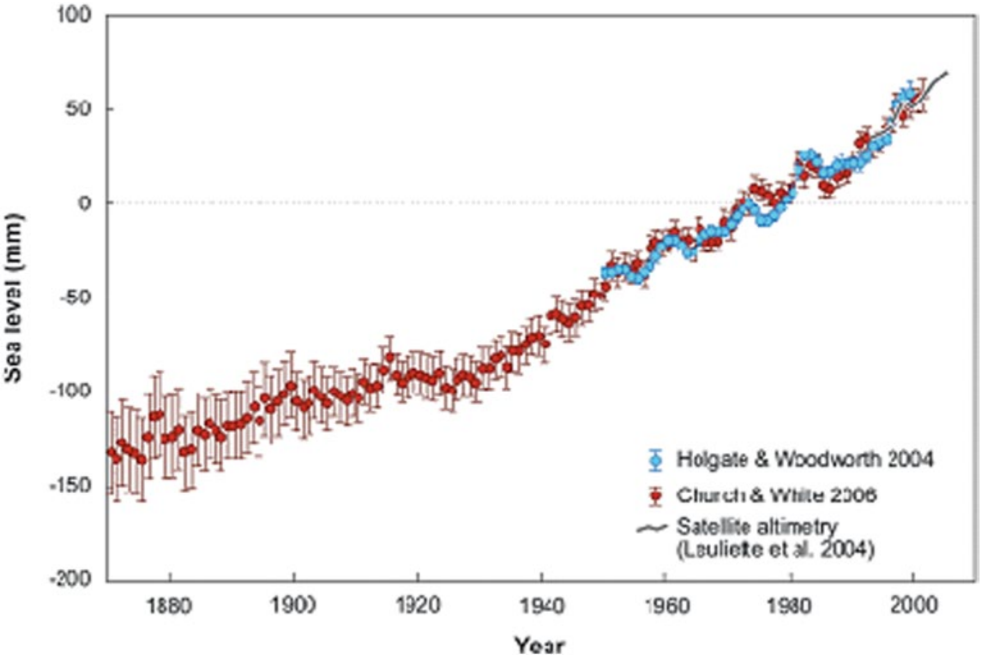


Fig. 3 Annual averages of global mean sea level from IPCC (2007). The *red* data are updated from Church & White (2006); the *blue* data are from Holgate & Woodworth (2004), and the *gray curve* is based on satellite altimetry from Leuliette et al. (2004). Error bars show the 90 % confidence limits. Zero represents the 1961–1990 averages for *red* and *blue* data. *Gray curve* represents a deviation from *red* data for the period 1993–2001. (Fitzgerald et al. 2008)

the average rate of sea-level rise was about 2.1 mm year^{-1}. These findings indicate that as the earth continues to warm, the rate of sea-level rise is increasing, and this is consistent with recent satellite altimetry measurements (FitzGerald et al. 2008; Fig. 3).

High subsidence rates complicate restoration efforts because of the resulting high rates of relative sea-level rise. Recent studies, however, suggest that subsidence in the 1970s and 1980s was high due to subsurface fluid withdrawal, especially oil and gas (Kolker et al. 2011). If subsidence is much lower than what occurred in the 1970s and 1980s, then total water level rise will not be as high as once predicted. On the other hand, the periodicity of water level variations at Grand Isle, and other areas, seem to be related to large scale meteorological phenomena in the North Atlantic such as the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO) (see Kolker and Hameed 2007; Kolker et al. 2011; van Oldenborgh et al. 2009; NOAA 2012). Water levels were higher than the long-term mean in the 1970s and 1980s and lower during the 1990s and 2000s, sometimes by up to five to 10 cm. High wetland loss rates in the 70s and 80s coincided with high water levels and low loss rates in the 90s and during the last decade coincide with low water levels. Thus, in five to ten years, there may be

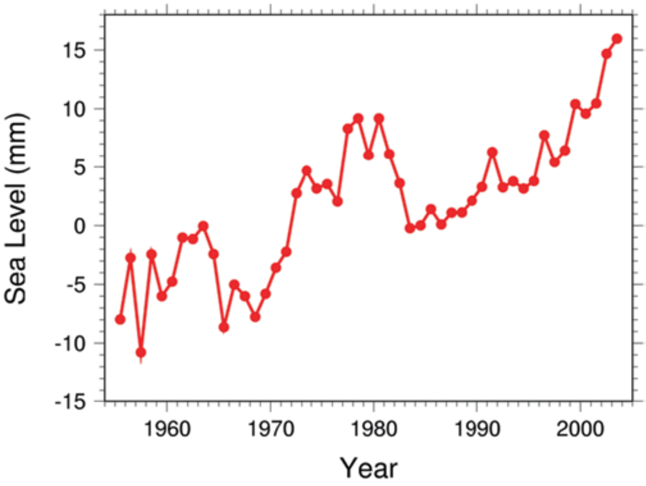


Fig. 4 Sea level change due to ocean warming (NOAA 2009)

another two to three decade period of high water levels and this may lead to increased wetland loss rates.

It is now increasingly certain that the frequency of strong hurricanes will increase in the twenty-first century. Emanuel (2005) reported that sea surface temperatures in the tropics increased by about 1 °C over the past half century. During this same period, total hurricane intensity or power increased by about 80 %. This increase in intensity was caused by an increased likelihood that storms would become more powerful and last longer, rather than occur in greater numbers. Similarly, Webster et al. (2005) reported an increase in the number of category 4 and 5 storms over the past several decades. Hoyos et al. (2006) analyzed factors contributing to hurricane intensity and concluded that the increasing number of category 4 and 5 storms over the 34 years between 1970 and 2004 was directly linked to the increase in sea surface temperatures. Knutson et al. (2010) summarized information on climate and tropical cyclones. Based on theory and results of dynamical models, they reported that warming will cause globally averaged intensity of tropical cyclones to shift towards stronger storms, with intensity increases of 2–11 % by 2100. Models also project decreases in the globally averaged frequency of tropical cyclones by 6–34 %, but substantial increases in the frequency of the most intense cyclones and increases in precipitation on the order of 20 % within 100 km of the storm center. Some have argued, however, that these increases are not linked to climate change but to decadal cycles in tropical storm activity (Goldenberg et al. 2001). Whether the recent intensification of hurricanes is due to climate change or is part of a multi-decadal cycle, it appears likely that the future will bring stronger hurricanes.

The factors that led to the 2011 Mississippi River flood are all consistent with climate change projections. The intense storms that delivered so much precipitation are largely a result of the interaction of warm air masses off a warming Gulf and colder continental air masses (Min et al. 2010; Pall et al. 2011). This gave rise to the very intense storms that have also been documented in many other parts of the world. Precipitation is generally expected to increase in higher latitudes as in snowfall due to a wetter atmosphere (IPCC 2007). Although no single weather event or flood can be attributed solely to climate change, the flood of 2011 is certainly consistent with climate projections. And given the trajectory of rainfall intensity in the temperate zone, floods like those in 2011 are likely to become more common. One possible indication of this trend is that the Bonnet Carre spillway, an overbank high water relief structure upstream of New Orleans on the Mississippi, has been opened 10 times in the past 80 years. It was opened three times during the first 40 years after it was built in the 1930s, while it has been opened seven times since 1973, during the second half of its operational life to date (Day et al. 2012).

Energy

The availability and cost of energy is expected to greatly affect natural resource management in the future. Over the past decade, much information has been published in the scientific literature (Masters et al. 1991; Campbell and Laherrére 1998; Kerr 1998; Bentley 2002; Deffeyes 2001, 2010; Hall et al. 2003; Heinberg 2003), primarily by petroleum geologists with extensive experience in oil exploration and production, that predicts a peaking of total world oil production soon, perhaps within a decade. This is expected to usher in an era when demand will consistently exceed supply. The price of energy can therefore be expected to increase significantly under even the most optimistic scenarios (Heinberg 2003). Indeed, global conventional crude oil production appears to have already peaked, and exploration attention is currently focused on unconventional reserves locked in tar sands, shales and ultra-deep water fields (Murphy and Hall 2011).

Projections of when world oil production will peak are based on modifications of an approach developed by M. King Hubbert who became famous based on his prediction in 1956 that U.S. oil production would peak in the early 1970s (Deffeyes 2001, 2005, 2010); it peaked in 1971 (Deffeyes 2001). Hubbert also predicted that world oil production would peak in the first decade of the twenty-first century, which now seems to be happening (See Deffeyes 2001 and Heinberg 2003 for a discussion of Hubbert's work). In essence, projections of future oil production and peak oil production use statistical and physical methods based on reserve estimates and the lifetime production profile of typical oil reservoirs. Oil production from reservoirs tends to follow a bell-shaped curve with a rapid increase in production followed by a relatively rapid decrease in production. Thus, by

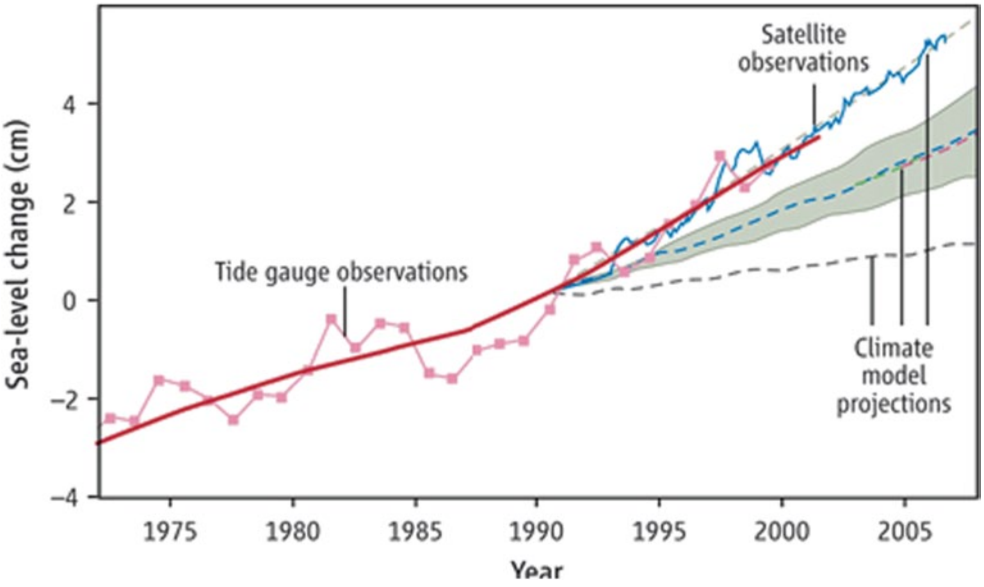


Fig. 5 Sea level change since 1975 compared to climate projection models. Observed sea level changes based on tide gauges and satellite observations (McCarthy 2009)

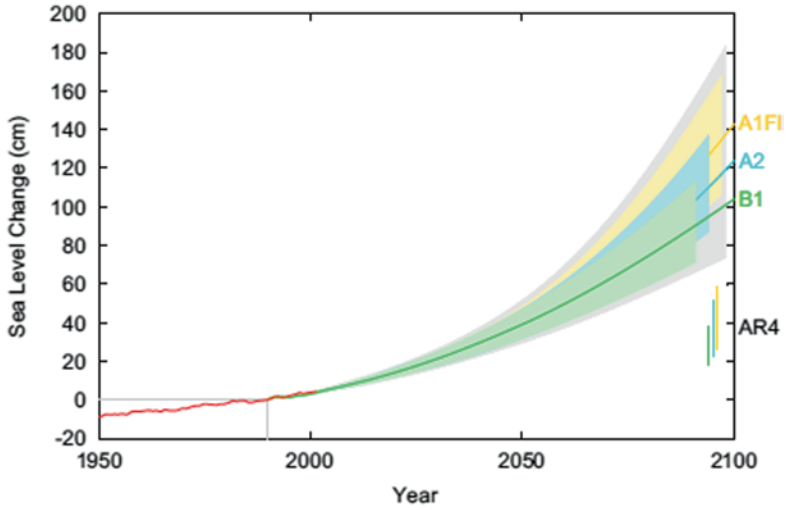


Fig. 6 Projection of sea-level rise from 1990 to 2100, based on IPCC temperature projections for three different emission scenarios (labeled on *right*, see Projections of Future Sea Level for explanation of uncertainty ranges). The sea-level range projected in the IPCC AR4 (2) for these scenarios is shown for comparison in the bars on the bottom right. Also shown is the observations-based annual global sea-level data (18) (*red*) including artificial reservoir correction (22). (Vermeer and Rahmstorf 2009)

knowing the early production history of a reservoir (or many reservoirs together) and an estimate of reserves, the time of peak production and total oil production can be estimated. Based on this information, a number of experts have predicted that world oil production will peak sometime during the first two decades of the twenty-first century (Masters et al. 1991; Campbell and Laherrére 1998; Deffeyes 2001; Bentley 2002; Heinberg 2003). Indeed, conventional world oil production is believed by some experts to be at the production peak today (Deffeyes 2010; Murphy and Hall 2011).

The Hubbert approach is based on the concept that oil discoveries in an area generally precede peak production by 30–40 years. For example, U.S. oil discovery peaked about 1940. World oil discoveries peaked by 1970 and have been falling since and recent success has been very low, despite increased drilling efforts (Cambell and Laherrere 1998; ASPO 2008; Fig. 8) and most estimates of ultimately recoverable oil have been about 2 trillion barrels since 1965 (Hall et al. 2003). Global production increased exponentially until about 1970 but the rate of increase has declined since. Production is now 2–3 times the discovery rate, and current production is mostly from reservoirs discovered 30 to 40 years ago. 400 or so giant and supergiant oil fields provide roughly 80 % of the world's petroleum, the vast majority of which were found before 1960 (Skrebowski 2004). Of these roughly one quarter are declining in production at an average rate of about 4 % annually. Also world oil demand is increasing, especially in China and India.

For the past few years, all drilling globally did not find even enough oil to pay for the drilling, implying that we may be approaching the end of a positive energy return on energy investment for searching for new oil (e.g., Hall and Cleve-

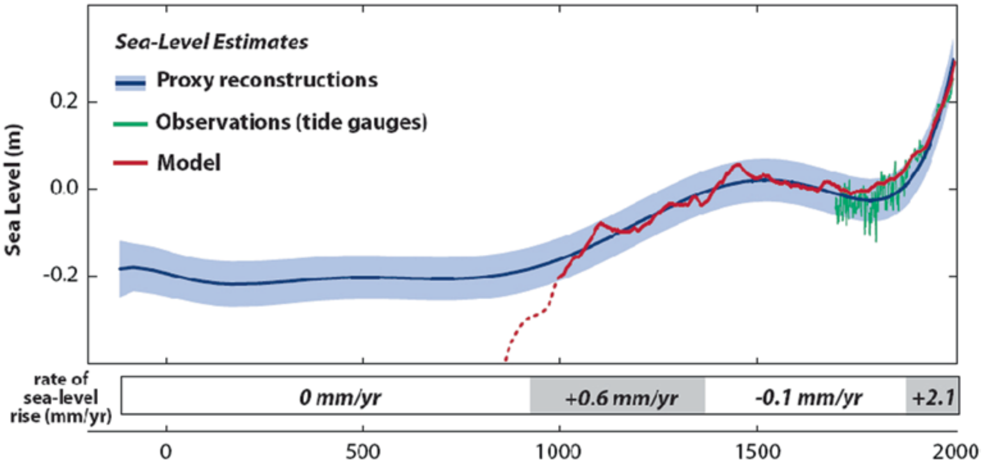
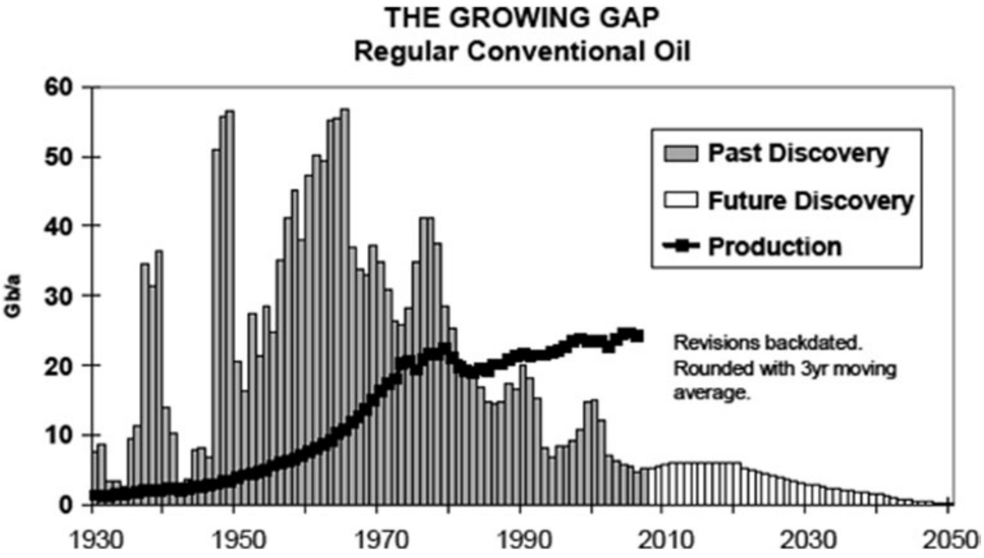


Fig. 7 Sea level evolution in North Carolina from proxy data (*blue curve* with uncertainty range, from Kemp et al. 2011). The *green curve* shows reconstruction based on tide gauges from around the world. The *red curve* shows results from a simple model connecting global temperature with sea level. For the last millennium the sea level curve follows what can be expected from temperature—the two independent reconstructions thus mutually reinforce each other by their consistency. Before 1000 AD there is a discrepancy: warm temperatures in the reconstruction used would lead to rising sea level, but the sea level reconstruction is flat. However, temperature data from before 1000 AD are sparse and less reliable, and lowering temperatures in this period by only 0.2 °C removes the discrepancy. Thus, a possible explanation for the discrepancy is that the temperature reconstruction is a little too warm before 1000 AD

Fig. 8 The rate at which oil is discovered globally has been dropping for decades and is projected to drop off even more precipitously in future years. The rate of worldwide consumption, however, is still continuing to rise. Thus, the gap between supply and demand of oil can be expected to widen. Data courtesy of the Association for the Study of Oil and Gas. (Hall and Day 2009)



land 1981; Hallock et al. 2014). Some have argued that additional discoveries will provide abundant oil well into the future (See Deffeyes 2001, 2010; Hall et al. 2003; Heinberg 2003 for reviews). But most estimates of ultimately recoverable oil (URO) have remained relatively constant since about 1965 at about 2 trillion barrels. This is the value of URO that most authors have used to predict the timing of peak oil production. Yearly oil discoveries peaked in the 1950s and 1960s and have declined substantially since, while we now consume about four barrels of oil for each one discovered.

One parameter that is being used to standardize discussions of energy use is the energy return on investment (EROI). EROI is the ratio of the value of energy embodied in oil at the point of sale to the cost of the energy required to discover and produce it. During the period when conventional oil production was increasing most rapidly, in the 1950s and 1960s, EROI was typically between 100:1 and 50:1 (Fig. 9). Since the 1980s, the average EROI for conventionally produced oil fell worldwide to between 15:1 and 10:1 (Cleveland et al. 1984; Cleveland 2005; Hall and Day 2009). Thus, it is taking more and more energy to find and produce oil. The EROI for non-conventional sources of oil (oil shale and oil sands) and most renewables are all less than 15:1, and most are substantially less than 10:1 (Heinberg 2003). The Canadian tar

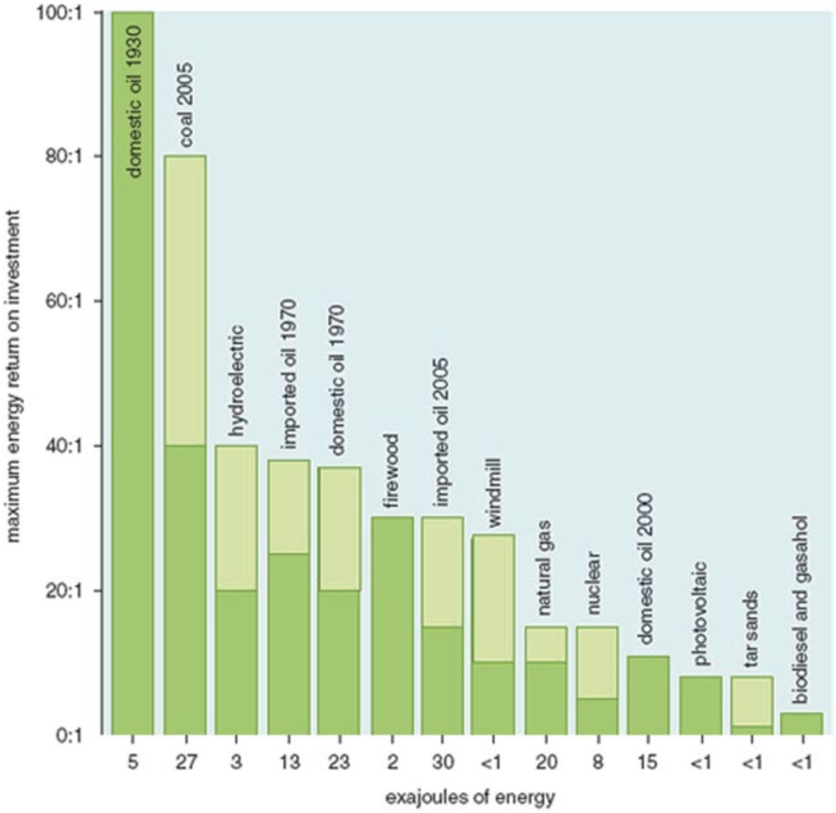


Fig. 9 The energy return on investment (EROI) is the energy cost of acquiring an energy resource; one of the objectives is to get out far more that you put in. Domestic oil production's EROI has decreased from about 100:1 in 1930, to 40:1 in 1970, to about 14:1 today. The EROI of most "*green*" energy sources, such as photovoltaics, is presently low. (*Lighter* colors indicate a range of possible EROI due to varying conditions and uncertain data.) EROI does not necessarily correspond to the total amount of energy in exajoules produced by each resource. (Hall and Day 2009)

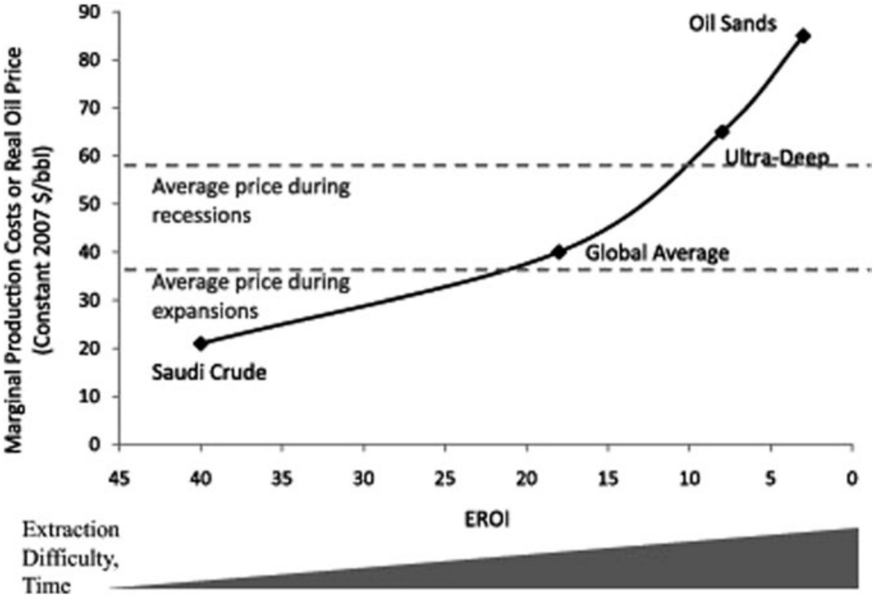


Fig. 10 Oil production costs from various sources as a function of the EROI of those sources. The dotted lines represent the real oil price averaged over both recessions and expansions during the period from 1970 through 2008. EROI data for oil sands come from Murphy and Hall (2010), the EROI values for both Saudi Crude and ultradeep water were interpolated from other EROI data in Murphy and Hall (2010), data on the EROI of average global oil production are from Gagnon et al. (2009), and the data on the cost of production come from CERA (2008). (From Murphy and Hall 2011)

sands now being promoted as an important future source of liquid fossil fuels have little or no net energy yield even without consideration of seemingly unavoidable environmental impacts (Murphy and Hall 2011; Fig. 10). Tar sands oil is a lower quality substitute for the easily accessible and readily useable sweet crude oil deposits that were largely exhausted during the twentieth century. The tar sands oil requires considerably more energy to extract and refine than conventional crude oil. This is also the case for other unconventional oil sources such as natural gas plant liquids and biofuels. The implication is that oil production will not be able to meet demand and that this will drive up the cost of all fuels to a point that energy-intensive restoration techniques that require substantial pumping will be unavailable in the long-term. It would normally be expected that increasing the cost of oil would result in increased production. But over the last decade, significant increases in oil prices have not resulted in increases in production. Indeed production has remained flat for much of the last decade (Murphy and Hall 2011).

The increasing price of oil over the last decade has had repercussions throughout the U.S. and global economy. Research shows that rising oil prices negatively impact the nation's GDP and inhibits economic growth (Hamilton 2009; Murphy and Hall 2011). Some analysts have reported that recent production of oil and gas from shale formations suggests that there are vast new supplies of oil and gas that will make these resources plentiful for decades to come (Moritis 2008; Tollefson 2010). However, such studies often lack careful quantitative analysis documenting actual reserves and disregard the costs required to extract the energy. Many analyses fail to include the increased energy and financial costs associated with shale plays. Such studies often imply that the problem is simply not enough drilling. However, increasing drilling effort does not always equate to an increase in production (Hall and Cleveland 1981).

Analysis of individual oil and gas fields in shale plays indicates that these sources of energy are not as plentiful as has been indicated (Berman 2012a). The higher energy yielding areas of shale formations are often concentrated around "sweet spots" or "active areas" that are much smaller in size than "undeveloped areas" (EIA 2011b). Berman (2012a, b) reported that shale gas has compensated for declines in conventional gas production. Most analysts forecast that high shale gas production will continue well into the future. However, most shale plays are characterized by steep decline rates compared to conventional oil and gas fields. This means more wells must be drilled in order to offset steeper well decline rates. Increased drilling activity in order to maintain production levels comes at a greater cost to the producer that must be passed on to the consumer at some point if the company is to remain profitable (Berman and Pittinger 2011).

But demand is increasing while production is beginning to decrease. Current natural gas prices are below production costs and this cannot continue if companies are to stay in business over the long term. Because of this, dry-gas drilling and production curtailments are significant. Since oil prices are high, there is a shift from gas to liquid-prone (oil) shale plays and this will reduce gas supply. In addition, high decline rates in shale gas wells will further reduce gas production. As a result, gas supply is beginning to decline as demand is increasing. LNG export will decrease gas supply further and likely drive up prices. Because of all these factors, it is doubtful that shale gas production will meet supply expectations unless gas prices are much higher.

For oil, shale reservoirs will not do as well as conventional fields and profitable shale oil production depends on high oil prices. Both gas and oil shale fields have high decline rates. It must be remembered that shale oil plays are not fields. Shale oil fields will represent 15% at most of a play area. Fields generally will peak in 3–5 years and then decline. The total contribution of shale oil to U.S. production is presently 900,000 barrels of oil per day and will probably not increase to more than 2 million barrels of oil per day (14% of consumption) or less because of high decline rates. The EIA estimates shale oil production will reach 1.3 million barrels per day by 2030 (EIA 2012). Oil prices must remain high to sustain the drilling required to replace annual base and add production.

Drilling history in the Bakken shale play, located in North Dakota, illustrates the increased costs associated with unconventional oil production. Almost 9000 wells have been drilled in the Bakken shale with less than 20 producing more than 800 barrels of oil per day. While conventional oil wells in the Gulf of Mexico, such as a well in the Thunder Horse field, produce tens of thousands of barrels per day, while an average well in the Bakken shale play produces less than 75 barrels per day. Thus, many more wells must be drilled in the Bakken in order to produce the amount of oil available from one conventional well in the deepwater Gulf of Mexico. Each well adds to the production costs that must eventually be passed on to the consumer if companies are to remain profitable.

Increasing energy prices going forward combined with depletion from existing wells in the Gulf of Mexico will directly impact the amount of money available for coastal restoration in Louisiana. Presently, the state budget is affected by the amount of energy produced in the state and money from the outer continental shelf (OCS) region. In 2017, an increasing percentage of federal OCS revenues will become available to coastal restoration as part of Phase II of the Gulf of Mexico Energy and Security Act of 2006 (BOEMRE 2012). The amount of money will depend on the amount of energy extracted in the federal OCS. It is therefore in the interest of the state and citizens to have an accurate understanding of potential energy production scenarios in the Gulf of Mexico. Energy production scenarios combined with energy price models could provide for increased accuracy in estimating the financial resources available to coastal restoration efforts in the state over the next decade.

Summary

In summary, information on climate trends documented by atmospheric scientists when coupled with projections of energy cost indicate that the way the Mississippi River and delta are currently managed may not be sustainable and that new approaches that involve less energy intensive approaches may be necessary. Maintaining the current flood control and navigation system is very energy intensive. Climate change will likely lead to accelerated sea-level rise, more intense hurricanes, and more large floods on the Mississippi. As indicated in Chap. 5, the river is seeking a different outlet and preventing this will become more difficult and expensive in the future. If this is quickly recognized and addressed, however, we believe that a sustainable trajectory can be achieved that will lead to a less ecologically destructive scheme for river management that also improves the long-term economic survivability of deep-draft navigation and protection from storms and the economy of south Louisiana in general. Such a trajectory can also lead to a more sustainable restoration of the coast.

Blum and Roberts (2009) have raised the question of the sustainability of the Mississippi River delta under the current management regime. They projected that almost all deltaic wetlands will disappear by 2100 given current management. But the past in this case need not be a prologue to the future. Like the responsiveness of sea level to temperature, deltaic systems are extremely sensitive to sediment supply, which is largely under human control for the Mississippi River. New and re-engineered existing river diversions can be used with the Atchafalaya/Wax Lake deltas and Bonnet Carre Spillway serving as prototypes that can be improved upon. But management should factor in other already observed climate change effects in the Mississippi River watershed, including alternating severe floods and droughts. Finally, it will be well advised to come up with energy-efficient projects that require less fossil energy for operation and maintenance so that performance is not hampered by energy scarcity or cost in the future. Increasing energy scarcity will likely make energy intensive activities such as building and maintaining levees, and pumping slurried sediments and drainage water much more costly. This position argues for river diversions rather than marsh creation via pipeline as a primary restoration device. Diversions take advantage of the natural energy of the River, particularly during high flow periods, to move sediment. Thus, they can operate effectively even if the price of oil goes up significantly. The more delta restoration and river management can depend on gravity and natural wetland formation processes, the more cost-effective its operations will be.

Because of projected sea-level rise and increases in the cost of energy, time is of the essence in terms of jumpstarting a large-scale sediment-reintroduction restoration program. The sooner new and re-engineered existing river diversions can be implemented, the more effective restoration can be. This is especially the case if large scale meteorological oscillations lead to high stands of sea level within a decade. In other words, time is of the essence. This evidence indicates that there will be a window of time in the next decade or two when climate impacts and energy costs are still moderate. This is the time to put resources into improving existing diversions and building new ones

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Summary and Conclusions: The Cost of Inaction and the Need for Urgency

John W. Day, G. Paul Kemp and Angelina M. Freeman

Abstract

The delta process is inherently dynamic, but no one alive today has ever witnessed a healthy period of stability through offsetting growth and decay. Consequently, only a full scientific understanding of how the Mississippi delta once formed and functioned under natural conditions can guide future restoration efforts. As the foregoing essays argue, living on the Delta means living with change. They present strong evidence that sediment diversions designed to restore wetlands in the Mississippi River delta will be effective and beneficial. Similarly, they argue that large-scale restoration will shift the locations of the major fisheries, but may represent the only hope of maintaining sustainable fisheries. And they explain why the system of levees and flood protection that currently provides crucial protection for human habitation must to be supplemented by extensive wetland regrowth. Additionally, they describe how the highly dynamic and changing coast is also impacted by subsidence, climate change, and sea level rise. Finally, they show that increasing energy costs will likely limit what can be done. Only by honestly examining the full range of challenges, and determining the best practices for adaptation, can policy-makers formulate informed decisions about the future of the Delta. We hope this book can make a substantial contribution to the success of this important process.

Keywords

Mississippi river delta · Wetland · Coastal restoration · River diversion · Delta cycle · Flood control · Adaptation culture · Climate change · Sea-level rise

Introduction

An understanding of how the Mississippi delta formed and functioned under natural conditions greatly informs restoration efforts. Liviu et al. (2014) and Condrey et al. (2014) describe the processes that led to the formation of the delta and how the delta functioned before significant human impact. Liviu et al. (2014) describe the development of the Mississippi delta. Mississippi delta restoration is informed by delta dynamics worldwide. In their natural state, all deltas were highly dynamic and interactive on a hierarchy of spatial and temporal scales.

Formation of the Mississippi delta began about 7,000 years ago when sea level stabilized at near its present level after rising nearly 150 m from a low stand about 15,000 years ago. The delta formed as a series of overlapping delta lobes. The Mississippi delta, like all deltas, is a result of a very complex set of processes acting at different temporal and spatial scales. There was an increase in wetland area in active deltaic lobes

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and wetland loss in abandoned lobes. But overall, there was an overall net increase in the area of wetlands over the past 7,000 years because the forces leading to delta growth were greater than the forces leading to delta deterioration.

The functioning of deltas is affected by a hierarchy of energetic forcings that occur on different spatial and temporal scales and affect the morphology and evolution of these systems as well as enhance their productivity (Day et al. 1997, 2007). These energetic events range from waves and daily tides to switching of river channels in deltas that occur on the order of every 1,000 years, and include frontal passages and other frequent storms, normal river floods, strong storms, and great river floods. The primary importance of the infrequent events such as channel switching, great river floods and very strong storms such as hurricanes is in sediment delivery to deltaic wetlands and in major spatial changes in geomorphology. The more frequent events such as annual river floods and frontal passages also are important in sediment dynamics on smaller spatial scales. Much of the human-caused deterioration of the delta can be understood as a reduction in these energetic forcings by such activities as leveeing and pervasive changes in hydrology.

Condrey et al. (2014) use historical information from early explorers in the late sixteenth and seventeenth centuries to paint a picture of deltaic functioning just prior to the beginning of significant human impact by European settlers. They explore the historic record for a description of the last naturally active delta complexes of the Mississippi River (LNDM) as the most appropriate restoration model for Louisiana's coast. Based on descriptions by the explorers Chaves, Barroto, Iberville, Evía, and Dumain, they conclude that the LNDM was a vast seaward-advancing arc that occupied, through four distributaries, all of the five most recent deltaic complexes of the Mississippi River and extended across all of coastal Louisiana east of the Chenier Plain. It was characterized by plumes of freshwater that extended for more than 10 km into the Gulf of Mexico during the spring flood of the Mississippi River and by a vast offshore oyster reef which functioned as both an impediment to navigation and an offshore harbor. Implications of their findings are discussed in light of Louisiana's current coastal restoration plans.

Restoration plans are informed by how people understand the coast. Muth (2014) discusses how there is no living memory of a natural delta. But whatever view people have of the river and delta, the real world teaches us one thing: the Mississippi River can build deltas. It is somewhat surreal to listen to opponents of river re-introduction insist that the river, re-directed by diversions into the collapsing delta, will not build land. The very ground beneath their feet belies their statements. Their fear of change is rooted in the false impression created by the shifted biophysical baseline that is their sole experiential reference point. We as humans did not evolve the innate capacity to comprehend physical changes taking place on a geological time scale—changes that take eons. But just as importantly, we have no innate capacity to internalize gradual change, such as happens in the natural cycle of delta building and decay. From a geological perspective, delta geology is instantaneous, but it is not so for humans. We are comfortable with stasis. Incredibly, during the last century in south Louisiana we managed to speed up the delta cycle to a pace that became noticeable even to us. Our reaction was to clamor for stability, for a return to a delta we remembered. But deltas don't work that way. Delta lobes grow, or delta lobes shrink. It is the delta process that gives stability, with offsetting growth and decay. No one alive in south Louisiana has lived in such a deltaic environment. But in the future, society can. And if the river is allowed to rebuild such a delta, our grandchildren might even get a glimpse of the abundance of wildlife and fish among which Native Americans once lived and which stunned the first visitors from the old world upon their arrival 300 years ago.

Bentley et al. (2014) discuss the potential for river diversions. River diversions have been proposed as major tools for coastal restoration. This is based on the idea that reconnecting the river to the deltaic plain mimics the way the delta functioned naturally.

But the suitability of diversions for land building has been the subject of vigorous scientific and policy debate. However, it is important to recognize that some diversions in Louisiana are designed for salinity and flood control, and not to build land. The land-building capacity of a diversion is fundamentally dependent on sediment supply, limited by the sediment retention rate, relative to subsidence, sea level rise, and compaction. If sediment supply amounts exceed these sink processes, then land will be built. Sediment diversions, designed to maximize sediment delivery, are being proposed as potentially important tools for land-building in the Mississippi River Deltaic Plain. Several current diversions show that such diversions can build land.

Part of the reason that diversions have been questioned is because of the size of diversions implemented thus far and potential impacts of river water on receiving basins. Thus, what can be said about the size and location of diversions. It is clear that they must be much larger than the Caernarvon and Davis Pond diversions and they must deliver more sediments, both fine and coarse, than these two diversions. Future diversions should approximate the size of the numerous natural diversions that occurred along the distributary channels as well as the Bonnet Carré Spillway, that regularly flowed at rates of 5,000 to 10,000 m^3/sec. The history of these diversions shows that large diversions need not function every year to be effective land builders. The Bonnet Carré has been opened about once a decade and elevations in the spillway between U.S. 61 and the lake have risen as high as 2.0 m, far outstripping subsidence and sea level rise. Information from the Atchafalaya/Wax Lake deltas, West Bay other sub-deltas in the Birds Foot delta, and Bonnet Carre serve as examples of how diversions can build land.

Climate projections indicate that if no aggressive action is taken, most coastal wetlands will disappear by 2100. This indicates that an aggressive program of very large diversions will be necessary to offset the projected large-scale loss of wetlands. Large diversions should be located as far inland within deltaic basins as possible. This would lead to a greater capture of sediment and restoration of coastal forested wetlands that are rapidly degrading. Building a series of very large diversions in the next decade would be a defense against rising energy costs because diversions like the Bonnet Carré Spillway can operate for more than a century with little energy subsidy following construction.

Questions have been raised that the effects of nutrients in the Mississippi River may have negative impacts on wetlands. Morris et al. (2014) address this question. It is generally accepted that the introduction of sediments per se will build wetlands, but the effects of nutrients and toxins may have unintended consequences that contravenes the benefits of sediment. However, sediment cores document alternating mineral and organic phases supports a model of a delta cycle in which peat marshes occur at end of delta cycle. Hence, peat marshes by definition are not sustainable in the delta.

Coastal wetlands maintain equilibrium with sea level, within limits, by sedimentation of inorganic and organic matter. Critical variables that determine sedimentation rate are the concentration of suspended sediment, primary productivity, relative elevation or flood duration, and kinetic energy. In estuaries where relative sea level is high, as in a subsiding delta, the concentration of suspended sediment in flood water and mineral sedimentation are critical to sustaining healthy marshes. When flooding with sediment laden water is low, relatively marsh elevation declines. There is ample empirical evidence that documents the fact that vegetation typical of coastal wetlands can thrive when sedimentation rates are experimentally raised. Or course the effectiveness of sediment diversions for marsh restoration in the delta will depend on how the sediments are distributed. Impounded wetlands are isolated from surface flow and will not benefit from diversions external to the impoundments.

Plant developmental processes and growth are greatly affected by nutrient loading. Generally, it is observed that plant root:shoot ratios decline as nutrient loading increases. However, with few exceptions, the absolute production of roots and shoots increases with nutrient loading. This is supported by numerous experimental works and field observations. Production of rhizomes also increases with nutrient enrichment. Plant species do not benefit equally from nutrient enrichment, and it can be anticipated that river diversions will result in shifts in plant community composition. Nitrophilous species such as Phragmites will in many cases replace native species. Moreover, river diversions will reduce salinity, and this too will shift species composition in places away from species typical of salt or brackish water habitats, e.g. Spartina spp. to less salt-tolerant species.

Gas flux measurements from the field indicate that respiration rates (CO_2 flux from the soil surface) increases with nutrient enrichment, but it is not clear if this is from increased root and rhizome respiration, decomposition of labile carbon, or decomposition of refractory carbon. Only if nutrients increase the decay of refractory carbon will it affect long-term accretion of organic matter. In equilibrium, the quantity of labile carbon is constant and therefore it does not increase the volume (elevation) of soil. There is evidence that phosphorus limits microbial production in some marshes, but this is not universal and its significance for overall decomposition and carbon sequestration is uncertain. Nitrate is an energetically favorable electron acceptor, close to O_2 in energy yield, and sediment diversions that are rich in NO_3 could actually stimulate the decay of organic matter that typically would resist decay under anaerobic conditions. However, this should only be a significant factor only in peat marshes, which represents an ephemeral stage in a deltaic system. Moreover, the effect of NO_3 could be compensated by dissolved and particulate organic matter in river water. This is an area that requires more research.

Primary production in coastal wetlands is limited primarily by the availability of nitrogen, and secondarily in some salt marshes by phosphorus. Empirical evidence documents that nutrient enrichment increases flooding tolerance in some wetland species. Further, nutrients appear to increase the salt tolerance in some species, but not in others. Ammonium is the dominant form of nitrogen available to wetland plants, but there are publications that show that nitrate is equally as good a source of nitrogen to marsh vegetation as is ammonium.

Nitrogen and phosphorus enrichment of "assimilation wetlands", wetlands receiving waste water, is not uncommon in the delta and provides a model, albeit an extreme case, for impacts of nutrients associated with sediment diversions. Research in assimilation wetlands documents that there are effects due to herbivory (e.g. nutria). Nitrogen fixation provides a major source of nitrogen to natural wetlands, probably in excess of what is derived from flood water. Typically there is more ammonium available in marsh pore water than there is nitrate and ammonium in flood water. The fate of most inorganic nitrogen applied to wetlands is either assimilation by plants or denitrification.

The biogeochemistry and distribution of inorganic nitrogen in marsh sediments varies with salinity. The cation exchange properties of soil changes dramatically with salinity. Sea water cations completely occupy the exchange sites on silts and clays at the salt water end of an estuary, effectively outcompeting ammonium for exchange sites. Consequently, at the salt water end of an estuary ammonium is largely free in solution, while at the freshwater end of the estuary ammonium is largely sorbed onto exchange sites. Moreover, sea water cations compete with ammonium for carriers on the root membrane and decrease the efficiency of ammonium uptake, i.e. the half-saturation constant for ammonium uptake increases. This explains why vegetation can be nitrogen-limited in an environment rich in ammonium.

In summary, there is strong evidence that sediment diversions designed to restore wetlands in the Mississippi River delta will be effective and beneficial. Wetland plant productivity should increase with nutrient enrichment, increasing the efficiency of sediment trapping and raising marsh surface elevation. There likely will be shifts in plant community composition, especially toward the freshwater end of the delta. Highly productive, nitriphilous species like Phragmites will likely replace less productive species and further increase sediment building capacity. There is good empirical evidence that nutrient enrichment will stimulate root and rhizome production, but to a lesser extent than aboveground production. The impact of nutrients on the preservation of soil organic matter is less certain, especially the effect of nitrate. However, this potential impact is a factor only in peat marshes, and the geological evidence suggests that peat is an ephemeral stage at the end of a delta cycle. Mineral sediment and nutrients will likely change plant community composition in peat-dominated wetlands, resulting in a marsh community that is sustainable and more resilient to disturbance.

Numerous investigations have demonstrated the relationship between fisheries yields and the high primary productivities that are typical of estuaries and estuarine plume ecosystems. Along with the loss of wetlands, presumably so goes the loss of the various functions related with them such as commercial harvests of fisheries. However, perhaps the most perplexing aspect of the Mississippi River delta ecosystem is the fact that there is little indication that fisheries productivity has decreased despite high rates of wetland loss. Why aren't landings decreasing? It is likely that fisheries of today reflect a degraded ecosystem attributable to environmental damages that began in the 1920s or earlier but that accelerated during the twentieth century. There are a few thorough reviews of differential use of habitat by estuarine fishes from other deltaic ecosystems that may allow us to speculate about how the loss of habitat in Louisiana may impact fisheries production. Greater than 75 % of the species that support fisheries in Louisiana are considered to be estuarine-resident or –dependent, and therefore it is likely to end badly for the Sportsman's Paradise if large-scale restoration is not possible, or if possible, not undertaken. Large-scale restoration will cause shifts in the locations of the major fisheries but it may be the only hope of maintaining sustainable fisheries. Cowan et al. (2014) address these issues.

It is widely understood that the artificial separation of the Mississippi River from its delta in Louisiana has caused ecological collapse and loss of thousands of square miles of wetlands. Emerging evidence indicates that current Mississippi River management is on a collision course with the biophysical trajectory of this iconic ecological and economic asset. An aspect that has received less national attention is the growing likelihood of economic dislocations caused by interruptions of navigation through the mouth of the river, one of the world's busiest shipping channels.

Most of the population of South Louisiana needs flood protection from both hurricanes and river floods. Risk from flooding grows with the continuing loss of a coastal wetland buffer; wetlands behind levees are threatened. The placement of levees is critical both for flood protection and for wetland health. There is growing recognition that levees ultimately put areas at more risk to dramatic events in exchange for protection for more frequent and moderate events. Coastal scientists and coastal levee system managers recognize that levees require substantial wetlands in front of them to reduce risk to storm wave action degrading them. Kemp et al. (2014) address issues of navigation and flood control.

Bailey et al. (2014) discuss adaptation and change within human communities in Louisiana. These communities are facing a highly dynamic and changing coast impacted by subsidence, climate change, sea level rise, rising energy prices, and financial constraints on governments. Some areas of the coast will be lost while others may be able to survive, at least for a while. People and communities will take actions and make choices based on knowledge of place and commitment to community. Support for communities should be oriented toward encouraging internal community support for risk awareness and risk reduction response, utilizing the communities' own social capital. The serious question for applied social scientists concerned with coastal Louisiana is can the local communities make a commitment to comprehensive non structural adaptive mitigation fast enough to keep up with the increasing risk to which they are subject? And can applied social and physical scientists make a contribution to this achievement? Scientists should clearly present the full range of challenges facing the coast, including climate and energy scenarios, and best practices for non structural/mitigation/adaptation methods so that informed decisions can be made. However, the window for learning about the threat and for appropriate responses is closing rapidly due to the escalating pace of increased risk.

In order to make informed decisions, communities need information on the likely impact of climate change and sea level rise on specific communities and the limitations of structural approaches to coastal protection, including high and recurring operation costs that may not be sustainable politically or otherwise. Without a realistic and overarching appreciation of the changes that are occurring, it may be that the protective actions that are taken have the effect of increasing risk. Constructions of elaborate levee systems are likely to encourage further investments behind those levees in homes and businesses that will be at risk when the levee systems fail. Coastal policies designed to confront rather than work with natural deltaic forces may send the wrong message to coastal residents, that it is safe to stay rather than continue the process of gradual retreat from the most vulnerable parts of the Louisiana coast.

Scientists concerned with human adaptation to change need to focus attention on issues of public policy and identify those parts of public policy that undermine the ability of coastal communities to have a voice in their futures, or result in investments that favor one set of actors over others. The role of scientists should be to clearly and honestly present information on climate, energy, ecosystem dynamics, human social system processes and large economic forces, that may make certain community resiliency options much more difficult, if not impossible, within current planning horizons. The role of scientists and policy planners is not be to tell communities what they must do, but to help them explore and implement risk-reducing options in as timely a manner as possible.

Cost of Restoration

Batker et al. (2014a) show that the cost of Mississippi delta restoration is high but so are the costs of no action. When coastal land disappears, the resources, the economic activities, and the communities that depend on it disappear as well. The ecology and economy of coastal Louisiana are at risk of being lost without changes in the way that the river and coastal wetlands are managed. The cost of delta protection and restoration has been debated for at least a decade, with estimates ranging from $ 14–150 billion. The Gulf Coast currently faces an annual expected loss of $ 14 billion if there is no action on restoration; losses are expected to increase in the future. The impact of the Mississippi River Delta is huge by conventional measures of employment and income. Economic activities related to the river account for nearly 2 million jobs and around $ 20 billion in annual income. The Gulf Coast is vulnerable to growing environmental risks today with $ 350+ billion of cumulative expected losses by 2030 due to hurricane damage that is directly related to wetland loss. In coastal Louisiana almost all economic activity is related directly or indirectly to the Mississippi River, its delta and the coastal wetlands of the Chenier Plain. The economic value of the Mississippi River Delta restoration can be documented through standard indices of economic activity such as GDP and jobs, and through the value of ecosystem goods and services. *Economic collapse on a large scale looms in the near future unless dramatic steps are taken to reverse the deterioration of the Mississippi River Delta.* Restoration of the delta is required to maintain its economic value. Batker et al. (2014b) estimate the value of ecosystem goods and services of the Mississippi delta to be at least $ 12–47 billion in benefits annually. Assuming this flow of services into the future, the delta's minimum capital asset value would be $ 330 billion to $ 1.3 trillion**.**

Between 80–90 % of Louisiana's economy, food, and quality of life is linked to coastal ecosystem goods and services. The economic health of the United States also depends on sustaining the navigation, flood control, energy production, and seafood production functions of the Mississippi Delta and river system, making Mississippi River Delta restoration critically important. These systems are at risk due to the degradation of coastal wetlands. The Mississippi River Delta ecosystems provide at least $ 12–47 billion in ecosystem goods and services benefits to the people of the United States every year. The economics are clear, an investment in costs to modernize the Mississippi River delta in ways that allow it to gain ground, and to sustain critical infrastructure far into the future is justified. A new emphasis on coastal restoration is required to maintain the economic vitality of this region.

Day and Moerscbaecher (2014) show that global climate change and increasing energy cost and scarcity pose significant threats to ecological and social systems of the coastal zone and to the restoration of the coast. In coming decades, these two factors will affect how much land can be built and maintained and dictate how sediment is delivered to the delta plain. They will also impact the ability of society to maintain navigation and flood control systems. In this section we review climate and energy issues and discuss their significance for coastal restoration.

Information on climate trends documented by atmospheric scientists when coupled with projections of energy cost indicate that the way the Mississippi River and delta are currently managed is not sustainable and that new approaches that involve less energy intensive approaches may be necessary. Maintaining the current flood control and navigation system is very energy intensive. Climate change will likely lead to accelerated sea-level rise, more intense hurricanes, highly variable flow of the Mississippi River with both more large floods and very low water years. As indicated in Chap. 5, the river is seeking a different outlet and preventing this will become more difficult and expensive in the future. If this is quickly recognized and addressed, however, it is likely that a sustainable trajectory can be achieved that will lead to a less ecologically destructive scheme for river management that also improves the long-term economic survivability of deep-draft navigation and protection from storms and the economy of south Louisiana in general. Such a trajectory can also lead to a more sustainable restoration of the coast.

Studies have projected that almost all deltaic wetlands will disappear by 2100 given current management and projected sea-level rise. But an aggressive restoration plan involving large-scale introduction of riverine sediments can offset these projected losses. New and re-engineered existing river diversions can be used with the Atchafalaya/Wax Lake deltas and Bonnet Carre Spillway serving as prototypes that can be improved upon. But management should factor in other already observed climate change effects in the Mississippi River watershed, including alternating severe floods and droughts. Finally, it will be necessary to come up with energy-efficient projects that require less fossil energy for operation and maintenance as possible so that performance is not hampered by energy scarcity or cost in the future. Increasing energy scarcity will likely make energy intensive activities such as building and maintaining levees, and pumping slurried sediments much more costly. This argues for river diversions rather than marsh creation via pipeline as a primary restoration device. Diversions take advantage of the natural energy of the River, particularly during high flow periods, to move sediment. Thus, they can operate effectively even if the price of energy goes up significantly. The more delta restoration and river management can depend on natural processes, the more cost-effective (from both economic and energy perspectives) restoration will be.

Because of escalating climate change impacts and increases in the cost of energy, time is of the essence in terms of jumpstarting a large-scale sediment-reintroduction restoration program. This evidence indicates that there will be a window of time in the next one to two decades when climate impacts and energy costs are still moderate. This is the time to put resources into improving existing diversions and building new ones.

Final Conclusions and Recommendations

This paper has reviewed a number of the pressing questions about coastal Louisiana restoration. While the challenges are technically, economically and socially complex, we believe there are solutions and that taking no action will result in a creeping disaster of continued land loss, disruption of major navigation operations, billions in economic losses and the degradation of one of the most ecologically important deltas in the world.

Although there has been a significant reduction in the sediment load to the Mississippi River Delta, there is a considerable amount of sediment remaining in the system. Redesigning river operations, including the use of diversions, while maintaining navigation could help restore fairly large areas of coastal Louisiana. It is also possible that the amount of sediment reaching the Delta will increase, as the area behind upstream sediment retention wing dams fills. Moreover, if climate results in drier condition over the Missouri basin, then we can expect that erosion will increase for drier soils. In the upper Mississippi and Ohio basins climates projections are for more precipitation and thus more water coming down carrying more sediments. In a future of energy scarcity, we will have to rely on gravity to move sediments to a greater extent.

Diversions are important for rebuilding and restoring the coast, but there are issues of scale and design and conflicts with other resources. Diversions will have to become larger and specifically designed to carry more sediment. Recent experience with Wax Lake, Big Mar, and West Bay show that new land can be rapidly built after a period of subaqueous development. The orientation of the conveyance channel connecting the river to the diversion outfall area should be designed to mimic the way that water would naturally flow as it leaves the river. At West Bay, for example, the conveyance channel initially constructed pointed upstream. As the channel evolved over time, the orientation shifted towards a downstream direction. Thus, it is clear that diversion size, outlet design, and location are important factors the design of diversions. Such considerations should be incorporated into future diversions.

Questions have been raised on the impact of nutrient impacts on wetlands by reducing belowground root growth and soil strength. The evidence supporting this idea is not conclusive and more study is needed. There are a number of documented case studies where river input has not led to marsh deterioration, such as in marshes around Atchafalaya Bay and Fourleague Bay. Wetlands in the Bonnet Carré Spillway and sediment deposition after the 1927 man-made crevasse at Caernarvon provide additional documentation of the impacts of large diversions. Also, coastal wetlands in the Mediterranean with strong riverine input are healthier and have high rates of accretion. Future diversion projects should strive to enhance mineral sediment input. It is unclear whether marsh loss at Caernarvon during Katrina, for example, was more a factor of a large area of fresh to low salinity marsh that are inherently less stable rather than due to nutrient enrichment. In addition, nutria have been shown to strongly graze enriched marshes and thus can have a much stronger impact on root biomass than direct nutrient effects. At any rate, future diversions should strive to introduce as much sediments as possible.

The impact of restoration activities on fisheries is complicated by the fact that fishing pressure itself is perhaps the dominant impact on the community of organisms that are fished. Fisheries productivity has been related to a number of factors, including nutrient loads, wetland area, shallow depths, tidal mixing, and primary productivity. A complicating factor is that the large wetland loss in the Mississippi delta has not led, at least not yet, to a decline in fisheries. It has been suggested that one of the things that maintains the fishery is the length of the land water interface, which increases with wetland loss, at least up to a point. If however, most of the delta wetlands disappear, there will likely be major impacts on fisheries. As delta marshes disappear, many of the species that support fisheries now (shrimp, crabs, oysters, and a number of nekton) may become less abundant while those dependent on a phytoplankton food chain, such as anchovies, may become more abundant. Large river diversions for restoration could shift the spatial distribution of fishery species but not the overall productivity of coastal Louisiana fisheries.

In order to be politically and economically viable, coastal restoration must accommodate navigation needs. It is increasingly obvious, however, that the current navigation system is unsustainable. Increasing flow lines with the same discharge and the potential for the river to seek new outlets well inland of the head of passes are indications that the system is no longer functioning in the manner intended. Dredging and other costs are increasing, and the results are less satisfactory. Thus, a change in navigation and flood control is inevitable regardless of what is done with restoration. The 80 year-old approach of the MR&T focusing almost solely on navigation and flood control is incompatible with delta restoration, and unsustainable in and of itself. Increasing flow lines with the same discharge and the potential for the river to seek new outlets well inland of the head of passes are indications that the system is no longer functioning in the manner intended. Costs are increasing to achieve fewer results. Opportunities exist for restoration, navigation, and flood control to be managed compatibly but the process of transition is not being anticipated. The transition can be planned and orderly, but taking no action regarding restoration will likely to lead to a sudden and catastrophic loss of navigation capacity.

Flood protection in the delta must focus on flooding threats from both the river and hurricanes. For decades, coastal Louisiana relied on the use of earthen levees in an attempt to protect developed areas from these threats. But the aftermath of Katrina showed that there are many places in the delta where earthen levees are impossible to build and maintain at elevations high enough to sustain urban communities. Pile-supported structures are an option but raise the cost by an order of magnitude, making widespread use infeasible for most small towns. The use of levees to protect against hurricanes is probably too expensive without the buffering effects of wetlands. The effects of stronger hurricanes, sea-level rise and increasing energy costs will further increase the costs of reliance on levees. Levees often enclose large areas of wetlands that are leading to their deterioration. With deterioration, surge can build up within leveed areas thus partially negating the protection provided by levees.

Historically people settled in the coastal zone to take advantage of the subsistence and employment opportunities related to the harvest of renewable and non-renewable resources. Over generations, a group of coastal communities with unique relationships to the wetlands have developed. However, for the last several decades residents have been moving away from the coast because of the disruption of these wetlands by human induced and natural processes. The environmental setting is increasingly tenuous. Coastal peoples are adjusting in several ways: relocating; staying in place with structural and non-structural adaptations; altering their spatial, physical and social processes; and by only periodically occupying the coast for the harvest of natural resources and for navigation. Further adaptations of the physical and social structures may be required to continue living along the coast as increasing climate change, land loss and energy costs bring additional challenges to coastal communities.

Restoration costs will be very high but the current economy is not sustainable without restoration in some form. In coastal Louisiana almost all economic activity is related directly or indirectly to the Mississippi River and delta. Restoration of the delta is required to maintain this economic activity because of the importance of the high ecosystem service values. It is likely that the structure of the economy and how it is carried out must change as the viability of coastal communities decreases. If proper planning is not in place, then the economy will be faced with a series of catastrophes that will make the economy unstable. Thus proper and aggressive planning is fundamental to maintaining the economy.

The economic health of coastal Louisiana is important to the economic health of U.S. Louisiana is vital for U.S. energy supplies, exports of agricultural commodities and coal, fisheries, and tourism. These are all threatened by coastal deterioration. The environmental infrastructure (ecosystem goods and services) supports these economic activities. It is likely that maintenance of the coastal economy and its role in the national economy will sometimes involve a shift from a place where people live to a place where they go to work and play.

Climate-change impacts are projected to become more severe in coming decades. Sea-level rise by 2100 has been projected at one meter or more. There will likely be more intense hurricanes. Climate change may also result in more large floods on the Mississippi River. At the same time, energy prices will likely rise significantly. Thus, while climate change will make coastal restoration more challenging, energy costs will limit options. These two factors will impact all of the activities discussed thus far in this paper. Planning for management and restoration needs to specifically incorporate these two factors.

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Index

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