The Regulation of Peace River



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A Case Study for River Management

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WITH CONTRIBUTIONS BY
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Preface

This monograph reports a 40-year history of geomorphological change along a large, northward-flowing boreal river following the construction of a major dam for the production of hydroelectricity. There already are reports in the literature of summary effects of regulating the flow of a river and of a few investigations that have revisited monumented cross sections as a means to learn something about rates of post-regulation change. There are also several reviews of what we know about the effects of damming rivers. But, so far as I know, there is no longitudinal study that has systematically documented post-regulation change downstream over anything like so long a period as 40 years.

This study mainly reports field results, the observations of 40 years of post-regulation change; hence it is mainly descriptive. Some low-level theories about river response to changing governing conditions are tested and Chapter 11 presents theoretically derived predictions about the potential ultimate adjustment to the regulation of the river, absent further significant disturbance. However, there is much material in the data generated by this study that may give rise to further model studies in the future. The main focus is the geomorphology of the river but, since it has an important influence over changes along the river, the evolution of riparian vegetation has also been recorded. Today, the majority of flow regulation studies focus on ecological consequences: beyond the riparian vegetation, ecological effects are not considered in this study. A number of fisheries studies related to engineering projects have been conducted along the subject river but there is no summary account available of continuing change.

The subject river is Peace River, a 1900-km long tributary of Mackenzie River in northwestern Canada. The studied reach is the 1220 km below the two extant dams, which are located in the Rocky Mountain front ridge. Peace River is a northward flowing boreal river, which lends two exceptional features to the study. First, it is strongly influenced by seasonal ice effects. Many regulated rivers in Canada are so affected, but I am not aware of any major study that has sought out the peculiar effects of ice action on such a river: such an investigation is a part of the present study. Second, most of the remaining free-flowing rivers in the Northern Hemisphere are boreal rivers, and most flow north toward the Arctic. This study, then, might exemplify effects that may be expected following the regulation of flow in these rivers.

This study began in the early 1970s, shortly after the first dam was closed (1967). A retrospective study of the river in its natural regime was recovered by the use of air photographs and hydrological records. The earliest photos date from 1950. The river has been visited every 5 to 7 years since and, in the initial 150 km below the dams, a set of monumented cross sections, originally installed by the British Columbia Hydro and Power Authority, has been resurveyed on each visit. Morphology and vegetation have been repeatedly mapped along about 62% of the 1200-km downstream reach, including continuous mapping for the first 275 km below the dams. The same reaches, selected to be representative of the sequential morphological styles of the river, have been mapped each time. Limited resources precluded complete mapping. The data derived from these exercises form the basis for the study. What has been accomplished has been limited by available resources: no doubt there are changes that have remained undetected, and the mapped data are subject to unquantified interpretive error. Nonetheless, patterns of change are clear, consistently explicable, and undoubtedly representative of what has occurred along the entire river.

The organization of the book is slightly unusual. Each chapter has been written as a stand-alone document so that readers with particular interests may study only a portion of the book with full understanding. This leads to repetition of a certain amount of background information which has, however, been held to a minimum. This also means that each chapter is signed by a different group of authors. I am deeply grateful for the interest and participation over many years of these colleagues, each of whom has brought special expertise to the project that I do not possess and thereby substantially strengthened it. But I remain responsible for the overall design and execution of the study (and, it must reluctantly be admitted, for its shortcomings).

Margaret North established the protocols for the vegetation studies and directed the field work on vegetation. She has remained engaged throughout the project. Lars Uunila conducted the ice studies. In addition, Lars directed the production of all the river maps through the 1998 mapping. Chris Ayles analyzed the survey data from the proximal reaches. Jiongxin Xu, visiting from the Chinese Academy of Sciences, undertook a wide-ranging preliminary analysis of much of the morphological data, developing results that are reflected in the final analyses. Brett Eaton has participated in the latest surveys and conducted the model studies of changing hydraulic geometry of the river. While not a co-author, Brian Klinkenberg provided critical help late in the project to recover certain of the mappings that had been marooned on obsolete data storage devices.

Generations of students gained experience in this project. Major contributions came from Arnold Moy, who produced a substantial number of the maps, Julie Beer, who kept coming back for the field vegetation studies, and Rowan Arundel, who completed the most recent mappings. Others who have assisted in the field and laboratory include Chris Adderley, Jason Barraclough, Julie Beer, David Campbell, Damon Chan, Matt Chernos, Cathy Christie, Judy Cudden, Claudia von Flotow, David Graham, Judy Haschenburger, Stephen Herold, Christiaan Iacoe, Deborah James, Graham Lewis, Lesley Kalmakoff, Karen Kranabetter, Nick Manklow John Matechuk, Tom Millard, Michael Miles, Ashley Perkins, David Reid, Steve Rice, Rick Richardson, Ken Rood, Charles Tremewen, Tom Welsh, Arelia Werner, Lea Zecheva, and Andre Zimmermann. Most of these people have gone on to develop significant careers in environmental science or environmental management. If I have forgotten anyone I apologize but, after 35 years …

Rosemary Cann and Kevin Gillard, map and air photo curators at the University of British Columbia Department of Geography provided major help by locating, documenting and ordering hundreds of air photographs. Paul Jance and Eric Leinberger, cartographers in the Department of Geography produced the superb diagrams, which convey much of the data gathered during the project. Eric is responsible for the final production and coordination of all the diagrams. I deeply appreciate the efforts of these highly skilled co-producers of the monograph.

The British Columbia Hydro and Power Authority has cooperated by providing background data and by facilitating access to certain sites along the river, but the study has been conducted entirely independently of the Authority. Financial support for the study has come from the Natural Sciences and Engineering Council of Canada (NSERC) and from the "Northern River Basins Study," a federal-provincial study undertaken by the governments of Canada, Alberta, and the Northwest Territories in the 1990s to examine development pressures in the Mackenzie River system, with attention focused on Peace and Athabasca rivers. I wish to express special appreciation to NSERC: its Discovery Grants program provides ongoing research support to university scientists and has supported my work continually for more than 40 years. Without the prospect of such continuing support, a long-term project of this sort could not be undertaken. It is simply the most sensible program for support of scientific research in the world.

Michael Church
December 31, 2013

This book is accompanied by a companion website at

http://blogs.ucb.ca/peaceriver/

Further information on this website can be found in the Appendix on pp. 273–4.
All figures and tables from the book are also available for downloading from

www.wiley.com/go/church/peaceriver

CHAPTER 1

On regulated rivers

1.1 Setting a context

Humans have dammed rivers since antiquity to control water levels and flows. Purposes have included direct control of water levels for water supply, flood protection, and navigation; water storage for domestic and irrigation use; diversion of waters for water and land management; and the capture of hydraulic power. The first significant dams were constructed in the arid Middle East, including both Mesopotamia and Egypt. The earliest known structure (in modern Jordan) dates from about 5000 years ago. In addition, early dams were constructed by the Hittites in Anatolia, and in the Harappan civilization of the eastern Indus plain. The purpose of these earliest water projects was water supply for domestic use and irrigation, and water level control.

The Romans advanced the art of dam construction dramatically by their invention of waterproof mortar. They established almost all of the basic dam designs and built structures—many still extant—up to 50 m in height, again principally for water supply and control. At the same time, Chinese hydraulic engineers were constructing extensive irrigation systems, exemplified by the reservoir and canal system at Dujiangyan on Minjiang (Min River) in Western Sichuan which remains, after 2200 years, operational (though much re-engineered) today. Engineers of the Islamic era initiated the use of mill dams, establishing the direct use of hydropower to accomplish work. Raising water and grinding power were the major applications.

These early developments came together in Western Europe in the Middle Ages with the employment of dams both for water control and for the development of water power. Many of the first adaptations occurred in the Low Countries, where water level control was critical for the effective use and secure occupation of land.

A water turbine was first demonstrated in France in 1832 and the first useful hydroelectric power was generated in 1878 at Cragside in Northumberland, United Kingdom (a small, domestic installation). Commercial hydroelectric power generation began in the United States in 1881 with the first Niagara Falls station and by 1890 there were more than 200 plants in the country. From the early twentieth century, hydro-generation became a widespread source of electric power and an integral part of comprehensive water management projects, exemplified by the Tennessee Valley project in the United States.

The 1911 commissioning of Roosevelt Dam on the Salt River, Arizona, marked the inception of the era of very large dams—ones capable of holding more than one cubic kilometer of water. Today there are more than 45 000 "high dams" (>15 m height) in the world (Figure 1.1) and more than a million dams overall. Hydroelectric power generation remains the reason for only a small percentage of those dams (~3%), but essentially all of the largest ones that have the most dramatic impact on river morphology and ecological function.

The impact of large dams on the affected waterway is a comparatively recent concern. Early attention was drawn to the physical effects of Elephant Butte Dam (1915) on the channel of Rio Grande River (Lawson, 1925). Lane (1934) and Shulits (1934) drew more general attention to the topic. With the acceleration in construction of large dams after 1945, attention to the downstream morphological effects, in particular, was reemphasized. Along with the proliferation of large dam projects in the United States came a spate of papers reporting observations (Stanley, 1947; Hathaway, 1948; Mostafa, 1957; Hammad, 1972; summarized in Galay, 1983) and analyzing the physical problem of channel bed degradation (e.g., Tinney, 1962; Komura and

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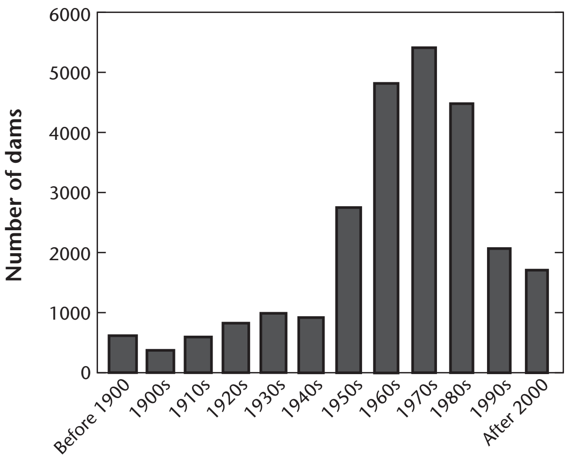

Figure 1.1 Construction of large dams in the world. Summary to 2000 based on data of the International Commission on Large Dams as reported by World Commission on Dams (2005); figure for 2000 to 2010 is an estimate based on data in the World Commission report. Data exclude China that has about 22 000 large dams (nearly half the world total of about 46 000 dams), virtually all constructed since 1950.

Simons, 1967; Ashida and Michiue, 1971)—the most commonly observed phenomenon in the immediate downstream reach of the river.

Petts (1984a) subsequently gave a comprehensive overview of river regulation, extended by Petts and Gurnell (2005). He noted that regulation of an alluvial river alters the equilibrium between water flows and imposed sediment load that (presumably) previously existed, so that changes occur in one or more of cross-sectional geometry, gradient, and river planform in the attempt to regain equilibrium (see also Andrews, 1986; Carling, 1988). One should add riverbed sediment texture to the list. More specifically, Petts pointed out (1984a, p. 119) that the rate and direction of downstream channel change following regulation is governed by the relative frequency of sediment delivering events from unregulated tributaries and of reservoir release flows competent to move sediment resident in or delivered to the mainstem. He described channel adjustments in the regulated mainstem as follows:

- passive response: mainstem flows reduced below the level of competence to move the riverbed sediments, so the active channel simply shrinks within the preexisting channel zone by progradation of vegetation (in this case there may be no further morphological response; the channel has, in effect, ceased to be an alluvial channel);
- degradation due to sediment "starvation" downstream of the dam, by far the most commonly documented response (see Galay, 1983; also Wolman (1967); Williams and Wolman (1984)), largely in rivers with beds composed of sand or fine gravel that can still be mobilized by the regulated flows;
- aggradation due to sediment inputs to the river that it is no longer competent to move downstream, the most common source being tributary inputs of relatively coarse sediment (e.g., Petts, 1984b).

Responses are commonly complex, both spatially and temporally (Petts and Gurnell, 2005). For example, degradation immediately downstream of the dam may be succeeded by aggradation farther downstream as the evacuated sediment is flushed into distal reaches with lower gradient and transport competence. Progradation of vegetation into the former channel zone may promote fine sediment trapping during high flows, hence aggradation may follow channel shrinkage. With the lapse of time, initial aggradation at tributary junctions may steepen gradients sufficiently to promote onward movement of sediment, shifting the locus of aggradation downstream. Furthermore, as the period of regulation lengthens, the probability increases for competent flows to occur as the result of unusual releases from the dam or extraordinary tributary inflows. Complex response may also result from changes in bed material downstream, so that proximal gravel-bed reaches may behave differently than distal sand-bed channels (e.g., Pickup, 1980; Gaeuman *et al.*, 2005). Farther downstream, as well, the fraction of the contributing area that is regulated declines, so the reassertion of a more natural hydrological regime attenuates many of the proximal effects (Gregory and Park, 1974).

Since Petts's early review, a detailed survey of the downstream effects of dams in the United States has been contributed by Williams and Wolman (1984), whose investigations strongly reinforced the impression that the most common proximal response is degradation, whilst Chien (1985) has presented a systematic discussion of degradation processes, giving particular attention to sedimentary aspects. Both of these studies were focused on sand-bed streams.

Brandt (2000), in a new review, focused attention on the gradation response to regulation of a river by more detailed consideration of the disturbed balance of sediment load and sediment transporting capacity. Straightforwardly put, if post-regulation load is less than transporting capacity, degradation will occur, provided that flows remain competent to move channel bed material, whereas, if sediment load exceeds transporting capacity or competence (a common situation immediately below tributary junctions), aggradation will occur. Brandt pointed out that the degradational response is apt to be vertical (i.e., channel incision will occur) if the streambed sediments are fine (silt, sand, and possibly pebble gravel), but lateral (banks and bars erode) if the sediments are coarse. Grams *et al.* (2007) have distinguished these processes as "incision" and "evacuation" (of sediment). Conversely, aggradational response is apt to be vertical if sediments are coarse (which may also entail some widening), but lateral, leading to the channel becoming narrower and deeper, if the sediments are fine. The differing responses are related to the different modes of transport and deposition of coarse and fine materials and associated characteristic differences in the relative strength of river bed and banks. Gaeuman *et al.* (2005) have described an interesting range of these responses in a river that undergoes a gravel-to-sand transition.

Surian and Rinaldi (2003) further characterized channel responses to flow regulation by focusing on morphological style, noting the tendency for regulated channels to assume more simple morphologies (to move from braided toward single thread form, for example) and, concomitantly, to incise and become narrower. Combining these insights, based on an exhaustive survey of regulated Italian rivers, with knowledge of characteristic associations between channel sediments and channel style, their results are broadly consistent with Brandt's conclusions.

Grant *et al.* (2003) have codified probable morphological responses to regulation by comparing measures of sediment supply and of competent flow duration before and after regulation, and Schmidt and Wilcock (2008) have advanced this topic to semiquantitative precision by proposing metrics for the prediction of the geomorphological effects of flow regulation and sediment interception at dams. Most recently, Grant (2012) has essayed the general problem of predicting morphological and sedimentological change in response to flow regulation in gravel-bed rivers.

More recently than the growth of concern over the physical effects, concern has been expressed over the ecological implications of damming streams (e.g., Ward and Stanford, 1979; Petts, 1984a; Bravard *et al.*, 1986; Ligon *et al.*, 1995). Obvious direct impacts are the interruption of free passage along the river for fishes and other mobile aquatic organisms, interruption of material and nutrient transfers downstream, modification of the downstream water quality (in particular, water temperature and sediment concentration), and change of hydrological regime. The latter two effects may confuse temporal signals for movements and other activities by various aquatic organisms. Shields *et al.* (2000) further pointed out the reduction in lateral channel movement of most rivers under regulated regimes, a consequence of reduced bed material transport, which reduces renewal and diversity of riparian vegetation and aquatic habitat.

Graf (2006), in a direct comparison of upstream unregulated reaches with downstream regulated reaches in American rivers, related changes in hydrological regime to consequent changes in river morphology and pointed out the direct effects on aquatic and riparian ecosystems. Poff *et al.* (2007) went further and claimed that regional homogenization of river flows (see also Magilligan and Nislow, 2005; Assani *et al.*, 2006) and morphology as the result of flow regulation is leading to dominance of aquatic and riparian ecosystems by cosmopolitan and nonindigenous biota at the expense of locally adapted biota. Most recently, Vörösmarty *et al.* (2010) contextualized flow regulation by dams in the larger overall context of threats to water security for humans and ecosystems.

It remains that, while changes in river morphology and in aspects of both aquatic and riparian ecosystems have been documented in numerous cases, there is no actual longitudinal study of the course of development of downstream morphological changes in a major river system following the closure of a large dam. Furthermore, there have been few studies at all on boreal river systems (but see extensive work on ecological impacts on Swedish rivers, reviewed by Renöfält *et al.* (2010)). The boreal rivers of the northern hemisphere, located in Scandinavia, Russia, Alaska, and Canada represent most of the remaining free-flowing large rivers in the northern hemisphere, but they are increasingly the focus of water resource development today (Dynesius and Nilsson, 1994). Hence it is important to understand the particular effects of flow regulation on boreal rivers and, more generally, the manner in which those effects develop. In this work, we report the downstream physical effects of a major hydroelectric power development on Peace River, a northward flowing, boreal river in Northwestern Canada, for the first 40 years following dam closure in 1967.

Like most northwardly flowing, boreal rivers in the world, Peace River drains marginally settled and wilderness terrain. There are few gauging points along the river and limited access. Consequently, much of the information for the study has been drawn from mapping based on air photography. Photography has been flown approximately every 10 years since the first comprehensive coverage in 1950. Therefore, our first data are derived from the 1950 coverage and the 17-year period to 1967 constitutes the "control period" for our study, when natural processes determined morphological and ecological changes along the river.

1.2 Peace River

Peace River drains 293 000 km^2 of the Canadian provinces of British Columbia and Alberta toward the Arctic Ocean via Slave and Mackenzie Rivers. Its headwaters lie in the Northern Rocky Mountain Trench in British Columbia where Parsnip and Finlay rivers formerly joined at Finlay Forks (the site is now inundated by Lake Williston, the reservoir formed by W.A.C. Bennett Dam). From there, it flowed more than 1300 km to the east and north, entering Peace–Athabasca Delta beyond Peace Point (Figure 1.2). Today, virtually the entire flow bypasses the delta built into Lake Athabasca, instead entering directly into Slave River. Peace River is a boreal river with a strongly nival runoff regime augmented by a precipitation maximum in early summer. The persistence of ice cover for up to six months of the year is an important feature of the regime. Since the river flows "down north," breakup occurs first in the headwaters, leading to the potential for major ice-jam flooding to occur farther downstream. Mean annual flood at Peace Point, the most distal gauging station (1115 km below the dams[1]), under the natural regime was 9820 m^{3}s^{-1}, but it was already 5840 m^{3}s^{-1} at Hudson's Hope[2], in the Rocky Mountain water gap through which the river passes, with only 24% of the drainage area. On an annual basis, half of the runoff emanates from the mountains upstream of Hudson's Hope. Mean annual flow at Hudson's Hope in recent years has been 1135 m^{3}s^{-1}.

In December 1967, the British Columbia Hydro and Power Authority (BC Hydro) closed W.A.C. Bennett Dam, constructed 27 km west of Hudson's Hope. The impounding of Peace River created, in Lake Williston, the world's fourth largest reservoir (at 74.3 km^3 capacity, it currently is ranked seventh) and the dam remains one of the world's larger earth-fill barrages. Since then, water release from Lake Williston has been governed by hydroelectric power generation requirements. Some years later, a second dam and powerhouse were added in Peace Canyon, 20 km downstream (Figure 1.3), essentially a run-of-river plant which has little further effect on flows. Together, the two facilities regulate the runoff from 72 750 km^2 and are capable of generating 3430 MW, making them currently (i.e., 2012) the fifteenth largest project in the world.

From Peace Canyon Dam the river flows 1223 km to the Peace–Athabasca delta. At Peace Point, the regulated mean annual flood is 5360 m^{3}s^{-1}, 55% of the preregulation value. The altered flow regime (Figure 1.4) has set in train a suite of changes in the morphology of the river channel downstream, with consequent ecological effects. Several researchers over the last 30 years have investigated these changes (cf. Kellerhals and Gill, 1973; Kellerhals, 1982; Church, 1995; Church *et al.*, 1997). Hydroecological results from a major study of the Peace–Athabasca river system (the "Northern River Basins Study") in the period 1991 to 1998 were summarized by Prowse and Conly (2002a, 2002b).

In contrast to the sources of water in the Peace River drainage basin, the mountain headwaters consist predominantly of limestone and metamorphic terranes that yield comparatively little sediment. The river east of the mountains flows through the Alberta Plateau, underlain by moderately to weakly lithified sediments of late Mesozoic age in the Western Canada sedimentary basin. The consequence is that, even before regulation, almost

[1]River distances in this monograph are measured from Peace Canyon Dam, currently the farthest downstream dam on the river. It is located 20.4 km downstream from Bennett Dam.

[2]The place name is variously given as "Hudson's Hope" and "Hudson Hope." The municipality refers to itself as Hudson's Hope, and that name will be used in this monograph.

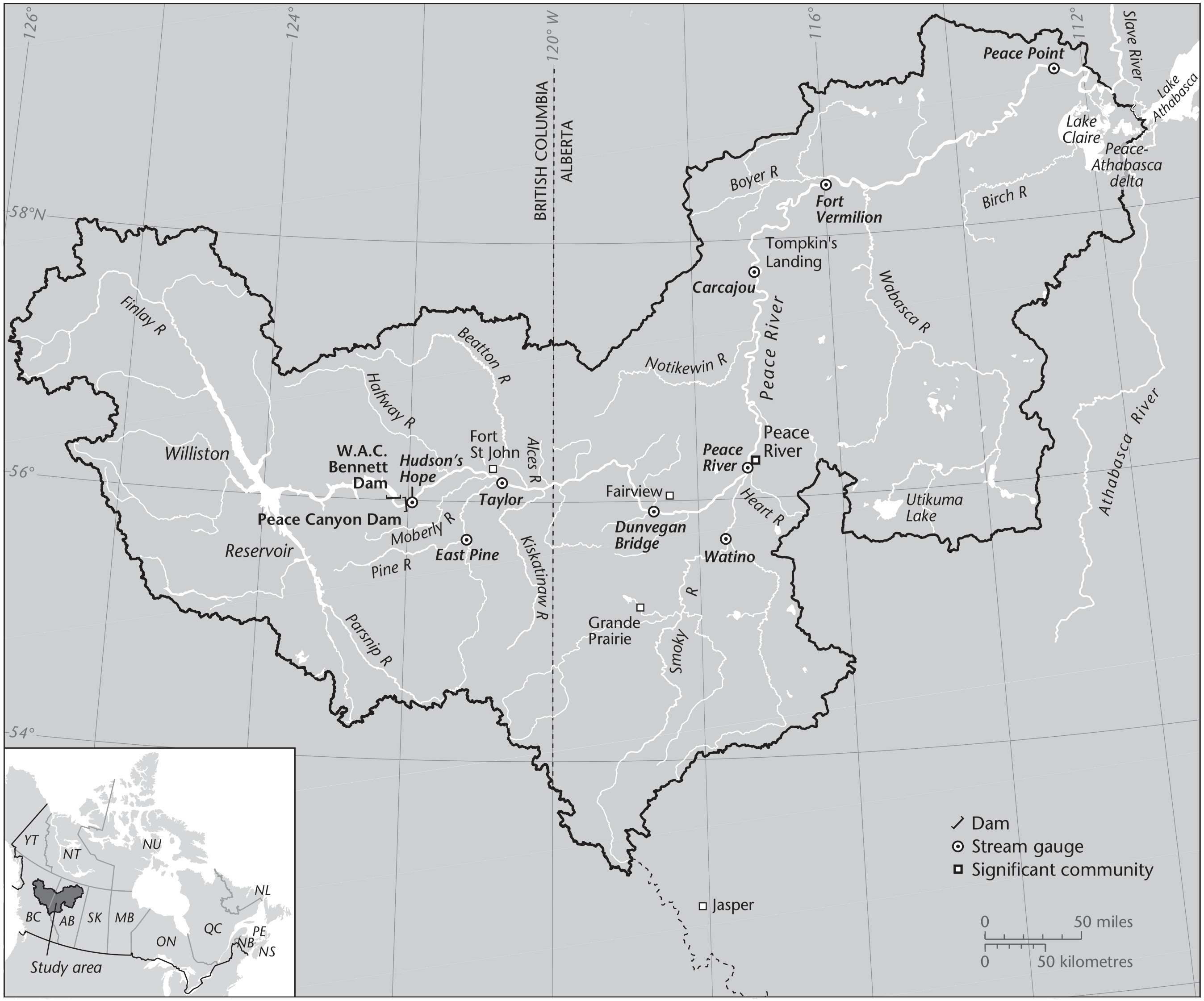

Figure 1.2 Peace River basin, showing principal settlements and stream gauges, and principal tributaries of Peace River.

Figure 1.3 Peace Canyon Dam, in the front ridge of the Rocky Mountains, northeastern British Columbia, Dinosaur Lake beyond. The dam is 20.4 km downstream from W.A.C. Bennett Dam, which impounds the reservoir known as Lake Williston. The white water immediately below the dam is formed by rock ridges on the channel bed. River flow is 970 m^3s^{-1} (Photo courtesy of M. J. Miles).

all of the sediment yielded to the river was derived from east of the mountains—that is, downstream from the site of the dams.

A remarkable consequence of the distributions of water and sediment sources, then, is that the regulation of Peace River at Bennett Dam has dramatically changed only one of the three major governing factors of river regime, the flow distribution, whilst scarcely affecting the second, the sediment yield to the river, and, of course, not affecting at all the third, the regional topographic gradient down which the water and sediment load must be passed. The effective manipulation of only one principal governing condition is relatively exceptional on a major river. It presents to us a quasi-experimental opportunity to study the effect, at full scale in the landscape, of manipulating that condition, other conditions remaining approximately unchanged (see Church (2011) on inadvertent geomorphological "experiments").

Of course, the other conditions do not remain entirely unchanged, being subject to the effects of varying weather and climate. But, in such a large system, natural fluctuations at seasonal to annual scale that govern the major response elements of the riverine system have comparatively small incremental effect over a period of decades in comparison with the abrupt and radical effect of flow regulation. The opportunity to study the effect of the primary hydrological change whilst sediment yield to the river remains similar to its pre-regulation regime adds significance to the study. (See Phillips *et al.* (2005) for an example of sediment only manipulation.)

There is a second quasi-experiment embedded in this study. The need for maintenance works at Bennett Dam led BC Hydro, in 1996, to draw down the reservoir by running the spillway at full capacity for eight consecutive weeks. After 24 years of operation in which flows did not exceed 3100 m^3s^{-1} at Hudson's Hope (and were normally less than 2000 m^3s^{-1}), the river was subject to release flows of more than 4000 m^3s^{-1} for a prolonged period. That flow is about two-thirds the pre-regulation mean annual flood and just over half pre-regulation bankfull (as established by Kellerhals *et al.* (1972)) throughout the British Columbia reach, but was effectively bankfull for the post-regulation period as far downstream as the Town of Peace River (TPR; 376 km downstream) in Alberta. The event was displaced in timing by only two or three weeks from that of a normal pre-regulation freshet and constitutes a notable "experiment" on the putative effectiveness of a frequently quoted "dominant flow" at full scale in a major river. A further instructive comparison is gained by the occurrence, in 1990, of the flood of record on the lower river,

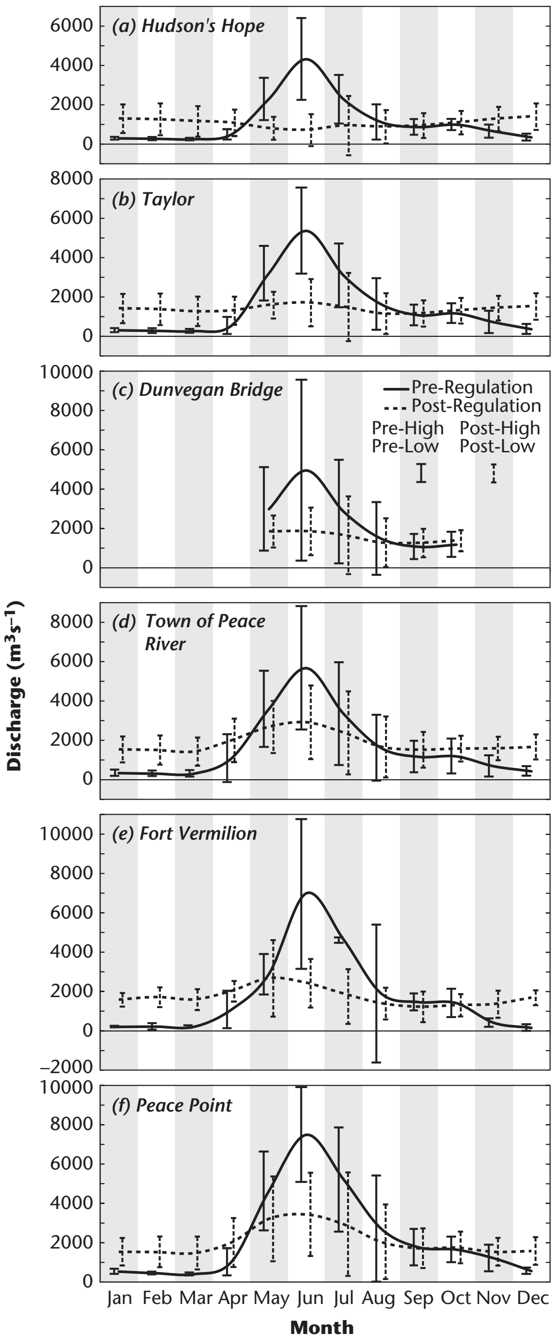

Figure 1.4 Natural and regulated mean annual flow regime at principal gauges along Peace River: (a) Hudson's Hope, km 5 below Peace Canyon dam; (b) Taylor, km 103; (c) Dunvegan Bridge, km 276; (d) Town of Peace River, km 378; (e) Fort Vermilion, km 812; (f) Peace Point, km 1116.

when flows exceeding 12 000 m^3s^{-1} were experienced, but for only a day or two.

1.3 Some precedents

An important precedent for this study in respect of sediment influx is Andrews's (1986) report of the downstream effects of Flaming Gorge Reservoir on the Green River of Utah. That river drains 115 772 km^2, of which 39 083 km^2 is regulated. A representative 37% of the flow, but only 2.1% of the sediment load is derived from the 34% of the drainage basin that lies above the reservoir. Andrews has inferred from sediment budget considerations that the first 110 km of the river below the dam are degrading (though the initial 20 km are largely protected by rock boundaries); then there is a 158 km reach that has maintained equilibrium; finally, a 396 km reach to the confluence with Colorado River is aggrading. This pattern of gradation is determined by sediment recruitment from tributaries. The proximal reach is starved of what sediment previously came from the headwaters but, downstream, the unregulated tributaries eventually add sufficient sediment to overwhelm the reduced transporting capacity of the river. An important feature of this case is that the sediment is essentially entirely silt and sand, mainly carried in suspension. Predictably, then (following Brandt (2000)), the river has narrowed along its entire course (see Allred and Schmidt (1999) and Grams and Schmidt (2002) for detailed descriptions of channel narrowing by construction of an inset, low floodplain). Furthermore, the river is carrying its suspended load at capacity, as indicated by the lack of change since regulation in sediment rating curves at successive measurement stations. These circumstances differ from those in Peace River. An interesting lesson of the case is that significant impacts of the regulation occur hundreds of kilometers beyond the dam—aggradation occurring beyond the point at which the proportion of regulated area falls below 0.4.

A case more like that of Peace River, but on a much smaller scale, is the River North Tyne in the United Kingdom, downstream from Kielder Reservoir (Sear, 1995). Like Peace River, the proximal reaches exhibit wandering morphology and a cobble-gravel bed. After a decade of regulation, the major effects were variable but very modest scour and aggradation on riffles and in pools, respectively; the growth of confluence bars at tributary entrances; and the deposition of sandy berms along the channel margins.

Superficially the closest analogy with Peace River immediately below the dams is provided by Snake River, Wyoming, in the reach below Jackson Lake Dam (Marston *et al.*, 2005; Erwin *et al.*, 2011) in Jackson Hole. The lake is natural and the dam, established in 1907 but rebuilt in 1911, raises the water level by 12 m to provide seasonal water storage for irrigation far downstream. Since the large lake captures essentially all inflowing sediment, this is another case in which the flow regime has been altered but the sediment transport regime has not. Below the dam, sediment is recruited to the gravel-bed river by delivery from tributaries—the two principal ones being only a short distance from the dam—and from erosion of channel banks and late Pleistocene outwash terraces into which the river is well incised. At the dam, the mean annual flow of the river is 41 m^3s^{-1}, so the river is only about 3.5% of the magnitude of Peace River. From bedload transport measurements made in Snake River and in the two principal tributaries, Erwin *et al.* (2011) concluded that Snake River is not only capable of transporting all the incoming load—which is somewhat finer gravel than found in the bed of Snake River—but that Snake River is actually mildly degrading. This controverts predictions for the likely effect of flow regulation in a gravel-bed river.

There are several possible reasons for this appearance. An important one is that, although flow is regulated, the regime is not dramatically altered. There is a reduced spring freshet but late summer flows—when irrigation water is needed—are double what unregulated flows would have been, and still competent to move gravel. Hence the duration of competent flow has been increased from 20% of the year to 30% of the year. Another possible reason for the unexpected outcome is that the river gradient increases downstream by a factor of about three between the tributary confluences and the Snake River sediment transport measurement point, the result of tectonic activity on the adjacent Grand Teton fault. Finally, whilst degradation is claimed, and the river clearly has degraded into Pleistocene outwash in Holocene time, the physical signs of recent degradation (the dam is a century old) are not obvious. The old floodplain remains only one or two meters above summer water level and is still occasionally wetted (R. Marston, personal communication, September 2012), while the river bed itself remains significantly armored. Certainly, however, the expected accumulation of tributary-delivered gravel has not occurred. The floodplain nevertheless has become more terrestrial in aspect since regulation (Marston *et al.*, 2005), with extensive Narrowleaf Cottonwood (*Populus angustifolia*) forests becoming decadent and giving way to Colorado spruce (*Picea pungens*).

The study of Gaeuman *et al.* (2005) presents other analogies with Peace River inasmuch as the Duchesne River includes both gravel-bed and sand-bed reaches. Flow reductions early in the twentieth century accompanied by an increase in fine sediment supply prompted narrowing of the gravel-bed reach and bed aggradation in the sand-bed reach. A later increase in flood magnitudes produced channel widening and bed aggradation in the gravel-bed reach, and degradation and channel narrowing in the sand-bed reach, all in conformity with Brandt's (2000) predictions. Most recently, increased water diversions have eliminated flood flows and increased the duration of low flows, leading to general channel narrowing and the progradation of riparian vegetation on the channel margins.

Peace River presents similar research opportunities. The bed is cobble gravel from Hudson's Hope to the Smoky River confluence (km 368 downstream) near TPR, Alberta (Figure 1.2). From there to near Tompkins Landing (km 674), the bed is sandy gravel, while in the reach downstream to the Peace–Athabasca delta it is primarily sand. There is the opportunity, then, to study the comparative response to regulation of channel reaches with characteristically different sedimentology and consequent morphology. The comparison is not perfect: downstream increments to flow and sediment load from tributaries act to reduce the degree of regulation whilst augmenting the sediment load. While the natural annual hydrograph is inverted at the dam due to major power generation in winter, a "normal" regime (with spring freshet) is reestablished downstream, commencing at Pine River, 101 km below the dams. Among the tributaries, Smoky River is by far the largest, contributing a substantial spring flood and sediment load to the Peace. TPR, then, marks a major division point for study of the river. The reaches upstream of the Smoky confluence and TPR (Figure 1.2) will be referred to as "the upper river," the balance of the course as "the lower river."

1.4 The program

This paper introduces a series of reports of the river's post-regulation channel adjustment over the first 38 years. Particular attention will be given to the 148 km reach between the dam and the British Columbia—Alberta border where the flow regulation is most severe and the consequent morphological changes might be expected to be strongest. However, studies are extended throughout the 1115 km course to Peace Point, the most distal gauge on the river. Changes in the Peace–Athabasca delta, beyond Peace Point, have been the subject of major studies and numerous reports (summarized by the Peace–Athabasca Delta Project Group (1973), Prowse and Conly (1996; 2002b), Peters and Prowse (2001) and Timoney (2013)).

Chapter 2 introduces the primary effects of the regulation of Peace River—the changes effected in the flow regime and the regime of sediment transport in the river. Chapter 3 discusses the regrading of Peace River, the consequence of scour and sedimentation along the river, while Chapter 4 examines the consequences of the change in effective base level represented by the regulation of Peace River for the final few kilometers of the river's tributaries. The focus of both these chapters lies within the "upper river," the 376 km reach from the dams to TPR, where the effects are most evident. Chapter 5 analyzes the history of stream gauging along Peace River to examine changes in the hydraulic geometry of the river consequent upon regulation and the two subsequent notable flood events. From the results of gauging station analyses a downstream hydraulic geometry is synthesized and changes through time are documented.

Chapter 6 discusses the ice regime of Peace River in the era of flow regulation. This chapter is focused on the Alberta reach of the river where ice effects remain severe. In much of the British Columbia reach, winter ice cover has become rare or transitory since regulation. The data for this chapter largely derive from a field reconnaissance conducted along the length of the river as far as Fort Vermilion, Alberta (km 812). Chapter 7 examines morphological changes to the river from the dams to Peace Point, 1100 km downstream. The data are derived from periodic air photo surveys mapped into a Geographic Information System. The entire river was not mapped: instead five reaches were selected to represent the major morphological "types" of the river. The total mapped length covers about 750 km, or 62% of the river length below the dams.

Chapters 8 and 9 discuss the evolution of the riparian vegetation in the regulated regime, respectively in the British Columbia and Alberta reaches. The observations for British Columbia are based on combined field and air photo studies while the Alberta results are based mainly on air photo interpretation, using British Columbia results as a guide. In view of the principal source of the data, the analysis is conducted at the community level.

In chapter 10, aspects of the 1990 and 1996 floods are reviewed in greater detail and lessons drawn for the impact of a single substantial flood in a regulated channel. Chapter 11, in contrast to the empirical basis of the rest of the study, reports an exercise using rational river regime theory to predict the ultimate form that the river may take as the result of flow regulation and the time scale to effect the adjustment. The predictions are tempered in light of observed morphological change along the river to date.

Some reflections on the Peace River study close the monograph.

The overriding objective is to provide as thorough a documentation as observations permit of the downstream physical effects of the regulation of a large boreal river. The work does not, in the main, concern itself with modeling or with prediction of effects. In view of the dominance of observational reporting, the study may appear somewhat anachronistic in the new scientific world dominated by modeling exercises. It is the senior author's opinion, however, that modeling is often employed as a substitute for inadequate (for whatever reason) observations, but that modeling exercises can only be as reliable as the observational data that are employed to calibrate or confirm the model. Hence, there remains a major need for rich descriptive exercises. Certainly, the data of this study will offer a basis for many subsequent modeling efforts.

References

Allred, T. M. and Schmidt, J. C. (1999) Channel narrowing by vertical accretion along Green River near Green River, Utah. *Geological Society of America Bulletin*, 111, 1757–1772. doi:10.1130/0016-7606 (1999)111<1757.CNVAA>2.3.CO;2

Andrews, E. D. (1986) Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah. *Geological Society of America Bulletin*, 97, 1012–1023. doi:10.1130/0016-7606 (1986)97<1012:DEOFGR>2.0.CO;2

Ashida, K. and Michiue, M. (1971) An investigation of river bed degradation downstream of a dam. *Proceedings of the 14th International Association for Hydraulic Research World Congress*, 3, 247–253, Aug 29–Sept 5, Paris, France.

Assani, A. A., Stichelbout, É., Roy, A. G., and Petit, F. (2006) Comparison of impacts of dams on the annual maximum flow characteristics in three regulated hydrologic regimes in Québec (Canada). *Hydrological Processes*, 20, 3485–3501. doi:10.1002/hyp.6150

Brandt, S. A. (2000) Classification of geomorphological effects downstream of dams. *Catena*, 40, 375–401.

Bravard, J.-P., Amoros, C., and Pautou, G. (1986) Impact of civil engineering works on the successions of communities in a fluvial system. *Oikos*, 47, 92–111

Carling, P. A. (1988) Channel change and sediment transport in regulated U.K. rivers. *Regulated Rivers: Research and Management*, 2, 369–387.

Chien, N. (1985) Changes in river regime after the construction of upstream reservoirs. *Earth Surface Processes and Landforms*, 10, 143–159.

Church, M. (1995) Geomorphic response to river flow regulation: case studies and time scales. *Regulated Rivers: Research and Management*, 11, 3–22.

Church, M. (2011) Observations and experiments, in *The Sage Handbook of Geomorphology*, edited by K. J. Gregory and A. L. Goudie. Sage, London. pp. 121–141.

Church, M., Xu, J., Moy, A., and Uunila, L. (1997) Changes in morphology and riparian vegetation following flow regulation, Peace River 1968 and 1993. *NRBS, Project Report*, 102, 91 p. Northern River Basins Study, Alberta Environmental Protection, Edmonton, Canada.

Dynesius, M. and Nilsson, C. (1994) Fragmentation and flow regulation of river systems in the northern third of the world. *Science*, 266, 753–762.

Erwin, S. O., Schmidt, J. C., and Nelson, N. C. (2011) Downstream effects of impounding a natural lake: the Snake River downstream from Jackson Lake Dam, Wyoming, USA. *Earth Surface Processes and Landforms*, 36, 1421–1434. doi:10.1002/esp.2159

Gaeuman, D., Schmidt, J. C., and Wilcock, P. R. (2005) Complex channel responses to changes in stream flow and sediment supply on the lower Duchesne River, Utah. *Geomorphology*, 64, 185–206. doi:10.1016/j.geomorph.2004.06.007

Galay, V. J. (1983) Causes of river bed degradation. *Water Resources Research*, 19, 1057–1090. doi:10.1029/WR019i05p01057

Graf, W. L. (2006) Downstream hydrologic and geomorphic effects of large dams on American rivers. *Geomorphology*, 79, 336–360. doi:10.1016/j.geomorph.2006.06.022

Grams, P. E. and Schmidt, J. C. (2002) Streamflow regulation and multilevel floodplain formation: channel narrowing on the aggrading Green River in the eastern Uinta Mountains, Colorado and Utah. *Geomorphology*, 44, 337–360.

Grams, P. E., Schmidt, J. C., and Topping, D. J. (2007) The rate and pattern of bed incision and bank adjustment on the Colorado River in Glen Canyon downstream from Glen Canyon Dam, 1956-2000. *Geological Society of America Bulletin*, 119, 556–575. doi:10.1130/B25969.1

Grant, G. E. (2012) The geomorphic response of gravel-bed rivers to dams: perspectives and prospects, in *Gravel-Bed Rivers: Processes, Tools, Environments*, edited by M. Church, P. Biron, and A. Roy. John Wiley & Sons, Ltd, Chichester, UK. pp. 165–181.

Grant, G. E., Schmidt, J. C., and Lewis, S. L. (2003) A geological framework for interpreting downstream effects of dams on rivers, in *A Peculiar River*, edited by J. E. O'Connor and G. E. Grant. Vol. 7: Water Science and Application. American Geophysical Union, Washington, DC. pp. 203–219. doi:10.1029/007WS13

Gregory, K. J. and Park, C. (1974) Adjustment of river channel capacity downstream from a reservoir. *Water Resources Research*, 10, 870–873. doi:10.1029/WR010i004p00870

Hammad, H. Y. (1972) River bed degradation after closure of dams. *Journal of the Hydraulics Division* [Proceedings of the American Society of Civil Engineers], 98(4), 591–607.

Hathaway, G. A. (1948) Observations on channel changes, degradation, and scour below dams. *Report on 2nd Meeting of the International Association for Hydraulic Structures Research* [now International Association for Hydraulic Research], Stockholm, Sweden. pp. 267–307.

Kellerhals, R. (1982) Effect of river regulation on channel instability, in *Gravel-Bed Rivers*, edited by R. D. Hey, J. C. Bathurst, and C. R. Thorne. John Wiley & Sons, Chichester, UK. pp. 685–705.

Kellerhals, R. and Gill, D. A. (1973) Observed and potential downstream effects of large storage projects in northern Canada, *Proceedings of the 11th ICOLD Congress*, 1, 731–754.

Kellerhals, R., Neill, C. R., and Bray, D. I. (1972) Hydraulic and geomorphic characteristics of rivers in Alberta, *River Engineering and Surface Hydrology Report* 72-1, 48 p. Research Council of Alberta, Edmonton, Canada.

Komura, S. and Simons, D. B. (1967) River-bed degradation below dams. *Journal of the Hydraulics Division* [Proceedings of the American Society of Civil Engineers], 93(4), 14.

Lane, E. W. (1934) Retrogression of levels in riverbeds below dams. *Engineering News-Record*, 112, 836–838.

Lawson, J. M. (1925) Effect of Rio Grande storage on river erosion and deposition. *Engineering News-Record*, 103, 327–334.

Ligon, F. K., Dietrich, W. E., and Trush, W. J. (1995) Downstream ecological effects of dams. *BioScience*, 45, 183–192.

Magilligan, F. J. and Nislow, K. H. (2005) Changes in hydrologic regime by dams. *Geomorphology*, 71, 61–78. doi:10.1016/j.geomorph.2004.08.017

Marston, R. A., Mills, J. D., Wrazien, D. R., Bassett, B., and Splinter, D. K. (2005) Effects of Jackson Lake Dam on the Snake River and its floodplain, Grand Teton National Park, Wyoming, USA. *Geomorphology*, 71, 71–98.

Mostafa, M. G. (1957) Riverbed degradation below large capacity reservoirs. *American Society of Civil Engineers Transactions*, 122, 688–695.

Peace–Athabasca Delta Project Group. (1973) *Peace–Athabasca Delta Project, Technical Report and Appendices*, Vol 1, *Hydrological Investigations*, Vol. 2. *Ecological Investigations.* Government of Canada, Edmonton, Canada.

Peters, D. L. and Prowse, T. (2001) Regulation effects on the lower Peace River, Canada. *Hydrological Processes*, 15, 3181–3194. doi:10.1002/hyp.321

Petts, G. E. (1984a) *Impounded Rivers: Perspectives for Ecological Management*, John Wiley & Sons, Chichester, UK. 326 p.

Petts, G. E. (1984b) Sedimentation within a regulated river. *Earth Surface Processes and Landforms*, 9, 125–134.

Petts, G. E. and Gurnell, A. M. (2005) Dams and geomorphology: research progress and future directions. *Geomorphology*, 71, 27–47. doi:10.1016/j.geomorph.2004.02.015

Phillips, J. D., Slattery, M. C., and Musselman, Z. A. (2005) Channel adjustments of the lower Trinity River, Texas, downstream of Livingston Dam. *Earth Surface Processes and Landforms*, 30, 1419–1439. doi:10.1002/esp.1203

Pickup. G. (1980) Hydrologic and sediment modelling studies in the environmental impact assessment of a major tropical dam project. *Earth Surface Processes*, 5, 61–75.

Poff, N. L., Olden, J. D., Merritt, D. M., and Pepin, D. M. (2007) Homogenization of regional river dynamics by dams and global biodiversity implications. *Proceedings of the National Academy of Sciences of the United States of America*, 104, 5732–5737. doi:10.1073/pnas.0609812104

Prowse, T. D. and Conly, F. M. (1996) Impact of flow regulation on the aquatic ecosystem of the Peace and Slave Rivers, *NRBS Study, Synthesis Report*, 1. Northern River Basins Study, Alberta Environmental Protection, Edmonton, Canada.

Prowse, T. D. and Conly, F. M. (2002a) A review of hydroecological results of the Northern River Basins study, Canada. Part 1. Peace and Slave Rivers. *River Research and Applications*, 18, 429–446. doi:10.1002/rra.681

Prowse, T. D. and Conly, F. M. (2002b) A review of hydroecological results of the Northern River Basins study, Canada. Part 2. Peace–Athabasca Delta. *River Research and Applications*, 18, 447–460. doi:10.1002/rra.682

Renöfält, B. M., Jansson, R., and Nilsson, C. (2010) Effects of hydropower generation and opportunities for environmental flow management in Swedish riverine ecosystems. *Freshwater Biology* 55, 49–67. doi:10.1111/j.1365-2427.2009.02241.x

Schmidt, J. C. and Wilcock, P. R. (2008) Metrics for assessing the downstream impacts of dams. *Water Resources Research*, 44, W04404, 19 p. doi:10.1029/2006WR005092

Sear, D. A. (1995) Morphological and sedimentological changes in a gravel-bed river following 12 years of flow regulation for hydropower. *Regulated Rivers: Research and Management*, 10, 247–264.

Shields, F. D., Jr, Simon, A., and Steffen, L. J. (2000) Reservoir effects on downstream channel migration. *Environmental Conservation*, 27, 54–66.

Shulits, S. (1934) Experience with bed degradation below dams on European rivers. *Engineering News-Record*, 112, 838–839.

Stanley, J. W. (1947) Effects of dams on channel regime. Proceedings of the First Federal Interagency Sedimentation Conference, May 6–8, 1947, Denver, CO. United States Government Printing Office, Washington, DC. pp. 163–186. Available at http://pubs.usgs.gov/misc/FISC_1947-2006/pdf/1st-7thFISCs-CD/1stFISC/ (last accessed Apr 5, 2014).

Surian, N. and Rinaldi, M. (2003) Morphological response to river engineering and management in alluvial channels in Italy. *Geomorphology*, 50, 307–326. doi:10.1016/S0169-555X(02)00219-2

Timoney, K. P. (2013) *The Peace–Athabasca Delta: Portrait of a Dynamic Ecosystem*. University of Alberta Press, Edmonton, Canada. 595 p.

Tinney, E. R. (1962) Process of channel degradation. *Journal of Geophysical Research*, 67, 1475–1480.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullavin, C. A., Reidy Liermann, C., and Davies, P. M. (2010) Global threats to human water security and river biodiversity, *Nature*, 467, 555–561. doi:10.1038/nature09440

Ward, J. V. and Stanford, J. A. (1979) *The Ecology of Regulated Streams*, Plenum, New York. 398 p.

Williams, G. P. and Wolman, M. G. (1984) Downstream effects of dams on alluvial rivers. *United States Geological Survey, Professional Paper*, 1286. 83 p.

Wolman, M. G. (1967) Two problems involving river channel changes and background observations, in *Quantitative Geography. Part II: Physical and Cartographic Topics*, edited by W. L. Garrison and D. F. Marble.No. 14: Northwestern University Studies in Geography., Northwestern University, Evanston, IL. pp. 67–107.

World Commission on Dams. (2005) *Dams and Development*, United Nations Environment Program, New York. Available at http://hqweb.unep.org/dams/WCD/report/WCD_DAMSreport.pdf (last accessed Aug 15, 2011)

CHAPTER 2
The regulation of Peace River

2.1 Introduction

Peace River drains approximately 293 000 km^2 of the Canadian provinces of British Columbia and Alberta toward the Arctic Ocean via Slave and Mackenzie Rivers. Its headwaters rise in the northern Rocky Mountain Trench in British Columbia. From there, it flows more than 1300 km to the east and north, entering the Peace–Athabasca Delta beyond Peace Point (Figure 2.1) from where its waters continue toward the Arctic Ocean as Slave River. The natural regime of the river was strongly dominated by nival runoff augmented by a precipitation maximum in early summer so the hydrograph resembled an "event" hydrograph on an annual time base. The persistence of ice cover for five to six months of the year is a second important feature of the regime. Breakup proceeds downstream from the headwaters, creating the potential for major ice-jam flooding.

Mean annual flood at Peace Point under the natural regime was about 9800 m^{3}s^{-1}, but it was already 6000 m^{3}s^{-1} at Hudson's Hope with only 24% of the drainage area. On an annual basis, half of the runoff derives from the mountains upstream of Hudson's Hope. Indeed, much of the more northerly part of the drainage basin in the Alberta Plateau is subhumid wetland that contributes little or no actual runoff at all.

In December 1967, the British Columbia Hydro and Power Authority (BC Hydro) closed W.A.C. Bennett Dam, located 27 km west of Hudson's Hope in the water gap through which the river breaches the main ridge of the Rocky Mountains. Since then, water release from Lake Williston and the downstream flow have been governed by hydroelectric power generation requirements. Some years later, a second dam and powerhouse were added in Peace Canyon, 20 km downstream. The effect of the power stations has been to establish in the reach immediately downstream from the dam an "inverted" runoff regime with a winter maximum of flow. A weakly dominant late spring freshet is reestablished only after the river passes the Pine River confluence, some 100 km downstream from Peace Canyon Dam.

The headwaters of Peace River (Figure 2.1) lie in the dominantly limestone ranges of the northern Rocky Mountains and in the metamorphic terrane of the Omineca Mountains. Sediment yield from these mountains, apart from the mobilization of sand and silt from glaciolacustrine deposits along mountain valleys, is low. Over most of its course below Bennett Dam and east of the mountains, the river is deeply entrenched into the high plains of the Alberta Plateau (Figure 2.2). The rocks underlying the plateau dominantly are moderately to weakly lithified shale and sandstone of Cretaceous age (Figure 2.3). In addition, there are substantial Pleistocene sediments along the valley, including ancient outwash gravels deposited in the ancestral Peace River valley and extensive glaciolacustrine silts of both interglacial age and late glacial age deposited in lakes formerly impounded west of the Laurentide ice sheets (Mathews, 1978, 1980; Hartman and Clague, 2008). Tributaries draining the Alberta Plateau deliver abundant sediment to the river while landslides (Figure 2.4), dominantly in the Kaskapau (Lower Smoky Formation (Fm.)) and Shaftesbury (Upper Fort St. John Fm.) shales (Figure 2.3) and in Quaternary lacustrine sediments (Cruden *et al.*, 1990; Severin, 2004), episodically yield more sediment, and might even dam Peace River temporarily. The most recent damming event was the 1973 Attachie landslide (Figure 2.4c) at the Halfway River confluence (Evans *et al.*, 1996), which blocked the river for about 12 hours. Severin (2004) has catalogued 465 slides along the British Columbia Peace River while Cruden *et al.* (1990) reported that more than 60% of the valley walls have failed in Alberta downstream to Fort

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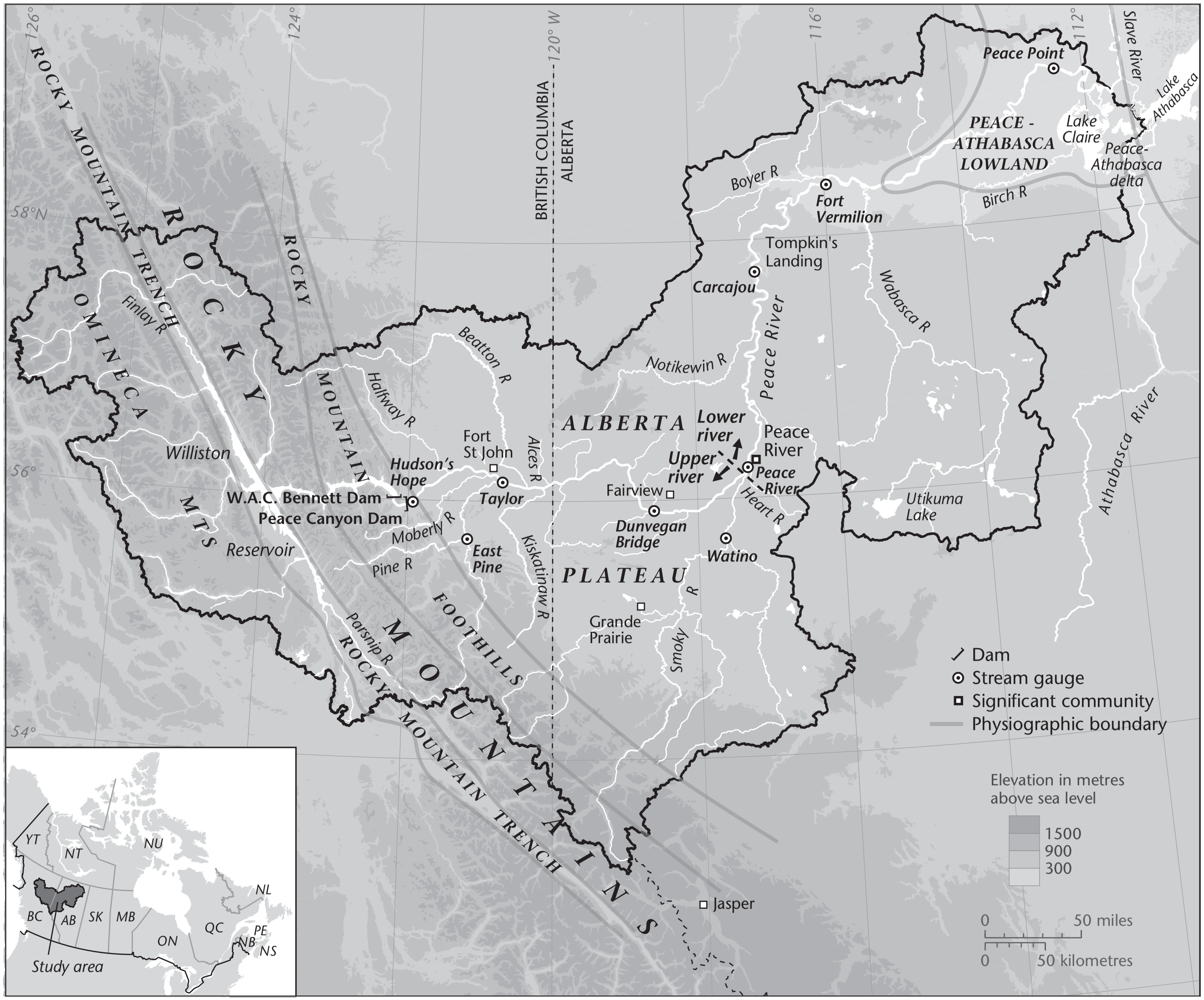


Figure 2.1 Peace River basin, showing the main tributaries. Physiographic units and the principal division of the river are shown and the principal gauges are marked.

Figure 2.2 Peace River: (a) incised below the Alberta Plateau, view upstream near Fort St. John, British Columbia, May 28, 2009, flow is 1195 m^3s^{-1} (Photo courtesy of M. J. Miles); (b) view upstream near Carcajou, Alberta, where river incision is less dramatic, June 27, 1996, flow is approximately 5400 m^3s^{-1}.

Vermilion: it is scarcely an exaggeration to say that, east of Cache Creek, a minor tributary 81 km from Bennett Dam, the river valley sides are a continuous landslide for more than 800 km. A consequence of this geography and geology is a general increase downstream in the yield of sediment to the river (Figure 2.5). This is a common pattern in Canadian wildlands that is interpreted as a Pleistocene legacy (Church and Slaymaker, 1989; Church *et al.*, 1999), the major source of sediment being glacial valley fills directly eroded by the river. In the Peace system, the causes also lie in the friable bedrock of the Alberta Plateau.

The conditions described above create the remarkable circumstance that the regulation of the river has dramatically altered the flow regime, one of the three principal controls on river processes and morphology, while a second, the sediment regime, remains virtually unchanged. This is unusual inasmuch as most dams not only modify the flow regime but even more assuredly intercept a relatively significant sediment load introduced from upstream, so that the effects of both changes are confounded downstream.

The particular objective of this paper is to analyze aspects of the changed hydrological and sediment transport regimes of the river pertinent to understand the morphological changes and the response of riparian vegetation along the river.

2.2 Hydrology

2.2.1 Hydrography and runoff sources

Below the dams, the major tributaries drain the Alberta Plateau (Figure 2.1). They include Halfway, Moberly, Pine, Beatton, and Kiskatinaw Rivers in British Columbia and Smoky, Notikewin, Boyer, and Wabasca Rivers in Alberta. The most important are right-bank tributaries, particularly in Alberta, probably because the east-northeasterly dip of the Alberta Plateau determines that the northwest water divide lies closer to the main river. The single most important tributary is Smoky River, which delivers a substantial annual nival flood and a large sand load, while the second most important is the cobble gravel–bedded Pine River. Both have mountain headwaters. There is no significant regulation of any tributary except that Moberly River runs through a large, natural mainstem lake that controls 56% of the drainage area, while the river downstream of the lake largely drains wetlands. Many of the more northerly Alberta tributaries also drain extensive areas of wetlands that retain much of the water supply.

The makeup of annual runoff in the Peace River system is illustrated in Figure 2.6 and shows that most of the water derives from the mountain headwaters. One half of the runoff derives from 24% of the area that makes up the regulated headwaters of Peace River proper. The Alberta Plateau contributes less than 40% of the flow from more than 75% of the drainage area, the balance arising in the mountain headwaters of some tributaries. Consequently, flow regulation at the dams has a large effect on flows throughout the downstream course of the river.

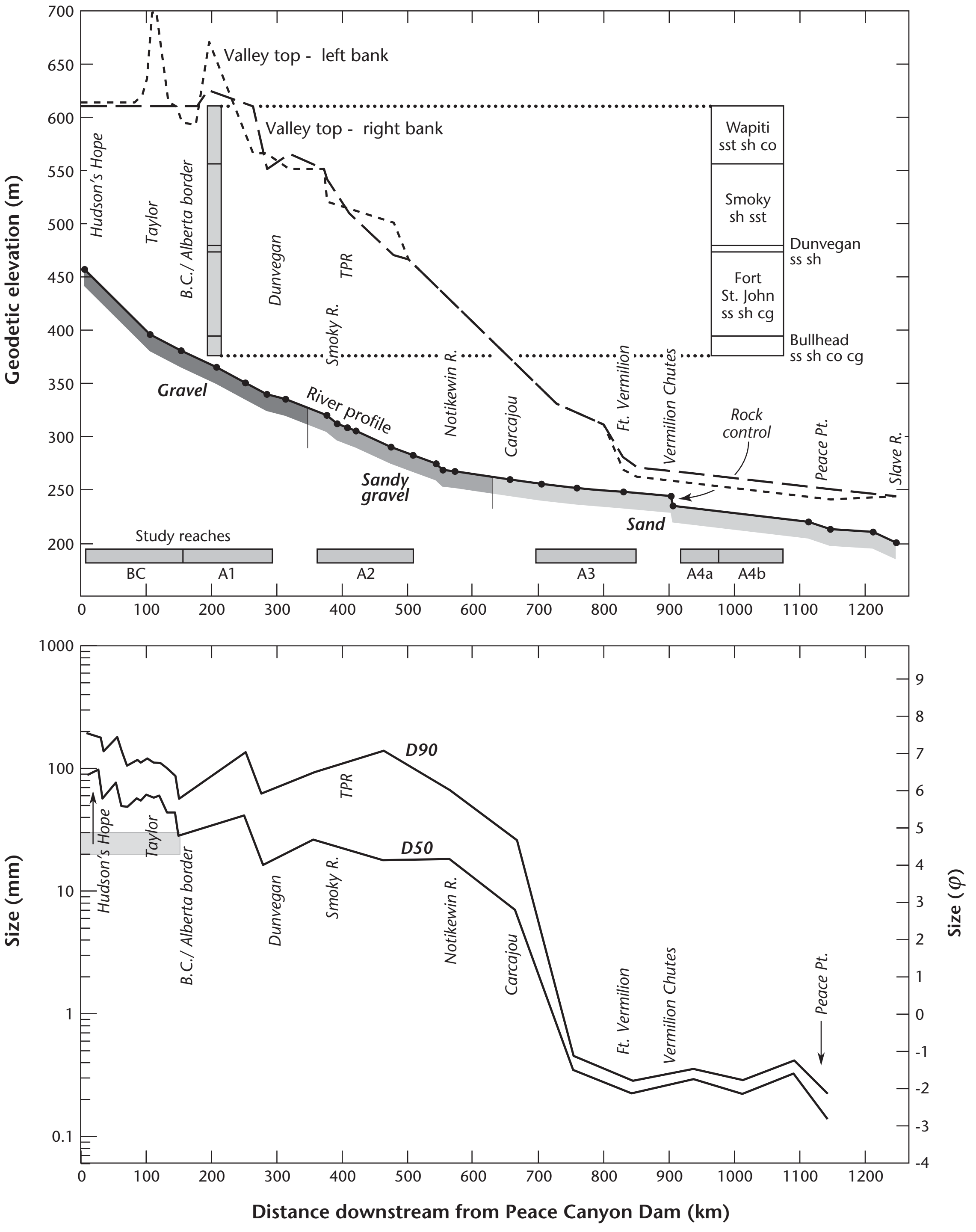


Figure 2.3 Channel gradient, elevation of the adjacent upland, and surface bed material grain size along Peace River. Locations of the principal points of interest are indicated. Elevations based on 1:50 000 NTS maps and on Kellerhals *et al.* (1972); geological section is generalized from Douglas *et al.* (1970). Codes for rock types within named formations: sst = sandstone; sh = shale; co = coal; cg = conglomerate. Grain size data from Shaw and Kellerhals (1982), with supplementary data for the British Columbia reach from Church and Kellerhals (1978); the grey shaded area represents the range of sizes of subsurface bed material in the British Columbia reach: there is no discernable trend.

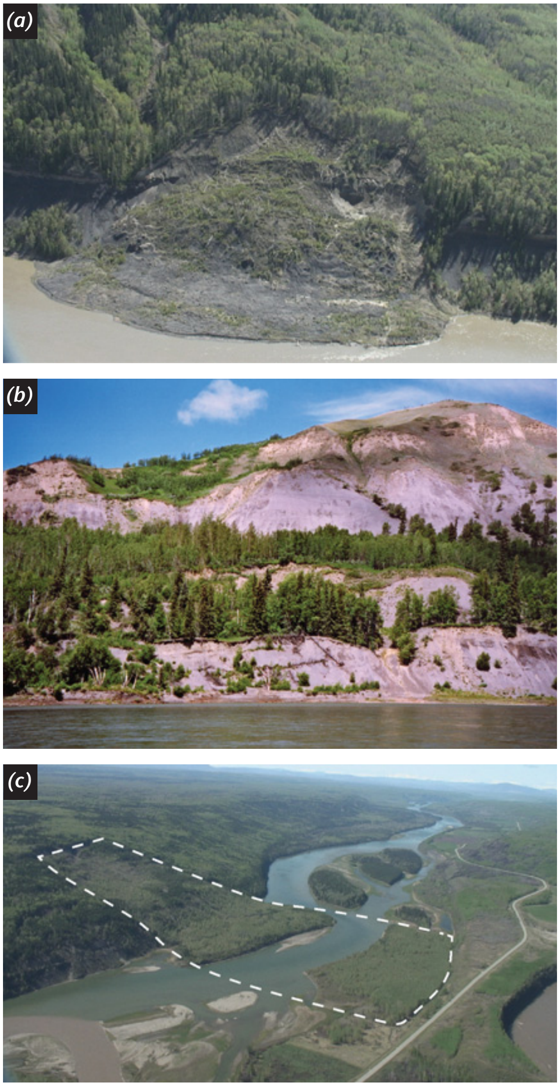


Figure 2.4 Landslides along Peace River. (a) Slump near Tea Creek, British Columbia Peace River. (b) Block glides, left bank near Fort St. John, British Columbia. (c) The Attachie Slide of 1973, which dammed the river: extent of slide deposit outlined (Photos 5(a) and (c) courtesy of M. J. Miles).

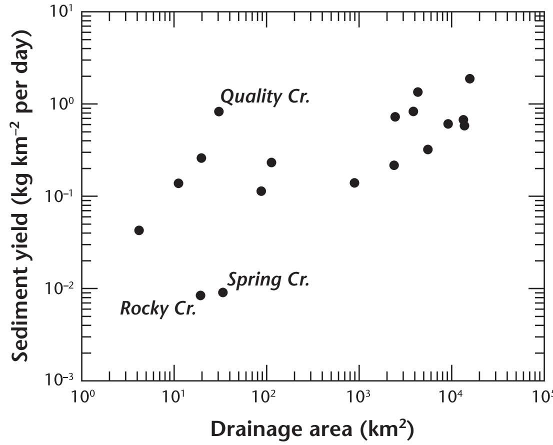


Figure 2.5 Graph of specific sediment yield in the Peace River drainage basin, based on suspended sediment load records of the WSC. Quality Creek is a small basin in the Moberly drainage that experienced an exceptional flood during a brief (two-year) record of suspended sediment yield, hence the result is undoubtedly inflated. Rocky Creek and Spring Creek are small basins on relatively resistant rocks in the headwaters of Smoky River.

2.2.2 Climate and runoff

Climate throughout the drainage basin is boreal continental, with warm summers, long, cold winters, and modest precipitation featuring an early summer maximum. The accumulated winter snowfall is disproportionately important as a source of runoff. To properly analyze the hydrological effects of flow regulation, it is necessary to recognize climate variation since the time of regulation. Accordingly, the differences between climate normals for 1941 to 1970 (before regulation) and 1971 to 2000 (after regulation) are presented for several long-term stations in the basin (Figure 2.7). At most stations, there has been a small increase in precipitation between the two periods but, what is much more striking, summer precipitation has increased significantly (on average, by 17% at the stations analyzed), while winter precipitation has declined. Accordingly, snow accumulation has systematically declined except in the autumn in the most northerly portion of the basin, on average by 13%. Temperature has increased throughout the basin, but the increase is confined almost entirely to the winter and early spring months. A significant decline in autumn temperatures occurred in the northernmost part of the basin, and is probably associated with the exceptional increase in snowfall there in those months.

Winter warming has not been sufficient to affect the snow accumulation season, although short-lived mid-winter thaws may now be more common in the southern part of the basin. Snow, however, is hydrologically more effective precipitation since spring snowmelt occurs in a relatively short period when the ground is either frozen or moist, producing a high runoff ratio. In comparison, summer rainfall is often hydrologically

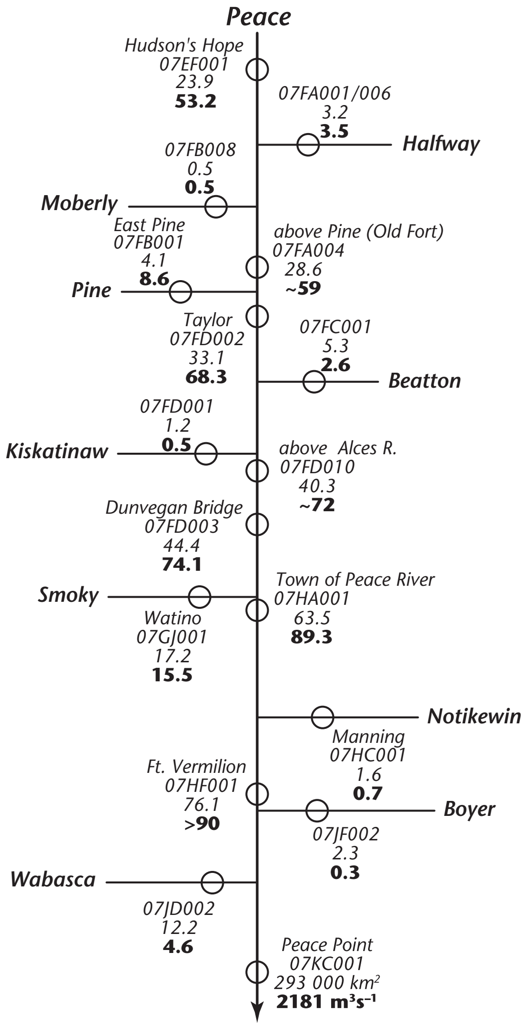


Figure 2.6 Network diagram showing the distribution of area and runoff in Peace River basin (data based on the period 1973 to 1998). Gauge numbers are WSC codes. Italic figures for each gauge represent the fraction of total drainage area and bold figures represent the fraction of flow, both figures being based on the drainage area and mean annual flow at Peace Point, which are reported as absolute values. There are minor discrepancies amongst the flow fractions because the underlying flow data are based on different periods.

ineffective since it falls onto dry soils in this generally subhumid region and is subsequently evaporated or transpired. Notwithstanding this observation, major summer storms do generate significant synoptic runoff in Peace River basin. Overall, however, the changing seasonal pattern of precipitation is associated with declining mean runoff in the basin (see the following paragraphs; also Prowse and Conly (1998)).

Climate trends are more clearly discerned by the examination of time sequences of key characteristics. In Figure 2.8, cumulated departures plots are presented for annual precipitation and annual snow accumulation at several stations in the drainage basin. They show that a significant change in hydroclimate occurred in about 1976. While the longer-term pattern for total precipitation shows additional strong turning points, winter snow accumulation is dominated by the 1976 shift. This result is highly coherent with the Pacific Decadal Oscillation (Mantua *et al.*, 1997), also shown in Figure 2.8, an index of North Pacific Ocean climate known to have a significant correlation with weather over western North America (Latif and Barnett, 1994). Colder and snowier winters from the late 1940s until the mid-1970s have given way to warmer and drier winters since. More specifically, Moore and McKendry (1996) showed that winter snowpack in their regions I (Alberta Plateau in British Columbia) and K (Northern Rocky Mountains, including Peace River headwaters) declined abruptly in the 1976 to 1977 winter and remained below the 1966 to 1992 average until the winter of 1988 to 1989, with the sole exception of 1981 to 1982, while Romolo *et al.* (2002) related these phenomena to changing patterns of winter synoptic weather types. Thermal climate was strongly affected by the 1976 shift in weather, but is also influenced by a long-range trend of climate warming in the Canadian prairies (Gan, 1998; Zhang *et al.*, 2000) that is part of an evident global trend (IPCC, 2007). There appears, then, to be abundant indication of reduced water supply since regulation.

The climate indications are borne out in the data of annual runoff (Figure 2.8) from the tributaries with montane headwaters (Pine and Smoky Rivers) but is not so obvious in the runoff record of the rivers of the dry Alberta Plateau and is evident in the flood record only of Pine River. On Peace River itself, the effect is very subtle (Figure 2.9) since, within the limitation of the total water supply, flows are largely determined by hydro power needs, and the reservoir easily permits year-to-year adjustments in flow. However, the effect is quantitatively evident in summary data of annual runoff given in Table 2.1, which shows that mean annual flow declined after regulation by between 2% and 10%. The irregular distribution of values precludes simply assigning the change to evaporation from the reservoir.

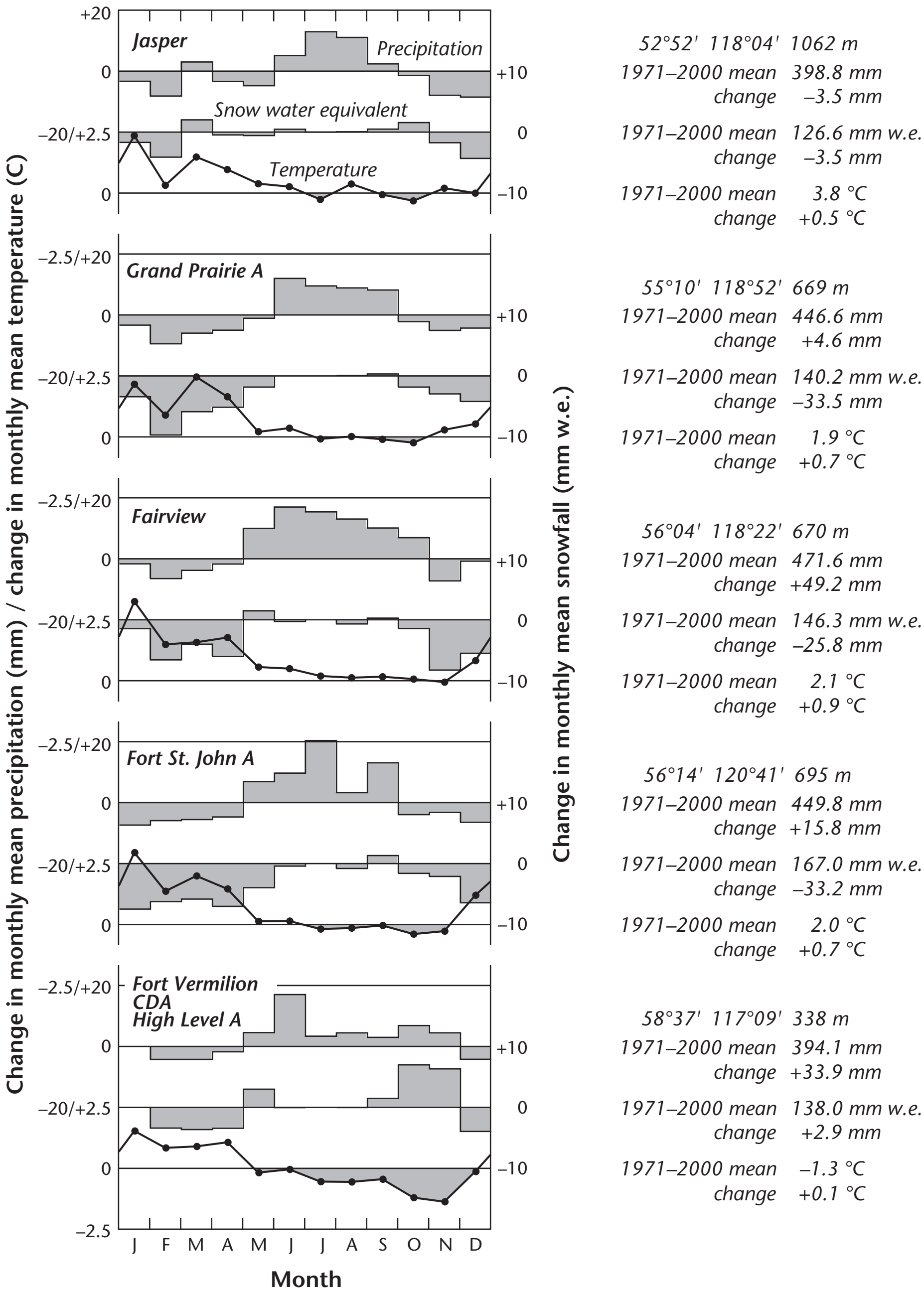
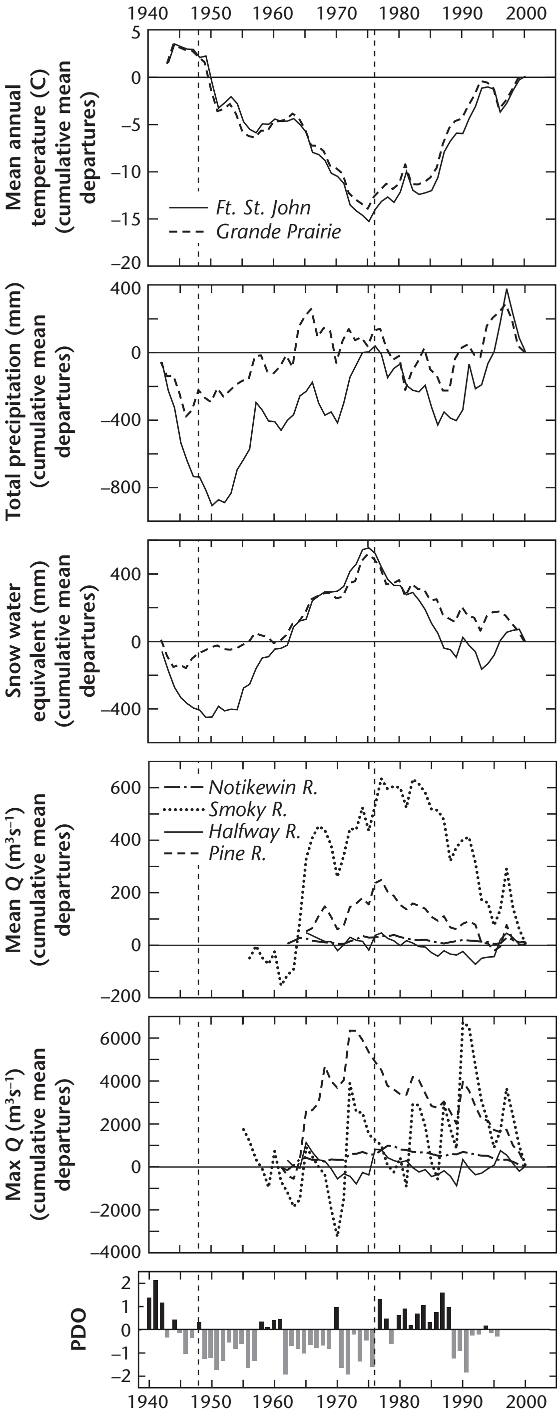


Figure 2.7 Differences between climatic normals for 1971 to 2000 (regulated period) minus 1941 to 1970 (unregulated period). Successive plots for each station are mean monthly precipitation, mean monthly snow accumulation, and mean temperature. The displayed stations (see Figure 2.1 for locations) are selected to represent the entire basin. Jasper is actually outside the basin headwaters, but is the only mountain headwater station with sufficiently long records. Fort Vermilion CDA/High Level A represents a record in which the station was moved between the two normal periods. The two stations are at similar elevation on opposite sides of the river, but this comparison remains less strict than the others. More generally, it is probable that some of the change in precipitation between the two normal periods is due to the deployment of shielded rain gauges in the later period. Snow water equivalent is estimated as 0.1 times accumulated depth, a standard practice at meteorological stations in Canada. Codes: *A*, airport; *CDA*, Canada Department of Agriculture.



In fact, the changes are consistent with the observed decline in winter snowpack in the region, indicating that spring nival runoff has indeed effectively declined.

The seasonal distribution of flow was, of course, dramatically changed by regulation (Figure 2.10). The dams have eliminated late spring flooding from the headwaters, while increasing winter flow. At Hudson's Hope, June flows are 33% of pre-regulation magnitude, while winter flows have increased by five times. The time of year when peak flow occurs has been shifted from June to winter at Hudson's Hope, but the freshet is weakly reestablished in June at Taylor, British Columbia, by the effect of Pine River inflow. The regulation effect is attenuated downstream by the addition of tributary flows but, even at Peace Point, the mean annual flood is only 55% of its pre-regulation value (Table 2.1), while winter flows have increased by three times. The increase in winter flow between Hudson's Hope (+1073 m^3s^{-1}) and Peace Point (+1082 m^3s^{-1}) is only nine cumecs.

Seasonal variability of flow can be indexed by the coefficient of variation of flows. For the annual variation of monthly mean flows, the coefficient was in excess of 1.0 in the pre-regulation period all the way down the system (Figure 2.11), whereas it declined after regulation to values generally between 0.3 and 0.6, signaling a large decline in annual flow variation.

2.2.3 Flood regime

The flood regime of Peace River has been dramatically affected by regulation. Figure 2.12 illustrates the time sequence of floods at the principal Peace River gauges and the estimated magnitude–frequency relations before and after regulation, while Figure 2.13 shows the variation in absolute and relative flood magnitude downstream. Mean annual flood is reduced by

←

Figure 2.8 Cumulated departure plots for climate in the Peace River basin (Fort St. John and Grande Prairie temperature, total precipitation and snow accumulation). Also annual flood (nival) for Pine and Smoky Rivers, and for Halfway and Notikewin Rivers, tributaries largely or entirely draining the Alberta Plateau. A positive slope (rising graph) indicates flows persistently above the long term average and a negative slope indicates flows persistently below the average. The Pacific Decadal Oscillation index (Mantua *et al.*, 1997) is also shown: significant changes in the index, indicating major changes in weather patterns over western North America, occurred in 1948 and 1976.

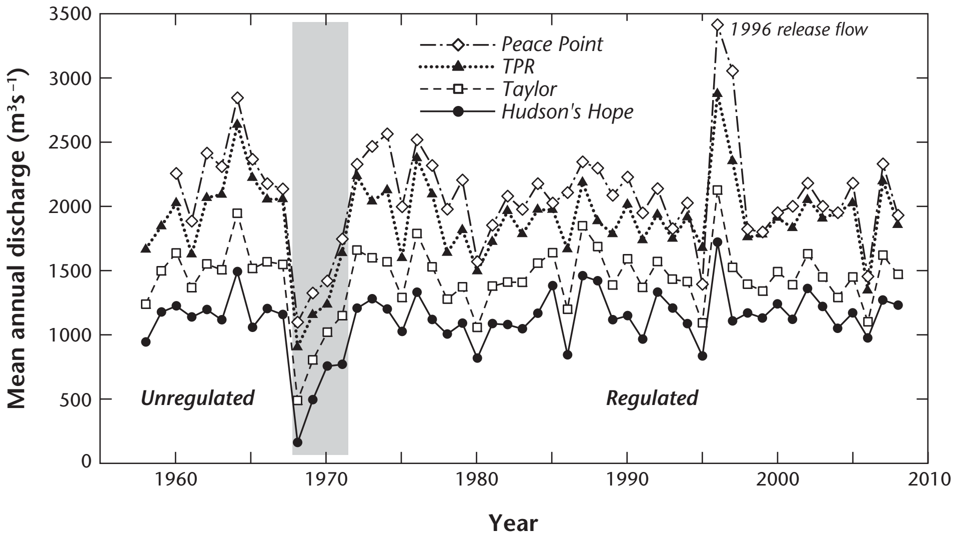


Figure 2.9 Time series of mean runoff at principal Peace River stations. Shaded region is the period of reservoir filling.

about two-thirds at Hudson's Hope and by about 45% at Peace Point. More extreme flows are even more strongly depleted at Hudson's Hope, but less so farther down river, particularly beyond Smoky River, where a dramatic change occurs in the comparative magnitude of unregulated floods versus those in the regulated period. Consequently, although pre-regulation floods are not likely to occur in the upper river in the regulated regime, flood levels beyond the Smoky confluence simply become less common (Figure 2.12b). For example, the former mean annual flood at the Town of Peace River (TPR) is now a 20-year event, while the 1990 flood of record, reckoned to be a 100-year flood in the pre-regulation regime appears, in the regulated regime, to

Table 2.1 Summary data of Peace River mainstem hydrometric stations

Station Name	WSC[a] No.	Drainage area (km²)	Distance below dams[b] (km)	Mean annual flow (m^3s^{-1}) Pre-reg.[c]	Post-reg.[d]	% change	Mean annual flood (m^3s^{-1}) Pre-reg.[c]	Post-reg.[d]	% change
Hudson's Hope	07EF001	69 900	6.5	1198_{1949+}	1135	−5	5843	1927	−67
Above Pine R.	07FA004	83 900	93	–	–	–		2211_{1980+}	
Taylor	07FD002	97 100	103	1560_{1945+}	1456	−7	7213	2837	−61
Alces R.	07FD010	118 000	143	–	–	–		2902_{1992+}	
Dunvegan	07FD003	130 000	275	–[e]	–[e]	–	8275_{1960+}	3379	−59
Town of Peace River	07HA001	186 000	377	1919_{1957+}	1883	−2	9700	5564	−43
Carcajou	07HD001	210 000	635	–[e]	[e]	–	9997_{1960+}	–	–
Fort Vermilion	07HF001	223 000	808	2357_{1961+}	[e]	–	9577	4894[f]	−49
Peace Point	07KC001	293 000	1115	2327_{1959+}	2100	−10	9817	5691	−42

[a]Water Survey of Canada.
[b]Distance below Peace Canyon Dam.
[c]From the year indicated by subscript (under mean annual flow) through 1967.
[d]1973 to 2010, excluding 1996, except where a later start date (+) or earlier end date (–) is noted by subscript.
[e]Station operated seasonally: mean annual flow not available.
[f]Data only to 1978 and 2006 to 2010.

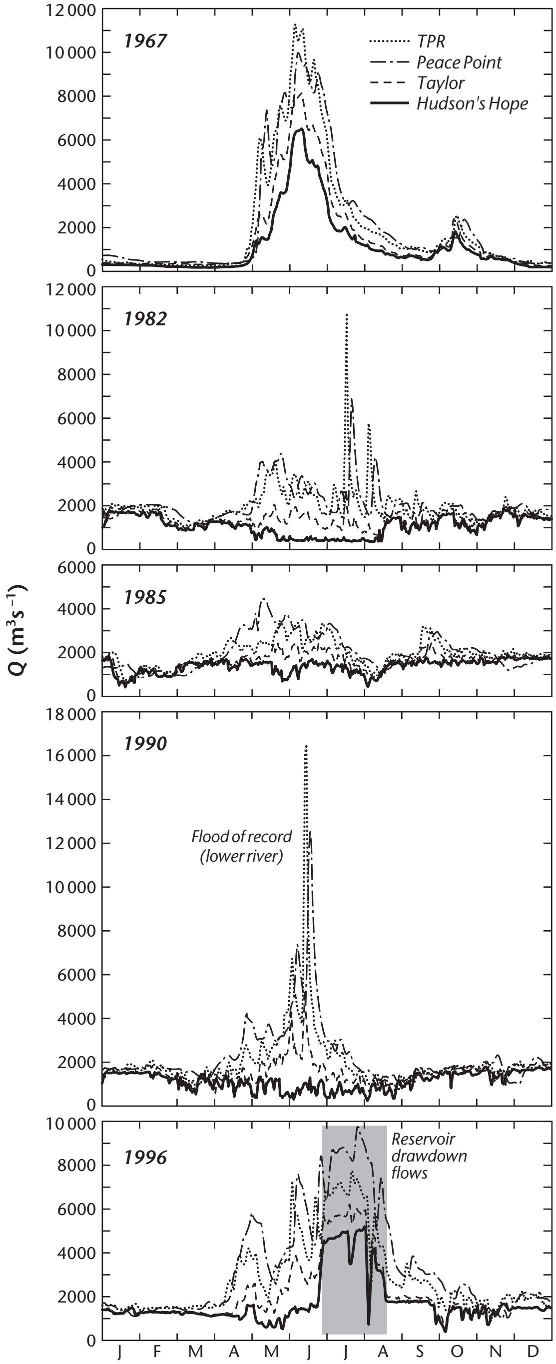


Figure 2.10 Mean annual hydrographs for unregulated (1967) and regulated periods (all other graphs) at Peace River mainstem stations. Taylor is immediately below the Pine River confluence and TPR is immediately below the Smoky River confluence. The 1967 record illustrates the normal nival flood on the river before regulation. The 1990 graph illustrates the flood of record on the river. Suspended sediment data at TPR (WSC Stn. 07HA001) are given in Figure 2.19 or 2.20 for all years in this figure except 1996.

have a nominal recurrence interval of about 800 years at TPR.

An interesting feature of Peace River floods is that their magnitude actually declines in the most distal part of the river (Figure 2.13a). There appear to be two factors contributing to this phenomenon. On one hand, the river turns north at TPR so that, farther downstream, spring thaw commences progressively later (by about 14 days between Peace River and Fort Vermilion), so increments to the nival flood become desynchronized downstream, especially from the large contribution of the southern Smoky Basin. On the other hand, the distal portion of the river basin is in any case drier, so that increments per unit increment of area become smaller.

The role of Smoky River in the flood hydrology of Peace River is important. Its drainage area of 53 000 km^2 is 28% of the area above TPR. Before regulation, its flood contributed 25% of the Peace River flood (comparing mean annual figures) but, since, it has contributed 45% of the downstream flood. The effect of regulation becomes much less significant, then, downstream from the Smoky confluence while interannual flood variability increases significantly, confirming this as an important division point for study of the river. This circumstance can be examined in another way by considering the change in relative flood magnitude through the basin. Before regulation, relative flood magnitude (the ratio of mean annual flood to mean annual flow) declined more or less regularly, but only modestly, in what may be recognized as a drainage basin scale effect (Figure 2.13b). After regulation, relative flood magnitude is dramatically reduced in the upper river, reaching a peak at the Smoky confluence, and declining thereafter in accordance with the scale relation for the basin. In the upper river, the headwater regulation dominates the trend of relative flood magnitude; in the lower river, it does not. This circumstance is perhaps best shown by

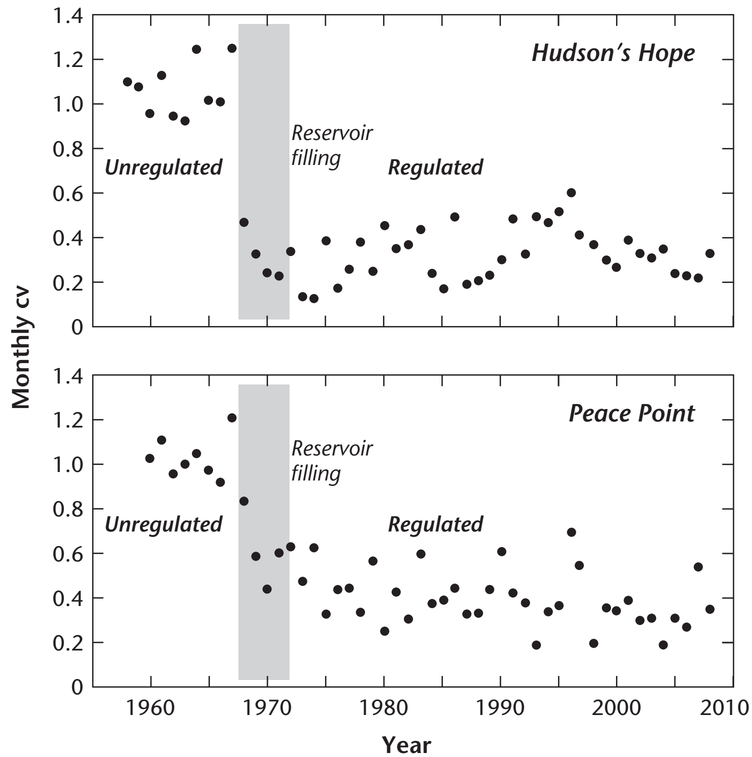


Figure 2.11 Annual coefficient of variation of monthly flows to illustrate seasonal flow variation before and after regulation. (a) Hudson's Hope. (b) Peace Point.

a plot of the ratio of pre-regulation flood magnitude to post-regulation flood magnitude (using mean annual flood as the index flow) versus the fraction of regulated area (Figure 2.13b). Normal drainage basin scaling appears to reassert itself at the Smoky confluence, where the regulated area proportion is 0.38.

Consistent with the declining influence downstream of regulation, the all-time flood of record on the lower river (June 13 to 17, 1990; 12 600 m^3s^{-1} at Peace Point) has occurred since regulation. It occurred as the result of late alpine snow melt, prolonged wet weather, and a major storm over the southern part of the basin. From June 10 to 12, rainfall exceeded 50 mm over most of the south-central part of Peace River basin, while more than 150 mm was recorded near Grande Prairie. Heavy precipitation was experienced as far north as Manning and as far west as Hudson's Hope. This event was also the flood of record at TPR (16 500 m^3s^{-1}) as the result of an 8620 m^3s^{-1} contribution from Smoky River. Farther downstream, dispersion of the flood wave actually reduced the peak flow. It was the post-regulation flood of record as far upstream as Taylor, British Columbia, reflecting the importance of the Pine River contribution, but not the all-time flood of record there.

The highest water levels on Peace River are not, however, associated with open water floods, but with ice jams during dynamic winter or spring ice breakups (Gerard and Karpuk, 1979; Uunila, 1997; Prowse and Conly, 1998). Figure 2.14 illustrates the history of ice-induced high water stages at TPR, which has the most comprehensive record of observations along the river. Here, the occurrence of high water is complicated by the relative timing of breakup and high flow on Smoky and Peace Rivers, but the history is representative of that at other sites along Peace River. Regulation has influenced the timing of freeze-up and breakup (Uunila, 1997; Conly and Prowse, 1998; Chapter 6), with full ice cover now occurring only intermittently in the first 300 km below the dam. At TPR, freeze-up has been delayed by about three weeks on average, but farther down the river changes in timing are small. Ice-induced high water influences channel-edge and overbank sedimentation, and ice directly causes shore zone scour and extensive damage to riparian vegetation (Uunila,

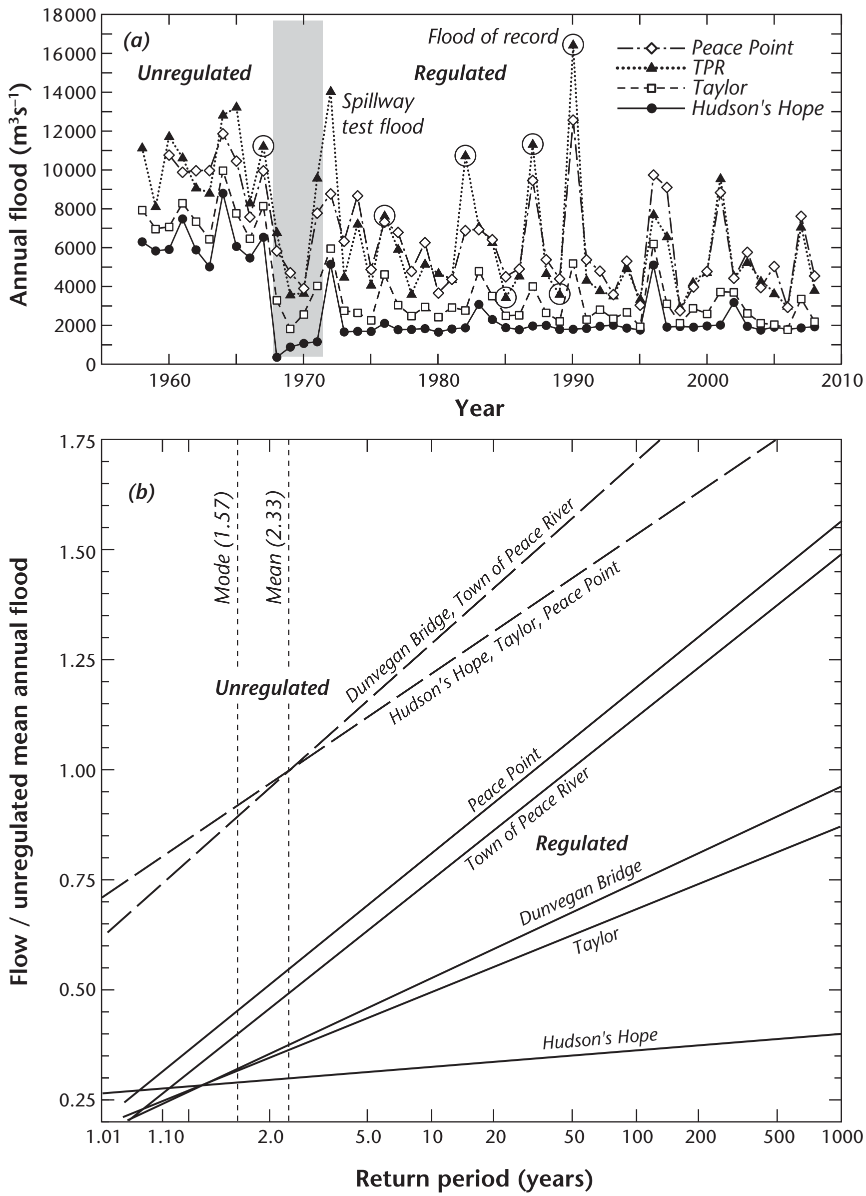


Figure 2.12 Estimates of floods along Peace River before and after regulation. (a) Time series plots of annual flood at principal Peace River stations. Points in the TPR record that are circled are years for which suspended sediment data that are given in Figure 2.19 or 2.20. (b) Flood frequency at gauges for which both pre- and post-regulation flows are available for at least 10 years. The common periods of record for the graphs are 1958 to 1967 (the only pre-regulation period for which all records are available) and 1980 to 1989. The common period of record was chosen to facilitate comparison. Modified from Figure 4 in Church (1995).

1997; Chapter 6). The history of high water events at TPR (Figure 2.14) implies that no systematic change in their potential magnitude has occurred since regulation, although the characteristically higher flows at freeze-up since regulation, and deliberate manipulation of reservoir releases at the time of breakup are both thought to have reduced the frequency of ice-induced high water, at least in the upper river.

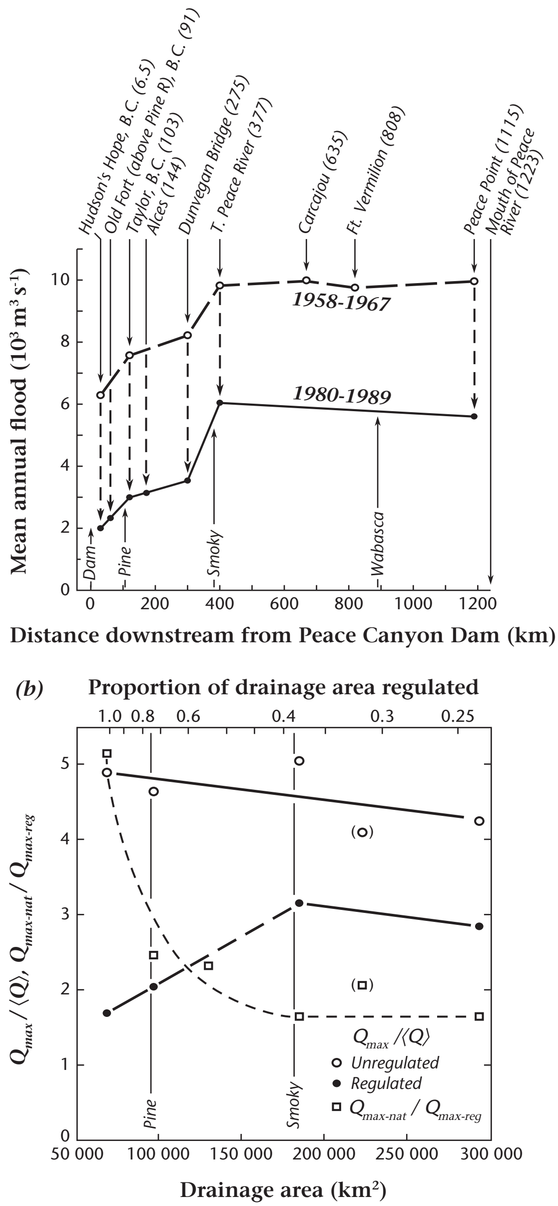


Figure 2.13 Variation of flood magnitude downstream. (a) Absolute magnitude of mean annual flood before and after regulation. Bracketed figures following station names are km downstream from the dam. Modified from Figure 4 in Church (1995). (b) Variation in relative flood magnitude with drainage area before and after regulation and variation of the ratio unregulated to regulated flood magnitude with proportion of regulated drainage area. All flood data refer to mean annual flood; the scale for relative flood magnitude is mean annual flow (which has not changed significantly). Bracketed points are derived from the unreliably short record at Fort Vermilion.

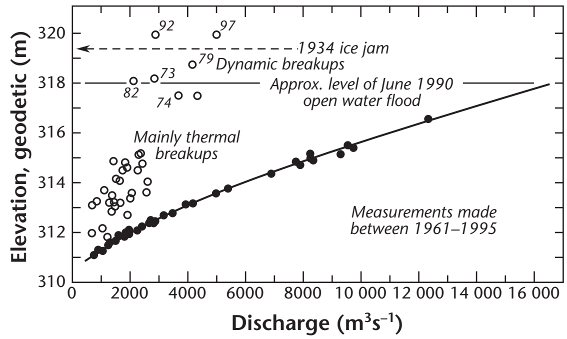


Figure 2.14 Peak water level versus discharge at the Town of Peace River (WSC Stn. 07HA001). Closed symbols and curve indicate the open water discharge measurements and stage-discharge relation. Open symbols indicate extreme ice-induced high water; and post-regulation years are identified. No flow datum is available for the 1934 ice jam (Analysis by L. Uunila).

2.2.4 Competent flows

For considerations of sediment transport and morphological adjustment of the river, the magnitude and duration of flows competent to move bed sediment are critical quantities. To help assess the effect of regulation on downstream flows, a "naturalized flow" sequence has been synthesized by BC Hydro on the basis of reservoir inflows and downstream gauged flows. Comparison with actual flows reveals the change in duration of flows of a given magnitude. The threshold of competence in the proximal, cobble-gravel reach of the river—that is, the threshold for bed disturbance—is estimated from bedload transport calculations (see Section 2.3.4) to be about 3000 $m^3 s^{-1}$. This is about one half the pre-regulation mean annual flood in the reach below Hudson's Hope. Using this estimate as a figure of merit, the daily flow record has been analyzed for the number of days that exceeded half-flood in comparison with the number indicated by the naturalized flow record at mainstem stations. The changes are graphically shown by comparing flow duration with the duration of naturalized flows (Figure 2.15).

In the Hudson's Hope reach, competent flows have been reached only during the spillway floods of 1972 and 1996 (64 days, mostly in 1996) (Figure 2.15a). At Taylor, where Pine River enters, competent flows were reached on 85 days between 1972 and 1998, only 0.9% of the time and only 8.1% of the days predicted under the naturalized regime (Figure 2.15b). Excluding the two spillway floods, the figure falls to 21 days, which is

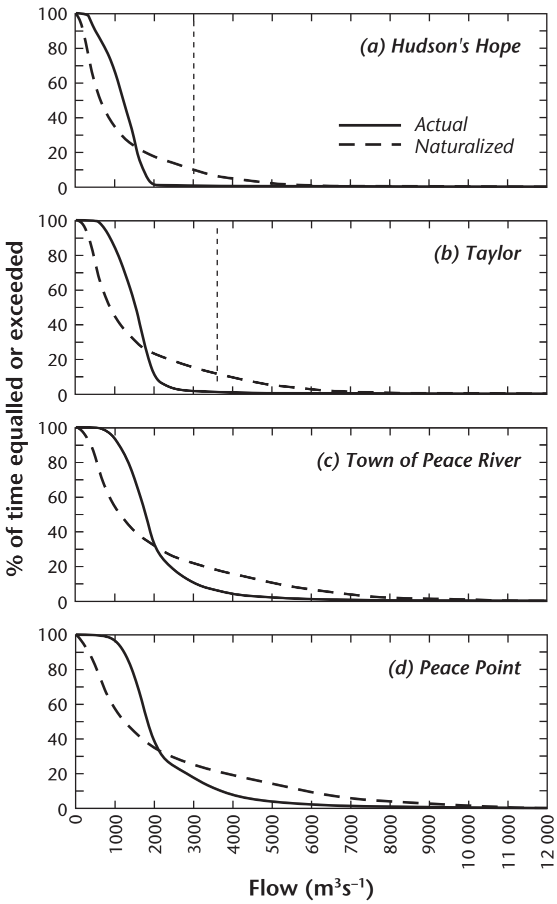


Figure 2.15 Flow duration curves for the period 1972 to 1999 compared with "naturalized flows"—the flows it is estimated would have occurred in the period if the dams had not been present. Vertical line indicates a nominal competence criterion for gravel entrainment from the bed in the upper river. See text for further details (Naturalized flows courtesy of British Columbia Hydro and Power Authority; analysis by C. P. Ayles).

2.2% of the days with naturalized flow. At TPR (below the Smoky River confluence), there apparently were competent flows on about 10% of the days—about half of the days predicted for naturalized flows. At Peace Point, the percentage of competent days rises to 15%. However, with the high sand content introduced into the lower river by Smoky River, and particularly in the sand-bed reach below Carcajou, competent flows probably actually occur a high proportion of the time and, indeed, sand is moved throughout the river much more readily than is implied by the above figures. In general, duration is decreased for all flows above 2000 m^3s^{-1} all along the river (1500 m^3s^{-1} at Hudson's Hope). It is evident that the regulation has had a dramatic effect on flow competence to transport bed material throughout the system. Peters and Prowse (2001) present a more thorough comparison of actual and naturalized flows, but do not broach the issue of sediment transport competence.

2.3 Sediment transport

The available record of sediment transport observations in Peace River is restricted to suspended sediment measurements by the Water Survey of Canada (WSC) at several hydrometric stations in Alberta and to miscellaneous measurements made in 1975 by BC Hydro in the British Columbia reach and in the principal British Columbia tributaries, and later by the WSC. The longest record (1966 to 1990) has been made at TPR (WSC Stn. 07HA001), immediately downstream from the confluence with Smoky River, which delivers by far the largest sediment load of any tributary. However, the record is tolerably comprehensive only in some years, so that there are limited possibilities for analysis. Amongst other stations, only Peace Point is reasonably comprehensive. Dunvegan records begin in 1975 but are based on very limited sampling.

2.3.1 Suspended sediment in the upper river

In 1975, during preliminary investigation of further dam sites on Peace River, BC Hydro conducted a program of suspended sediment sampling in the British Columbia reach and its principal tributaries (BC Hydro, 1975). Between 5 and 14 (mostly 12 to 14) samples were obtained at each sampled site and these data were made the basis for rating curve analyses which were convolved with flow duration curves based on the period 1961 to 1973 to estimate long-term suspended sediment loads. WSC measurements are consistent with those of BC Hydro. The basis is exceedingly tenuous and there are some apparent inconsistencies in the results. In the following paragraphs we present new estimates of suspended sediment transport, giving main emphasis to the derived suspended sediment budget for the river. To achieve the most consistent basis possible, suspended

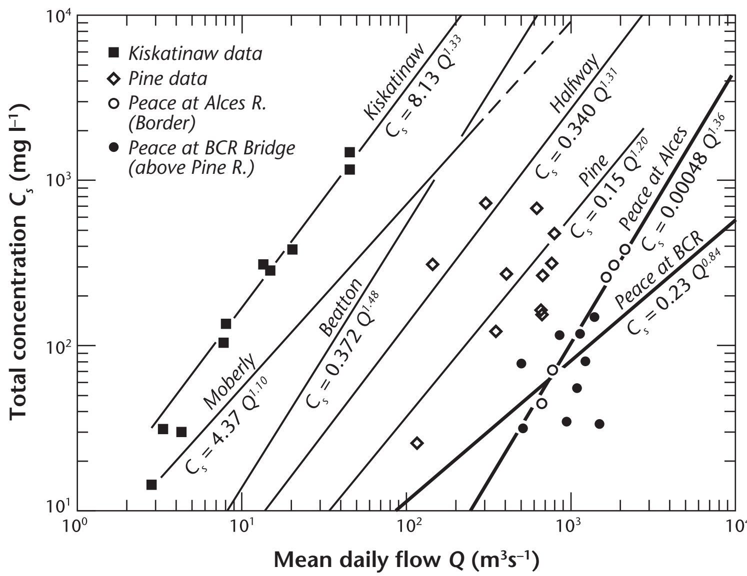


Figure 2.16 Suspended sediment concentration in the British Columbia reach of Peace River and in the major tributaries (Data from BC Hydro (1975)). Graphs from all stations are plotted together to facilitate comparison of the suspended sediment regime in each major tributary. Data are plotted for two Peace River stations, for Pine River (the largest tributary) and for Kiskatinaw River (showing the highest suspended sediment concentrations), but are suppressed for other stations to preserve clarity.

sediment has been estimated using flows for the 20-year period 1971 to 1990, corresponding with the period of the actual post-regulation record at TPR. Calculations were conducted using daily flows and the results, summed and averaged. For ungauged areas, estimates of sediment yield were based on calculated specific sediment yield for the most similar gauged area.

Figure 2.16 illustrates the suspended sediment rating curves derived from BC Hydro measurements for Peace River and its principal tributaries in the British Columbia reach. All tributary stations except Beatton River, known to be a prolific sediment producer, show a similar rate of change of suspended sediment concentration with flow, and it is not highly sensitive because most of the sediment is silt and clay (Figure 2.17). However, the characteristic concentration is different in each river. In general, the tributaries have higher concentrations than Peace River itself, in which concentrations are diluted by the large clear water contribution from the reservoirs. Moberly River is particularly revealing of sediment sources since it flows through a large lake that intercepts effectively all sediment derived from the headwaters. It nevertheless has the second highest suspended sediment concentrations, in general, for a given flow, all of the sediment necessarily derived from the incised lower course of the river in the Alberta Plateau.

The mean annual loads reported in Table 2.2 for the period 1971 to 1990 in the British Columbia reach are based on the rating curves displayed in Figure 2.16. It is immediately apparent that the results for the Peace River mainstem stations (Peace above BCR Bridge and Peace at BC–Alberta border—the station actually is immediately

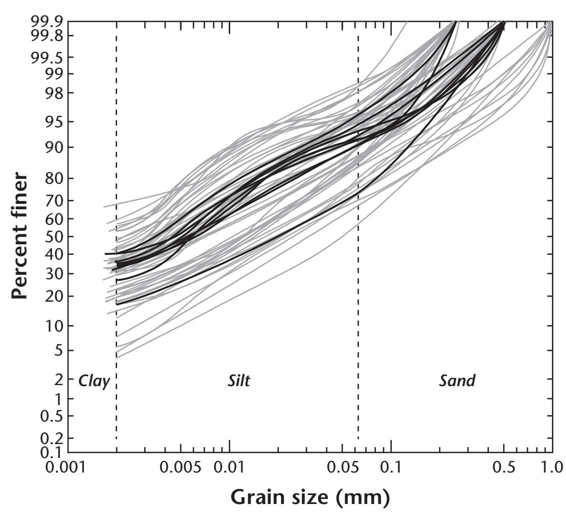


Figure 2.17 Mass plot of grain size distributions of suspended sediments from the British Columbia reach of Peace River and its principal tributaries. Note the strongly nonlinear ordinate axis. There are between 2 and 11 curves for each station. Most analyses derive from composites of several individual water samples. The emphasized curves are from Peace River below Alces River; that is, at the British Columbia–Alberta border (Data from BC Hydro (1975)).

Table 2.2 Estimates of long-term sediment yield in the Peace River basin, from measurements of suspended sediment[a]

Contributing area		Estimated yield (tonnes a^{-1})	Area (km^2)	Specific yield (tonnes km^{-2} a^{-1})
Upper Peace R[b]		*380 000*[c]	2432[d]	*157*
Halfway R		1 405 000	9402	149
Moberly R		90 000	1841	49[e]
Sum		*1 875 000*		
Peace R at BCR Bridge (from rating)		(4 018 000)	13 675[d]	(294)
Peace at BCR Bridge (estimate)[f]		*1 885 000*		
Net difference		*10 000*		
Pine R		1 956 000	13 533	145
Beatton R		4 417 000	16 058	275
Kiskatinaw		1 089 000	4367	249
Ungauged area below BCR Bridge		*420 000*	1677	*250*
Sum (inc. Peace at BCR Bridge)		*9 767 000*		
Peace R at BC-Alberta border		(14 325 000)	52 059[d]	(275)
Net difference		*4 558 000*		
Ungauged area: border-Dunvegan		*2 010 000*	8041	*250*
Sum (from BC border)		*11 777 000*		
Peace R at Dunvegan (07FD003)	M[g]	15 600 000	60 100[d]	260
Peace R at TPR (07HA001)	F	35 045 000	116 000[d]	291
Smoky River[h]		*16 880 000 to 20 940*	*50 300*	*335 to 416*
Peace R at Peace Point (07KC001)	F	37 800 000	223 000[d]	169
Difference from TPR		*2 755 000*		
Notikewin R (07HC001)	M	220 000	4680	47
Boyer R (07JF002/003)	M	497 000	9110	55
Estimated contribution from lower basin[i]		*5 350 000*	*107 000*	*50*[i]

[a] Based on sediment sampling by BC Hydro (1976, Table 1 and Figure 15); results have been recomputed using flow records for the period 1971 to 1990; and on compilations by Carson and Hudson (1997) of WSC suspended sediment records at Alberta stations. Alberta data are restricted to the period 1971 to 1990 and the listed stations have 15 years or more of record within this period. All data rounded to 1000 tonnes. Estimated quantities in italics.

[b] Ungauged area between between Peace Canyon Dam and the BCR Bridge.

[c] This estimate is ratioed up from seasonal measurements made on Peace River below Lynx Creek and on Farrell Creek, downstream from Hudson's Hope. The ratio used (3.9) was that derived for the difference between the sediment yield during the measurement period (June to August, 1975) and the estimated long-term annual sediment yield for Halfway River, which drains the adjacent terrain of similar character.

[d] Area below the Peace Canyon Dam only.

[e] Specific yield for Moberly River considering only the area below the lake is 111 tonnes km^{-2} a^{-1}.

[f] Estimate by applying the specific yield derived for Halfway River (see text for discussion).

[g] F = full sediment observing program; M = miscellaneous measurements only; code in parentheses is the WSC station number.

[h] By area ratio from Dunvegan, 0.9 of the areal difference between Dunvegan and TPR.

[i] Product of lower basin area, 107 000 km^2 × 50 tonnes km^{-2}, the mean of Notikewin and Boyer River specific yields.

upstream of Alces River) are anomalously high in comparison with loads delivered by the tributaries: the discrepancy between mainstem loads and the sum of tributary contributions, including adjustments for ungauged areas (Figure 2.18a), is about four million tonnes. There is a plausible reason for this. The 1975 measurements that constitute the basis for the rating curves were made during a low-flow year just two years after the Attachie slide (Figure 2.4c) fell into Peace River. Erosion of the slide mass yielded a surcharge of sediment to Peace River for some years afterward, which is undoubtedly reflected in the Peace River measurements of the period. Accordingly, supplementary estimates have been made of the annual sediment flux at these mainstem stations by multiplying the contributing area by an estimate of the specific yield derived from the

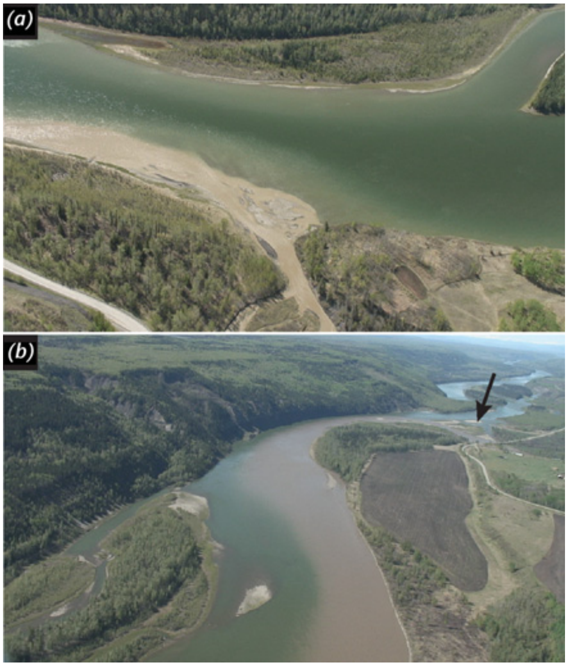


Figure 2.18 (a) Suspended sediment entering Peace River from ungauged Farrell Creek, May 28, 2009. Farrell Creek enters Peace River 24 km below Peace Canyon Dam (Peace River flow is right to left). (b) Suspended sediment plume originating from Halfway River (arrow). View upstream, May 28, 2009; flow is 1195 m^3s^{-1} (Photo courtesy of M. J. Miles).

tributary measurements. At BCR, this brings the sediment budget into approximate balance, but this should not be surprising since the figures are based almost entirely on the observed sediment yield from Halfway River (Figure 2.18b). It appears that the sediment yield of the BC reach of Peace River is the order of 10 million tonnes a^{-1}, some allowance being made for unmeasured sediment yielded directly from the banks of the mainstem. Specific yield above Pine River is about 150 tonnes $km^{-2}a^{-1}$, while below the Pine confluence it is about 250 tonnes $km^{-2}a^{-1}$. The difference is reasonable: the tributaries to Pine River drain significant mountain and highland terrain; those farther east mostly or entirely drain the Alberta Plateau. The data plausibly reflect the growing dominance of the friable lithologies of the Alberta Plateau in the drainage areas of downstream tributaries, though the increasing proportion of arable land may be implicated in the pattern as well. The specific yield from Moberly River is anomalously low, despite the high sediment concentrations, because the upper half of its drainage is controlled by Moberly Lake and much of the remaining area is wetland.

The material represented in the suspended load (Figure 2.17) is remarkably fine. It is composed of 20% to 50% clay, and up to 70% clay in the Beatton and Kiskatinaw Rivers. Sand constitutes about 5% to 10% of the load at the Alberta border, though up to 30% or 40% in the Pine and Moberly Rivers, and as little as 2% in the distal tributaries. There is abundant evidence of sand deposition on the channel margins downstream from the Pine River confluence, and the overall gradational trend in the river below the Moberly confluence is aggradational (Chapter 3) with more than 0.5 m of sedimentation in some surveyed cross-sections. This order of aggradation sequesters some material in the river below the Pine confluence. In comparison, there is no indication of systematic aggradation upstream of Moberly River. Allowing an average of 0.1 m of aggradation, as much as two million tonnes of sand may have been deposited, but this amounts to only some 50 000 tonnes a^{-1} and could not be resolved within our budget.

The indicated transport at Dunvegan, the first WSC sediment station on Peace River, is 15.6 million tonnes, in comparison with an incoming estimate of 11.8 million tonnes, so that the discrepancy persists. Dunvegan data are based on WSC measurements, mostly only one to three measurements per year taken during freshet and so the annual load may easily be systematically overestimated. The annual load at Dunvegan probably is close to 12 million tonnes. No error margins may be placed on these exceedingly approximate figures.

2.3.2 Suspended sediment in the lower river

The comparatively well-established mean annual load at TPR for the period 1971 to 1990 is 35.0 million tonnes, 19.4 to 23.3 million tonnes more than at Dunvegan (Table 2.2). Most of this difference is plausibly assignable to Smoky River, for which there are no measurements anywhere along the lower course. The load assigned to Smoky River, 17 to 21 million tonnes a^{-1} (by area ratio from Dunvegan) indicates a specific annual yield of 335 to 416 tonnes km^{-1} from the basin, which exceeds the yield from upper Peace River but is plausible when the greater agricultural development of the basin is considered. It is possible, however, that TPR loads are overestimated because many of the individual measurements are based on a single vertical that may disproportionately sample the Smoky River plume.

At Peace Point, the river is estimated (on the basis of a 20-year record) to carry 37.8 million tonnes annually, an increase of only 2.8 million tonnes over TPR. There are few observations in the lower basin. Two tributaries of the lower river with some sediment measurements indicate specific annual yields of about 50 tonnes km^{-1}, so there undoubtedly is a large decline in sediment mobilization here, probably because of the increasing fraction of wetland and declining area of arable land in the more northerly region, and because the declining valley walls along both the main river and the tributaries become less failure-prone. Assigning this specific yield value to the lower basin, the gross contribution is estimated as 5.4 million tonnes a^{-1}. On this reasoning, approximately 2.6 million tonnes a^{-1} of sediment is being deposited in the lower river. At TPR, 13.4% of the suspended load is sand, that is about 4.5 million tonnes. A significant portion of this material is deposited on the river bed between TPR and Peace Point, most of it above Fort Vermilion.

2.3.3 The suspended sediment record at the Town of Peace River

Historical records at TPR permit a direct investigation of changes in suspended sediment transport in Peace River associated with the regulation. In order to investigate the change, the years 1967 and 1982 have been selected for a direct comparison. The mean annual flows of these two years were 2070 m^3s^{-1} and 1980 m^3s^{-1}, respectively, and mean annual floods were 11 300 m^3s^{-1} and 10 800 m^3s^{-1}. Total suspended sediment load of the two years was 34.6 and 40.3 million tonnes, the larger total in the later year being accounted for by the occurrence of two summer floods. These values are rather similar. However, because of regulation and summer weather, the hydrographs (Figure 2.10) and sediment load graphs (Figure 2.19) of the two years are markedly different. A rating curve based on data of daily mean flow and suspended sediment concentration is plotted for each year in Figure 2.19. The graph for 1982 plots above that for 1967 indicating that, for the same water flow, suspended sediment concentration (hence sediment transport) is higher in the post-regulation period. Median rating functions for the two years are as follows:

$$1967:\quad C_s = 2.8\times10^{-1}Q^{1.65}\quad (n = 139;\ r^2 = 0.88),$$
$$1982:\quad C_s = 5.2\times10^{-1}Q^{1.82}\quad (n = 124;\ r^2 = 0.57),$$

wherein C_s is suspended sediment concentration in $mg\ m^{-3}$ (usually determined from one measurement per day) and Q is daily mean flow (m^3s^{-1}). The straightforward explanation of the plots is that, in the post-regulation period, the characteristically lower discharges through the spring and summer periods, when most of the sediment is mobilized, lead to higher concentrations of sediment in the water column. In comparison with the British Columbia rating curves, those from TPR are rather more sensitive. This is probably because Smoky River contributes a significant increment to the sand load, transport of which is more sensitive to flow stage than is silt-clay.

In the post-regulation period, different years exhibit variations in the relation between flow and sediment yield. Figure 2.20 gives sediment load plots for several years. The years 1987 and 1990 were ones with high flows and the relations appear to have three segments. At the upper end is a flood flow domain in which dQ_s/dQ declines, presumably when the sediment supply becomes limited as flow continues to increase. Similarly, sediment load is relatively insensitive to changes in discharge during the lowest flows of winter, when base flow from the sediment yielding tributaries is diluted by the relatively large clear water release from the dam. This phenomenon does not appear in the two-year record before regulation. Other high-flow years, for example, 1982, appear not to exhibit the upper "insensitive" domain, nor do years when flows do not exceed 4000 m^3s^{-1}, that is, years with no significant flood. The reason why flood years are inconsistent is not clear; it may have to do with the origin of the runoff and sediment, but may also be as simple as the lack of high-flow measurements.

Figure 2.20 also shows that ratings vary from year to year. Significant sediment hysteresis is evident in some years. The origin of runoff, particularly in the Smoky basin—a function of spring and early summer weather—and the episodic occurrence of major landslides into the river are reasons for this variability, which is the rule for suspended fines in most rivers.

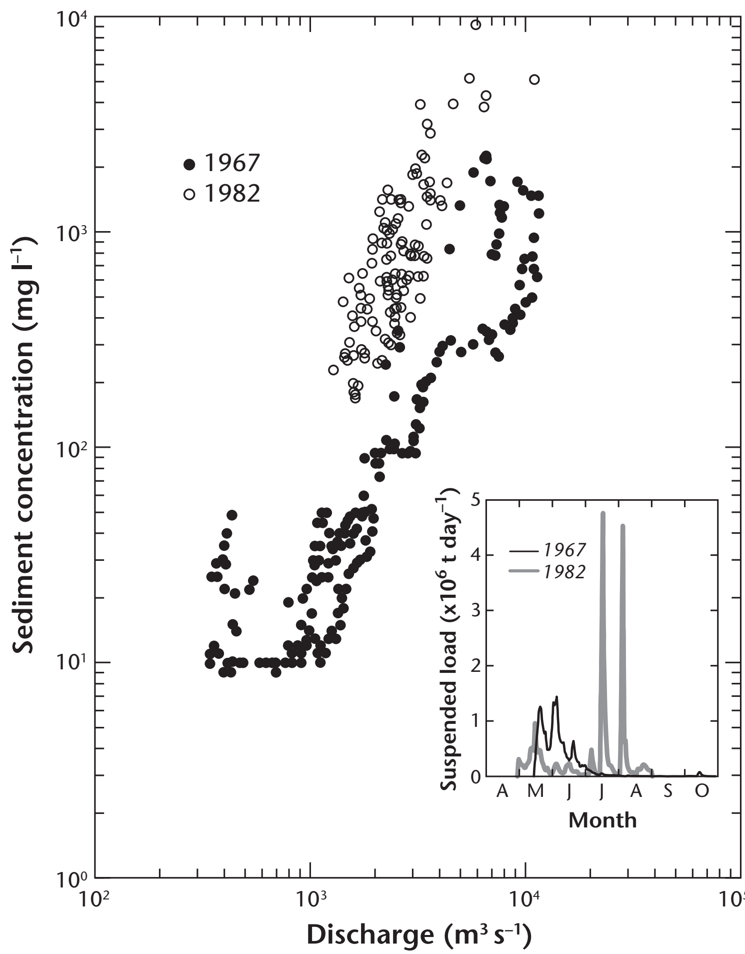


Figure 2.19 Suspended sediment concentration ratings for Peace River at the Town of Peace River (WSC Stn. 07HA001) for 1967 and 1982. Annual hydrographs for these years are given in Figure 2.10.

Annual suspended sediment load is related to some measure of annual water yield in many rivers. In Figure 2.21, annual load at TPR is correlated with mean annual flow. The post-regulation flows show a good relation with $L_s \; \alpha <Q>^4$ approximately, wherein L_s is annual suspended sediment load (tonnes) and $<Q>$ is mean annual flow (m^3s^{-1}). The two pre-regulation years of data are insufficient to establish a relation, but it appears that it may have fallen to the right of the post-regulation trend, as would be required by the arguments related to the comparison of individual annual ratings above. The differing results from the two pre-regulation years, which had virtually identical flow volumes, are explained by the 1967 freshet being substantially larger than that in 1966.

Similarly, the reservoir-filling years are displaced to the left, indicating still higher sediment loads per unit flow, the highest of all being the lowest flow year, 1968. These data make clear that the river is capable of carrying substantially more sediment in suspension than is actually transported. The fine sediment supply to Peace River, most of it derived from bank collapse and landslides along tributaries, remains supply limited.

A factor that might complicate suspended sediment load estimation at TPR is the surge in suspended sediment concentration that accompanies dynamic ice breakup (Milburn and Prowse, 1996). Such an event happened at TPR and upstream in 1974—a year with high sediment load. It is not normal to make measurements during breakup because of the danger to

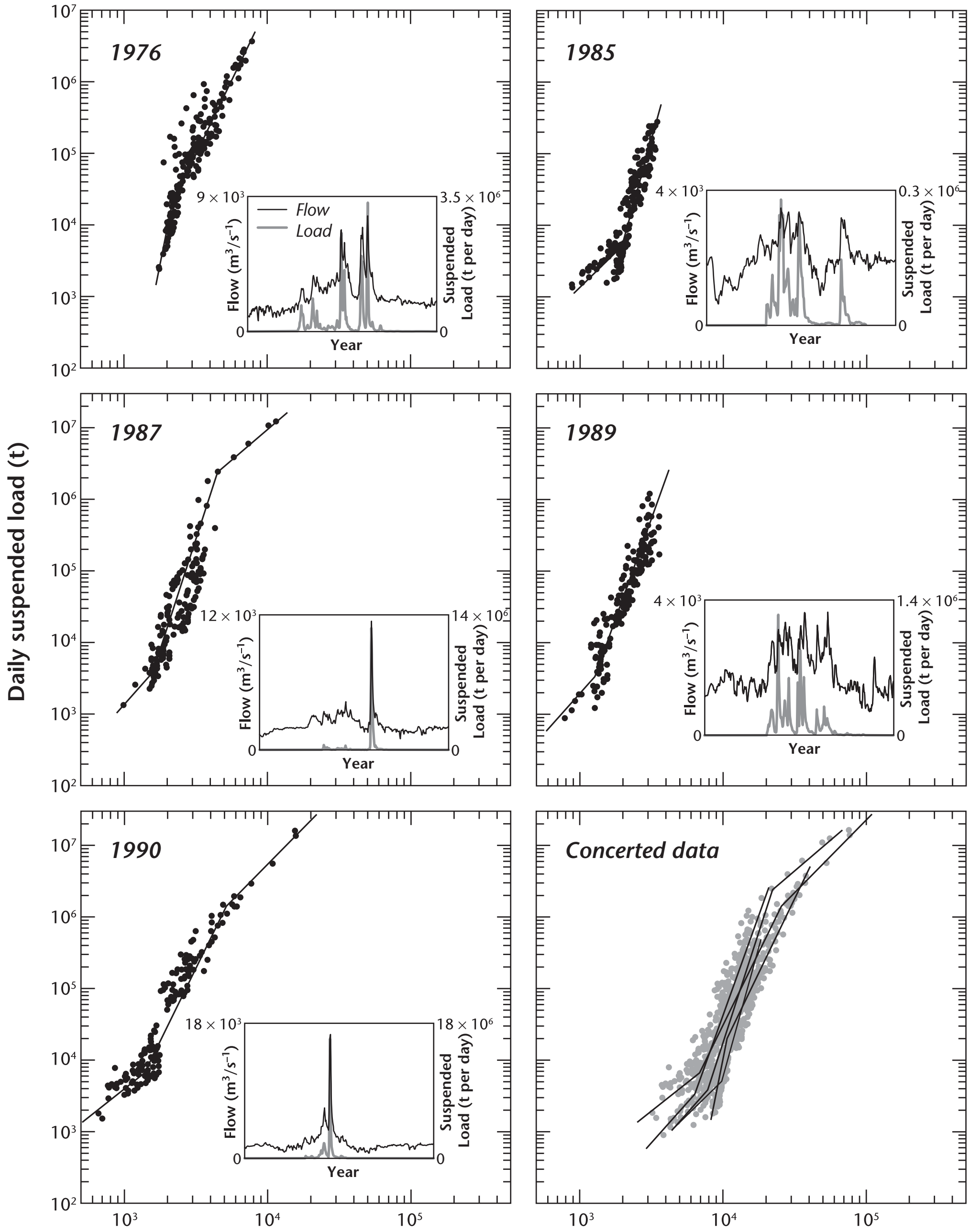


Figure 2.20 Suspended sediment load ratings for various years in the post-regulation regime. The lower right panel shows the concerted data and individual annual rating curves. Data for 1982 (Figure 2.19) are not included in this plot. Data from WSC Stn. 07HA001.

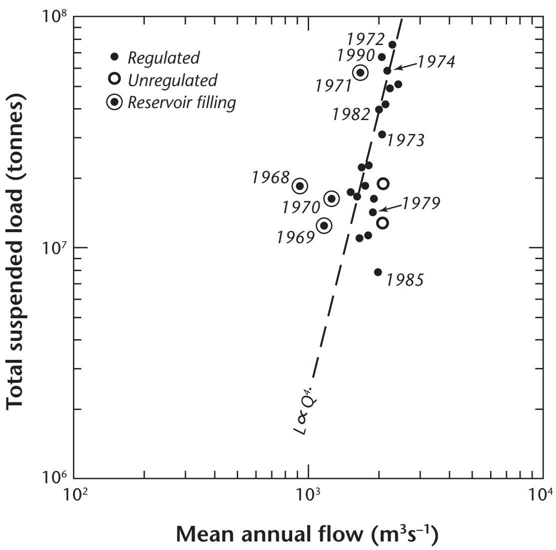


Figure 2.21 Correlation between annual suspended sediment load and mean annual flow, Peace River at the Town of Peace River (WSC Stn. 07HA001).

personnel. It is known, however, that ice scour and water surge associated with rapid breakup mobilize significant amounts of fine sediment from the streambed and banks, which then may flow under the downstream ice ahead of the breakup. There is no critical evidence with which to assess this effect at TPR, so that it remains a potential source of bias in years with significant ice jams.

The 1972 sediment yield is highest of all years. Though spillway tests of short duration occurred in this year, it was by no means the highest flood year. But it was the first year with flood flows following reservoir filling. Sediment yield in 1971 was also higher than might be expected. These results probably reflect flushing through the river of the accumulation of fine sediment from the several anomalously low-flow years preceding.

2.3.4 Bedload

There are no measurements of bedload transport in Peace River. In the British Columbia reach of the river, computations have been made by the present writer and are summarized in Table 2.3. Of these calculations, it can be said that an attempt was made to confirm the selected formula using measurements made in a river similar in

Table 2.3 Estimates of bedload transport in Peace River and principal tributaries[a]

Reach	Computed transport (tonnes a^{-1})[b]	Basis	Bed fraction[c]	Grain size (mm)[d]	
				D_{35}	D_{65}
Halfway R	6900	Modified Einstein[e]	0.3	17	51
Moberly R	37 000	Meyer–Peter	0.5	21	62
Pine R	8600	Modified Einstein	0.3	92	40
Beatton R	1300	Modified Einstein	0.2	81	15
Kiskatinaw R	14 000	Meyer–Peter	0.1	5	96
Peace R at BCR	0	Modified Einstein	0.4	15	38
Peace R below. Alces	2800	Modified Einstein	0.4	11	61

[a]Several formulae developed for gravel-bed rivers were tested using data from Elbow River (Hollingshead, 1971), a river of character similar to the Peace River tributaries on which measurements have been made. The modified Einstein formula was chosen for use based on its superior performance for that river. The Meyer–Peter formula was adopted in the case of the two steepest tributaries, for which the Einstein formula returned improbably low results.

[b]Based on a computationally derived rating curve using hydraulic geometry from surveys, convolved with a flow rating curve.

[c]Based on the fraction of bed area visually determined to have deposits that appeared to have been mobilized recently. Much of the bed of all these rivers consists of stable lag cobble.

[d]Based on bulk analyses.

[e]The formula was forced to conform with measured flows and velocities (in its original form, the formula assumes that no gauging is available and computes these results).

many respects to the main tributaries (but much smaller than Peace River itself), and that adjustments were made for the obviously significant portion of the streambed that appeared to be stable (details in Table 2.3). The grain size determinations were based on samples taken from gravel deposits in Peace River deemed to be recent (and reported in BC Hydro (1975)).

The indicated bedload transport in the lowermost part of the principal tributaries is, in all cases but Moberly River, much less than 1% of the estimated suspended load. For Moberly River, significant transport is indicated, which is consistent with the fact that it flows below eroding rock bluffs in the lowermost part of its course (Figure 2.22) and with the appearance of active sedimentation at the confluence with Peace River. The small result for Beatton River is reasonable; the lowermost portion of its course is flat and appears to be inactive, and the "delta" at its mouth is restricted to a small bar. The Pine River result appears to be anomalously low in comparison with the active appearance of the lowermost part of the river. An alternative estimate of bedload transport in the lower Pine can be made by estimating aggradation in the bed of Peace River immediately downstream from the confluence. Three significantly aggraded survey cross-sections downstream exhibit an average of 0.86 m of aggradation, while the Taylor gauge indicates 0.50 m from specific gauge analysis (Chapter 3). These two estimates of aggradation bracket annual sedimentation volumes (bulk) of 17 500 to 30 000 m^3, which translates into approximately 25 000 to 40 000 tonnes a^{-1} of sediment delivered, most of which would be gravel carried on the bed. This is about 1% of the suspended load, and appears to be more reasonable for this river.

A second set of bedload transport estimates was made by Ayles (2001) from river morphology in the lower Halfway and Pine Rivers. He measured changes in the area of river bars between 1970 and 1997 from air photos and calculated sediment transport by using field-surveyed bar heights and estimating transport distance as the distance to the first significant sediment accumulation downstream from a point of significant erosion. He estimated annual bed material transport of 7700 tonnes a^{-1} near the mouth of Halfway River and 15 000 tonnes a^{-1} near the mouth of Pine River. The Halfway result is consistent with the formula estimate, while the Pine result is of similar order to the estimates given above and higher than the formula estimate: the morphological estimates are probably the more reliable.

There is no bedload transport indicated in Peace River at the BCR Bridge, and this result is probably correct. The bed morphology there was stable for many years and changed only modestly after the 1996 flood. Above Moberly River, the channel bed has extensive periphyton growth (Figure 2.23), indicating no disturbance. Moberly River appears to deliver a significant sediment charge but it is doubtful that it escapes the immediately downstream reach, and much of it is trapped in the prograding delta-fan of the river. The fan has backwatered Peace River upstream and significant

Figure 2.22 Lower Moberly River, showing actively eroding valley bluffs and gravel deposits in the river; view upstream from over the confluence with Peace River, May 28, 2009: flow is approximately 40 m^3s^{-1} (Photo courtesy of M. J. Miles).

Figure 2.23 (a) Macrophyte growth on the emergent bed of upper Peace River above Halfway River. (b) Macrophyte growth with heavy siltation, emergent bed of upper Peace River above Moberly River confluence.

aggradation begins in the reach immediately upstream of Moberly River, indicating limited transport there, probably sourced from landslides a short distance farther upstream. Indeed, some bars along the river clearly incorporate landslide debris (Severin, 2004).

At the Alberta border, the bedload transport is indicated to be only a few thousand tonnes and that is surprising, considering the proximity of the mouth of Kiskatinaw River. However, that tributary appears to contribute the order of 10^4 tonnes at most, much of which remains sequestered in tributary mouth bars. One concludes that the regulation has largely immobilized the gravel bed of Peace River. In particular, the river appears today to be incompetent to carry away the gravel load delivered from the most active tributaries, each of which delivers on the order of 10^4 tonnes a^{-1}. These results are consistent with the findings on the duration of nominally competent flows reported above.

This condition appears to persist as far as the Smoky confluence, and the large increment there to the suspended sediment load of the river probably continues to dwarf the bedload, even though there must be substantial sand movement over the bed downstream from TPR. The gauging station at TPR is located on a bedrock sill and there is no indication of abundant gravel movement across the sill. At TPR, the suspended sediment record fairly reliably is a record, then, of the sediment load of the river.

2.4 Discussion and conclusions

In late 1967, BC Hydro commenced regulating Peace River and thereby imposed primary hydrological changes on the river. These included the following:

- a reduction in annual maximum flows to about 30% of pre-regulation flows immediately below the dams, and to about 60% of pre-regulation values more than 1000 km downstream;
- increase of winter flows by as much as five times along the river;
- a reduction of seasonal flow variation to between 30% and 50% of pre-regulation values;
- reduction in the occurrence of competent flows by an order of magnitude.

It is shown that changes in hydroclimate occurred around the time of regulation. There has been an increase in summer precipitation and a significant decline in winter precipitation, with the main change probably occurring in 1976 to 1977. This has reduced total runoff since spring snowmelt is much more hydrologically effective than summer precipitation. Despite these changes, the flood of record on the lower river occurred in June 1990, and the event was significant as far upstream as Pine River. Hence, significant natural events may still generate extreme flows in the river. In 1996, reservoir drawdown generated a prolonged flow that essentially represented post-regulation bankfull as far downstream as TPR, demonstrating that exceptional reservoir operations may also create relatively extreme events for hundreds of kilometres downstream.

Regulation of flows has influenced the timing of ice formation in the river and the extent of the river that is subject to persistent, complete ice cover, but appears not to have significantly affected the breakup regime.

Because most of the sediment load is introduced into the river downstream from the dams, the effects on sediment transfer along the river are entirely responses to the primary hydrological changes. Significant effects appear to include the following:

- a shift in suspended sediment ratings toward higher concentrations of fine sediments being carried in the water column;
- no significant shift in the total mass of suspended fines transported;
- indication that sands are being deposited in the reaches below Pine River, British Columbia, and downstream from Smoky River;
- reduction of competence to move gravel in the upper river to near zero duration: in particular, there appears normally to be no significant bedload movement upstream of Pine River;
- consequent accumulation of gravels near tributary junctions where significant gravel loads are delivered to Peace River.

A tentative sediment budget is presented for the suspended sediment load of the river (Table 2.2), which constitutes nearly the entire load, although not necessarily the morphologically important load. Data of sediment transport are sparse and all measurements in British Columbia are probably influenced by their recovery in a low-flow year and the occurrence of a major landslide into the river only two years prior, so that the main results must be regarded as inferential or conjectural.

In terms of Petts's (1984) typology of river responses to regulation, the sediment transport investigations and sediment budget imply that Peace River above Pine River exhibits mainly passive adjustment; downstream from Pine River, an aggradational response related to tributary sediment delivery appears to be in train. The post-regulation sediment regime suggests that the classic degradational response will be limited to local sites along the river. In terms of the appearance of fine sediments along the channel edges, growth of bars at tributary confluences, and localized aggradation and degradation, the response in the upper river is qualitatively similar to that observed by Sear (1995) on the River North Tyne in the United Kingdom.

In order to examine the river response domain as codified by Schmidt and Wilcock (2008), we require estimates of $q_{\text{MAF-reg}}/q_{\text{MAF-nat}}$, in which q is the specific flood discharge (i.e., discharge per unit width, here indexed by mean annual flood), $q_{s\text{-reg}}/q_{s\text{-nat}}$, in which q_s is the specific sediment load, and τ^*, the Shields number, a nondimensional measure of the competence of the flow. (In their examples, Schmidt and Wilcock used $Q_{\text{reg}}/Q_{\text{nat}}$, and similarly for sediment and assumed a constant channel width; here the adjustment in channel width to carry the smaller flows has been considered by taking the square root of these ratios, in keeping with the well-known width scaling relation of hydraulic geometry.) To compute τ^*, we require estimates of the riverbed surface material and river depth, d, at the index flow. For natural flows, we adopt values from Kellerhals *et al.* (1972) for mean annual flood at each of the stations listed in Table 2.1. For post-regulation flow depth, we adjust the pre-regulation value according to the ratio indicated by hydraulic geometry (Church, 1995; see Chapter 5). For the adjustment of sediment load, we require an estimate of the load formerly delivered from the reach above the dams. This is problematical, since there are no measurements. Regional analysis of clastic sediment yield (Church *et al.*, 1999) suggests that sediment yield in Peace River headwaters is the order of 1000 tonnes per day from a drainage area of 10^4 km^2. This estimate scales to about 2.5 million tonnes a^{-1} for the 69 900 km^2 headwater area. This amount is added to the post-regulation estimates of suspended sediment transport (from Table 2.2) to derive ratios of post- to pre-regulation specific load and the results are plotted in Figure 2.24. They show extreme sediment deficit at Hudson's Hope, as one very well knows, and very slight sediment surplus elsewhere along the river. Values of τ^* suggest that the river was barely able to move the gravel bed before regulation ($0.047 \leq \tau^* \leq 0.070$) but that sand could be moved in suspension all along the river. After regulation, $0.039 \leq \tau^* \leq 0.052$ for gravel which, given the imbricated bed, indicates very low to no transport of gravel; sand might still be moved ($\tau^* > 0.17$ everywhere). These results are consistent with the observed stability of the upper river and with deposition of sand along the channel margins downstream from Pine River. For gravel, it is known that the river is incompetent for all but about 1% of the time, and only barely competent then. However, delivery from the gravel-supplying tributaries has not changed, so the river is in sediment

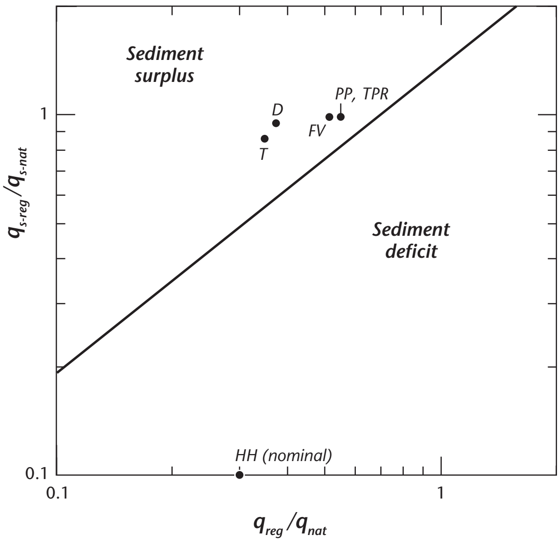


Figure 2.24 Schmidt and Wilcock (2008) type diagram for Peace River stations downstream from the dams. The diagram has been modified to display direct observables. See text for details.

surplus in the vicinity of tributary junctions, and this is confirmed by aggradation in those places, most notably at the mouths of Moberly and Pine rivers. Overall, the results confirm the inferences from Petts (1984).

Because of the effective decoupling of primary hydrological change from the sediment regime of the river, the regulation of Peace River provides an important opportunity to study the isolated effect of major changes in only one of the three principal governing conditions of river regime and morphology. Furthermore, the long downstream reach and changing morphological style of the river allow observations to be conducted over a significant range of morphologies. These effects are studied in the succeeding chapters.

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References

Ayles, C. P. (2001) Regulation-induced channel gradation in the Peace River. M.Sc. thesis, 182 p. The University of British Columbia.

BC Hydro (British Columbia Hydro and Power Authority). (1975) Peace River Sites C and E. River regime and morphology. *Report* 783, Hydroelectric Design Division, Vancouver, Canada. Various pagination. (This report was not generally circulated.)

Carson, M. A. and Hudson, H. R. (1997) Sediment dynamics and implications for sediment associated contaminants in the Peace, Athabasca and Slave River basins. *NRBS Study, Project Report*, 133, 86 p (plus tables, figures, and appendices). Alberta Environmental Protection, Edmonton, Canada.

Church, M. (1995) Geomorphic response to river flow regulation: case studies and time scales. *Regulated Rivers: Research and Management*, 11, 3–22.

Church, M. and Kellerhals, R. (1978) On the statistics of grain size variation along a gravel river. *Canadian Journal of Earth Sciences*, 15, 1151–1160. doi:10.1139/e78-121

Church, M. and Slaymaker, O. (1989) Disequilibrium of Holocene sediment yield in glaciated British Columbia. *Nature*, 337, 452–454. doi:10.1038/337452a0

Church, M., Ham, D., Hassan, M., and Slaymaker, O. (1999) Fluvial sediment yield in Canada: scale analysis. *Canadian Journal of Earth Sciences*, 36, 1267–1280. doi 10.1139/e99-034

Conly, F. M. and Prowse, T. D. (1998) Temporal changes to the ice regime of a large cold-region river due to flow regulation, in *Ice in Surface Waters*, edited by H. T. Shen. Balkema, Rotterdam, The Netherlands, pp. 41–48.

Cruden, D. M., Ruel, M., and Thomson, S. (1990) Landslides along the Peace River, Alberta. *Proceedings of 43rd Canadian Geotechnical Conference*, 1, 61–68. Geotechnical Society of Canada.

Douglas, R. J. W., Gabrielse, H., Wheeler, H. O., Stott, D. F., and Belyea, H. R. (1970) *Geotectonic Correlation Chart for Western Canada*, Geological Survey of Canada, Ottawa, Canada.

Evans, S. G., Hu, X.-Q., and Enegren, E. G. (1996) The 1973 Attachie Slide, Peace River Valley, near Fort St. John, British Columbia, Canada: a landslide with a high velocity flowslide component in Pleistocene sediments, in *Landslides*, vol. 2, edited by K. Senneset. Proceedings of the 7th International Symposium on Landslides, Jun 17–21, 1996,Trondheim, Norway. A.A. Balkema, Rotterdam, The Netherlands. pp. 715–720.

Gan, T. Y. (1998) Hydroclimatic trends and possible climate warming in the Canadian prairies. *Water Resources Research*, 34, 3009–3015. doi:10.1029/98/WR1265

Gerard, R. and Karpuk, E. W. (1979) Probability analysis of historical flood data. *Journal of the Hydraulics Division* [Proceedings of the American Society of Civil Engineers], 105, 1153–1165.

Hartman, G. M. D. and Clague, J. J. (2008) Quaternary stratigraphy and glacial history of the Peace River valley, northeast British Columbia. *Canadian Journal of Earth Sciences*, 45, 549–564. doi:10.1139/E07-069

Hollingshead, A. B. (1971) Sediment transport measurements in a gravel river. *Journal of the Hydraulics Division*, [Proceedings of the American Society of Civil Engineers]) 97, 1817–1834.

IPCC [Intergovernmental Panel on Climate Change]. (2007) Climate Change 2007: the physical science basis, in *Contribution of Working Group I to the Fourth Assessment Report*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller. Cambridge University Press, Cambridge.

Kellerhals, R., Neill, C. R., and Bray, D. I. (1972) Hydraulic and geomorphic characteristics of rivers in Alberta. *River Engineering and Surface Hydrology Report* 72-1, 48 p. Research Council of Alberta, Edmonton, Canada.

Latif, M. and Barnett, T. P. (1994) Causes of decadal climate variability over the North Pacific and North America. *Science*, 266, 634–637.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., and Francis, R. C. (1997) A Pacific interdecadal oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*, 78, 1069–1079.

Mathews, W. H. (1978) Quaternary stratigraphy and geomorphology of Charlie Lake (94A) map area, British Columbia. *Geological Survey of Canada, Paper*, 76-20, 25 p.

Mathews, W. H. (1980) Retreat of the last ice sheets in northeastern British Columbia and adjacent Alberta. *Geological Survey of Canada, Bulletin*, 331, 22 p.

Milburn, D. and Prowse, T. D. (1996) The effect of river-ice break-up on suspended sediment and select trace-element fluxes. *Nordic Hydrology*, 27, 69–84.

Moore, R. D. and McKendry, I. G. (1996) Spring snowpack anomaly patterns and winter climatic variability, British Columbia, Canada. *Water Resources Research*, 32, 623–632. doi:10.1029/95WR03640

Peters, D. L. and Prowse, T. D. (2001) Regulation effects on the lower Peace River, Canada. *Hydrological Processes*, 15, 3181–3194, doi:10.1002/hyp.321

Petts, G. E. (1984) *Impounded Rivers: Perspectives for Ecological Management*, John Wiley & Sons, Ltd, Chichester, UK. 326 p.

Prowse, T. D. and Conly, F. M. (1998) Effects of climatic variability and flow regulation on ice-jam flooding of a northern delta. *Hydrological Processes*, 12, 1589–1610. doi:10.1002/(SICI)1099-1085(199808/09)12:10/11<1589::AID-HYP683>3.0.CO;2-G

Romolo, L. A., Prowse, T. D., Blair, D., Bonsal, B., and Martz, L. W. (2002) The synoptic climate controls on snowpack accumulation in the upper reaches of the Peace River basin. *Elements* [Newsletter of the Canadian Geophysical Union], 20, 25–29.

Schmidt, J. C. and Wilcock, P.R. (2008) Metrics for assessing the downstream impacts of dams. *Water Resources Research*, 44, W04404, 19 p. doi:10.1029/2006WR005092

Sear, D. A. (1995) Morphological and sedimentological changes in a gravel-bed river following 12 years of flow regulation for hydropower. *Regulated Rivers: Research and Management*, 10, 247–264.

Severin, J. M. (2004) Landslides in the Charlie Lake Map Sheet, Fort St. John, M.Sc. thesis, The University of British Columbia.

Shaw, J. and Kellerhals, R. (1982) The composition of recent alluvial gravels in Alberta river beds. Geological Survey, *Bulletin*, 41, 151 p. Alberta Research Council, Edmonton, Canada.

Uunila, L. S. (1997) Effects of river ice on bank morphology and riparian vegetation along Peace River Clayhurst to Fort Vermilion. *Proceedings of 9th Workshop on River Ice*, Fredericton, N.B. National Research Council of Canada, Associate Committee on Hydrology, Ottawa, Canada. pp. 315–334.

Zhang, X., Vincent, L. A., Hogg, W. D. and Niitsoo, A. (2000) Temperature and precipitation trends in Canada during the 20th century. *Atmosphere-Ocean*, 38, 395–429.

CHAPTER 3

Downstream channel gradation in the regulated Peace River

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3.1 Introduction

River regulation has inspired a large body of research, much of it concerning downstream effects on river channel form. Direct alterations to flow and sediment regimes have produced a wide range of consequent morphological responses. Typical changes (see Petts, 1984a; Williams and Wolman, 1984) include channel degradation below the dam (Lane, 1934; Galay, 1983) due to sediment entrainment by the clear water passing through the dam, bed armoring (Livesey, 1963; Rasid, 1979; Hadley and Emmett, 1998) due to selective entrainment by the regulated flows, and aggradation accompanied by reduced channel capacity due to sedimentation (cf. Rasid, 1979; Schumm and Galay, 1994; Van Steeter and Pitlick, 1998) or colonization of upper bars and backchannels by riparian vegetation (Taylor, 1978; Johnson, 1998). Aggradation particularly occurs where unregulated tributaries deliver sediments into the regulated channel (King, 1961; Howard and Dolan, 1981; Petts, 1984b; Hanks and Webb, 2006). Channel pattern changes may also be observed as part of the series of transitional channel morphologies (Xu, 1996). All of these morphological adjustments represent an attempt to establish an equilibrium channel form for the newly imposed flow and sediment regimes (Andrews, 1986; Fassnacht *et al*., 2003).

A key element of post-regulation channel adjustment is river gradient. This may be altered through a change in sinuosity or in channel pattern, or by the raising or lowering of mean bed elevation via channel gradation. Degradation reduces slope as a counteradjustment to reduced sediment supply. In contrast, aggradation occurs as a means of increasing slope and restoring depleted sediment transport capacity when flow is reduced. Changes in channel cross-sectional morphology usually accompany channel gradation (Brandt, 2000). In bedload dominated systems (meaning, in general, gravel-bed rivers) sediment evacuation from a reach—the signal effect of degradation—occurs principally as bank erosion with only limited lowering of the more or less effectively armored bed. On the other hand, aggradation in such rivers occurs as vertical rise in bed level as sediments are deposited into new bar features. In contrast, in suspended load dominated systems (in general, sand-bed or silty rivers) degradation is dominated by vertical lowering of the bed, whilst aggradation is dominated by lateral deposits that also narrow the channel.

Vertical gradation is particularly important in confined or entrenched rivers with limited latitude for horizontal channel adjustment. Peace River in northern British Columbia and Alberta, Canada represents such a case. Shortly after it was dammed (1967) by the British Columbia Hydro and Power Authority (BC Hydro), Kellerhals and Gill (1973) made the following predictions about the channel adjustments that would follow in the proximal, gravel-dominated channel of Peace River:

- absence of degradation below Bennett Dam due to reduced flows over the naturally armored, cobble-gravel bed;
- aggradation at downstream tributary mouths, causing steps in the long profile; and

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Companion website: www.wiley.com/go/church/peaceriver

- reduced channel capacity via slow filling of scour holes, bar abandonment, and colonization by terrestrial plants.

Subsequent investigations (e.g., Kellerhals, 1982) have essentially expanded and corroborated these points. More recently, Church (1995) used the relations of hydraulic geometry to predict, at reach scale, the final reductions in width, depth, average velocity, and meander wavelength that should develop under the regulated flow regime. Field evidence suggests that most of these predicted adjustments are in progress. The timescale for completion of the changes associated with gradation was projected to be the order of 10^3 years (Church (1995); see also Chapter 11), although most of the change was expected to occur within the first century: after that, further change probably will be confounded with the effects of other factors affecting the hydrological and sediment regimes of the river.

Changes around tributary junctions are particularly important because flow and, possibly, sediment load change abruptly at these places. What happens will depend on the ratios of streamflow, sediment load, and sediment caliber between the two upstream branches, the main channel and the tributary. The summary effect of these factors may act to change the hydraulic geometry, including channel gradient, and bed material characteristics in the main channel both upstream and downstream from the confluence—upstream in view of possible backwater effects. In an early analysis, Rhoads (1987) proposed that only tributaries draining 0.6 to 0.7 as much area as the main channel (or, by implication, carrying more than 60% of flow as the main channel) would produce consistent effects. Effects might certainly be observed for more disparate ratios, but they would not be consistent. However, Rice (1998) and Benda *et al.* (2004) showed that effects may be detected for far more extreme ratios—as low as 0.01 in humid regions, and much lower for regulated systems in which the mainstem might be deprived of significant flood flows. The major factor promoting such extreme ratios is sediment caliber. Large materials that may be delivered from steep tributaries, either in floods or in debris flows, may not be further moveable once deposited at the confluence. Ferguson and Hoey (2008) have recently given a comprehensive review of the hydraulic and sedimentological factors that lead to various channel changes at tributary confluences, while Curtis *et al.* (2010) have specifically considered conditions at tributary junctions in regulated rivers.

Heretofore, channel gradation has been assessed only in general terms, with general degradation and aggradation at tributary junctions cited as the most common responses. Our goal in this study is to present a quantitative assessment of channel gradation on the regulated Peace River using data of monumented cross-sections over the 147-km reach immediately downstream from the dams (the British Columbia reach) (Figure 3.1). The response is expected to be most immediate and strongest in this reach. Some additional observations are included as far downstream as Dunvegan, Alberta (274 km from Peace Canyon dam) and specific gauge analyses are reported for all the active gauges along the river.

3.2 Reach description

Peace River basin (Figure 3.1: inset) occupies approximately 293 000 km^2 in northern British Columbia and Alberta. Its headwaters lie in the northern Rocky and Omineca Mountains. East of the mountains, the river principally drains the Alberta Plateau, eventually reaching the Peace–Athabasca Lowland near Lake Athabasca and draining to the Arctic Ocean via Slave and Mackenzie Rivers. The Peace has a mean annual flow of 1135 m^3s^{-1} at Hudson's Hope, where it leaves the mountains, and 2100 m^3s^{-1} at Peace Point, near the river's end (Table 3.1; Figure 3.1). Along most of its course below Bennett and Peace Canyon dams, the river is entrenched by more than 100 m within the surrounding plateau so that partial or total confinement of the channel is common.

The bed of Peace River in the first 10 km below Peace Canyon Dam is bedrock controlled. It is then dominated by cobble gravel to the Smoky River confluence, 369 km below the dam. In the British Columbia reach, surface bed material D_{90} varies from about 190 mm near Lynx Creek to about 90 mm at the Alberta border. D_{50} in this reach varies between 90 and 50 mm (Church and Kellerhals, 1978). The ratio D_{90}/D_{50}, a "sorting" coefficient, accordingly falls in the range 1.8 to 2.0. In the Alberta reach, D_{90} averages 36 mm down to the Smoky confluence (368 km below Peace Canyon dam), whilst D_{50} varies from 16 to 8 mm (Shaw and Kellerhals, 1982). Subsurface bed material D_{50} averages about

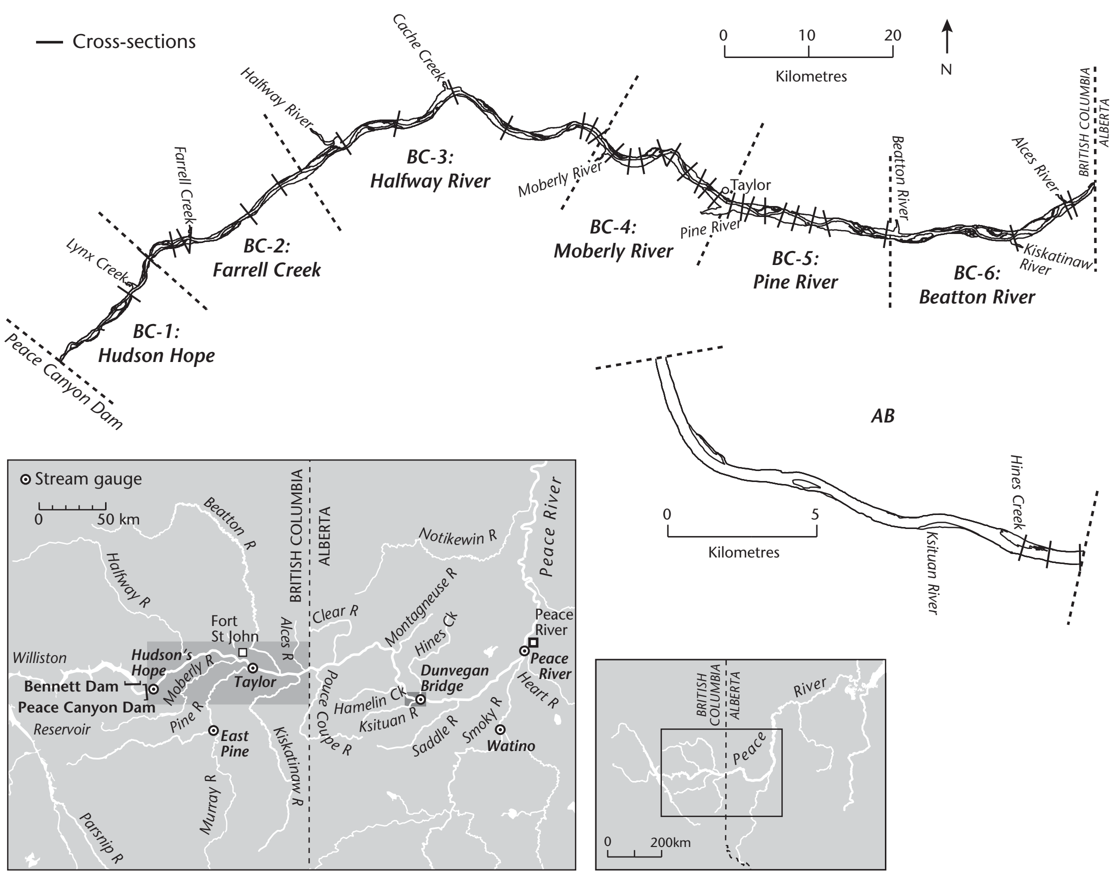

Figure 3.1 Map of the study reach showing the location of survey cross-sections and the defined British Columbia Sub-reaches: inset, Peace River basin, showing the reach studied in Alberta.

25 mm throughout the BC reach, hence the armor ratio (D_{50surf}/D_{50sub}) declines from 7.6 to 2.0 between Peace Canyon and the border.

Beyond the Smoky confluence, the bed consists of sandy gravel to about km 675, where the gravel/sand transition occurs. The river in British Columbia has a wandering channel pattern, with irregular, shallow bends and frequent islands. At the Alberta border, it becomes confined within a deep, postglacially excavated valley all the way to Dunvegan. Major tributaries include Halfway, Moberly, Pine, Beatton, and Kiskatinaw rivers in British Columbia, and Pouce Coupe, Clear, and Smoky rivers in Alberta. Amongst these, the Smoky is by far the largest, contributing a substantial flood and sand load to Peace River. Pine River is the largest tributary in British Columbia and the second largest in the Peace basin.

Peace River became regulated with the closure, at the end of 1967, of W. A. C. Bennett Dam near Hudson's Hope, where the river leaves the mountains. The mountainous headwaters above the dam generate most of the runoff (54% of the runoff from 24% of the contributing area) but relatively little sediment, so regulation did not appreciably affect the sediment influx to the downstream reach (see Chapter 2). The principal hydrological effects of Bennett Dam have been the reduction of peak flood discharges and substantial increase of winter flows. Reservoir storage has significantly damped spring meltwater floods, as releases are governed by demand for hydroelectricity. The post-regulation mean annual flood

Table 3.1 Summary data of Peace River mainstem hydrometric stations

Stn. name	WSC[1] no.	Distance below dam (km)	Mean annual flow (m^3s^{-1}) Pre-reg.[b]	Post-reg.[c]	% change	Mean annual flood (m^3s^{-1}) Pre-reg.[a]	Post-reg.[c]	% change	Records available for specific gauge
Hudson's Hope	07EF001	6.5	1198_{1949+}	1135	−5	5843	1927	−67	–
Abv. Pine R.	07FA004	93	–	–	–		2211		1979 to present
Taylor	07FD002	103	1560_{1945+}	1456	−7	7213	2837	−61	1945 to present
Alces R.	07FD010	143	–	–					1974 to present
Dunvegan	07FD003	275	*	*	–	8275	3379	−59	1960 to present
Town of Peace River	07HA001	377	1919_{1957+}	1883	−2	9700	5964	−43	1915 to 1932 and 1957 to present
Carcajou	07HD001	635	*	*	–	9997_{1960+}	–	–	1961 to 1966
Fort Vermilion	07HF001	808	2357_{1961+}	*	–	9577	4894	−49	1915 to 1922 and 1961 to 1978
Peace Point	07KC001	1115	2327_{1959+}	2100	−10	9817	5691	−42	1962 to present

[a]Water Survey of Canada
[b]From the year indicated by subscript (under mean annual flow) through 1967.
[c]1973 to 1995, except where an earlier end date is noted by subscript.
*Station operated seasonally: mean annual flow not available.

at Hudson's Hope has declined by 67%, from 5843 m^3s^{-1} before dam closure to 1927 m^3s^{-1} since (Table 3.1). Downstream, flow contributions from unregulated tributaries gradually reduce the effects of regulation. Yet even at Peace Point, 1115 km below the dams, the mean annual flood has dropped by 42% from 9817 to 5691 m^3s^{-1} (Table 3.1). Since closure, there have been two notable flood releases from the dam, in 1972 and 1996. These floods were separated by a 24-year period of continuously regulated flows.

From a geomorphic perspective, the main phenomenon of interest is the reduced incidence of bed sediment-transporting flows. For gradation in the upper river, which requires mobilization of the bed gravels, it appears that flows greater than about one half the pre-regulation mean annual flood are required. The latter (just over 3000 m^3s^{-1}) approximates the threshold for significant gravel transport in the British Columbia reach as calculated via the Einstein sediment transport formula (Chapter 2). Since regulation, normal flows released from the dam have not reached this level. The total actual number of such high-flow days (most of them during release flows) is only 6% of the number predicted by computed "naturalized flows" for Hudson's Hope, rising to 8% at Taylor (Pine River confluence) (see Chapter 2 for more detailed analysis). This is a clear illustration of the impact of Bennett Dam on the potential for sediment transport in Peace River.

3.3 Methods

To assess post-regulation channel gradation, two main techniques were employed: comparison of repeatedly surveyed cross-sections and specific gauge analysis of historical rating curves. In addition, to more completely assess river adjustment, planform changes in sinuosity, braiding index, and channel area were analyzed using air photos and morphological change maps. Changes around significant tributary confluences were further investigated using methods outlined by Rice (1998), Benda *et al*. (2004), Ferguson and Hoey (2008), and Curtis *et al*. (2010). The following sections describe these methods.

3.3.1 Cross-sections

In 1968 and 1975, 55 monumented cross-sections were established by survey contractors on behalf of BC Hydro along Peace River between Hudson's Hope and the British Columbia–Alberta border. Thirty-five of these sections were resurveyed by surveyors from the University of British Columbia in some or all of the years 1979, 1981, 1986, 1991, 1998, and 2005 (the balance being lost or located in the bedrock-controlled reach near the dam), and are analyzed in this report. Cross-sections have also been established near Dunvegan, Alberta, by a variety of contractors and agencies, and three were analyzed. The British Columbia sections are monumented by iron pins tied to geodetic datum so that they can also form the reference for long profile surveys. The locations of the 38 analyzed cross-sections are presented in Figure 3.1.

At the sections, bank surveys have been accomplished with a level, theodolite, infrared tellurometer or "total station," depending on the year and the section. These surveys have generally included all major breaks in slope and vegetation type but, in 1991, many of the bank surveys were shortened as the upper banks are no longer active under the regulated hydrologic regime. Channel surveys were performed by boat using a recording sonar. Vertical control for the channel surveys was achieved by establishing the water surface elevation during the bank survey. In most years, horizontal control was established by periodically surveying a boat-borne target from the bank. The positions of intervening points on the river bottom were then estimated by interpolating between these "fixes." The boat was kept on the survey line by sighting along parallel range poles and targets installed on the line. Channel surveys generally were repeated at least twice. In the two most recent surveys, differential GPS was used for horizontal position.

Error sources for the cross-sectional data include mistaken reading and transcribing of survey data, depths less than the sonar blanking distance (1 m), air bubbles and waves affecting the sonar signal during survey runs, failure to keep the boat on-section, imprecise measurement of depths and distances on sonar traces, and the assumption of a flat water surface. Church and Rood (1982) provided a detailed discussion of methods and error in the cross-sectional surveys. They estimated that, in the worst case, channel survey techniques may produce error of ±0.2 m vertically, which is comparable with feasible short-term bed level fluctuations in a river the size of Peace River. The main reason for such an error would be lateral variations in water level across the section. The mean such difference was found, from replicated surveys, to be 0.08 m. Horizontal error was estimated to be up to ±9 m in the earlier surveys. This is mostly of concern near the river banks, where it might combine with relatively high bed lateral slopes to produce biased estimates of bed elevation, hence false indications of change from survey to survey. On a two-degree offshore gradient, a nine-meter navigation error could produce a depth bias error of 0.3 m and, on a five-degree gradient, 0.8 m. For this reason, anomalous cross-sectional changes near the water's edge are treated sceptically. Line navigation errors are mitigated by the fact that, in a river the size of the Peace, channel geometry and features can be expected to change relatively little within short along-stream distances from the true section location. For summary analysis, the error range is accepted to be ±0.16 m (i.e., 2×0.08 m). This is equivalent to the D_{90} size of bed material in the proximal reach and about $3D_{90}$ at the Alberta border.

For each section, all available years of data were plotted together. Temporal patterns of cross-sectional change were qualitatively assessed, and the sections were classified into five general gradation response types for the period 1967 to 2005: stable, aggrading, fan prograding, degrading, and scour/fill. To qualify as unstable, the channel must exhibit consistent change in form beyond the assessed vertical survey precision. Changes were quantified by calculating net gradation. To achieve this, cross-sectional areas below a common elevation were subtracted from year to year. The change in cross-sectional area was then divided by channel width, as determined from morphological maps of the river (described below) to give an estimate of mean vertical change. The common water level was chosen to remove the upper river banks, with the goal of excluding changes caused by nonfluvial processes such as animal trampling and slope failure. To highlight long-term patterns of change, net gradation was calculated over the longest possible period at each section.

The methods for measuring and analyzing the cross-sections are comparable with those used by the United States Army Corps of Engineers and US Bureau of Reclamation, as reported by Williams and Wolman (1984), and the number of resurveys analyzed in our study is similar to the number used by those authors as the basis for their analyses.

3.3.2 Specific gauge

Historical stream gauging notes, rating curves, and rating tables are available for the Peace River at eight Water Survey of Canada (WSC) gauging stations (Table 3.1). Specific gauge analysis, which tracks the vertical movement of rating curves over time, was used to estimate local degradation or aggradation. The length of the Peace River gauging history allows comparison of pre- and post-regulation specific gauge trends at some locations. In some instances, consecutive rating curves were not comparable due to changes in the gauge location or datum. Otherwise, all possible comparisons have been made.

At each station, all comparable rating curves were plotted together, allowing visual interpretation of gradation trends. To assess gradation quantitatively, stage change was computed at a flow 0.8 times the pre-regulation mean annual flood, which is about half pre-regulation bankfull at stations with a defined bankfull level, except Carcajou, where it is 0.8 bankfull. This flow was chosen to avoid spurious results due to changing bed topography (a risk at low flows), as well as breaks in the rating curve at overbank flows and false interpolation of the upper end of the rating curve due to sparse measurements (Hamilton and Moore, 2011). At the three British Columbia stations, absence of post-regulation high-flow records forced the adoption of lower reference flows: 0.4 MAF above Pine River and 0.6 pre-regulation MAF at Taylor and at Alces River.

Error in stream gauging is variable due to diverse measurement methods and meteorological conditions. In addition, rating curves have often been hand-drawn so their exact form may be subjective. In general, though, Peace River curves have a consistent form, suggesting that between-year comparisons should be valid. Using a precision of ±6% for flow measurements (cf. Pelletier, 1988) and a recent rating table from the Town of Peace River (TPR; #10, dated October 29, 1990), we calculate an outside error term of approximately ±0.15 m for specific gauge analyses, comparable with our assessed error of cross-section change.

3.3.3 Planform analysis

Our principal information sources for planform changes are a series of maps depicting morphology and riparian vegetation along Peace River, produced from air photographs by computer-controlled photogrammetry (see Chapter 8 for a discussion of the construction of these maps), and the photos themselves. Coverage is continuous from the dam to Dunvegan. For analysis, the river is divided into relatively uniform sub-reaches according to morphological features and position relative to major tributary rivers (see Figure 3.1).

Channel pattern change was assessed by calculating sinuosity, braiding index, and channel area change (using digital versions of the maps in a GIS) and tracking changes in these parameters through the post-regulation years. Sinuosity was calculated by dividing main-thread channel length by valley length. The braiding index was derived by counting the number of channels crossed by a transect line. Transects were digitized at approximately 1-km intervals along the river, and individual results were averaged within sub-reaches (see Figure 3.1). To reduce error from varying water levels between map dates (see below), channels were considered to include all unvegetated morphological units, including water, bare bar surfaces, and unvegetated backchannels. This is a conservative measure, since it continues to count gradually overgrowing backchannels until they are completely vegetated. To gauge floodplain encroachment, the change in total channel area was also tracked between map dates.

Error sources and magnitudes in the Peace River mapping project are reported in Chapter 8 and in detail by Church *et al.* (1997). Mapping errors are unlikely to be an issue in the sinuosity analyses as the position of the main thread can reliably be mapped at a range of flows up to flood stage and checked from extensive experience of navigation on the river. Braiding index and channel area are subject to error due to inconsistent water levels from one map period to the next as secondary channels are occupied at higher flows and bars are exposed at lower flows. Visual inspection of the maps suggests that the inclusion of both bare bar and water surfaces as "channel area" largely compensates for these concerns.

For comparison, changes in the "normally wetted channel" were assessed directly from air photos by measuring thalweg length and total connected channel length (including secondary channels), and forming a second braiding index as the quotient total channel length/thalweg length. This measure is less precise than the first braiding index but it yields a measure of channel morphology that remains independent of the exact flow. The air photos used depicted the river within the range of normal operating flows; that is, between 1100 and 2000 m^3s^{-1} between Hudson's Hope and the Pine River confluence, and between 1400 and 3000 m^3s^{-1} below Pine River (cf. Table 3.1).

3.3.4 Tributary confluence effect

To determine which confluences might plausibly influence the morphology of Peace River we computed probabilities from logistic regressions presented by Rice (1998) and by Benda *et al.* (2004). The logistic regression has the general form:

$$P_e = \exp(g(x_1, x_2 \ldots))/[1 + \exp(g(x_1, x_2 \ldots))] \quad (3.1a)$$

in which P_e is the probability that the tributary will affect mainstem morphology and $g(x)$ is a discriminant function based on data of effective and ineffective tributary junctions. Rice (1998) gave the function:

$$g = 8.68 + 6.08\ \log(A_t/A_m) + 10.04\ \log(A_t S_t) \quad (3.1b)$$

in which A_t and A_m are the drainage areas of the tributary and mainstream respectively and S_t is the bed gradient (therefore derivable from maps) of the tributary in the reach just above the confluence. $A_t S_t$ is, then, a surrogate measure of tributary stream power, hence capacity to yield sediment volume and caliber to the mainstem. Rice's data were derived from the drainage basins of Pine and Sukunka rivers—the former a major tributary of Peace River and the latter a tributary of Pine River. Derived in the same region, these functions ought to be approximately applicable to the upper Peace River. Benda *et al.* (2004) gave

$$g = 3.79 + 1.96\ \log(A_t/A_m) \quad (3.1c)$$

for humid mountains, and

$$g = 0.96 + 1.47\ \log(A_t/A_m) \quad (3.1d)$$

for "semiarid" mountains in the North American Cordillera. These two equations might both be relevant inasmuch as the uppermost tributaries of Peace River drain the east slope of the Rocky Mountains with a substantial nival flood, whereas tributaries farther east drain the distinctly subhumid Alberta Plateau. However, their derivation is extraregional.

We have no direct measure of tributary confluence effects except when channel cross-sections are located close to confluences. Those cross-sections are reconsidered in this context. Further evidence of morphological changes conditioned by tributary–mainstem interactions is interpreted from air photos and the channel maps, and from direct studies of Peace River sediment textures.

Some speculative progress can be made by considering hydraulic adjustments at tributary confluences. Ferguson and Hoey (2008) gave the following condition based on regime theory concepts:

$$\frac{S_d}{S_p} = \left[\frac{(\tau_c/\tau)(w_d/w_p)^{2/3}(D_d/D_p) + (1-\tau_c/\tau)(1+LR)^{2/3}}{(1+Q_t/Q_p)^{3/5}(w_d/w_p)^{1/15}(D_d/D_p)^{1/10}}\right]^{10/7} \quad (3.2a)$$

in which S indicates channel gradient, D is bed material surface grain size, τ indicates shear stress and τ_c is critical shear stress, LR is the sediment load ratio between the tributary and the upstream mainstem, and Q is discharge: p indicates the upstream (proximal) mainstem, d is the downstream (distal) mainstem, and t indicates the tributary. In the case when $\tau \approx \tau_c$ (the condition obtaining in Peace River near peak regulated flows) the formula simplifies to:

$$\frac{S_d}{S_p} = \left[\frac{(w_d/w_p)^{3/5}(D_d/D_p)^{9/10}}{(1+Q_t/Q_p)^{3/5}}\right]^{10/7} \quad (3.2b)$$

which further simplifies to:

$$\frac{S_d}{S_p} = \left(\frac{D_d}{D_p}\right)^{9/7}\left(\frac{w_d/w_p}{Q_d/Q_p}\right)^{6/7} \quad (3.2c)$$

to estimate the effect of the tributary addition of water to the regime condition of the mainstem. (The second bracket further simplifies to q_p/q_d, in which q is specific discharge, but the fully displayed form more clearly enumerates the influential factors. If mainstem width does not change, then the last bracket is simply Q_p/Q_d. In fact, the further reduced form reveals that bed material grain size is very nearly simply proportional to stream power.)

The Ferguson–Hoey formula is intended to predict regime gradient changes past a tributary confluence; that is, it purports to reflect average conditions upstream and downstream. Fortunately, all of the significant tributaries in British Columbia except Kiskatinaw River fall close to sub-reach limits (see Figure 3.1). We have determined the average channel width upstream and downstream over a distance of 15 to 20 channel widths to represent regime width. Channel widths are quite variable locally due largely to channel splitting about islands. Pre-regulation grain size is drawn from the data displayed in Figure 3.10 over comparable distances. Post-regulation grain size is drawn from recent sampling around Moberly and Pine Rivers. It is assumed that grain size has not changed significantly at other confluences because of either greatly disparate size between Peace River and the tributary or the restriction of tributary drainage to the friable lithologies of the Alberta Plateau. The specification of Q_d is based on gauged or estimated Q_2 (the flow with a two-year return period) for each channel (data in Table 3.6). This is an approximation since such a flow does not occur at the same time in both the tributary and Peace River.

Curtis *et al.* (2010) began from the Shields parameter $\theta = dS/RD$, in which d is flow depth and R is the submerged sediment specific weight. Using the D'Arcy–Weisbach flow resistance formula to eliminate depth, they found $\theta = \frac{1}{2R}\left(\frac{fQ^2S^2}{gw^2D^3}\right)^{1/3}$. Then, defining $\theta^* = \theta_r/\theta_n$, the ratio of values associated with regulated and unregulated (natural) flows, respectively, we find (assuming constant f)

$$\theta^* = \left(\frac{Q^* S^*}{w^*}\right)^{2/3} D^{*-1} \tag{3.3a}$$

in which $Q^* = Q_r/Q_n$, $S^* = S_r/S_n$, $w^* = w_r/w_n$, and $D^* = D_r/D_n$. Again, if $\theta^* \approx 1$ (implying threshold conditions and low or negligible bed material transport in the mainstem, in both the natural and regulated regimes, which appears reasonable as a first approximation in Peace River since in both the natural and regulated regimes significant bed material movement occurs only during occasional high flows), we obtain

$$S^* = w^* D^{*3/2}/Q^* \tag{3.3b}$$

which estimates the effect of regulation on regime conditions at the confluence. The equation has a functional form similar to that of Equation 3.2c but, in view of the different comparison (and the introduction of a different flow resistance formulation), differs in explicit representation. We obtain data as for the Ferguson–Hoey calculations except that, now, w^* is based on the width contraction of Peace River at the tributary confluence in comparison with width in the immediate upstream reach, while D^* is based on measurements at the confluence.

Equations 3.2b and 3.3b may be applied to Peace River at tributary junctions provided we have sufficient information, the former to indicate the ratio of equilibrium gradients upstream and downstream; the latter to indicate gradient change at the confluence.

3.4 Observations

3.4.1 Cross-sections

Observations are summarized in Table 3.2. We first give a description and examples of each gradation response type.

Stable cross-sections exhibit no net trend in gradation. In some instances, the section has remained virtually fixed over the past 30 years; one such case is Section 23 (Figure 3.2a), located upstream of Farrell Creek and one of the most proximal sites regularly surveyed (see Table 3.2 for section distance below Peace Canyon Dam). The maximum vertical change in this section was on the order of 0.3 m in the left channel thalweg from 1975 to 1981, with subsequent years falling between these two surveys. The right channel has been even more stable. Other stable sections have displayed greater cross-sectional activity over the years, but no consistent trend, with the bed elevation fluctuating about some mean level. At least part of these apparent changes certainly derives from survey error.

Aggrading cross-sections show a consistent depositional trend since regulation. This class includes sections characterized by gradual, general aggradation across most of the channel, an example of which is Section 119 (Figure 3.2b), located approximately 6.1 km upstream of the Pine River confluence. This site showed aggradation across most of its width from 1975 to 1986, stabilizing by 1991. It degraded during the 1996 flood but subsequently returned to an aggradational trend. In other cases, aggradation is more localized within a cross-section. A good example is Section S10 (Figures 3.2c, 3.4), located at the Taylor bridge, 1.7 km below the Pine confluence. This section underwent dramatic aggradation (up to 3.2 m) in the main channel from 1968 to 1975. Deposition continued at a slower pace through 1986, and appeared to have stabilized by 1991, but major new aggradation occurred after the 1996 flood. Just downstream, at Section 125, the aggradation began more slowly, accelerated between 1981 and 1986, and continued through 2005. Together, these two sections reveal the downstream growth of a new bar composed of Pine River gravel. In still other sections, aggradation has occurred in the form of enhanced sedimentation on existing bars, in some cases transforming these into new floodplain surfaces (e.g., Sections S9 and S8). Aggradation is common (42% of all sections: see Table 3.3), but appears to have been slowing at many sections by the early 1990s.

Section Y (Figure 3.2d), located immediately downstream from the mouth of Halfway River, is a singular example of aggradation. At this site, massive deposition from the nearby Attachie Landslide occurred in 1973, filling the entire channel with up to 6.3 m of sediment. A more typical phase of sedimentation followed, with most aggradation between 1975 and 1991 occurring on

Table 3.2 Summary of cross-section data

xs	Distance[a] (km)	Location	Gradation to 1991	Gradation 1991 to 1998	Gradation 1998 to 2005	Gradation Total	Response type	Remarks
16	11.8	u/s Lynx Cr	0.21				Stable/aggrading	On bedrock; r/b slide-prone
17	16.8	d/s Lynx Cr	0.0				Stable	On bedrock; stable
S4	20.3	u/s Farrell Cr	−0.21	0.05	−0.21	−0.37	Stable/degrading	u/s end of island; fluctuating but stable
23	21.4	u/s Farrell Cr	0.33	−0.22	−0.05	0.06	Stable	d/s end of island; fluctuating but stable
S3	23.8	Farrell Cr fan	−0.09	−0.21	0.36	0.06	Fan prograding	Scour/fill
X2	30.4	d/s Farrell Cr	−0.03	0.14	−0.14	−0.03	Stable	Straight reach
S1	35.5	At Farrell Cr settlement	−0.34		0.10	−0.24	Degrading/stable	l/b slide prone; head of island
Y	45.5	d/s Halfway R	3.42	−1.09	0.42	2.75	Aggrading/degrading	Attachie slide (1973) deposit, later scoured
S2	52.8	d/s Halfway R	−0.08	0.37	−0.30	−0.01	Aggrading/degrading	d/s Attachie accumulation*
B	60.5	At Cache Cr	−0.11	0.13	−0.17	−0.15	Scour/fill	On shifting riffle d/s creek mouth
S5	68.5	u/s Wilder Cr	−0.05	−0.08	−0.08	−0.21	Scour/fill	r/b bluff eroding
C	78.6	d/s Tea Cr	0.51	0.02	−0.31	0.22	Aggrading/degrading	At head of Moberly R backwater
107	79.6	u/s Moberly R	0.34	−0.18	−0.16	0.0	Scour/fill	l/b slumping; Moberly R backwater
108	81.1	u/s Moberly R	0.60	0.44	0.21	1.25	Aggrading	l/b slumping; Moberly R backwater
S6	84.6	d/s Moberly R; Site C	0.68				Aggrading	On bar comprising Moberly R deposits
112	85.5	d/s Moberly R	−0.04	0.78	−0.07	0.67	Aggrading	l/b eroding cliff
113	86.8	d/s Moberly R	0.20	−0.35	−0.36	−0.51	Aggrading/degrading	Riffle crest migrates u/s
D	91.2	Old Fort	−0.01	−0.78	0.050–0.74		Degrading	Riffle downcutting; eroding r/b cliff
117	92.4	Kirchbaums' farm	1.33	−0.68	−0.23	0.42	Aggrading/degrading	Bend apex; l/b slumping
119	95.3	u/s BCR trestle	0.78	−0.09	−0.40	0.29	Aggrading/degrading	On riffle
S7	97.4	BCR bridge	0.03	0.39	−1.40	−0.98	Aggrading/degrading	
121	98.4	u/s Pine R	0.08	−0.30	0.0	−0.22	Stable/degrading	Mid-channel bar head; Pine R backwater;
122	100.1	u/s Pine R	0.22	−0.25	−0.46	−0.49	Aggrading/degrading	Pine R backwater
123	101.9	Pine R fan	0.31	−0.15	−0.68	−0.52	Aggrading/degrading	Ice scour; Pine R gravel deposition
S10	103.0	Taylor Bridge/ gauge~	1.61	0.07	0.49	2.17	Aggrading	Pine R fan; l/b eroding due to Pine outflow
125	103.5	d/s old Taylor landing	0.87	0.34	1.36	2.57	Aggrading	Pine R deposits
126	105.0	d/s Taylor	0.03	0.48	0.73	1.24	Stable/aggrading	Pine R deposits extending d/s
127	107.2	d/s Taylor	−0.35	0.36	−0.28	−0.27	Degrading/aggrading	Major logjam on r/b lost in 1996

(*continued*)

Table 3.2 (*Continued*)

xs	Distance[a] (km)	Location	Gradation to 1991	1991 to 1998	1998 to 2005	Total	Response type	Remarks
128	108.8	d/s Taylor	0.06	0.33	−0.28	0.11	Stable/aggrading	r/b ice damage on young floodplain
129	110.8	LeClerc's camp	0.26	−0.04	0.0	0.22	Aggrading/scour-fill	Actively aggrading bar; old bar-island
S9	112.8	u/s Beatton R	0.98	0.13	0.13	1.24	Aggrading	l/b bar complex becoming new floodplain;
Z	120.0	u/s Beatton R	0.86		−1.06	−0.20	Aggrading/degrading	Unstable ground on l/b—poor control
S8	135.6	Kiskatinaw R mouth[b]	0.11	−0.08	0.60	0.63	Fan prograding	Fan growth; erosion of island opposite
S11	143.4	Clayhurst bridge	0.14				Scour/fill	Section extensively disturbed by bridge
E6	144.7	d/s Alces R confluence	0.49	−0.04	0.28	0.73	Aggrading/scour-fill	
U1	274.6	u/s Dunvegan Bridge	0.88				Fan prograding	Lower Hines Cr fan
G	275.3	Dunvegan bridge; gauge	0.76				Fan prograding	1996 survey is post-flood
D1	276.2	Dunvegan Gardens	0.0				Stable	

[a]below Peace Canyon Dam
*back channel survey abandoned after 1981.

the left bank, probably largely consisting of sediment contributed by Halfway River. The thalweg was progressively raised and forced toward the right bank. A period of erosion between 1981 and 1986 may have been due to scour by river ice and erosion also has occurred in the 1996 flood, but there has been a return to aggradation since.

General degradation, the classic response to regulation, is seen at only two locations along Peace River. The first is Section S1, which crosses the head of a long mid-channel bar 13.1 km below Farrell Creek. Between 1981 and 1986, the channel here degraded by roughly 0.5 m across most of its width, stabilizing by 1991. The second example is Section S2, located 7.2 km downstream of the Halfway River confluence. At this site, a mid-channel bar steadily eroded from 1968 through 1986, and the bed apparently stabilized by 1991, but the 1996 flood deposited material here (likely derived from the reach represented by section Y). With the rest of the channel essentially stable, the net effect is a lowering of mean bed elevation. Both of these cases might represent local adjustments of flow through a riffle.

Sections categorized as scour/fill have shown significant erosion and deposition over the period of record, but with little apparent change in mean bed elevation. These sites are not considered stable because scour and fill have been progressive and systematic, rather than fluctuating about some mean bed level. One example is Section S5 (Figure 3.2e), 2.8 km upstream of Wilder Creek in the middle of the British Columbia reach. At this location, the river is actively eroding its right bank, a fluvial terrace. Compensating bar growth has occurred at the left side of the channel, next to an island. The period 1968 to 1981 was especially active and, again, the channel appeared to have stabilized by 1991 but has experienced net degradation since 1996. In contrast, at Section 107, in a backwatered reach 3.6 km upstream of the Moberly River confluence, the dominant change has

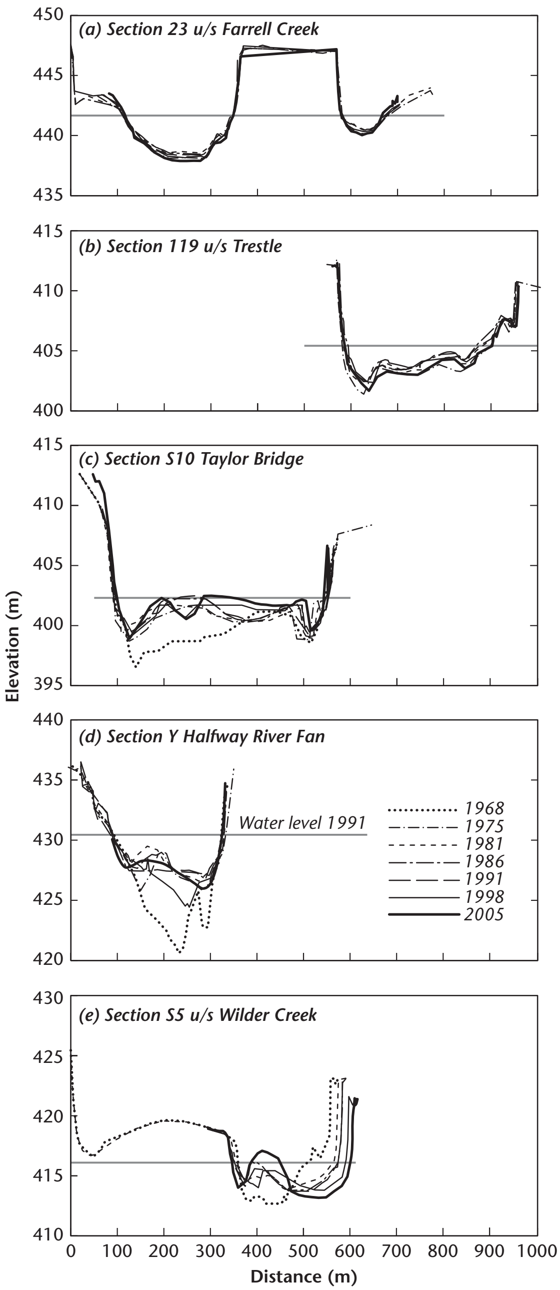

Figure 3.2 Cross-section histories for 38 years of regulated flows, illustrating typical patterns of channel gradation: (a) Section 23: stable; (b) 119: aggrading; (c) S10: aggrading; (d) Y: fan progradation; (e) S5: scour/fill.

been a progressive leftward shift of a large mid-channel bar. Here, mean bed elevation is absolutely unchanged despite an active cross-section.

Elsewhere along the river there has been a switch from aggradation to degradation at 11 of the sections where aggradation occurred immediately after regulation: in almost all cases, it appears that the switch was associated with the 1996 flood. At two sites a reverse trend has been observed—early degradation giving way to aggradation. These "complex" responses are not unlike those of fluctuating but stable sections; they simply have shown greater consistency within each phase. Two examples may be cited. The first, Section 113, underwent aggradation in the thalweg from 1975 to 1981, followed by degradation thereafter. The second example is Section 123, at the Pine River confluence. The river here experienced general aggradation from 1975 to 1979. The thalweg essentially stabilized by 1981, and the depositional front began to retreat through 1986 and, again, has continued since. These "cross-over" sites are summarily classified as aggrading or degrading, depending on the net effect to 2005.

Table 3.3 summarizes the frequency of occurrence of each gradation response type. During the 24-year post-dam period of normal regulated flows (1967 to 1991) the river from Hudson's Hope to Dunvegan was almost entirely stable or aggrading (including fan progradation), with degradation occurring at only 3 of 35 cross-sections; three others experienced scour/fill. Five of these six sites are located in the proximal half of the British Columbia reach, between Hudson's Hope and Moberly River, where bed material sediment supply is negligible. As Peace River approaches the Moberly confluence, the pattern of change becomes dominantly aggradational, with occasional stable sections. This remains true at Dunvegan, but we have no information for the intervening upper Alberta reaches. The period 1991 to 1998, which encompasses the 1996 drawdown flood, produced a significant change, however, with the number of degradational sites increasing to one-third of those surveyed in 1998 (10 sites). Most of the switchovers occurred near tributary confluences where there had been initial accumulation of sediment. It should be noted that the reduced number of sections surveyed in 1998 renders the comparison with the earlier period incomplete. Perhaps more surprising is that in the subsequent period (1998 to 2005) the shift in

Table 3.3 Number and frequency of occurrence of cross-sectional gradation response types

Period	1967 to 1995[a]		1996 to 1998[a]		1998 to 2005		1967 to 2005	
Response type	No	Fr	No	Fr	No	Fr	No	Fr
Stable	14	0.40	11	0.38	9	0.29	7	0.23
Aggrading	18	0.51	8	0.28	8	0.26	13	0.42
Degrading	3	0.09	10	0.34	14	0.45	11	0.35
Total sections	35		29		31		31	

[a]Dates are altered from the survey date of 1991 to reflect the assumed timing of the major change in cross-sections during the 1996 flood and immediately after. Data include British Columbia sections only.

gradation tendency continued, with 11 sites (45% of surveyed sites) showing degradation. Over the entire period of regulated flows, there has been a steady decline in the number of cross-sections that have remained stable while an initially high proportion of aggrading sites has given way to a growing preponderance of sites exhibiting mild degradation.

The spatial distribution of net gradation data (Figure 3.3) provides an objective view of channel adjustment and allows direct comparison with the specific gauge analysis. The dominant individual feature of the early period of normal regulated flows is the aggradational spike at Section Y. Bar growth due to Pine River sediment deposited at Sections S10 and 125 is also clearly shown as a prominent part of the dominantly aggradational trend downstream from Halfway River. More locally, it is apparent that the major tributaries (Moberly, Pine, Beatton, and Kiskatinaw rivers) each have provoked aggradation in the vicinity of the confluence, including an upstream backwater zone. In the later periods, this tendency has become more narrowly localized, with aggradation increasingly limited to the immediate vicinity of the tributary confluences and formerly aggrading sections elsewhere experiencing degradation. Except for fan progradation at Farrell Creek and Halfway River, the proximal reach has been generally stable over the years, with a few instances of degradation. The overall trend, 1967 to 2005, has been for the most prominent aggradation to occur at section Y (the transient result of a landslide upstream) and around Pine River mouth (the persistent result of a sediment delivering tributary), with the most notable sequence of degrading sites immediately upstream of Pine River. Nowhere, however, has degradation exceeded one meter and the average of degrading sites is −0.43 m.

At Dunvegan, Sections U1 and G showed fan growth to 1991 at the mouth of Hines Creek, though U1 has experienced sufficient compensatory erosion to produce slightly negative net gradation. The most distal cross-section (D1) is stable. Sampling density here is unusually high, with three sections in a 3-km reach. For a fairer comparison with the British Columbia reach, the sections could be averaged to produce a net aggradational signal for the area. The local variability at Dunvegan demonstrates, however, that changes registered at a single section may not fairly represent overall local channel behavior. This possibility must be borne in mind when interpreting all of the sections.

3.4.2 Specific gauge

Table 3.4 presents the net gradation results derived by specific gauge analysis divided into pre- and post-regulation periods (to 1995 and post-1995). The gauge above Pine River indicates marginal degradation from 1984 to 1992 which may reflect only local changes in the gauge section immediately downstream of a major bar. A significant chute developed in those years on the left bank below the bar, immediately in front of the gauge. The gauge at Taylor was stable before regulation, and aggraded 0.57 m after, supporting the cross-section results at S10 (Figure 3.4), which is at the gauge. The remaining stations to TPR indicate stability prior to 1996 except for marginal apparent degradation at Dunvegan immediately before regulation, when the section may have experienced major disturbance due to bridge construction.

At TPR, results from the earliest available pre-regulation record (1915 to 1922) are questionable due to poor data quality. However, this site is essentially on

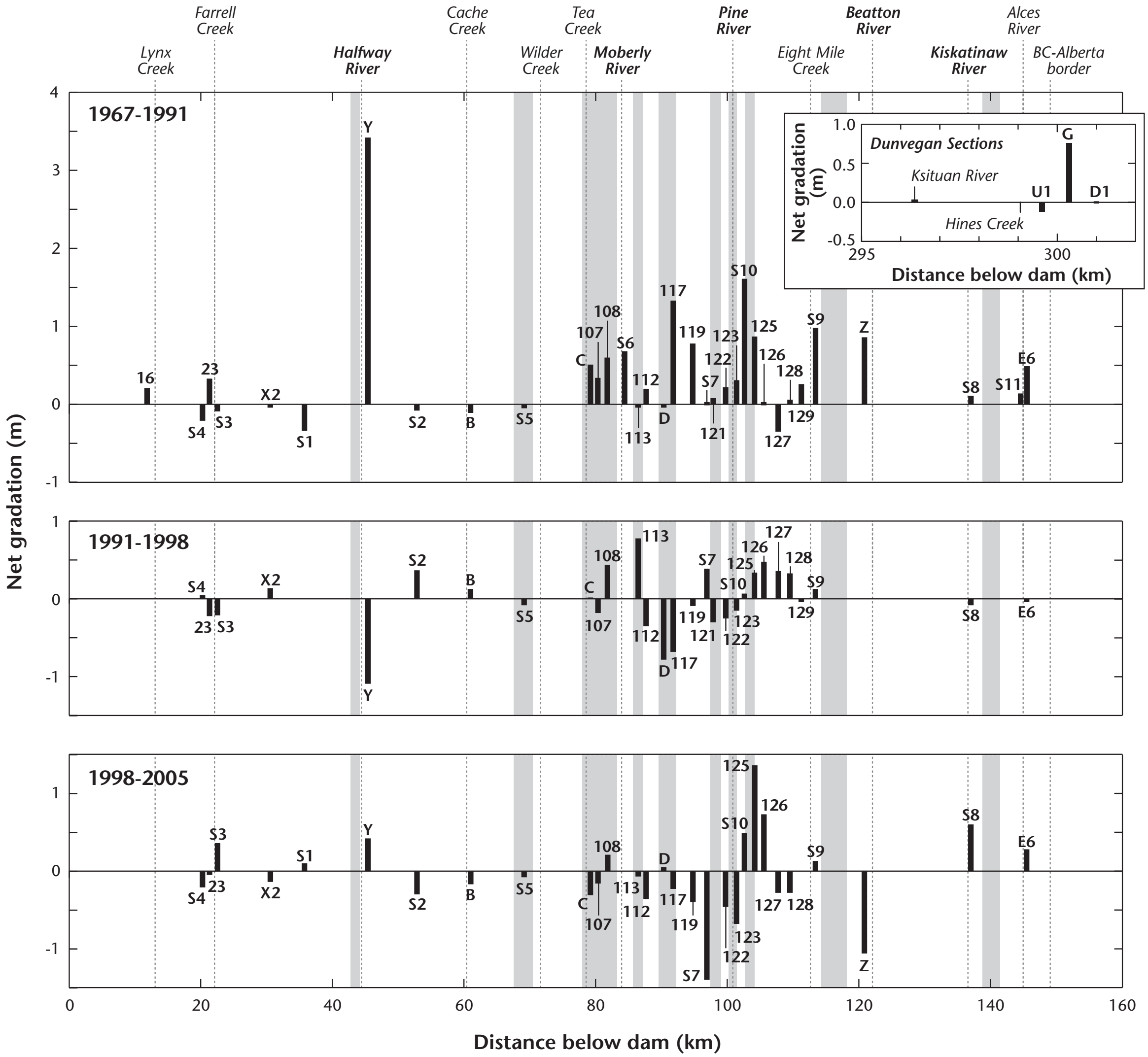

Figure 3.3 Net gradation results to 2005. Also shown, tributaries (major sediment delivering tributaries in bold) and the location of unstable sections of valley side (grey bars), including landslides, that have recently contributed sediment to the river.

bedrock, so the lack of significant gradation is reasonable and provides confidence in the method. After regulation, the gauge at TPR indicates marginal aggradation but, in view of the rock section, we guess that this represents no more than a rating adjustment for the apparent degradation calculated for the last years before regulation. At Carcajou and Fort Vermilion, there is evidence of net degradation throughout the record. These stations were decommissioned before and shortly after regulation, however, preventing clear analysis of post-regulation trends. The trends suggest that this proximal part of the sand-bed reach was naturally active, but the post-regulation results may be affected by the construction of the Fort Vermilion bridge between 1972 and 1973 (McLean and Anderson, 1980). At Peace Point, the trend reversed from aggradation to degradation about the time of regulation, leaving no net long term effect by 1995. At this site, the same rating curve was used from 1970 through 1993, suggesting that the channel has been stable for most of the post-regulation period.

Table 3.4 Net gradation derived by specific gauge analysis

Location	Net gradation (m)		
	Pre-regulation	**Post-regulation, to 1995**	**Post-1996**
Above Pine River	–	1983 to 1992	1992 to 1999
(07FA004)		−**0.18**	+**0.25**
Taylor	1964 to 1966	1966 to 1996	1996 to 1999
(07FD002)	0.0	+**0.57**	0.0
Alces River	–	1992 to 1995	1995 to 1999
(07FD010)		0.0	−**0.29**
Dunvegan	1964 to 1967	1967 to 1995	1995 to present
(07FD003)	−**0.18**	0.0	+0.15
Town of Peace River	1915 to 1922		
(07HA001)	+0.11		
	1964 to 1968	1968 to 1990	1990 to present
	−0.11	+**0.18**	0.0
Carcajou	1963 to 1966		
(07HD001)	−**0.28**		
Fort Vermilion	1962 to 1965	1965 to 1977	
(07HF001)	−**0.32**	−**0.20**	
Peace Point	1961 to 1967	1967 to 1995	1995 to present
(07KC001)	+**0.20**	−**0.18**	0.0

Rating curves are compared at a flow of 0.8 times the pre-regulation mean annual flood, except above Pine River (0.4 times), at Taylor and above Alces River (0.6 times) because of limited ranges of post-regulation flows there. Dates for comparisons vary because of the varying times when rating curves were reestablished. Positive values indicate aggradation; negative values indicate degradation. Significant results in bold.

The specific gauge results at Pine River and Taylor are well illustrated by superimposing the consecutive rating curves (Figure 3.5). These plots show that the gradation patterns at these sites have been consistent over the full range of gauged flows. At most of the other sites, where gradation has been less pronounced, the curves plot too closely together to be easily distinguished. In addition, successive curves often cross each other, suggesting that channel form may be changing without net effect on mean bed elevation.

3.4.3 Planform analysis

The sinuosity of Peace River is very low (1.04 in the British Columbia reach) and has remained essentially unchanged across all map periods and sub-reaches, with the difference never greater than 0.02 for any comparison. The first braiding index—describing overall channel configuration—has also been quite stable in most sub-reaches (Figure 3.6a), rarely varying by more than 0.10 over the entire period of record, but revealing a general drift downward—that is, toward a reduction in secondary channel length. This reflects both our methods and the primary style of planform adjustment on Peace River—gradual vegetative succession and siltation on high bars and in backchannels (cf. Church *et al.*, 1997; Chapter 7). The vegetation succession has been continuously interrupted by winter high water with ice (Chapter 6), so that the process may continue for some time before a backchannel finally overgrows completely with floodplain species, leading to a change in the braiding index. Exceptions occur in Sub-reaches BC4 and BC5 (Figure 3.6a). The braiding index declined in the former after 1980 because of the abandonment in 1986 and 1996 of two right-bank backchannels just above the Pine River confluence. However, the 1996 flood also influenced 1996 data because the river flooded over some islands, creating temporary single channels. The erratic results in BC-5 arise from a combination of backchannel abandonment, bar growth, and a minor channel avulsion.

In comparison, the second braiding index reveals a sharp decline in the normally wetted secondary

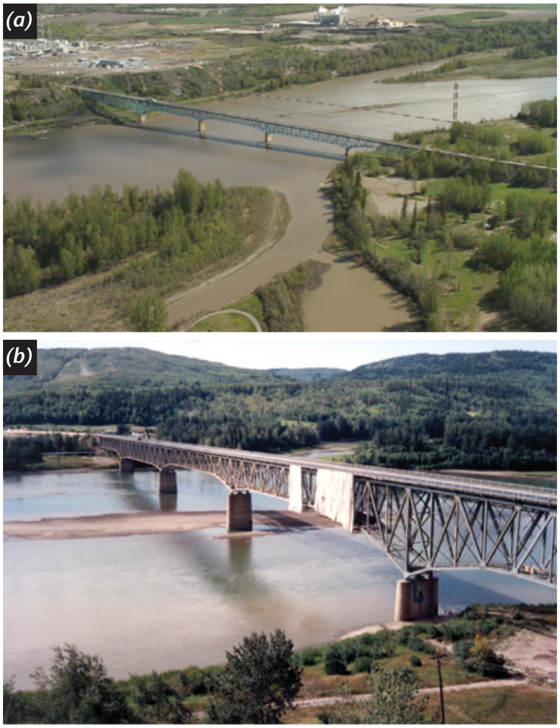

Figure 3.4 (a) View of Peace River looking downstream at Section S10, May 28, 2009, flow is 2020 m^3s^{-1}. This is the site of the Taylor gauge (WSC Stn. 07FD002), the principal gauge on the upper river. The gauge is located in the leftmost pier of the Alaska Highway bridge. The minor channels in the lower foreground are backchannels of the Pine River confluence that are dead-end sloughs except at the highest Pine River inflows (Photo courtesy of M. J. Miles). (b) View from the left bank on the downstream side of the Alaska Highway bridge showing the bar that has developed in the S10 and Taylor gauge section since regulation of the flows, flow is 750 m^3s^{-1}. The bar is obscured by higher water in part (a).

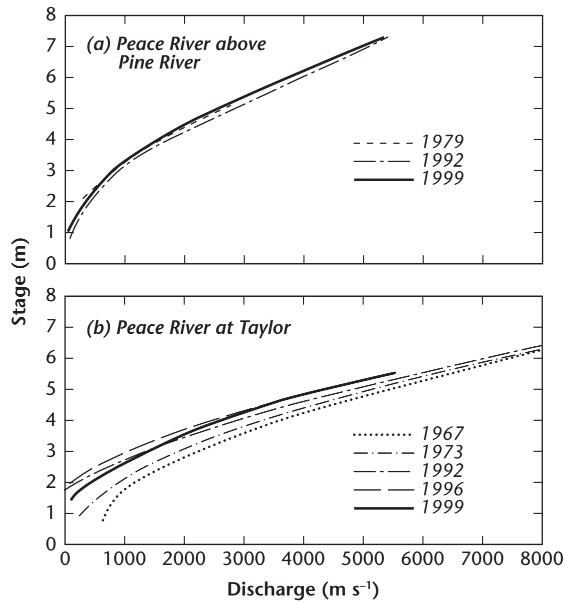

Figure 3.5 Rating curves for Peace River above Pine River (WSC Stn. 07FA004) and Peace River at Taylor (WSC Stn. 07FD002).

channel area immediately after regulation, the simple consequence of the failure of normal regulated flows to flood the highest secondary channels. Between 1967 and 1977, the secondary and backchannel length in the British Columbia reach declined from 287.6 to 159.9 km, almost all of the change being the immediate consequence of the elimination of the highest flows. Given the thalweg length of 147.7 km, the braiding index declined from 2.85 to 2.01. The value has subsequently changed very little, indicating the essential stability of the channel pattern in the British Columbia reach. From the Alberta border to Dunvegan, the channel is strongly confined and nearly entirely restricted to a single thread: no major change in channel pattern can occur.

The overall planform response is best demonstrated in the channel area change data (Figure 3.6b). In all sub-reaches except AB1, there was a steady decline in channel area from the late 1960s to the late 1980s. This reflects the progressive loss of unvegetated lower bank and backchannel areas to terrestrial vegetation succession (Chapters 9 and 10). The 1993 maps of Sub-reaches AB2 and AB3 show a continued decline in channel area. Sub-reach AB1 has maintained the same channel area over most of the study period because it is a very simple, almost continually confined reach with few backchannels to lose. After 1996 there are minor increases in channel area in some reaches, no doubt a legacy of the prolonged major flood in that year.

3.4.4 Confluences

Fan progradation is a specific type of aggradation occurring at tributary junctions. Fan progradation has been observed by survey at the confluences of Farrell Creek (Section S3; Figure 3.7a), Kiskatinaw River (Section S8; Figure 3.7b), and Hines Creek, near Dunvegan, Alberta (Section U1, not illustrated). At these sites, flow constriction due to fan growth has caused erosion near the

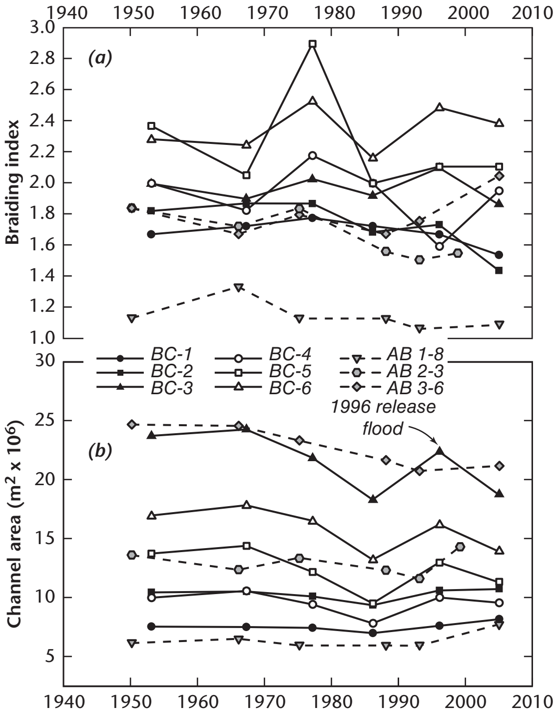

Figure 3.6 (a) First braiding index; (b) Channel area, by principal sub-reach. British Columbia data are recorded by sub-reach. Alberta data are given only for the gauge sub-reaches (AB1-8, Dunvegan; AB2-3, TPR; AB3-6, Fort Vermilion; no morphological data are available for Peace Point).

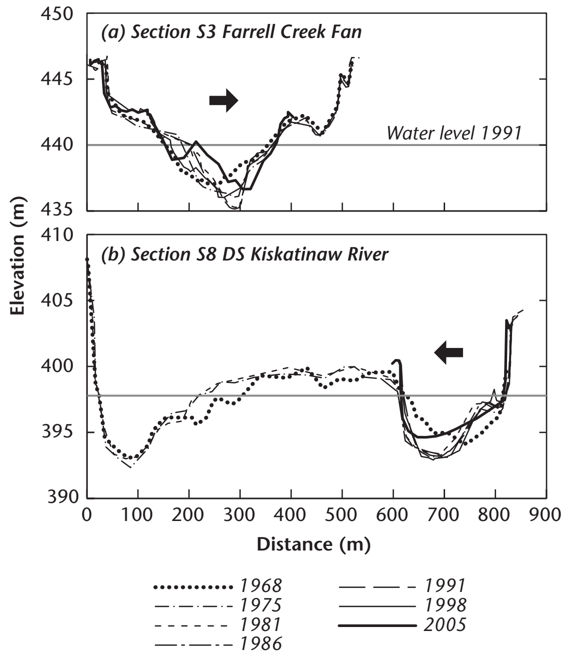

Figure 3.7 Cross-section histories at sections on prograding fans: (a) Farrell Creek (section S3); (b) Kiskatinaw River (section S8). Arrows indicate the direction of fan progradation.

opposite bank. It is also likely that the remarkable aggradation at section Y (Figure 3.2d), downstream from the Halfway River confluence, in the early period is in part the result of downstream advection of material from the tributary. This certainly is the case at Pine River, the most powerful tributary. Its inflow in flood characteristically exceeds the flow of Peace River so that it carries its bed material charge some distance downstream to be deposited in Peace River bars spanning sections S10 and 125 (see Section S10 in Figure 3.2 and Figure 3.4b). Similarly, downstream deposition of gravel from Moberly River is noted in Peace River.

To make a more systematic analysis of the potential effect of Peace River flow regulation on alluvial fan development and its influence, in turn, on the profile of Peace River, 19 tributary junctions were investigated, extending as far downstream as Dunvegan, 274 km below the dams. All tributaries in the British Columbia reach with a potential to prograde into the mainstem were studied, but only a selection of Alberta tributaries, including all with contributing area >500 km^2. Drainage area must be viewed somewhat sceptically, however, as a measure of tributary potential effectiveness since much of the area on the Alberta plateau which the tributaries ostensibly drain is in fact noncontributing (except possibly by seepage on the Peace River valley sides). Table 3.5 summarizes tributary measures and probabilities for the tributary to be effective in perturbing the main channel according to the formulae of Rice (1998) and Benda *et al.* (2004).

Rice's formula correctly classifies 16 of 19 junctions, with three nonsignificant junctions classified as significant. Benda's measure correctly classifies 11 of 19, with eight significant junctions classified as nonsignificant. The biases of the two classifications are reversed, with Rice apt to somewhat overpredict significance and Benda strongly prone to underpredict it. The Rice classification is, of course, calibrated for the region and includes a term to codify the strong sediment delivery from tributaries east of the mountains. The outstanding feature of the junctions is the propensity for even rather

Table 3.5 Tributary characteristics and probability to influence the channel of Peace River

Tributary[a]	Distance d/s dam (km)	Tributary area (km^2)	Area ratio	P_e[b] Rice	P_e[b] Benda[c]	Actual Peace channel contraction[d] 1950	1967	2005	Comments
Lynx Cr (*m*)	13.6	262	0.004	0.13	0.29	1.0	1.0	1.0	Very minor fan
Farrell Cr (*m*)	23.7	637	0.008	**0.84**	0.42	0.9	0.9	0.6	No effect on opposite bank
Halfway (*m*)	45.2	9 402	0.134	**0.98**	**0.89**	0.6	0.6	0.6	Pushes channel against high opposite bank
Cache Cr	61.7	893	0.011	**0.93**	0.13	1.0	1.0	1.0	No effect
Wilder Cr	77.0	97.4	0.001	0.004	0.03	1.0	1.0	0.8	Small fan skewed along channel
Moberly (*m*)	84.5	1900	0.023	**1.00**	**0.64**	1.0	0.9	0.5	Significant fan and d/s gravel splay; main channel divided
Pine (*m*)	101	13 560	0.161	**1.00**	**0.90**	0.7	0.5	0.5	Extensive d/s gravel splay; erosion on opposite bank
Beatton	123	16 058	0.165	**1.00**	0.45	1.0	1.0	1.0	Minor fan
Kiskatinaw	136	4 367	0.038	**1.00**	0.24	1.0	1.0	0.7	Peace channel divided
Alces	145	877	0.008	**0.93**	0.11	1.0	1.0	1.0	No effect
"Border creek"	148	31.8	0.0003	0.00	0.01	1.0		0.8	Fan present in 1950; in lee of river bar
Pouce Coupe	153	3 638	0.031	**1.00**	0.22	0.7		0.6	Major fan, strong d/s skew
Clear	167	2 958	0.024	**1.00**	0.19		0.7	0.7	Significant fan, d/s skew
Montagneuse	226	442	0.004	0.10	0.07	*	*	*	See note
Fourth Cr	250	228	0.002	**0.57**	0.05	0.8	0.7	0.7	
Hamelin Cr	252	722	0.006	**0.81**	0.09	0.6	0.6	0.6	Displaces the Peace River
Unnamed gully	256	13.2	0.0001	0.00	0.01	1.0	1.0	0.9	Similar gullies, with small fans in the Alberta reach
Ksituan	273	704	0.006	**0.91**	0.09			0.7	d/s skewed fan; affects opposite bank
Hines Cr	275	1647	0.013	**1.00**	0.14			0.6	Large fan, d/s skewed; affects opposite bank

*Fan projects 0.25 normal channel width, but is located on minor channel behind a major bar and does not affect the main channel
[a](*m*) indicates that the stream drains Rocky Mountain terrain (relatively high water yield).
[b]Probability for tributary to influence main channel morphology; bold figures are >0.5.
[c]Benda *et al.* (2004) quote error margins of approximately ±0.10 over most of the range of estimates. Rice (1998) gives no error specification.
[d]Expressed as (actual river width at greatest fan projection)/(average river width in the vicinity); 1.00 indicates no fan projection.

small tributaries to have some effect in constricting main channel flow.

More generally, the mountain-draining tributaries, except the small Lynx Creek, are all effective in perturbing the main river. This was true even before regulation except at Moberly River, where the tributary terminal fan has forced its way forward since regulation (Figure 3.8). Sediment deposits at Farrell Creek (Figures 3.9a and 3.9b) and Pine River have also, not surprisingly, prograded since regulation. The latter has delivered a major slug of gravel into bars downstream and, in addition, has projected subaqueous levees part of the way across Peace River at the confluence.

Amongst tributaries draining the Alberta Plateau in British Columbia, Wilder Creek, Kiskatinaw River, and the "Border creek" have prograded since regulation but it is a major surprise that Beatton River, the largest tributary by contributing area in the data set, has only a small confluence fan; rather, there is what might be called a "confluence bar" (Figure 3.9c). This river has

Figure 3.8 The terminal fan of Moberly River, May 28, 2009, Moberly River flow is approximately 40 m^3s^{-1} (Photo courtesy of M. J. Miles).

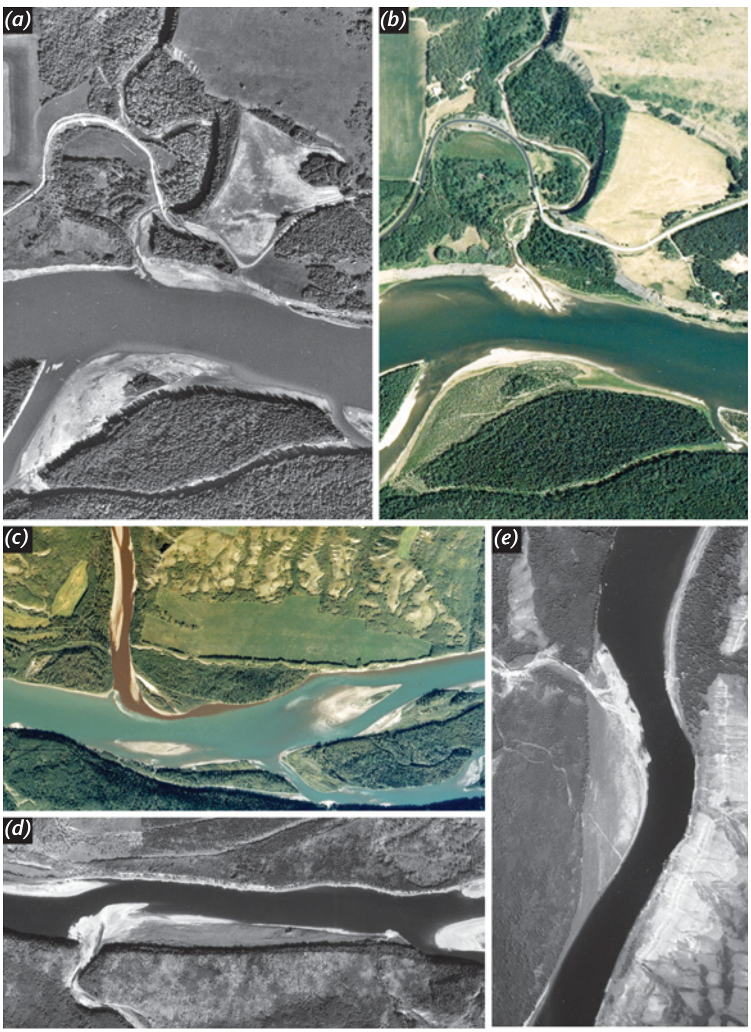

Figure 3.9 Some notable tributary confluences: (a) Farrell Creek in 1964 (part of photo BC5117-054); and (b) in 2006 (15BCC06070-109); (c) Beatton River confluence, 2005 (15BCC05129-82); (d) Pouce Coupe River, 2006 (AS5377B-260); (e) Hamelin Creek, 2006 (AS5377B-189).

incised to a low level in its lower course and has a gradient of only 0.00095 as it approaches Peace River (compare Pine River, much larger by flow, at 0.0013). Hence it contributes a large suspended sediment load but only a very minor load of pebble gravel to Peace River, yielding a tiny mouth bar/fan. There has nevertheless been aggradation at cross-sections upstream of the Beatton mouth, implying a backwater induced by the confluence.

Alberta tributaries mostly have fans that project into the mainstem and these fans have been in place since before regulation. They are typically strongly skewed downstream (Figure 3.9d and 3.9e). The effect is reminiscent of the downstream movement of gravel at Moberly and Pine Rivers but, whereas their gravel remains submerged in the main channel, the more widely graded sediments delivered from the Plateau tributaries have built bars and subaerial fans. Since regulation, even gullies as small as about 10 km^2 in contributing area can deposit small prograding fans. The steepness of the lower courses of the Alberta tributaries, tumbling into the confined river valley from the Plateau more than 200 m above, is a significant reason for their effectiveness in delivering to the river mouth sediment of a caliber able to resist onward movement in the mainstem. Further, whilst mean flow in these tributaries is small—reflecting the subhumid climate—annual floods resulting from rapid snowmelt or, more commonly, heavy summer convectional storms, may be 15 to 20 times greater than mean flow.

A further evidence of tributary influence on the Peace River mainstem is the variation in the texture of sediments upstream and downstream of the principal tributaries. This phenomenon was investigated for the British Columbia reach by Church and Kellerhals (1978); Figure 3.10 summarizes their principal relevant findings. The data clearly show the disruption created by the injection of coarse gravel from the steeper, more competent major tributaries into the mainstem. The figure describes conditions at the inception of regulation. Again, Beatton River is conspicuously seen to have no significant effect. Since then, sampling has

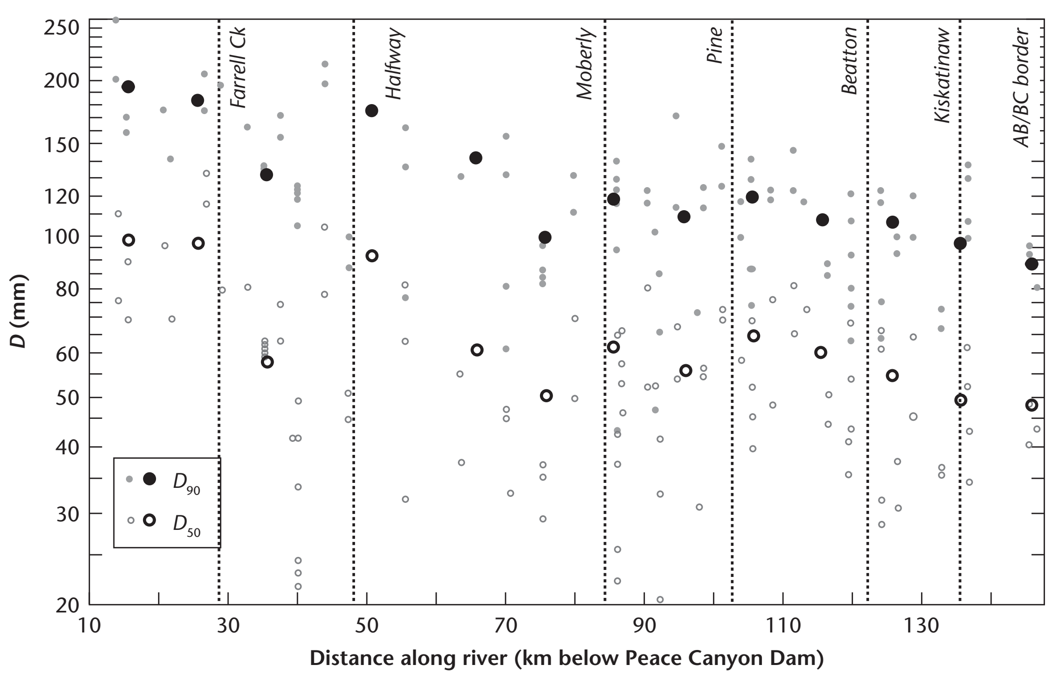

Figure 3.10 Generalized variation in bed material surface texture downstream in the British Columbia reach: note the upward displacement of grain size at each major tributary, except Beatton River. The data were collected in 1968 and 1975 and are considered to represent pre-regulation conditions on bar-head sites. The original data, 78 samples from 39 sites (grey spots), have been grouped by 10-km sub-reaches. The trends are exponential, as is widely experienced (see Rice and Church (1998) for further regional data; partially after Church and Kellerhals (1978), Figure 7).

been restricted to the reach between Moberly River and immediately downstream from the Pine confluence.

The variable effect of tributary confluences may be pursued further by investigating the formulations of Ferguson and Hoey (2008) and of Curtis *et al.* (2010) for expected effects at tributary confluences. We estimate regime conditions from sub-reach data in the British Columbia reach, and we know the channel contraction ratio, and something of its history, at 14 confluences that actually do affect the mainstem (Table 3.5) as far downstream as Dunvegan. Of these, we also have grain-size information for Halfway, Moberly, and Pine rivers, the major gravel-yielding tributaries. We speculate that Farrell and Wilder creeks are too small to have a significant impact on Peace River bed material, while the tributaries beyond the Pine River (i.e., Beatton River and those draining only the Alberta Plateau) probably deliver material too fine and friable to have a significant effect.

We have sufficient information to examine the Ferguson and Hoey (2008) regime prediction at six British Columbia confluences (Table 3.6). Comparisons are to a considerable degree compromised by data variability, but it appears that regime conditions are approached at Farrell Creek and Halfway River. The former is reasonable; Farrell Creek is much smaller than Peace River and, despite the prograding fan, probably presents no great perturbation to downstream regime. The Halfway result remains uncertain: we have no recent grain size data but we do know that the reach past the junction has been severely affected by the Attachie slide of 1973, which occurred immediately upstream from the confluence. Moberly and Pine Rivers present the appearance of nonregime conditions both in the natural and regulated regimes, an outcome that may be expected if the tributaries deliver bed material that cannot be transported onward in Peace River. Remarkably, data for Beatton River also predict nonregime conditions, while Kiskatinaw River appears to have been pushed into nonequilibrium by the flow regulation. Significant further changes in the Peace River channel may be expected at confluences from Moberly River downstream and, associated as they are with the disposition of sediment

Table 3.6 Regime change past tributary confluences[a]

Tributary[b]	Distance d/s dam (km)	D_d[c] (mm)	D_p[c]	w_d[d] (m)	w_p[d]	Q_{2trib} (m^3s^{-1})	Q_{2d}	Q_{2p}	Q_d/Q_p	S_d/S_p Calculated	Observed
Farrell n	23.7	132±40	195±78	383±116	390±100	*~40*	5880	5840	1.007	0.593±0.432	0.536
Farrell r		–	–	306±104	335±106	*~40*	1980	1940	1.021	0.551±0.422	0.765
Halfway n	45.2	176±70	132±40	380±108	410±62	715	*6560*	5850	1.121	1.229±0.853	1.511
Halfway r		–	–	272±142	325±98	715	*2040*	1950	1.041	1.196±0.979[e]	1.674
Moberly n	84.5	118±26	101±44	389±100	412±92	*70*	*6070*	6000	1.012	1.151±0.796	0.977
Moberly r		92±23	107±6	307±142	334±106	*70*	*2180*	2110	1.033	**0.745±0.430**	**3.591**
Pine n	101.0	120±30	113±66	440±148	402±72	1575	*7600*	6020	**1.263**	**0.956±0.830**	**1.865**
Pine r		109±8	97±7	326±106	329±52	1575	*3720*	2150	**1.730**	**0.720±0.201**	**1.618**
Beatton n	122.5	107±24	109±42	616±184[f]	485±188[f]	735	*7940*	7210	1.101	**1.103±0.724**	**2.349**
Beatton r		–	–	440±94	409±194[f]	735	*3630*	2900	**1.252**	**0.858±0.602**	**1.589**
Kiskatinaw n	135.5	89±14	107±24	410±170[f]	616±184[f]	170	*7420*	7250	1.023	0.546±0.305	0.896
Kiskatinaw r		–	–	340±166[f]	440±94	170	*3100*	2940	1.058	**0.603±0.421**	**1.366**

[a]In the notation, subscript *d* indicates downstream (distal) and *p* indicates upstream (proximal) from the confluence. In the table, italic quantities are estimated: for discharge, adjustments are based on drainage area; for grain size estimates are based upon an assumption of no change. Bold results are values considered to represent a significant change (discharge ratio) or a significant departure from the regime prediction (gradient ratio).

[b]n indicates natural regime; r indicates regulated regime. Some natural regime results may be invalid if bed material transport was considerable at mean annual flood magnitude.

[c]Average of barhead samples over 10 km downstream and upstream from the confluence, respectively. For natural regime, the values are based on measurements taken in 1968 and 1974 (Church and Kellerhals, 1978); for the regulated regime, measurements are based on 2001 and 2003 data that remain unpublished. Moberly proximal samples are only local in 2003.

[d]Average over 10 channel widths upstream and downstream from the confluence.

[e]Assumes no change in grain size ratio after regulation. See text for discussion.

[f]Anabranched reach.

delivered from the tributaries, may require centuries to be completed.

The formula of Curtis *et al.* (2010), in contrast to that of Ferguson–Hoey, is designed to predict changes at the confluence under regulation. It predicts a steeper gradient past all constricted confluences, with the increase as large as two times (Table 3.7). This is a consequence of the effect, in their formulation, of the severely reduced flows in the mainstem. The largest increases occur at the smallest tributaries because of the lack of any compensating flow or grain size effect. At the three principal gravel-delivering confluences (Halfway, Moberly, Pine) there is a distinct decrease in gradient upstream (identified by extended backwater; complicated at the Halfway confluence by the deposition of Attachie landslide material into the channel immediately upstream of the confluence), a sensible steepening of the gradient past the confluence as the river passes over the gravel deposited in the Peace River channel, and then a reduction downstream. The implication of these contrasting results is taken up in discussion.

It is perhaps significant that the maximum constriction achieved by tributary fans all along the river is the order of 40%; that is, river width at the fan is in most cases 0.6 to 0.7 of its unperturbed value nearby. The equilibrium width of the regulated channel, calculated from simple regime formulae, is expected to be about 0.62 as wide as the unregulated channel (Chapter 6).

Table 3.7 Tributary confluence characteristics

Tributary[a]	**Distance d/s dam (km)**	**Tributary area (km²)**	**Width contraction**	**Q_2 (m³s⁻¹)**[b,c]							
				Q_{trib}	**Q_{Pnat}**	**Q_{Preg}**	$\frac{Q_{trib}}{Q_{Pnat}}$ [c]	$\frac{Q_{trib}}{Q_{Preg}}$ [c]	$\frac{D_c}{D_p}$ [c,d]	$\frac{Q_{Preg}}{Q_{Pnat}}$ [e]	$\frac{S_{reg}}{S_{nat}}$ [f]
Farrell Cr (67)	**23.7**	**637**	**0.9**	***~40***	**5843**	**–**	**0.007**	**–**			
Farrell Cr (05)			**0.6**	***~40***	**–**	**1936**	**–**	**0.021**		**0.33**	**1.82**
Halfway	45.2	9 402	0.6	715	5843	1950	0.12	0.37	1.58	0.33	1.82
Wilder Cr (05)	77	97.4	0.8	*7.5*	*6550*	*2640*	–	0.003		0.40	2.0
Moberly (67)	**84.5**	**1900**	**0.9**	***70***	***6560***	**–**	**0.011**	**–**	**1.24**		
Moberly (05)			**0.5**	***70***	**–**	***2650***	**–**	**0.027**	**1.46**	**0.40**	**1.25**
Pine (67)	**101**	**13 560**	**0.7**	**1575**	**7213**	**–**	**0.22**	**–**	**1.16**		
Pine (05)			**0.5**	**1575**	**–**	**2853**	**–**	**0.55**	**1.46**	**0.40**	**1.25**
Kiskatinaw (05)	135.5	4 367	0.7	169	*7950*	*2900*	–	0.058		0.36	1.94
Border creek	147.5	31.8	0.7	1.5	8000	2930	–	0.001		0.37	1.89
Pouce Coupe (67)	**153**	**3 638**	**0.7**	**114**	**8000**	**–**	**0.014**	**–**			
Pouce Coupe (05)			**0.6**	**114**	**–**	**2930**	**–**	**0.039**		**0.37**	**1.62**
Clear	167	2 958	0.7	96	*8050*	*3000*	0.012	0.031		0.37	1.89
Fourth Cr	250	228	0.7	*~7.4*	*8100*	*3100*	0.001	0.002		0.37	1.89
Hamelin Cr	252	722	0.6	*~24*	*8150*	*3300*	0.003	0.007		0.40	1.50
Unnamed gully	256	13.2	0.9	*~0.5*	*8250*	*3425*	6×10^{-5}	1.5×10^{-4}		0.42	2.14
Ksituan	273	704	0.7	*~23*	*8250*	*3450*	0.003	0.009		0.42	1.67
Hines Cr	275	1647	0.6	*~50*	8275	3475	0.006	0.014		0.42	1.67

[a] Includes only those tributaries with significant width contraction. Entries marked "67" indicate conditions for the natural regime of Peace River in 1967, immediately before regulation; entries marked "05" represent conditions in 2005. Confluences with only one entry have not changed appreciably since regulation, except that a single entry annotated "05" indicates a contracted confluence in 2005 where no contraction existed in the natural regime. Entries in bold exhibit significant change since regulation.

[b] Values in italic represent estimates based on drainage area or on incremental drainage. Roman figures are based on gauges.

[c] *trib* denotes the tributary value; *Pnat* denotes Peace River value in the natural regime; *Preg* denotes the regulated Peace River value; *p* denotes the condition proximal (upstream) from the tributary confluence; *c* denotes the condition in the maximum contraction immediately below the tributary confluence.

[d] Data based on D_{50} of surface materials. Pre-regulation data from Church and Kellerhals (1978); post-regulation data collected in 2001 to 2003, not otherwise published. Where there is no entry, it is assumed that the ratio is ~1.0. In view of the relative size of the tributary basins and the geology of most tributary basins, this assumption is plausible for all except perhaps Farrell Creek. Ratio is equivalent to D^* of Curtis *et al.* (2010).

[e] Q^* of Curtis *et al.* (2010).

[f] S^* of Curtis *et al.* (2010), from Equation 3.3b.

The implication is that the channel along most of its length remains wider than it needs to be, while it has reached a limiting width at points of sediment influx and "active" width adjustment.

3.5 Discussion

The preceding results are brought together in Figure 3.11, which maps the net gradation response from each data site by sub-reach and major sediment sources such as tributaries and landslides. This map forms the basis for the following discussion.

3.5.1 Absence of channel degradation

The first important aspect of Figure 3.11 (see also Figure 3.3) is the near absence of significant regradation upstream of Moberly River—exception being made for the remarkable accumulation of sediment immediately downstream of Halfway River and the Attachie slide (Figure 3.2d). Farther downstream, aggradation and degradation alternate, with the main degradation being localized upstream from Moberly and Pine rivers. These effects developed after 1991 and probably were initiated by the 1996 flood. Even these sites appear to reflect localized erosion rather than general downcutting with the most severe degradation (Section S7) occurring where a notable riffle has been washed away. This is remarkable within the general literature on regulated rivers, wherein degradation below the dam is found to be nearly universal (cf. Williams and Wolman, 1984). The lack of general degradation was predicted for Peace River very early on (Kellerhals and Gill, 1973) due to its cobble-armored bed and its diminished floods, aided by the fact that sediment supply from the upper Peace was naturally limited (Church, 1995), and it is consistent with findings by Petts (1984b).

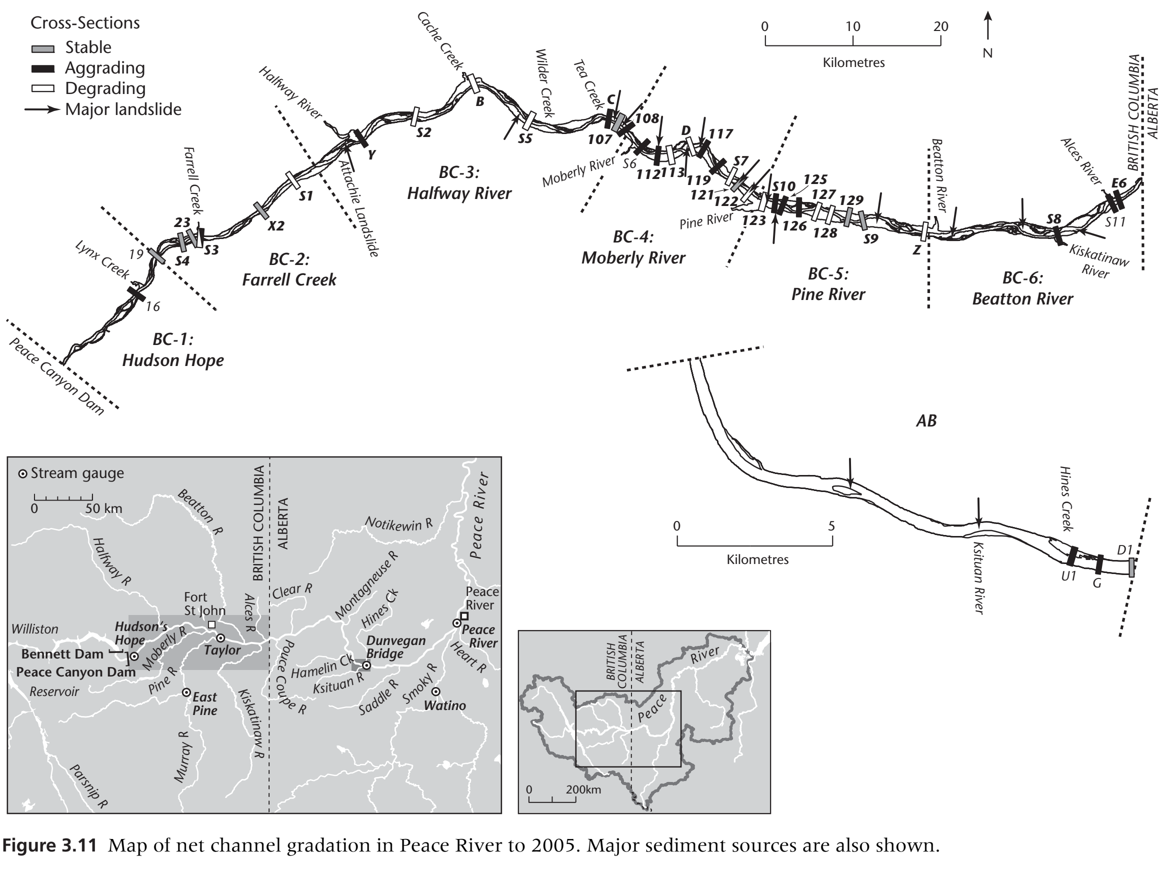

Figure 3.11 Map of net channel gradation in Peace River to 2005. Major sediment sources are also shown.

Our results show that the bed of the regulated Peace River is not static. Besides the above-noted cases, we observed several instances of localized channel incision opposite recent deposition (e.g., Sections S3 (Figure 3.7a); U1 and G (not illustrated)). Under exceptional flood flows, upper Peace River can still mobilize its bed.

3.5.2 Spatial variability of channel gradation

Figure 3.11 suggests that net channel gradation in the post-regulation Peace River varies at both local and reach scales. Locally, aggrading sites are interspersed with more stable sites, with individual deposition zones rarely exceeding five kilometers in length. This effect is most striking at the mouth of Halfway River (Section Y), where significant aggradation reached Section S2, a mere seven kilometers downstream, only after the 1996 release flood. The pattern is repeated near Moberly and Pine River confluences. The picture suggests that contemporary coarse sediment inputs to the Peace River are trapped at the first downstream site of flow divergence and bar sedimentation, the regulated flows being unable to disperse the material far downstream. This conjecture is reinforced by the distribution of major sediment sources, shown in Figures 3.3 and 3.11. Each aggrading site is a short distance downstream from a known sediment source (a significant tributary or major landslide), and nearly every source is followed by an aggrading site. Backwatered reaches above aggrading tributary junctions (e.g., Sections 108, 122, Z) may be efficient at trapping finer sediment, though this does not necessarily signal aggradation. This scale of variability in channel gradation supports the claim (Church, 1995) that Peace River is developing a stepped longitudinal profile. Downstream, in Alberta Reach 1, the stepped profile may have been a feature for a long time because fans were able to prograde significantly there even before regulation. The strong tendency for tributary confluences to control post-regulation aggradation has been noted (Petts, 1984b), but the significance of landslide sources of sediment has not previously been emphasized. Its significance (or lack thereof) obviously depends upon the nature of the valley-side slopes, including both material and stability.

The accumulation of sediment near lateral sources signals the general inability of the regulated flows to move a significant fraction of the introduced sediment. However, degradation during the 1996 flood in some erstwhile aggrading reaches indicates that exceptional flood flows may still redistribute bed material more widely within the Peace River channel.

Gradation also seems to vary at a scale of roughly 100 km, with the more distal British Columbia reach (from Section C to the British Columbia–Alberta border) showing more aggradation than the proximal reach. This appears to reflect the fact that the proximal reach contains few sediment sources other than the Attachie Landslide, Halfway River, and a handful of small tributaries (Figure 3.11). The smaller streams are relatively unimportant sediment contributors, as evidenced by the negligible fan progradation at Lynx Creek and Cache Creek (Section B). Nontributary sources in the proximal reach are rare as the river is bounded primarily by relatively competent bedrock upstream of Section 23, and by stable terraces for most of the reach between Sections 23 and C.

In contrast, from Section C downstream, sediment delivered by the larger tributaries such as Moberly and Pine Rivers is supplemented by frequent eroding banks, terraces and bluffs, and by a number of recent major landslides (Figure 3.11; see also Severin, 2004). The reach retains a complex morphology with extensive islands, bars, and secondary channels, suggesting that the long-term development of the river planform is also linked to sediment supply (*cf*, Grant *et al.*, 2003). This is especially true of Sub-reaches BC5 and BC6 (note, in Figure 3.6, their high braiding index) downstream of Pine and Beatton Rivers, the two largest tributaries in the British Columbia reach. Based on this analysis and the behavior of Section Y, it seems probable that if there were more sediment sources in the proximal reach, the entire British Columbia portion of the regulated river might be dominated by localized aggradation.

Farther downstream, data are more sparse and the spatial pattern of channel gradation cannot be outlined in detail. The Dunvegan sections exhibit a mixture of fan progradation and compensatory erosion, as at Farrell Creek. The offsetting activity at U1 gives way to stronger aggradation directly beneath the Dunvegan bridge (Section G). Yet Section D1, just two kilometers downstream of Hines Creek, has been perfectly stable, as has the reach in general according to the specific gauge results (Table 3.3). The pattern of localized aggradation at sediment sources is repeated 394 km below the dam where air photo analysis reveals that the Smoky River delta has prograded substantially into the mainstem since regulation. Again, aggradation has been limited in extent, with no convincing evidence of bed elevation change at TPR gauge eight kilometers farther downstream (Table 3.3). There are reports of shoaling at Carcajou, 632 km below Peace Canyon Dam (Church, 1995), suggesting that aggradation may be occurring there. At Fort Vermilion (808 km below the dam), there is no evidence of post-regulation channel regradation (Table 3.3), but neither are there any major sediment sources in the immediate reach. By this point, however, the hydrological effects of regulation are considerably diminished and the bedload is primarily sand. In these lower reaches, including the stable Peace Point gauge site, direct connections between channel behavior and river regulation become tenuous.

3.5.3 Channel cross-sectional morphology

Following Brandt (2000), aggradation in Peace River should be expressed as bar sedimentation raising the channel bed. Indeed, that is what is seen. On the other hand, degradation should be expressed as bank erosion. As a general phenomenon, this is not seen. Purely fluvial bank erosion (i.e., erosion of alluvial deposits, as opposed to river attack on failing valley-side slopes) occurs at a limited number of sites along the river, mainly in association with mixed scour and fill as the channel migrates laterally. In the regulated Peace River, bar erosion is the main observed mechanism of degradation, largely by chute development through riffles, though it does occur by lateral stripping of sediment as well. It is probable that the outer banks are not, in general, being attacked because flows, except the rare flood releases, are confined well within the limits of the former channel.

3.5.4 Confluences

Tributary confluences are the most conspicuous sites of aggradation along the upper river. There are two styles of aggradation: at the major, mountain-sourced, gravel-delivering tributaries (Halfway, Moberly, and Pine), powerful nival flows force gravel into the mainstem of the river, where it is deposited subaqueously over some (relatively short) distance downstream. Each of these rivers also has developed a subaerial fan—most prominently at Halfway River—which was present (but not conspicuous at Moberly River) before regulation. In comparison, tributaries delivering mainly finer, more friable sediments from the Alberta Plateau have developed subaerial fans that are notably skewed downstream. In most cases, these fans predate regulation.

In the absence of precise, field-derived measurements of stream gradient past the confluences, the implications of these deposits for the river are unclear. A formula of Ferguson and Hoey (2008), designed to estimate the effect of tributary confluence on equilibrium channel gradient predicts a decrease in gradient ratio downstream past the British Columbia tributaries, though an actual increase in gradient past the main, gravel-contributing confluences except at the Pine confluence where the increment to flow is also large. The formula is not specified for transient effects through the confluence itself and so the predicted effects are apt to be qualitatively correct for upstream/downstream comparisons only away from the immediate vicinity of the confluence. It must also be borne in mind, however, that the reduced formula (Equations 3.2b/3.2c) for zero transport in the mainstem may not be entirely valid. In fact, results to date are mixed, with an increase in observed gradient ratio at most confluences, dramatically so at the Moberly confluence, which is also visibly evident. At the Pine confluence, however, there has been a modest decrease in gradient ratio and at Beatton River a considerable decrease. For the dominant Pine River confluence, the gradient ratio after regulation has moved closer to the ratio of downstream to upstream gradients determined over a long distance (tens of kilometers), 0.70, as measured at the time of regulation. Altogether, the results emphasize the significance of deposition in the main channel of bed material delivered from the tributaries.

In comparison, the formula of Curtis *et al.* (2010) is designed to estimate gradient change in channel contractions at confluences and predicts an increase in gradient consequent upon the deposition of sediment in the confluence zone. Ratios fall in the range 1.25 to 2.0, which appear plausible for the immediate steepening over the tributary deposits. In summary, our relatively limited data do not permit a firm conclusion on either formulation but it is reasonable to expect that each formula, interpreted within its intended purpose, is giving qualitatively appropriate indications. This would reinforce further the appearance of a developing stepped profile.

3.5.5 Channel gradation and planform change: implications for channel gradient

Channel gradation and planform adjustment are both mechanisms for slope adjustment. The connection between the two is sediment supply, and the main sites of channel gradation and planform complexity occur where sediment is added to the river (Figure 3.11) but not effectively transported away.

According to previous studies (Church *et al.*, 1997), regradation has been accompanied by the steady succession of floodplain vegetation on upper bar surfaces and in secondary channels no longer regularly occupied by river flow (see Chapter 7). While this is supported by our analysis of channel area, data of our first braiding index suggest that channel pattern change has been slow (Figure 3.6). Some loss of secondary channels is apparent in Sub-reach BC4, but the pattern is absent from other studied reaches and accompanied by the remarkable stability of sinuosity. Topographically, the secondary channels still exist, and historical cross-sections show they have been slow to fill (Figures 3.2a and 3.2e). However, the second braiding index indicates that many secondary channels are no longer a part of the normally occupied channel bed. They persist chiefly because of the absence of siltation in the upper river (itself the consequence of the normally restricted range of flows) and the slow pace of vegetation succession. Their continued presence makes possible the accommodation of occasional major floods (see Chapter 10) without extensive channel reorganization.

Gradation changes have undoubtedly produced some local planform responses (e.g., bank erosion in response to local sedimentation). On the whole, however, gradation and planform adjustment seem to operate on different time scales, and largely independently of one another. It seems clear that the channel is taking on a stepped longitudinal profile as the result of prograding alluvial fans at many tributary confluences. This is illustrated in Figure 3.12, a schematic rendition of the net gradation results from the British Columbia cross-sections. Does this represent progress toward some new equilibrium between Peace River's channel form, sediment supply, and regulated hydrologic regime? Equilibrium demands a steepening of the channel

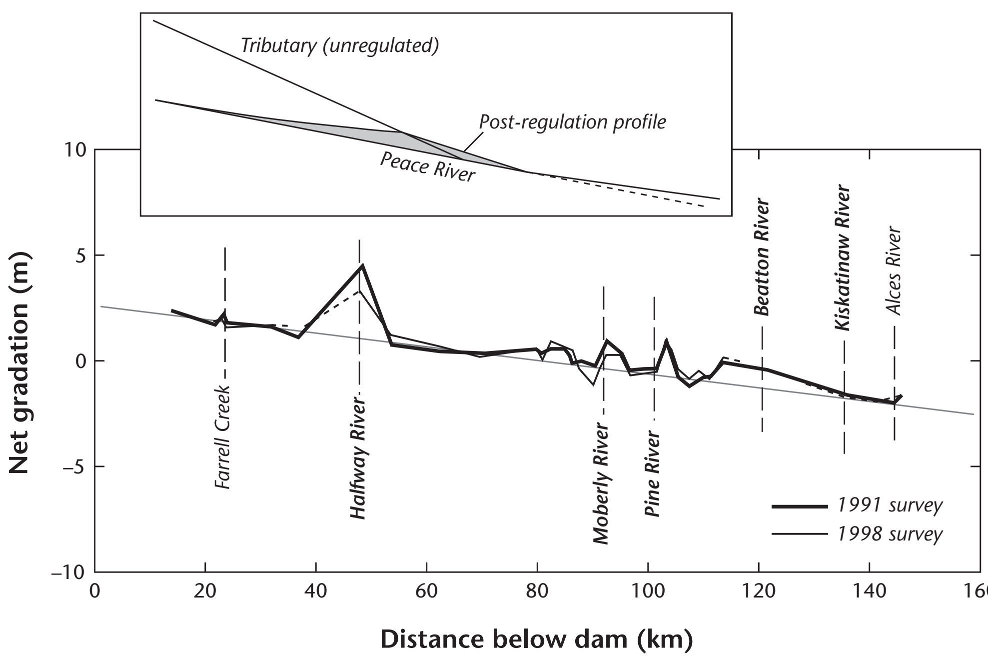

Figure 3.12 Schematic diagram showing the development of a stepped long profile in the British Columbia reach of Peace River. Note the backwaters and steepened reaches at aggradation zones. Vertical scale greatly exaggerated. Inset: sketch of the characteristic situation at a prograding tributary junction (see also Ferguson and Hoey, 2008, Figure 10.6b, which presents a simulation of the same effect).

gradient or a contraction of channel width to restore the river's competence to move sediment away from tributary sources (or the introduction of finer sediments, which has not occurred absent any significant change in tributary regime). Peace River has indeed become generally narrower as the result of regulation, but the general effect of reduced flows has been to produce a shallower channel with *increased* aspect ratio (see Chapter5). Until deposition of sediment in lateral bars produces a narrower, deeper channel, a gradient increase is the available degree of freedom. However, the bed elevation at the dam and in the bedrock-bound, sediment-starved most proximal reach is fixed and the sinuosity of the river already is very low, so that overall steepening does not appear possible. Steepening must therefore take the form of downstream-weakening aggradation below significant sediment sources, with compensating reduction in gradient elsewhere, as is achieved by a prograding fan creating a blockage in the channel. So far, aggradation is quite localized. The resulting channel steepening is indeed offset by reduced slope in a backwatered reach upstream from significant sediment sources and also, perhaps, by the downstream gradient requirement indicated by the Ferguson and Hoey formula. In the long term, locally increased slopes should promote the downstream progression of aggradation zones into the next backwater. An early example of this may be provided by the cross-sections below the Pine River confluence, where bar growth progressed from S10 to 125 through 1991, and possibly as far as 127 in the wake of the 1996 flood. The process in the intermediate term must be mediated by the unusual occurrence of competent flood flows, such as the 1996 flood; in the very long term, the local increase of gradient will promote increase of stream competence and onward movement of bed material.

3.6 Conclusions

This report presents a quantitative analysis of channel gradation in regulated Peace River. The prevalence of aggradation suggests that, in the long term, Peace River may be attempting to steepen its proximal bed to compensate for reduced peak flows. Localized aggradation at sediment sources, principally tributary confluences, is obvious in the British Columbia reaches, but the downstream extent of the pattern is uncertain. At some point, likely below the junction of Smoky River, regradation may become small due to gradual flood replenishment and fining of bed material. This issue remains to be investigated.

Based on an approximation developed by de Vries (1975), Church (1995) estimated that it would take the order of 1000 years for Peace River channel adjustments (see also Chapter11) to approach completion, though the majority of the work might be done in 50 to 100 years. For channel width, depth and current velocity, the latter figure is doubtlessly more reasonable, since these respond nearly as rapidly as the imposed hydrological change. Changes at some aggrading cross-sections have already begun to slow down and at others have reversed, but at still others they have begun only since the 1996 flood. If the next stage of aggradation is indeed its progression downstream from sediment sources, then the process will be a very long one in the upper river, contingent on the occurrence of unusual, competent floods. For example, aggradation below the Pine River confluence has proceeded seven kilometers downstream (to Section 127) in 38 years, for a nominal rate of progression of 185 m a^{-1}. At this rate, it will require about 60 years for the initial effect to reach the halfway point to the next major tributary (Beatton River), but much longer for the effect of the adjustment to be telegraphed through the entire river system. This circumstance is consistent with predictions made by Williams and Wolman (1984) by entirely different means for the largest rivers in their study, and with Church's earlier estimate.

In addition to confirming and extending the gradation predictions of previous researchers (Kellerhals and Gill, 1973; Church, 1995), our work highlights the importance of sediment sources, both tributary and valley-wall, in setting the spatial pattern of aggradation, and the local and transient nature of gradation in a competence-limited river. We have also shown that localized channel erosion may still occur in the regulated Peace River.

Within the general literature on regulated rivers, this study fills a substantial gap. In the British Columbia reach, the cross-section and specific gauge data provide one of the most complete records of channel gradation on a large regulated river. In an area of research where degradation and channel instability are the norm, the largely passive and aggradational character of the post-regulation Peace River provides a sharp and useful contrast. Finally, this project increases our general understanding of morphological responses in regulated gravel-bed rivers, and we hope it may contribute to improving their management.

Acknowledgments

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References

Andrews, E. D. (1986) Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah. *Geological Society of America Bulletin*, 97, 1012–1023. doi:10.1130/0016-7606 (1986)97<1012:DEOFGR>2.0.CO;2

Benda, L., Andras, K., Miller, D., and Bigelow, P. (2004) Confluence effects in rivers: interactions of basin scale, network geometry, and disturbance regimes. *Water Resources Research*, 40, W05402. doi:10.1029/2003WR002583

Brandt, S. A. (2000) Classification of geomorphological effects downstream of dams. *Catena*, 40, 375–401.

Church, M. (1995) Geomorphic response to river flow regulation: case studies and time scales. *Regulated Rivers: Research & Management*, 11, 3–22.

Church, M. and Kellerhals, R. (1978) On the statistics of grain size variation along a gravel river. *Canadian Journal of Earth Sciences*, 15, 1151–1160. doi:10.1139/e78-121.

Church, M. and Rood, K. M. (1982) Peace River surveys: 1979 and 1981. *Unpublished Report*. The University of British Columbia, Department of Geography. 54 p.

Church, M., Xu, J., Moy, A., and Uunila, L. (1997) Changes in morphology and riparian vegetation following flow regulation, peace river, 1968 and 1993. *NRBS Study, Project Report*, 102, 91 p. Northern River Basins Study, Edmonton, Canada.

Curtis, K. E., Renshaw, C. E., Magilligan, F. J., and Dade, W. B. (2010) Temporal and spatial scales of geomorphic adjustments to reduced competency following flow regulation in bedload-dominated systems. *Geomorphology*, 118: 105–117. doi:10.1016/j.geomorph.2009.12.012.

de Vries, M. (1975) A morphological time-scale for rivers. *Proceedings of the 16th International Association for Hydraulic Research World Congress*, 2, 17–23, Jul 27–Aug 1, 1975, São Paulo, Brazil.

Fassnacht, H., McClure, E. M., Grant, G. E., and Klingeman, P. C. (2003) Downstream effects of the Pelton-Round Butte hydroelectric project on bedload transport, channel morphology, and channel-bed texture, Lower Deschutes River, Oregon, in *A Peculiar River*, edited by J. E. O'Connor and G. E. Grant. Vol. 7: Water Science and Application Series. American Geophysical Union, Washington, DC. pp. 169–201. doi:10.1029007WS12

Ferguson, R. and Hoey, T. (2008) Effects of tributaries on main-channel geomorphology [Chapter 10], in *River Confluences, Tributaries and the Fluvial Network*, edited by S. Rice, A. G. Roy, and B. L. Rhoads. John Wiley & Sons, Ltd, Chichester, UK. pp. 183–208.

Galay, V. J. (1983) Causes of river bed degradation. *Water Resources Research*, 19, 57–1090. doi:10.1029/WR019i05p01057

Grant, G. E., Schmidt, J. C., and Lewis, S. L. (2003) A geological framework for interpreting downstream effects of dams on rivers, in *A Peculiar River*, edited by J. E. O'Connor and G. E. Grant. Vol. 7: Water Science and Application Series. American Geophysical Union, Washington, D.C. pp. 203–219. doi:10.1029/007WS13

Hadley, R. F. and Emmett, W. W. (1998) Channel changes downstream from a dam. *Journal of the American Water Resources Association*, 34, 629–637.

Hamilton, A. S. and Moore, R. D. (2012) Quantifying uncertainty in streamflow records. *Canadian Water Resources Journal*, 37, 3–21. doi:10.4296/cwrj3701865

Hanks, T. C. and Webb, R. H. (2006) Effects of tributary debris on the longitudinal profile of the Colorado River in Grand Canyon. *Journal of Geophysical Research*, 111, F02020, 13 p. doi:10.1029/2004JF000257

Howard, A. D. and Dolan, R. (1981) Geomorphology of the Colorado River in the Grand Canyon. *Journal of Geology*, 89, 269–298.

Johnson, W. C. (1998) Adjustment of riparian vegetation to river regulation in the Great Plains, USA. *Wetlands*, 18, 608–618.

Kellerhals, R. (1982) Effect of river regulation on channel instability, in *Gravel-Bed Rivers*, edited by R. D. Hey, J. C. Bathurst, and C. R. Thorne. John Wiley & Sons, Ltd, Chichester, UK. pp. 685–705.

Kellerhals, R. and Gill, D. (1973) Observed and potential downstream effects of large storage projects in northern Canada. *Proceedings of the 11th ICOLD Congress*, 1, 731–754.

King, N. J. (1961) An example of channel aggradation induced by flood control. *United States Geological Survey, Professional Paper*, 424B, 29–32.

Lane, E. W. (1934) Retrogression of levels in riverbeds below dams. *Engineering News-Record*, 112, 836–838.

Livesey, R. H. (1963) Channel armouring below Fort Randall Dam, *United States Department of Agriculture, Miscellaneous Publication*, 970, 461–470.

McLean, D. G. and Anderson, M. D. (1980) Hydraulic and morphological processes on the Peace River near Fort Vermilion. *Report*, SWE 80-2, 188 p. Alberta Research Council, Transportation and Surface Water Engineering Department.

Pelletier, P. M. (1988) Uncertainties in the single determination of river discharge: a literature review. *Canadian Journal of Civil Engineering*, 15, 834–850. doi:10.1139/188-109

Petts, G. E. (1984a) *Impounded Rivers: Perspectives for Ecological Management*. John Wiley & Sons, Ltd, Chichester, UK. 326 p.

Petts, G. E. (1984b) Sedimentation within a regulated river. *Earth Surface Processes and Landforms*, 9, 125–134.

Rasid, H. (1979) The effects of regime regulation by the Gardiner Dam on downstream geomorphic processes in the South Saskatchewan River. *The Canadian Geographer*, 23, 140–158.

Rhoads, B. L. (1987) Changes in stream channel characteristics at tributary junctions. *Physical Geography*, 8, 346–361.

Rice, S. (1998) Which tributaries disrupt downstream fining along gravel-bed rivers? *Geomorphology*, 22, 39–56.

Rice, S. and Church, M. (1998) Grain size along two gravel-bed rivers: statistical variation, spatial pattern and sedimentary links. *Earth Surface Processes and Landforms*, 23, 345–363. doi:10.1002/(SICI)1096-9837(199804)23:4<333::AID-ESP847>3.0.CO;2-Z

Schumm, S. A. and Galay, V. J. (1994) The river Nile in Egypt, in *The Variability of Large Alluvial Rivers*, edited by S. A. Schumm and B. R. Winkley. American Society of Civil Engineers, ASCE Press, New York. pp. 75–102.

Severin, J. M. (2004) Landslides in the Charlie Lake map sheet, Fort St. John. M.Sc. thesis. The University of British Columbia.

Shaw, J. and Kellerhals, R. (1982) The composition of recent alluvial gravels in Alberta river beds. *Alberta Geological Survey, Bulletin*, 41, 151 p. Alberta Research Council, Edmonton, Canada.

Taylor, K. V. (1978) Erosion downstream of dams, in *Environmental Effects of Large Dams*, edited by W. V. Binger. Report by the Committee on Environmental Effects of the United States Committee on Large Dams. American Society of Civil Engineers, New York. pp. 165–186.

Van Steeter, M. M. and Pitlick, J. (1998) Geomorphology and endangered fish habitats of the upper Colorado River. 1. Historic changes in streamflow, sediment load and channel morphology. *Water Resources Research*, 34, 287–302. doi:10.1029/97WR02766

Williams, G. P. and Wolman, M. G. (1984) Downstream effects of dams on alluvial rivers. *United States Geological Survey, Professional Paper*, 1286, 83 p. U.S. Government Printing Office, Washington, DC, USA.

Xu, J. (1996) Channel pattern change downstream from a reservoir: an example of wandering braided rivers. *Geomorphology*, 15, 147–158.

CHAPTER 4

Tributary channel gradation due to regulation of Peace River

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4.1 Introduction

Within the literature on regulated rivers, much attention has been paid to post-regulation changes in channel morphology. Comparatively few reports exist, however, of how these changes are transmitted to tributary streams. For the most part, tributaries are discussed in terms of their role as (probably unregulated) contributors of flow and sediment to the regulated river (cf. Williams and Wolman, 1984; Andrews, 1986; Ferguson and Hoey, 2008). Yet tributaries downstream from a dam may undergo significant morphological changes themselves.

Damming a river generally changes the effective base level of downstream tributaries, through either reduction in mainstem water levels, alteration of the timing between mainstem and tributary flooding, or mainstem degradation (Kellerhals, 1982; Germanoski and Ritter, 1988). The result is steepening of the tributary slope near its mouth, leading to upstream-progressing channel degradation (Taylor, 1978; Petts, 1984). Although studies in natural streams suggest that such base level effects should not extend far upstream (Leopold and Bull, 1979), research on dammed rivers indicates that the effect can be significant. The process has been documented in tributaries of the Missouri River (Galay, 1983), the Russian Don River (Petts, 1984), and the Osage River, Missouri (Germanoski and Ritter, 1988), leading to such problems as undermining of bridge footings and increased sedimentation below tributary confluences. The effect is analogous to that of channel incision due to sea or lake level change or knickpoint propagation in channelized rivers (Daniels, 2002). Tributary steepening due to base level fall may also accelerate bank erosion and channel instability (e.g., Hassan and Klein, 2002). In addition to these downstream studies, observations on tributaries upstream of a dam (Xu, 2001) have revealed complex aggradation and degradation cycles linked to fluctuating reservoir water levels.

Instances of tributary degradation have been observed in the regulated Peace River basin in northern British Columbia, Canada. At Lynx Creek, undermining of the highway bridge immediately after dam closure prompted installation of a riprap boulder rapid to armor the bed (Kellerhals and Gill, 1973). Farther downstream, at Farrell Creek, another bridge was undercut, necessitating its replacement (Kellerhals and Gill, 1973). At this site, degradation of one meter was found to extend for a distance of 300 m upstream of the mouth (Kellerhals, 1982). Farther still downstream, Pine River underwent rapid bank erosion above the confluence, and this was tentatively attributed to degradation (Kellerhals, 1982), although no measurements were made.

Beyond these relatively casual observations, there has heretofore been no attempt to measure the magnitude, upstream extent, or basin-wide spatial occurrence of tributary degradation along Peace River, nor any assessment of whether other gradation mechanisms may be at work. This information gap is repeated in the literature on regulated rivers. Accordingly, our goal in this chapter is to provide a systematic characterization of tributary gradation in the regulated Peace River basin. Main

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The Regulation of Peace River: A Case Study for River Management, First Edition. Michael Church.

Companion website: www.wiley.com/go/church/peaceriver

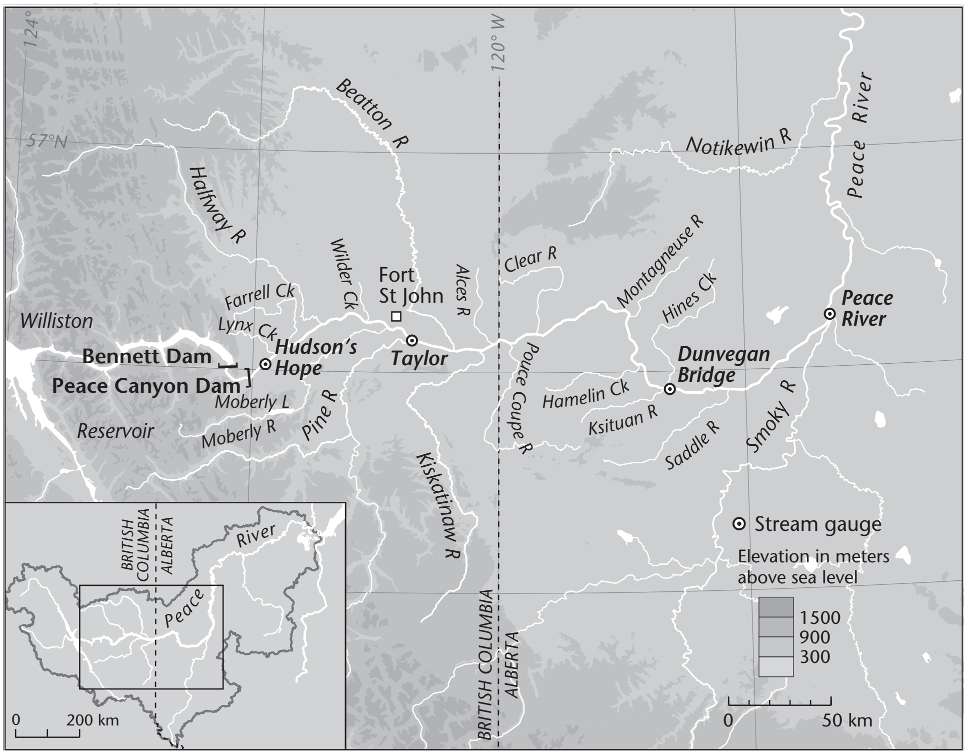

Figure 4.1 Map of study reach, showing tributary study sites.

attention is directed to the 143 km reach immediately below the dams where the effects are expected to be greatest.

4.2 Study sites

Peace River (Figure 4.1) rises in the Rocky and Omineca Mountains of northern British Columbia. It flows eastward across the high plains of the Alberta Plateau, turning north and northeast before ending at the Peace–Athabasca Delta in northeastern Alberta. The river has been regulated for the purpose of hydroelectric power generation since the closure of W.A.C. Bennett Dam in 1967. At Hudson's Hope, just below Bennett Dam, the post-regulation mean annual flood is 1900 m^3s^{-1}, a reduction of 67% from the pre-regulation mean annual flood of 5843 m^3s^{-1}. The flood is gradually restored lower in the Peace basin due to flows from unregulated tributaries, but even at Peace Point, near the river's terminus, the mean annual flood has declined from 9817 to 5360 m^3s^{-1} (a 45% decrease) since regulation.

This study considers the distal portions of major Peace River tributaries located between the dam and Smoky River in Alberta, where a major change in the degree of flow regulation occurs. After initial investigation using medium-scale aerial photography and consideration of accessibility, sites chosen for detailed study were Farrell Creek and Halfway, Moberly, Pine, Beatton, Kiskatinaw, and Alces Rivers in British Columbia, and Hines Creek and Smoky River in Alberta (Figure 4.1). Though Lynx Creek has reportedly undergone post-regulation degradation, it has been omitted from analysis because its artificially armored bed obscures the morphological evidence. Despite its position quite far (394 km) below Bennett Dam, Smoky River was included because it is the largest tributary in the Peace basin, and it carries a large sand load, giving it considerable potential for aggradation.

In their distal reaches, the studied rivers have many similarities. All except Smoky River are cobble gravel–bed rivers deeply incised into the surrounding landscape (Rocky Mountain foothills for the uppermost tributaries, and Alberta Plateau for the rest, with the latter group flowing over more friable rock and incorporating a substantial fine sediment load), having cut through layers of postglacial sediments, and shale and sandstone bedrock

Table 4.1 Basic information for tributary sites

	Farrell Creek	Halfway River	Moberly River	Pine River	Beatton River	Kiskatinaw River	Alces River	Hines Creek	Smoky River
Distance below Peace Canyon Dam (km)	23.7	41.2	84.5	101.0	122.5	135.5	143.5	275.1	368.2
Drainage area (km^2)	637	9400	1900	13 560	16 058	4367	877	1647	51 860
WSC gauge no. (07-)	–	FA001	FB008	FB001	FC001	FD001	FD004/5	FD008	GJ001
Gauge location (km from mouth)	na	4.21	30	80	28	40	28	18	64
Gauging period	na	1961 to 1983, 1984 to present[a]	1980 to present	1961 to present	1961 to present	1944 to 1950, 1962 to present	1963, 1985 to present	1971 to 1991	1916 to 1921, 1955 to present
Mean annual flow (m^{3}s^{-1})	5[b]	77	12	190	53	10	0.5	3	352
Mean annual flood (m^{3}s^{-1})	49[b]	723	73[c]	1634	781	152	10	30	2724
Low-level air photo years	1970 1989	1970 1988	1970 1997	1970 1997	1970 1987	1970 1987	1970 1987	1974 1997	–
Medium-scale air photo years	1953 1964 1977 1986 1996 2006	1953 1967 1977 1986 1996 2006	1953 1967 1977 1986 1996 2005	1953 1967 1977 1986 1996 2005	1953 1964 1977 1986 1996 2005	1953 1964 1977 1986 1996 2005	1953 1964 1977 1986 1996 2005	1950 1961 1974 1988 1993 2005	1950 1970 1974 1988 1993 2005

Drainage areas were derived by polar planimeter and from gauge notes. For rivers with more than one gauge, the most distal site was used.

[a]The Halfway gauge was moved in the early 1980s.

[b]Farrell Creek is ungauged; its flows are scaled from those of the Halfway River based on drainage area.

[c]The Moberly MAF is relatively low due to the natural regulating influence of Moberly Lake.

(Mathews, 1963; Holland, 1976). Their valleys are narrow and, within these confines, the rivers frequently run against high bluffs and fluvial terraces. Contemporary floodplains are narrow and discontinuous. The tributaries have generally been degrading in postglacial time as Peace River itself has degraded, though occasional braided reaches (especially in Moberly River) suggest they may experience localized, transitory episodes of aggradation. All have built fans of varying size into the main channel of Peace River (Chapter 3), a process now accelerated by regulation of the mainstem. Basic hydrological characteristics of the tributaries are provided in Table 4.1.

4.3 Potential tributary gradation

Two opposing gradation mechanisms may influence the lower reaches of tributaries to the regulated Peace River:

1. Upstream-progressing degradation may occur as reduced water levels in the mainstem cause an effective lowering of tributary base level (Figure 4.2a). The resulting increase in tributary gradient would enhance sediment transport competence, allowing the tributary to downcut. Stream gradation due to base level change tends not to progress very far upstream (Leopold and Bull, 1979); consequently, this effect is expected to be strongest near the mouth.
2. Aggradation may occur where fan growth is prominent. Since regulation, the fans of most Peace River tributaries have prograded into the main channel (Chapter 3) due to the reduced ability of the mainstem to transport coarse sediment away. Tributary fan progradation extends the distance the tributary must travel to reach base level. This reduces tributary gradient and stream power, promoting aggradation at the tributary mouth (Figure 4.2b).

Depending on the magnitude of effective local base level change and the rate of tributary mouth sedimentation, aggradation might slow, reverse, or prevent degradation. If a tributary lacks sufficient stream power to erode the bed, no gradation effect may be experienced, leaving the tributary mouth "perched" above the typical water levels of the regulated river.

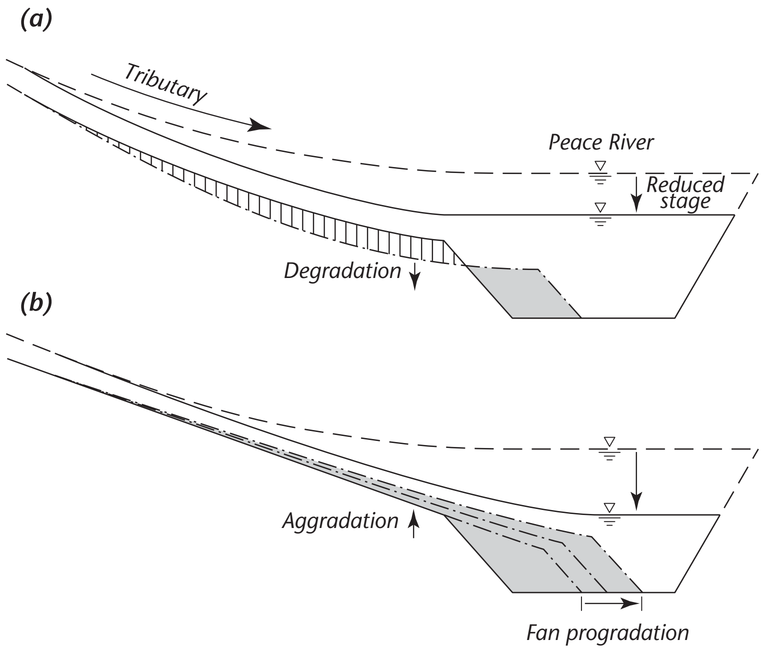

Figure 4.2 Lower tributary gradation scenarios following mainstem regulation: (a) degradation due to reduced water levels in the mainstem; (b) aggradation due to tributary fan progradation. Peace River is viewed in cross-section, the tributary in longitudinal section.

To assess quantitatively the amount of degradation expected, we have analyzed the post-regulation fall in Peace River stage during tributary floods at sites with sufficient flow records. For all tributary floods exceeding the mean annual flood, water levels at the nearest upstream gauge in Peace River were compiled for the day when the tributary event peaked. These stages were averaged within the pre- and post-regulation periods, and the difference between the two periods provides an estimate of the upper limit for degradation. This method is not of high precision. The sites have short pre-regulation flow records, Peace River gauges are not ideally located at tributary confluences, and tributary gauges are located quite far upstream on Pine and Smoky rivers. Bearing these limitations in mind, the analysis shows mean post-regulation mainstem stage drops of between 0.5 and 3.1 m at the various tributary junctions (Table 4.2). There is no clear downstream trend, despite the progressive downstream restoration of the Peace flood. This observation may not be significant within the limits of precision, but it suggests that there may be some importance to the changed relative flood

Table 4.2 Tributary–mainstem stage disparity analysis

River	Distance below dam	Reference Peace River Gauge	Average Peace stage during tributary floods (m)		Stage difference (m)
			Pre-regulation	*Post-regulation*	
Halfway	45.2	Hudson’s Hope (07EF001)	6.70 (*n* = 4)	4.23 (*n* = 19)	2.5
Pine	101.0	Taylor (– Pine) (07FD002)	4.61 (*n* = 7)	1.53 (*n* = 9)	3.1
Beatton	122.5	Taylor (07FD002)	4.66 (*n* = 4)	3.35 (*n* = 20)	1.3
Kiskatinaw	135.5	Taylor (07FD002)	4.22 (*n* = 3)	3.73 (*n* = 15)	0.5
Smoky	368.2	TPR (– Smoky) (07HA001)	11.31 (*n* = 5)	9.73 (*n* = 11)	1.6

Mainstem stages (based on average daily flows) are taken from rating curves for the nearest upstream gauging station. For the Pine and Smoky Rivers, gauges just below the confluence were used, with the tributary discharge subtracted from the mainstem flow. The number of tributary flow events used to derive average mainstem stage is given in parentheses.

timing between Peace River and its various tributaries after regulation.

One other factor further complicates assessment of the effectiveness of the mainstem stage drop. Some tributary fans have prograded significantly since regulation, thereby constricting the main channel. This effect creates an upstream backwater that may act to reduce the effective stage drop at the tributary mouth. The actual effect will, then, depend on such local factors as just where, along the fan perimeter, the tributary enters the mainstem.

4.4 Methods

4.4.1 Air photo interpretation

Historical air photo interpretation was used initially to seek out examples of post-regulation tributary gradation. Observed (Kellerhals, 1982) and potential degradation (Table 4.2) are on the order of one meter, near the limit of photogrammetric resolution, requiring that identification be based on visible planform changes rather than on direct measurement. The primary morphological indicators of degradation are channel and bar areas which appear to have become vegetated after regulation. Except in cases of lateral channel migration (a restricted process in these confined streams), bar abandonment indicates a reduction in frequency of inundation. In other words, as the tributary has become entrenched, its former bar surfaces have become young floodplains or terraces. Aggradation is also visible on air photos: channel instability, as indicated by extensive bar development and bank erosion, may indicate a reach experiencing net sedimentation.

Initially, sites were studied on medium- or small-scale aerial photographs (1:30 000 to 1:80 000) taken between 1950 and 1996. To improve the level of discernible detail, large-scale photos (1:6000 to 1:20 000) were acquired for all British Columbia sites and Hines Creek. Medium-scale photos were considered sufficient for the larger Smoky River. For each site, major planform changes between photo dates were compiled. Particular attention was paid to the gradation indicators described above, especially changes occurring after 1967, the year of dam closure. Photographic evidence was used to guide field efforts, especially site selection and upstream extent of study.

Field work took place in July and August 2000, 33 years after dam closure. The objectives of the program were to confirm degrading or aggrading sites and to quantify observed changes through surveying and dendrochronology on new floodplain surfaces. Smoky River was not included in the field program due to limited time and resources.

4.4.2 Surveying

Each site was reconnoitered for signs of gradation by observing overgrown bar surfaces and looking for breaks in elevation between adjacent bars and older floodplains. Vegetated bar and channel surfaces were surveyed to determine whether or not they showed degradation. This entailed measuring the elevation differences between young floodplains and adjacent older floodplains, and between young floodplains and new bartops (or buried gravel surfaces beneath the young floodplains). If the young floodplain fell between the old surface and new bartop in height, the difference was regarded as an estimate of degradation (Figure 4.3). Ideally, these surfaces should lie in succession away from the current channel, but the fragmented tributary floodplains occasionally offered no reasonable comparison. In some locations, young floodplains could be compared to surfaces slightly upstream or downstream by adjusting for the longitudinal water surface slope between locations. Old floodplains provide a more reliable comparison than current or buried bartops, as the latter tend to be quite variable in elevation, while floodplains are relatively uniform. Surveys were conducted with standard rod and level, with some distances measured by hip chain.

Survey results are subject to a variable amount of instrument and operator imprecision, particularly sights over long distances. For efficiency, morphological units were surveyed using spot elevations, rather than mapping the terrain more thoroughly to obtain average elevations. The necessary judgments about appropriate positions for measurement introduce an unquantifiable amount of error into the elevation comparisons. An important problem is distinguishing old floodplains from low pre-regulation terraces. This difficulty is especially troubling on large tributaries like Halfway and Pine rivers, where the pre-regulation floodplain was quite high. Surfaces were classified as pre-regulation terraces only if their elevation was inconsistent with other floodplain segments, or if they contained mature white spruce (*Picea glauca*) or aspen (*Populus tremuloides*), species which are uncommon on lower floodplains along

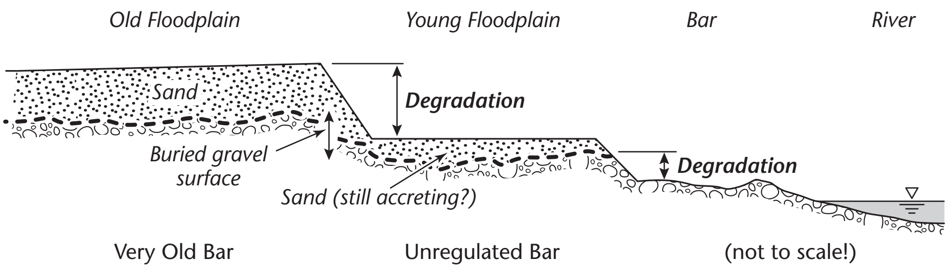

Figure 4.3 Schematic diagram of the methods for estimating tributary degradation by surveying floodplain and bartop levels, showing old (i.e., pre-regulation) floodplain; young (post-regulation) floodplain; old and active bartops.

Peace River. Silverberry (*Elaeagnus commutata*), a common terrace shrub, was not used as an indicator, as there has been sufficient time since regulation for it to establish on former (now terraced) floodplains. A final source of error in the gradation surveys is the fact that the young, post-regulation floodplains may still be accreting (Figure 4.3). This means that the relative height of these surfaces above the modern bartop may be underestimated, while the relative elevation of the old floodplain may be exaggerated. These error sources, mainly unavoidable, suggest that survey results must be interpreted as only an approximate estimate of gradation, rather than as a precise measure.

4.4.3 Dendrochronology

To conclude that tributary degradation is related to regulation of the Peace, the timing and rates of morphological changes must be considered. The date of initial succession from bartop to young floodplain can be determined only approximately from aerial photographs due to the limited number of dates for which photos are available. Precision can be improved by dendrochronology. Determining the age of the oldest tree on the surface in question provides an estimate of how long the surface has been sufficiently dry to support woody vegetation.

Vegetation samples were taken by increment boring or by collecting an entire disc of wood. Young cottonwoods (*Populus balsamifera* ssp. *balsamifera*; but see Chapter 8 for additional species notes), alders (*Alnus incana*) and willows (*Salix* spp.) predominate on the young floodplains and generally provided good, clear samples. Cores were dried, straightened, and glued onto wooden supports. Samples were prepared by standard methods. For growth ring counting, samples were wetted, illuminated, and placed on the stage of a 20-power stereo microscope. This provided a clear image of the wood cells and allowed damaged core sections to be identified, reducing the possibility of miscounting. Since the goal of the dendrochronological work was to date the young floodplains, it was not necessary to obtain a representative sample of tree cores. Some bias may have occurred, however, if the oldest tree was overlooked or misidentified.

4.4.4 Specific gauge analysis

Water Survey of Canada (WSC) gauges exist on all of the subject tributaries except Farrell Creek (Table 4.1). Their records might potentially be used to assess channel gradation via specific gauge analysis, wherein the changing vertical position of rating curves over the years is used to assess channel gradation at a gauge site. Tributary degradation originates at the mouth, and the lower reaches are expected to show the strongest gradation response. In view of this, only the original Halfway River gauge (WSC Stn. 07FA001), located four kilometers above the confluence, is close enough to the mouth to be useful. This gauge was located on the left bank from 1961 to 1977. Around 1977, a large mid-channel gravel bar developed, with most flow occupying the right channel. A new gauge was installed on the right bank and used as the primary reference until 1983, before the gauge was moved 17 km upstream to its current location. The left and right bank gauges had the same datum and their rating curves can be directly compared (A. Stalker, Water Survey of Canada, personal communication, 2000). The upper site, however, is too far upstream to be of use. Rating curves for Halfway River frequently have been updated, providing excellent data for specific gauge analysis as well as constituting evidence of a naturally active channel.

Error factors for the Halfway River specific gauge analysis are calculated as in Chapter 3. In this river, the gauging error of ±6% translates into ±43 m^3s^{-1} about the mean annual flood of 723 m^3s^{-1}. Using rating curve #17 (dated October 30, 1981) from the lower station, this would represent stages between 3.0 and 3.11 m. Specific gauge results at this site must therefore exceed ±0.06 m to be considered significant.

In addition to these analytical methods, anecdotal evidence of tributary gradation was obtained through conversation with Mr Floyd Erickstad, former bridge foreman with the British Columbia Ministry of Transportation and Highways, North Peace Highways District. Mr Erickstad was involved in bridge construction and maintenance along the Peace River from 1956 to 1994 and is well informed on trends of scour at bridge piers.

4.5 Observations

Table 4.3 summarizes the key observations for all sites. Specifically, it lists young surfaces with reasonable survey comparisons and gives their age, as estimated by dendrochronology, and the magnitude of local gradation revealed by the survey. The locations of the survey lines are shown on site maps, examples of which are illustrated (Figures 4.5, 4.6, 4.8 to 4.10). The observations are presented as case studies in downstream order.

4.5.1 Farrell Creek

Farrell Creek enters Peace River from the north approximately 24 km below Peace Canyon Dam. Its 637 km^2 drainage basin lies almost entirely in the Rocky Mountain foothills. In several locations near its mouth, Farrell Creek flows on shale bedrock; channel width at the mouth is about 25 m. Channel degradation was documented here when the old highway bridge footings were undermined shortly after regulation of Peace River. Although the bridge has been replaced, the old south footing is still in place (Figure 4.4a), with the adjacent channel incised one meter into the shale. Local degradation must be of at least this magnitude, as the footing would originally have been set at or beneath thalweg level.

Air photos reveal numerous bars which became forested between 1970 and 1989 (Figure 4.5). On the Farrell Creek fan, an extensive area has been colonized by cottonwood, alder, and willow; dendrodating suggests the surface has been forested since at least 1980. The development of this young floodplain partly reflects reduced flooding in the Peace, as the lower fan is essentially a bar in the mainstem. Near survey lines F1 and F2 (Figure 4.5), however, the fan would likely have been entirely maintained by Farrell Creek, and survey data comparing the young and former floodplains suggest that the channel at this location has degraded by 1.4 m (Table 4.3).

Similar examples occur at transects F2, F5, and F6, where young floodplains aged between 16 and 29 years (in the year 2000) were found to be 0.8, 0.6, and 0.4 m lower in elevation, respectively, than adjacent old floodplains. The systematic order of these results is compelling evidence for upstream propagating degradation, although F4 indicates an anomalously high 1.3 m change. Morphological changes at transects F3 and F4 may be atypical, however, as the channel here was created by a meander cutoff in the late 1960s. Another unsurveyed bar on the right bank upstream of F6 has also become vegetated since 1970 (Figure 4.5). Mean degradation over all surveyed sites is 0.92 m ($n = 10$).

4.5.2 Halfway River

Halfway River also drains the Rocky Mountains and foothills, entering Peace River from the north, 45 km below Peace Canyon Dam. It is the third-largest tributary by drainage area and mean annual flood in the regulated British Columbia reach (Table 4.1), with channel width at the mouth about 130 m. There is anecdotal evidence of degradation at the mouth: within a few years of the regulation, highway bridge workers observed that Halfway River had eroded up to several meters of riverbed gravel and was running near bedrock (F. Erickstad, personal communication, 2000).

Air photos (Figure 4.6) show a consistent pattern of bars becoming vegetated between 1970 and 1988, suggesting that degradation occurred. Only at transect H4 has bar overgrowth been accompanied by noticeable opposing bank erosion, and this seems insufficient to compensate for the lost active bar area. At H2, just upstream of the highway bridge, a large right-bank bar complex was forested in about 1976. The distal portion of this young floodplain is 0.3 m lower than the older floodplain at its center (see 1970 photo in Figure 4.6). The bar survey here indicates 1.5 m of degradation (Table 4.3). Results are less clear at the upstream end of the transect, where the contemporary bar surface is unusually high.

Across the river, the large left-bank point bar complex was mostly vegetated after 1970. The young floodplain

Table 4.3 Survey data of tributary channel degradation

Site	Surface	Minimum age (years)[a]	Comparison	Gradation (m)	Comments
Farrell					
F1	LB YFP(delta)	20	LB OFP	−1.4	
F2	RB YFP	16	RB OFP	−0.8	
	MC bartop	–	RB YFP gravel	−1.1	
Old bridge	Base of footing	–	Base of thalweg	−0.9	
F3	RB VYFP	10	RB OFP	−0.9	Much of YFP still looks like active bar
F4	RB bartop	–	LB YFP gravel	−1.3	LB is abandoned channel head (gravel at surface)
F5	LB YFP	29	LB OFP swale	−0.6	
	LB bartop	–	LB YFP gravel	−1.2	YFP has surface gravel; modern bartop poorly defined
F6	LB YFP	18	RB OFP	−0.6	
	LB bartop	–	LB YFP gravel	−0.4	
Halfway					
H1	–	–	–	–	Halfway delta; no reliable comparisons
H2	RB YFP	24	RB OFP (island)	−0.3	
	RB bartop	–	RB YFP gravel	−1.5	
H3	LB YFP	14	LB mature FP	−0.8	
	LB mature FP	32	LB OFP	−0.1	OFP measured in a swale; generally higher
H4	RB YFP	20	RB OFP	−0.4	OFP may be too low (silted-in old beaver dam pond)
	RB bartop	–	RB YFP gravel	+0.6	
H5 LB	LB YFP	12	LB OFP	−1.2	OFP recently terraced? (very old cottonwood; young spruce)
	LB bartop	–	LB YFP gravel	−0.8	Modern bartop d/s from site; adjusted for water sfc. slope
Moberly					
M1	VYFP north of road	17	OFP north of road	−0.3	OFP is a fragment on the Moberly delta
	LB high bartop	–	LB VYFP gravel	+0.2	Surface gravel on high bar
M2	RB YFP	10	RB OFP	−0.8	
	RB bartop	–	RB YFP gravel	−0.4	Surface gravel on front of YFP
M3	LB YFP	11	LB OFP	+0.1	
M4	LB VYFP	10	LB OFP	−0.8	OFP is a fragment in front of large, older surface
	LB bartop	–	LB VYFP gravel	−0.4	Adjusted for d/s water sfc. slope
M5	RB YFP	21	RB OFP	+0.1	
	RB bartop	–	RB YFP gravel	−0.7	Bartop poorly defined
	LB YFP	30	RB OFP	−0.3	
Pine					
P1	Island YFP	17	RB OFP	−2.9	OFP may have been terraced (very high)
	Island bartop	–	island YFP gravel	−0.8	
P2	RB YFP	23	RB OFP	−0.8	RB floodplain seems subject to ice activity
	RB bartop	–	RB YFP	−0.4	Surface gravel on YFP
P3	LB YFP	12	LB OFP	−1.7	
P4	Upper island YFP	14	Lower island OFP	−1.1	OFP may have been a terrace; adjusted for water sfc. slope
	Bartop blw. Islands	–	Upper YFP gravel	−0.9	Adjusted for water sfc. slope

Table 4.3 (*Continued*)

Site	Surface	Minimum age (years)[a]	Comparison	Gradation (m)	Comments
Beatton					
B1	Delta rear YFP	27	Rear OFP	−0.5	OFP is irregular fringe along base of higher FP/terrace
B2	RB YFP	–	RB upper OFP	−2.2	OFP may have been a terrace; YFP elevation may be low
B3	RB YFP	10	RB upper OFP	−0.7	
	RB YFP	10	RB lower OFP	−0.4	Adjusted for water sfc. slope
Kiskatinaw					
K1	RB YFP	13	RB OFP	−1.2	
K2	LB YFP	9	RB OFP at K1	−1.9	Adjusted for water sfc. slope
	LB bartop	–	Old channel gravel	−1.1	Apparent degradation since 1989
K3	LB YFP	10	RB OFP at K1	−1.4	Adjusted for water sfc. slope
	LB bartop	–	LB YFP gravel	−0.6	
Alces					
A1	–	–	–	–	No reliable comparisons
A2	LB YFP	9	LB OFP	−0.4	
A3	–	–	–	–	No reliable comparisons
A4	–	–	–	–	Tributary to Alces; no reliable comparisons
Hines					
HC1	–	–	–	–	YFP seems to be ice-controlled; no reliable comparisons
HC2	–	–	–	–	YFP seems to be ice-controlled; no reliable comparisons
HC3	LB YFP	42	LB OFP	−0.1	There are spruce on both low floodplains

FP, floodplain; Y, young (postregulation); VY, very young (<10 years); O, old (preregulation); RB, right bank; LB, left bank; MC, mid-channel; d/s, downstream; sfc, surface. Negative gradation values indicate degradation.

[a] Ages are based on dendrochronology of the oldest sampled tree on the surface and are referenced to the year 2000.

here was dated to about 1986, and found to be 0.8 m lower than an older (1968) floodplain behind it (Figure 4.6; Table 4.3). This floodplain level is, in turn, at least 0.1 m lower than the oldest floodplain on the transect, which formerly was a forested island in the bar complex (Figure 4.6). The young floodplains at H4 and H5 date to 1980 and 1988, respectively, and they indicate degradation of 0.4 and 1.2 m (Table 4.3). Bartop survey at H5 suggests degradation of 0.8 m, but the bartop at H4 is anomalously high. Several unsurveyed bars, including one on the right bank upstream of H5 (Figure 4.6), also appear to have vegetated since regulation. Average gradation over six sites accepted as representative (Table 4.3) is −0.83 m.

Results of the Halfway River–specific gauge analysis are presented in Figure 4.7; the cumulative gradation data are based on the stage for 0.8 times the mean annual flow. The Halfway rating curves have been updated almost annually, indicating that the cross-section has a history of instability. This is reflected in Figure 4.7, as the bed elevation at the lower station, 500 m upstream of H4 (Figure 4.6), fluctuated from 1971 to 1976. Between 1976 and 1977, the channel appears to have degraded by nearly 0.1 m, but this result is close to the limit of analytical precision. After the gauge was moved to the right bank in 1977, the bed was stable until the gauge was decommissioned in 1983. The overall observed trend is downward but the record is too brief for certainty.

4.5.3 Moberly River

Moberly River enters the regulated Peace River from the south, 84 km below Peace Canyon. Its 1900 km^2 watershed drains primarily mountain and foothill terrain, but

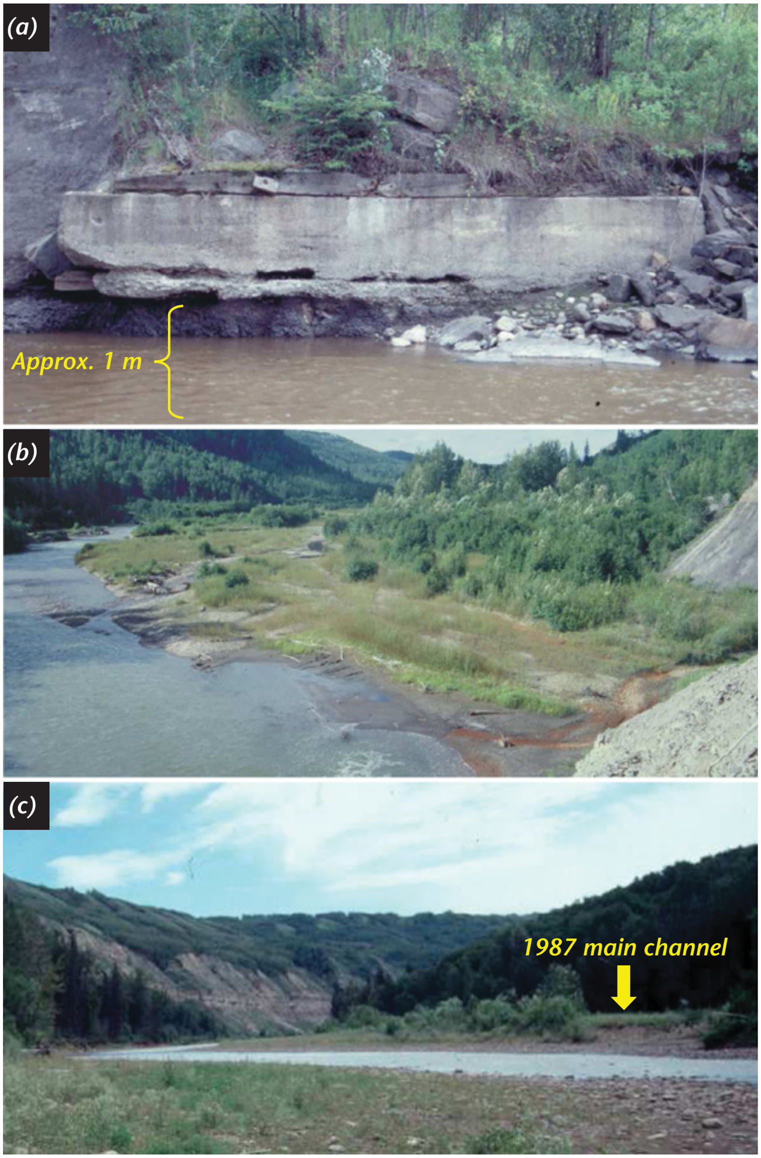

Figure 4.4 Photographs of tributary gradation: (a) degradation at the pier of the old Farrell Creek bridge; (b) Moberly River, showing a vegetated old bar surface (young floodplain); (c) overgrown former channel at transect K2, Kiskatinaw River.

the river is interrupted roughly 150 km from the mouth by Moberly Lake (Figure 4.1). The Moberly is exceptionally active in its lower reaches (see Figure 4.8a), with a low floodplain, frequent braiding, and a history of channel instability which appears, from air photo evidence, to date from sometime between 1953 and 1967. The channel may be over 100 m wide in braided reaches, but as narrow as 20 m where the flow is single thread. Relatively high bedload transport is estimated in this river (Chapter 2).

As with the other tributaries, air photos of Moberly River (Figure 4.8) show that its fan has vegetated considerably since 1970. Nevertheless, this fan has remained more active than others, with a shifting flood channel and roughly half its surface area bare of perennial vegetation. On transect M1, just west of the contemporary flood channel, an old floodplain fragment was found to be 0.3 m higher than the adjacent young floodplain (dated to 1983). This is a topographically variable area, and a more extensive young floodplain (1991) east of

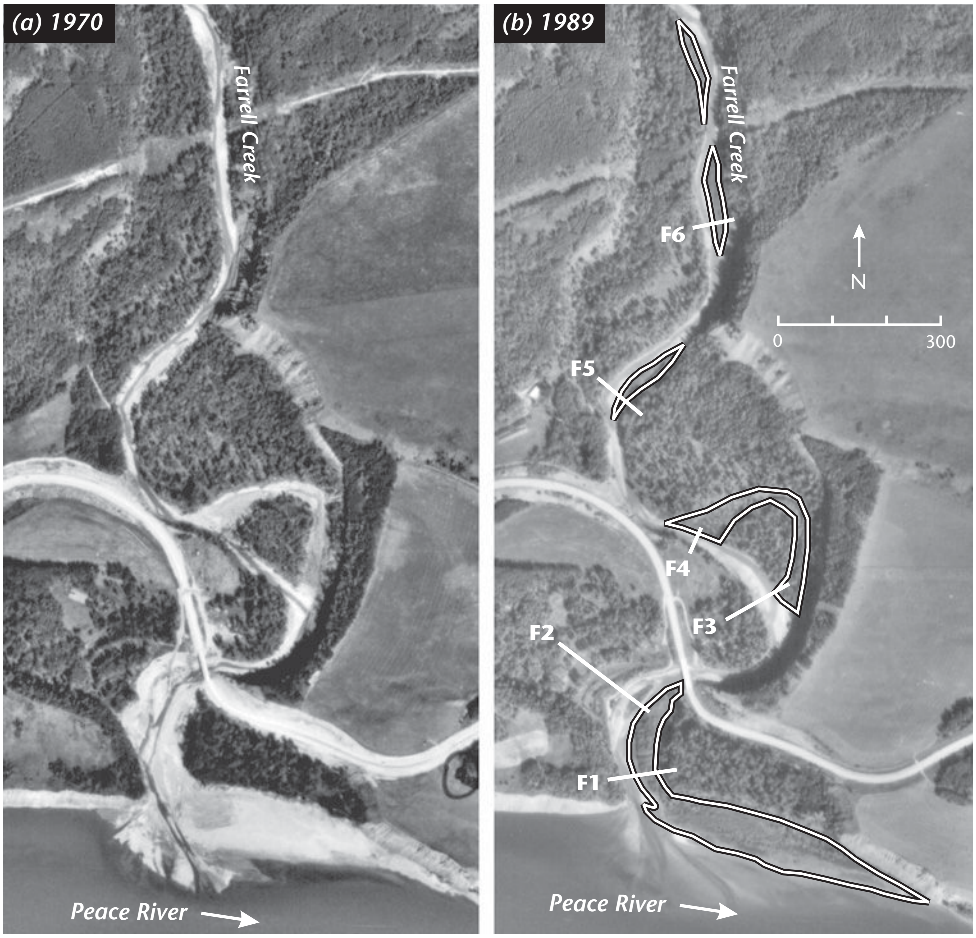

Figure 4.5 Historical aerial photographs of Farrell Creek (a) shortly post-dam (photo BC7277-242), and (b) in 1989 (30BC89061-32). Young floodplains, developed between the two dates, are outlined in (b) and surveyed transects are labeled (Ayles, 2001, Figure 3.8, p. 86).

the flood channel was surveyed at 1.3 m lower than the same old floodplain fragment (Table 4.3).

Numerous bars upstream of the fan have also become forested, but here, this seems mainly to result from lateral channel migration, and bars lost to floodplain succession are generally offset by new bar growth. One example of possible localized degradation occurs at transect M2, where the river encounters a steep bedrock outcrop on its left bank. The right-bank bar has become a young floodplain (1990) 0.8 m lower than the old floodplain behind it. The elevation of this older surface may be exaggerated, however, as the river runs around it upstream and may have built it to a higher water level. At other transects, results suggest a mixture of degradation and aggradation reminiscent of localized evacuation and deposition of sediment. For example, the old floodplain at M3 is 0.10 m lower than the young floodplain (Table 4.3). The area around M4 is highly braided. Results there suggest slight degradation, but the new floodplain is very young (1990) and not measurably higher than the active bar surface. At M5, in a single-thread reach, the right-bank young floodplain (1979) indicates 0.1 m of aggradation (Table 4.3). The young floodplain on the left bank (1970) backs onto an old, low terrace (only 0.8 m higher, but populated by large spruce trees); the only valid comparison is with the right-bank old floodplain, and this indicates 0.3 m of aggradation.

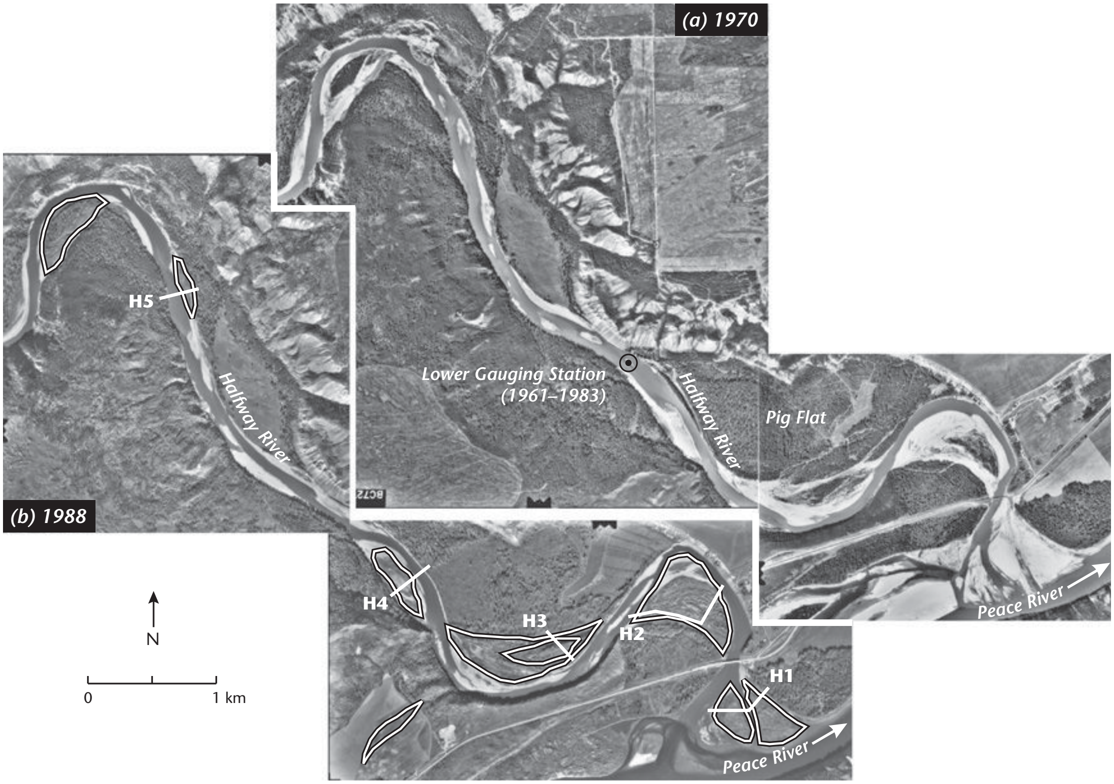

Figure 4.6 Historical aerial photographs of Halfway River (a) shortly post-dam (photos BC7279-070 and 118), and (b) in 1988 (BC88088-171 and 180). Young floodplains developed between the two dates are outlined in (b) and surveyed transects are labeled (Ayles, 2001, Figure 3.10, p. 88).

In summary, there appears to be evidence for degradation at the Moberly confluence but a short distance upstream the evidence becomes equivocal, perhaps not surprising given the appearance of significant bed material transport in this river. However, average gradation over nine sites (Table 4.3) is −0.33 m.

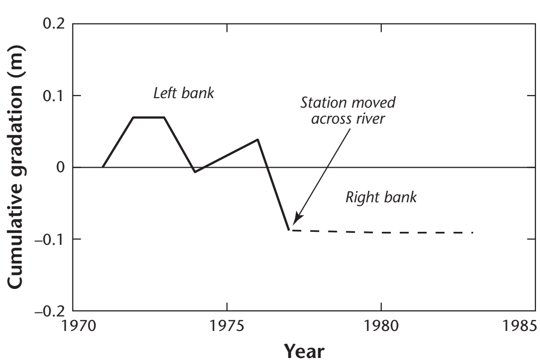

Figure 4.7 Halfway River specific gauge analysis for the lower station (WSC Stn. 07FA001). Results are for $Q = 578\ m^3s^{-1}$.

4.5.4 Pine River

Pine River enters the Peace from the south, about 101 km below Peace Canyon. It is the largest tributary by flow volume in the British Columbia reach, with a drainage area of 13 560 km^2 and channel width on the order of 250 m near the mouth. The Pine River channel, with a mean annual flood of 1575 m^3s^{-1}, is remarkably active. In the most distal bend, the right bank has been eroded several hundred meters since 1970, although this area is now congested with new bar deposits. Across from transect P1 (Figure 4.9), an entire segment of floodplain was removed by left bank erosion. These erosive events seem to have been instigated by the formation (sometime before 1967) of the large bar crossed by transect P2. A large mid-channel bar has formed since 1970 above the mouth of Septimus Creek and, over the same

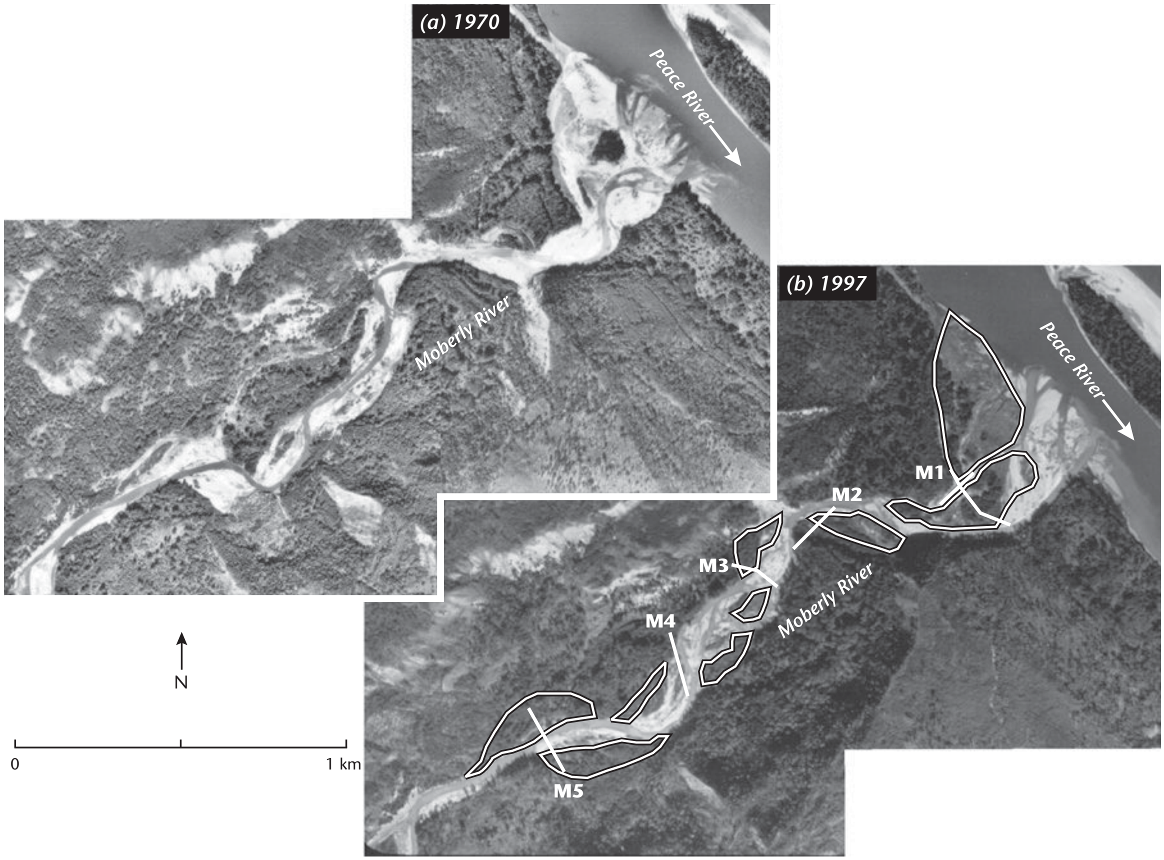

Figure 4.8 Historical aerial photographs of Moberly River (a) shortly post-dam (photos BC7278-233 and BC7279-045), and (b) in 1997 (30BCC97159-192 and 211). Young floodplains developed between the two dates are outlined in (b) and surveyed transects are labeled (Ayles, 2001, Figure 3.14, p. 93).

period, near transect P4, two left bank channels have been filled and partially vegetated (Figure 4.9).

Surveying at Pine River was limited by its size and high flow. As at the other tributaries, the Pine fan has mostly become young floodplain, possibly due to reduced flow in Peace River. The first survey transect (P1) crosses a young floodplain located where the main thread flowed in 1970. This surface, dated to 1987, lies 2.9 m below the adjacent old right-bank floodplain (Table 4.3), but this high, older surface may have been a terrace. Comparing the local bartop to the height of gravel buried beneath the young floodplain suggests degradation of 0.8 m, but this figure is also suspect, as it does not exceed local bar topography. Better data are provided by transect P2. At this site, the young floodplain (1977) is 0.8 m lower than the adjacent old floodplain, which was likely a young floodplain fragment in 1970 (Figure 4.9). The right active bartop here was measured at 0.4 m below the gravel surface of the young floodplain. Degradation is plausible here since no compensating channel migration accompanied the afforestation of the bar.

Data from the upper two sites also point to degradation, though their floodplains are of questionable comparability. Behind the vegetated bar of transect P3, the old floodplain is 1.7 m above the adjacent young floodplain (1988), but it is high enough possibly to be an old terrace, though it lacks typical terrace trees. Upstream, transect P4 includes two former islands which are now connected to the left bank. Here, the young floodplain of the upstream island was surveyed to the old floodplain of the downstream island, immediately beside the channel. The results (Table 4.3) show degradation of 1.1 m, but the old floodplain may have been a terrace prior to regulation, as it contains some aspen trees. The bar

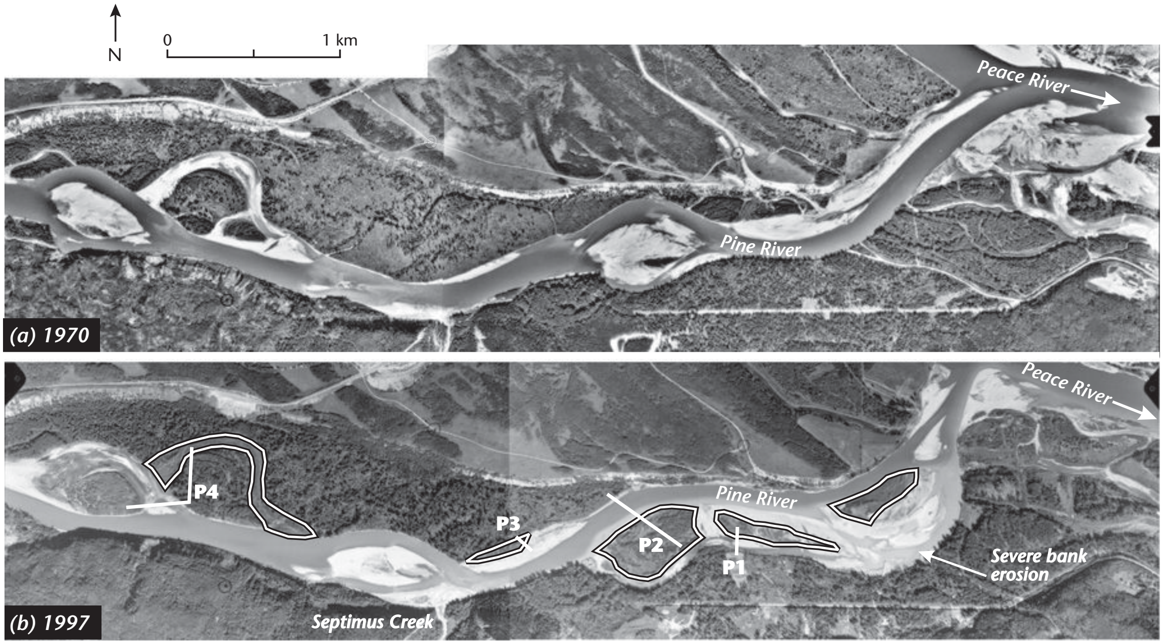

Figure 4.9 Historical aerial photographs of Pine River (a) shortly post-dam (photos BC7278-57/59), and (b) in 1997 (30BCC97159-101/103). Young floodplains developed between the two dates are outlined in (b) and surveyed transects are labeled (Ayles, 2001, Figure 3.15, p. 96).

survey in this area also indicates degradation, showing a 0.9 m drop from the buried gravel beneath the young floodplain to the active bartop. Average gradation over six confidently measured sites (Table 4.3) is −0.95 m.

4.5.5 Beatton River

Beatton River enters Peace River from the north, 123 km below Peace Canyon Dam. Its watershed lies almost entirely in the Alberta Plateau, and though at 16 058 km^2 it is the largest tributary by area in the British Columbia reach, it delivers much less flow than Pine River. It carries a large suspended-sediment load and a small gravel load (Chapter 2), and its channel width is approximately 150 m near the mouth. Despite this, the river has a remarkably small fan, perhaps reflecting its finer sediment load. The distal Beatton River flows in a deep, narrow canyon with floodplains and terraces, infrequent and small. In fact, the first floodplain segment of any size (transect B3) is four kilometers from the mouth.

Surveys on the Beatton were inconclusive due to local site conditions. The Beatton fan (transect B1) and an infilled Peace backchannel opposite (transect B2) have both become overgrown with young floodplain vegetation since regulation. Survey data suggest some degradation (Table 4.3), but the old floodplains used for comparison likely were controlled by Peace River water levels rather than Beatton River flow. At transect B3, a complex of bars and two islands have largely been vegetated since 1970, though portions of it appear still to be active. The survey crossed the downstream end of the distal island where the old island floodplain grades into younger surfaces toward the south backchannel exit. The highest young floodplain here (dated to 1990) is 0.7 m lower than the adjacent old floodplain, and 0.4 m lower than the old floodplain downstream of the backchannel mouth (Table 4.3). These results suggest local channel degradation. However, aerial photographs (not shown) reveal that this bend has undergone two channel switches in the past 50 years. The young floodplains around B3 may still be accreting as the recently abandoned backchannel silts in. Young and old floodplains in this bend are remarkably high (up to 3.2 m above bartop), and apparent ice damage on trees was noticed up to three meters above the oldest surface. It appears that this sharp, active bend experiences

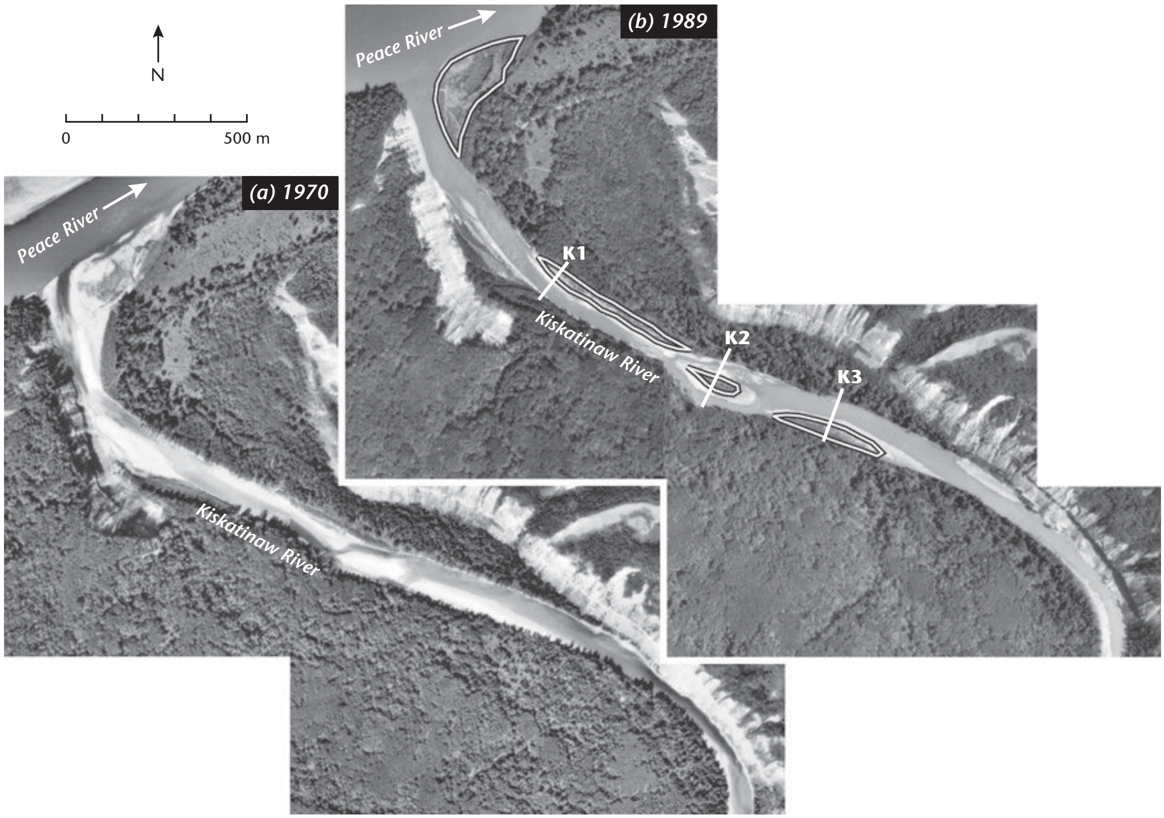

Figure 4.10 Historical aerial photographs of Kiskatinaw River (a) shortly post-dam (photos BC7276-304 and BC7277-11), and (b) in 1987 (BC87008-10 and BC87029-26). Young floodplains developed between the two dates are outlined in (b) and surveyed transects are labeled (Ayles, 2001).

ice-jamming and backwater sedimentation which may overwhelm any regulation-induced channel gradation. Nonetheless, the average gradation over the four measured sites is −0.95 m, which is consistent with the sites farther upstream.

4.5.6 Kiskatinaw River

Kiskatinaw River enters Peace River from the south, 136 km below Peace Canyon. Though its headwaters are in the Rocky Mountains, much of its basin drains the Alberta Plateau. The Kiskatinaw is relatively small (mean annual flow = 10 m^3s^{-1}) but flashy, with a mean annual flood of 152 m^3s^{-1} (Table 4.1). In the study reach, it is confined on its left bank by colluvium at the base of high bluffs, and by occasional small terrace fragments. The right bank, from just above transect K3 to the fan (Figure 4.10), is flanked by a continuous series of narrow, flat surfaces. At K3 and K2, abundant old spruce suggests that these are pre-regulation terraces. At K1, however, the vegetation is almost exclusively old cottonwood trees, indicating that this site may have been active Kiskatinaw floodplain prior to regulation. Below K1, the old floodplain gives way to Peace River floodplain and the Kiskatinaw fan.

The Kiskatinaw River fan and several other bars have been overgrown with young floodplain species since regulation (Figure 4.10). At K1, the right-bank young floodplain, dated to 1987, is 1.2 m lower than the adjacent old floodplain. At K2 and K3, similar young floodplains have developed on old bars on the left bank. Comparing these surfaces to the old floodplain at K1 (adjusting for water surface slope) reveals them to be 1.9 m and 1.4 m lower, respectively (Table 4.3). Bartop surveys support these results. At K2, surficial gravel in the left backchannel was found to be 1.1 m higher than the active left bartop. At K3, the surface gravel in another left backchannel was surveyed at 0.6 m higher than the current bartop (Table 4.3). All of these figures point to post-regulation degradation in the study reach. Interestingly, degradation at K2 appears to have occurred since 1990. At this site, the main thread in 1989 ran left of the young floodplain (Figure 4.10). By 2000, the main flow had switched to the right channel, which has downcut by roughly one meter, while the left channel had become secondary and overgrown with grasses (Figure 4.4b). Medium-scale photography shows that the main flow has repeatedly switched sides at this island since the late 1960s, possibly in consequence of the upstream propagating, progressive channel degradation. Average measured gradation at Kiskatinaw sites is −1.24 m ($n = 5$).

4.5.7 Alces River

Alces River is a small stream entering the Peace immediately below the Clayhurst bridge, 143 km below Peace Canyon Dam and four kilometers before the British Columbia-Alberta border. It drains an 877 km^2 basin which lies entirely within the Alberta Plateau, and delivers a mean annual flood of only 10 m^3s^{-1} (Table 4.1). The lower Alces frequently runs against colluvium at the foot of its steep valley-wall bluffs, but several small, low terrace fragments are also found along the lower reach. The Alces fan is small and low enough that the regulated Peace River has kept it free of floodplain vegetation. Reportedly, some downcutting of the Alces channel was observed at the highway bridge across its mouth, though the erosion was not so extensive as to endanger the structure (F. Erickstad, personal communication, 2000).

Several bars on the Alces have become vegetated since 1970 but field results do not show convincing evidence for degradation. Rather, fragmentary young floodplain surfaces appear to be associated with either river ice scour or lateral channel migration. For example, at transect A2, 580 m from the mouth, a large left-bank bar has become a young floodplain since 1970. This surface (dated to 1991) is 0.4 m lower than the older floodplain behind it (Table 4.3), but there has been offsetting right-bank erosion, suggesting this may be a case of point bar growth.

4.5.8 Hines Creek

Hines Creek is another small stream entering Peace River from the north, just upstream of the Dunvegan bridge and 274 km below Peace Canyon. Despite a relatively large watershed area of 1647 km^2, its mean annual flow is only three cumecs (mean annual flood = 30 m^3s^{-1}), reflecting the dry climate of the prairie it drains. Hines Creek has a large fan for its size, suggesting that it has a fairly high sediment load. The fan was mined for gravel for bridge construction in the early 1960s. By 2000, the fan had largely been refilled and overgrown by grasses and small shrubs.

There is no clear indication of post-regulation channel gradation in Hines Creek. No obvious cases of bar colonization by floodplain species between 1961 and 1997 can be discerned. In the field, several small young floodplains were noticed, but they do not occupy 1961 bar surfaces, so they may be maintained in a "young" state by ice disturbance. Frequent ice-jam flooding might also explain the unusual height (over two meters higher than the bartop) of discontinuous floodplains on both banks. Only at one site was a lower, young floodplain found. This unusual surface has surficial gravel and an odd species mix of grasses, alder (the oldest dated at 42 years) and young spruce. It is backed by an older floodplain (or terrace), populated by dense spruce and cottonwood, at roughly the same elevation (Table 4.3)—a plausible immediate source to the younger surface of spruce seeds.

4.5.9 Smoky River

Smoky River is the largest tributary in the Peace River basin. It rises in the Rocky Mountains near Jasper, Alberta, but it primarily drains the Alberta Plateau. The Smoky carries a substantial sand load and, below its confluence, the bed of Peace River begins to grow sandy.

Morphological change maps based on analysis of historical aerial photographs of Smoky River (Figure 4.11) reveal that the fan has prograded into Peace River by up to 200 m and has filled the area behind a delta-front island. There has been substantial bar accretion around islands downstream from the confluence, and backwater has developed for about 18 km upstream on Peace River. Net bar growth at and near the Smoky confluence between 1968 and 1993 was 0.53×10^6 m^2, but the fan retained proportions of bare and vegetated surface areas similar to those of 1968. Exposed surface has been extended by 0.71×10^6 m^2 and riparian forest by 0.20×10^6 m^2, but there has been a loss of 0.25×10^6 m^2 of forest as well. Major changes at the confluence include a downstream shift in the main

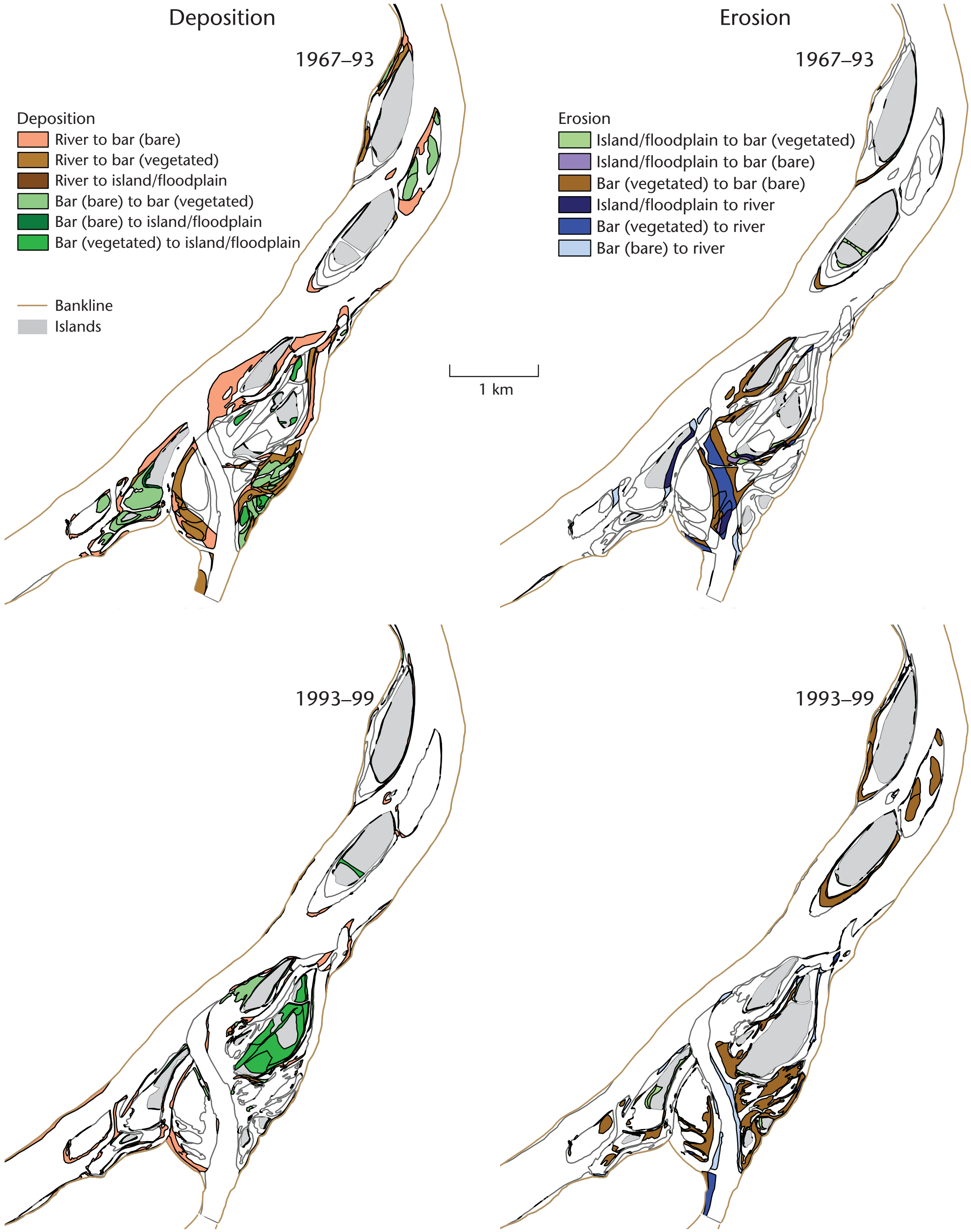

Figure 4.11 Map of the confluence of Smoky River with Peace River, showing morphological changes between 1967 and 1993, and between 1993 and 1999. The latter period includes the major 1996 flood (for which, see Chapter10).

channel of Smoky River so that it now flows directly into Peace River. Formerly, it entered the Peace via a sinuous channel at the upstream limit of its fan. The former secondary channel along the downstream edge of the fan has been virtually abandoned. These changes are almost certainly the consequence of the lower water levels in Peace River when the spring flood occurs in Smoky River so the tributary stream, which is now the dominant channel in flood, flows on a relatively steep gradient into Peace River. Overall, the distal Smoky River has taken on a more braided appearance, suggesting its primary response since regulation may have been aggradation. For 13 km upstream of the confluence, the principal morphological activity between the photo dates on Smoky River was bar growth, with five bars having expanded substantially over this period. The upstream appearance of aggradation is consistent with the progradation of the fan at the confluence.

4.5.10 Summary of channel gradation observations

At Lynx Creek, Farrell Creek, and Halfway River, there is clear evidence of post-regulation channel degradation. This was already known for the first two sites, primarily due to erosion problems at highway bridge piers. Further investigation at Farrell Creek reveals a consistent pattern of bars having been colonized by young floodplain vegetation since regulation. Survey data suggest that the site has degraded between 0.4 and 1.4 m (average 0.92 m), in accordance with the one meter undercutting of the old bridge that was observed in the field and previously reported. Halfway River presents a similar case on a larger scale. It also features numerous overgrown bars, and survey data suggest degradation has ranged from 0.4 to 1.5 m. Specific gauge data (Figure 4.7) are inconclusive: they indicate 0.1 m net degradation at the lower station, a near-insignificant result which may be due to flow division around a mid-channel bar and the early abandonment of the station. Air photos show recently vegetated bars beyond the upper limit of the field study reaches. On this evidence, degradation may have progressed as far upstream as 2.5 km in Farrell Creek and 12 km in Halfway River.

Below the Halfway River, the story grows more complex. In some locations, Moberly River shows evidence of up to 0.8 m of degradation (transect M2, and the west part of M1) and the average gradation at surveyed sites is −0.33 m. However, there is also evidence for local aggradation, and photo evidence supports this tendency originating before the regulation of Peace River. Given its high sediment load, the Moberly may generate enough bed material to offset any general degradation that might have occurred. Certainly, the distal fan has prograded into the Peace River channel since regulation Chapter 3).

Pine River also seems to have undergone mixed gradation since regulation. Near its mouth, aerial photographs indicate the dominant processes have been bank erosion and offsetting sedimentation. These seem to have been instigated by the pre-1967 growth of a major bar near P2. Farther upstream (up to six kilometers) there are several young floodplains that indicate channel degradation on the order of 0.4 to 1.7 m, and the average of confidently surveyed sites is −0.95 m. It seems, then, that the Pine River may be degrading, but the trend is complicated by sedimentation at the mouth. This may be because the Pine, like Moberly River, is a significant producer of coarse sediment.

Beatton and Alces rivers are cases where gradation evidence is compromised by local conditions, preventing any firm conclusion on the effects of regulation. Alces River reportedly underwent some scour near its bridge after regulation, but morphological evidence does not indicate any degradation above the bridge. Between these sites, however, Kiskatinaw River appears to have degraded between 0.6 and 1.9 m in the river's lower two kilometers (Table 4.3; mean of surveyed sites −1.24 m). Above the field sites, the river enters a narrow canyon without floodplain, so the upstream extent of channel gradation is unknown. The recent abandonment of the left channel at transect K2 suggests that degradation may still be active at this site, though it is possible that scour in the right channel is a transient outcome of the concentration of flow in a single channel there. This stream was reportedly "actively degrading" in the early 1970s (BC Hydro, 1976), so its apparent contemporary incision may be the joint product of regulation of the Peace River and natural degradation.

The final two sites, Hines Creek and Smoky River, are located considerably farther downstream (Table 4.1) in an area where ice effects in Peace River remain significant (Uunila, 1997; Chapter 6). At Hines Creek, near Dunvegan, there is no evidence of channel gradation, but morphological evidence suggests the strongest influence here may be ice activity. Aerial photographs of Smoky River, nearly 400 km below Bennett Dam and the greatest sediment producer of all Peace tributaries, show that the main morphological change since regulation has been bar expansion up to 11 km above the confluence and significant progradation of the fan into the channel of Peace River. There are no signs of degradation: the fan seems to have remained active, and there are no examples of young floodplains replacing bars except where secondary channels have been abandoned.

Among the proximal tributaries, channel degradation has been the most common response over the past 30 years. However, with increasing distance from the dam, ice effects appear to become more prominent at tributary mouths, obscuring evidence of or perhaps negating degradation. Aggradation due to tributary fan extension may have played a role in offsetting degradation in Moberly and Pine Rivers, and in the aggradational response of Smoky River. Because of severe ice effects below the Smoky confluence (Chapter 6) it is unlikely that unequivocal evidence for degradation can yet be discerned farther downstream.

4.6 Discussion

4.6.1 Timing and fates of channel gradation

It is reasonable to ask whether the documented changes can reliably be attributed to changes in the Peace River flow regime. At most sites, medium-scale aerial photographs from the early 1950s on indicate that systematic overgrowth of bar surfaces (the main visible evidence of degradation) became prevalent only after regulation. This investigation also shows that pervasive bar growth in the lower Smoky River has been a new development since 1967, which may be related to the reduced capability of the mainstem to clear all the sediment delivered by Smoky River away from the vicinity of the confluence.

Rates of post-regulation change in the tributaries are difficult to assess. Most evidence suggests that there was a rapid initial response that has now slowed or stopped. Near the mouths of Lynx and Farrell Creeks, roughly one meter of erosion was reported in 1972, and surveys at Farrell Creek in 1972 and 1975 reportedly showed no further change (BC Hydro, 1976). Surveyed degradation values at Farrell Creek in 2000 remained near one meter. These facts suggest that most of the initial degradation occurred in these small, cobble-armored creeks during the first few years after regulation—possibly, in fact, during the reservoir-filling period of very low Peace River flows between 1968 and 1971—and that the process may now be inactive. The trend may have slowed due to fan progradation and resulting aggradation, or simply because the creek lowered its bed sufficiently to restore an equilibrium slope, or onto more resistant substrate. However, the upstream extension of degradation demonstrated in Farrell Creek may be a more recent development. The larger Halfway River may have a similar history; scour around the old bridge pier was reported before the mid-1970s, when the bridge was replaced (all three bridges invoked in this discussion are located within a few hundred meters of their tributary mouth). However, evidence for degradation remained equivocal through 1983 at the old gauge site, four kilometers upstream.

The age of young floodplains can also provide insight into degradation timing and rates. Among the degrading sites, young floodplains in 2000 ranged in age from 9 to 29 years (Table 4.3). The latter figure (taken from transect F5 at Farrell Creek) suggests that, within three years of regulation, the bed elevation of Farrell Creek had dropped enough for some bars to be colonized by floodplain species. The oldest young floodplains in the Halfway and Pine Rivers (at transects H2 and P2) were aged at 24 and 23 years, respectively (Table 4.3), again suggesting that substantial degradation must have occurred within eight years of regulation at these sites. Not all young floodplains are this mature, however. The range of ages of all young floodplains surveyed (Figure 4.12) suggests that degradation has occurred at variable rates both within and between sites, or that young floodplain development is influenced by other variables. In the Kiskatinaw River, for example, all three of the surveyed young floodplains were dated at 13 years or less (in 2000). This could mean that degradation is slower (and perhaps ongoing) there, or that local conditions such as channel instability, the sequence of major floods, or ice effects prevented floodplain vegetation from promptly establishing after regulation of the Peace.

4.6.2 Tributary gradation pattern downstream

The results of this project point to a downstream pattern of gradation response among the subject tributaries. Degradation is clearest near the dam, as exemplified

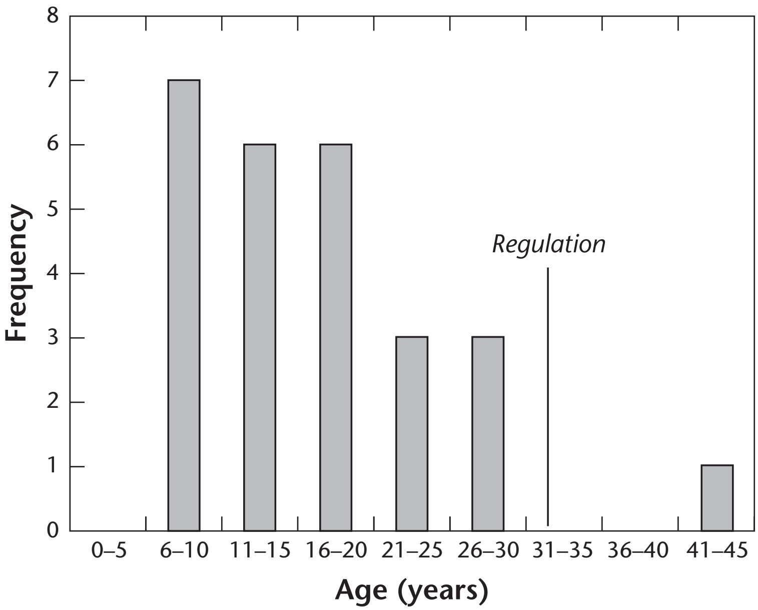

Figure 4.12 Distribution of dendro-ages obtained on young floodplains. Concerted results for all surfaces listed in Table 4.3 (Ayles, 2001, Figure 3.27, p. 114).

by Lynx Creek, Farrell Creek, Halfway River, and Pine River. Farther downstream, degradation is attenuated or obscured by local factors such as sediment load (Moberly River) and ice regime (Alces River and Hines Creek—both small). The degrading Kiskatinaw River seems to be an exceptional case, given its location quite far below the dam, but local regime factors may be at play in this unusually steep channel, leading to natural "background" degradation. Farthest downstream, Smoky River appears to have been aggrading since dam closure. Conceptually, this trend makes sense: as Peace River flows away from the dams, its floodwaters are gradually restored by flow from unregulated tributaries while ice effects become an important obscuring factor. At some point, the degradation mechanism must become too weak to be perceptible within the morphological changes induced by natural river dynamics. Pine River, the largest British Columbia tributary, might represent a significant step in attenuation. The most important aspect of the adjustment may be the reestablishment of approximately synchronous times for high water in both tributaries and the mainstem below Pine River. Another likely transition point is the junction with Smoky River, where significant water and sediment charges are added to the mainstem. The response of Smoky River may be exaggerated due to its exceptional size and sediment load.

The observed downstream pattern may be compared with potential degradation estimates based on mainstem–tributary stage disparity (Table 4.2). The estimates and survey results (Table 4.3) are of the same order of magnitude, and the potential estimates drop significantly near the Alberta border. Halfway and Pine Rivers, with the highest potential for degradation, indeed appear to have degraded. Kiskatinaw River has degraded despite having a low apparent potential for degradation, reinforcing the case for local factors in this river suggested by the BC Hydro (1976) report of early post-regulation degradation. Smoky River, according to Table 4.2, has some degradation potential which apparently has not been fulfilled.

While the potential degradation estimates are not of high precision, they underline the fact that local conditions in individual tributaries are critical in determining their response to regulation. Basin hydrology dictates that there must be a downstream diminishment of tributary gradation, but clearly this is mediated by local factors such as tributary flood timing in comparison with the mainstem, sediment supply, and ice regime. A similar pattern of downstream diminishing tributary degradation was observed by Germanoski and Ritter (1988) in small tributaries near a small dam in Missouri, USA, suggesting that the phenomenon has some generality.

4.7 Conclusions

In the mainstem Peace River, regulation has altered the primary governing variable of flow, leading to substantial morphological changes (cf. Church, 1995; Chapters 3 and 7). The downstream tributaries have experienced a consequent lowering of effective base level. Prior to this study, it was expected that degradation would be the most common response on the tributaries. This has, in fact, been found at the most proximal sites, especially the relatively small Lynx and Farrell creeks and the larger Halfway River—the first major tributary—all located above the Pine River confluence in British Columbia. Farther downstream, the influence of regulation begins to be obscured by other factors such as tributary sediment supply, ice regime, and the degree of flood synchronization between tributary and mainstem. Pine River appears to be degrading, although its significant sediment load has also caused distal bar growth, fan progradation, and aggradation in the Peace mainstem below the confluence (Chapter 3). Excluding Moberly River, the mean gradation of all the sites above Kiskatinaw River, near the Alberta border, is roughly −0.9 m. Aggradation appears to be the principal post-regulation trend in the lower Smoky River, and may have been a factor in Moberly River.

Many of the methods we have used to detect tributary gradation have substantial margins of error. This is inevitable given the goal of reconstructing three decades of channel gradation with no pre-regulation data other than air photos. Yet even within this constraint, a reasonably clear pattern has emerged, and it is consistent with the hydrological changes imposed on Peace River by Bennett Dam. While our work has not yielded precise rates of post-regulation tributary gradation, it clearly establishes the change as being the order of one meter within 100 km of the dams and it provides an initial outline of the basin-wide gradation response of a large regulated river. This represents substantial progress in an under-explored aspect of regulated rivers.

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References

Andrews, E. D. (1986) Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah. *Geological Society of America Bulletin*, 97, 1012–1023. doi:10.1130/0016-7606 97<1012:DEOFGR>2.0.CO;2, 1986

Ayles, C. P. (2001) Regulation-induced channel gradation in the Peace River. M.Sc. thesis, The University of British Columbia, Vancouver, Canada. 182 p.

BC Hydro (British Columbia Hydro and Power Authority). (1976) Peace River Sites C and E. River regime and morphology. *Report* 783, Hydroelectric Design Division, Vancouver, Canada. (This report was not generally circulated.)

Church, M. (1995) Geomorphic response to river flow regulation: case studies and time scales. *Regulated Rivers: Research & Management*, 11, 3–22.

Daniels, J.M. (2002) Drainage network adjustment following channelization, Homochitto River Basin, Mississippi, in *Cultural and Physical Expositions: Geographic Studies in the Southern United States and Latin America*, vol. 36, edited by M. Steinberg and P. Hudson. Geoscience and Man Publications, Baton Rouge, LA. pp. 291–308.

Ferguson, R. and Hoey, T. (2008) Effects of tributaries on main-channel geomorphology [Chapter 10], in *River Confluences, Tributaries and the Fluvial Network*, edited by S. Rice, A. G. Roy, and B. L. Rhoads. John Wiley & Sons, Ltd, Chichester, UK. pp. 183–208.

Galay, V.J. (1983) Causes of river bed degradation. *Water Resources Research*, 19, 1057–1090. doi 10.1029/WR019i05 p01057.

Germanoski, D. and Ritter, D. F. (1988) Tributary response to local base level lowering below a dam. *Regulated Rivers: Research & Management*, 2, 11–24.

Hassan, M. A. and Klein, M. (2002) Fluvial adjustment of the lower Jordan River to a drop in the Dead Sea level. *Geomorphology*, 45, 21–33.

Holland, S. S. (1976) *Landforms of British Columbia, A Physiographic Outline*. Bulletin 48. British Columbia. Department of Mines and Petroleum Resources, Victoria, Canada. 138 p.

Kellerhals, R. (1982) Effect of river regulation on channel instability, in *Gravel-Bed Rivers*, edited by R. D. Hey, J.C. Bathurst, and C. R. Thorne. John Wiley & Sons, Ltd, Chichester, UK. pp. 685–705.

Kellerhals, R. and Gill, D. (1973) Observed and potential downstream effects of large storage projects in Northern Canada. *Proceedings of the 11th ICOLD Congress*, 1, 731–754.

Leopold, L.B. and Bull, W. B. (1979) Base level, aggradation, and grade. *American Philosophical Society Proceedings*, 123(3), 168–202.

Mathews, W.H. (1963) *Quaternary Stratigraphy and Geomorphology of the Fort St. John Area, Northeastern British Columbia*. British Columbia Department of Mines and Petroleum Resources, Victoria, Canada. 22 p.

Petts, G.E. (1984) *Impounded Rivers: Perspectives for Ecological Management*. John Wiley & Sons, Ltd, Chichester, UK. 326 p.

Taylor, K.V. (1978) Erosion downstream of dams, in *Environmental Effects of Large Dams*, edited by W. V. Binger. Report by the Committee on Environmental Effects of the United States Committee on Large Dams. American Society of Civil Engineers, New York. pp. 165–186.

Uunila, L. (1997) Effects of river ice on bank morphology and riparian vegetation along Peace River, Clayhurst to Fort Vermilion, in. *Proceedings of the 9th Workshop on River Ice, Fredericton, Canada*, compiled by S. Ismail. National Research Council of Canada, Ottawa. pp. 315–334.

Williams, G.P. and Wolman, M. G. (1984) Downstream Effects of Dams on Alluvial Rivers. *United States Geological Survey*, *Professional Paper*, 1286, 83 p. U.S. Government Printing Office, Washington, DC, USA.

Xu, J. (2001) Adjustment of mainstream-tributary relation upstream from a reservoir: an example from the Laohahe River, China. *Zeitschrift für Geomorphologie*, 45, 359–372.

CHAPTER 5
The hydraulic geometry of Peace River

5.1 Introduction

The regulation of Peace River in 1967 by the closure of W.A.C. Bennett Dam abruptly changed the distribution of flows downstream; in particular, the magnitude of the mean annual flood at the dam was reduced by a factor of three. Even at the downstream extremity of the river basin, 1200 km on, the flood was reduced by 45%. High flows were essentially eliminated in the reach immediately below the dam and their frequency severely reduced everywhere in the river. Since it is the high flows that mould the river channel, significant changes in the form of the channel might be anticipated to require considerable time to occur. Partly effected by passive shrinkage of the active channel zone within the confines of the former, unregulated channel, and partly by local erosion and sediment deposition, a channel of different dimensions and, possibly, shape should emerge from such drastic regulation.

The form of a river channel can be summarized in the hydraulic geometry of the channel. The purpose of this chapter is to investigate the changing hydraulic geometry of Peace River through an analysis of stream gauging observations.

Peace River is a large, eastward and northward flowing, boreal river, a major headwater of the Mackenzie River system of northwestern Canada. The river rises in the Rocky Mountain trench in northeastern British Columbia and breaks through the Rocky Mountains to flow east into the Alberta Plateau. W.A.C. Bennett Dam and the later Peace Canyon Dam are located in the water gap of the Rocky Mountains where they control 52% of the basin runoff emanating from the upper 24% of the drainage basin. East of the mountains, the river flows in a valley excavated up to 250 m into the Alberta Plateau. A cobble-gravel river in the first 370 km below the dams, it becomes a sandy gravel river below the Smoky River confluence. Near Tompkins Landing, 674 km from the dams, the gravel–sand transition occurs and the river has a sand bed beyond that, but with rock control in two places. Hence, the hydraulic geometry of the river reflects a changing channel regime downstream.

There are only six gauges along the river with records that include both pre- and post-regulation periods; three additional gauges give period information (Figure 5.1). The gauges are maintained by the Water Survey of Canada (WSC), from which data presented in this chapter were obtained.

The pre-regulation mean annual flood at Hudson's Hope, immediately below the dams was 5843 m^3s^{-1}, but it is now 1900 m^3s^{-1} (Figure 5.2). Regulated flows have rarely exceeded the 3000 m^3s^{-1}, nominally considered to be the flow at which bed-material transport is initiated in the upper river (Chapter 2), so the proximal reach is now essentially non-alluvial. There is limited suspended sediment in this reach and river channel adjustment has almost entirely been passive. The first major tributary Pine River—enters 101 km below the dams at Taylor, British Columbia, and raises the regulated mean annual flood to 2837 m^3s^{-1}, a 2.5 times reduction from 7213 m^3s^{-1} and essentially equal to the estimated threshold flow for bed-material movement. Smoky River, entering at km 368, just above the Town of Peace River (TPR), Alberta, is the largest tributary on the river: it raises the mean annual flood to 5564 m^3s^{-1}, a 1.6 times reduction and moderately above the competence limit for gravelly bed material. Gravel transport presumably is also facilitated by the large sand load introduced by this tributary. Flows change little between TPR and Peace Point, the most distal gauge, due to the asynchronous timing of the spring runoff peak from

The Regulation of Peace River: A Case Study for River Management, First Edition. Michael Church.

Companion website: www.wiley.com/go/church/peaceriver

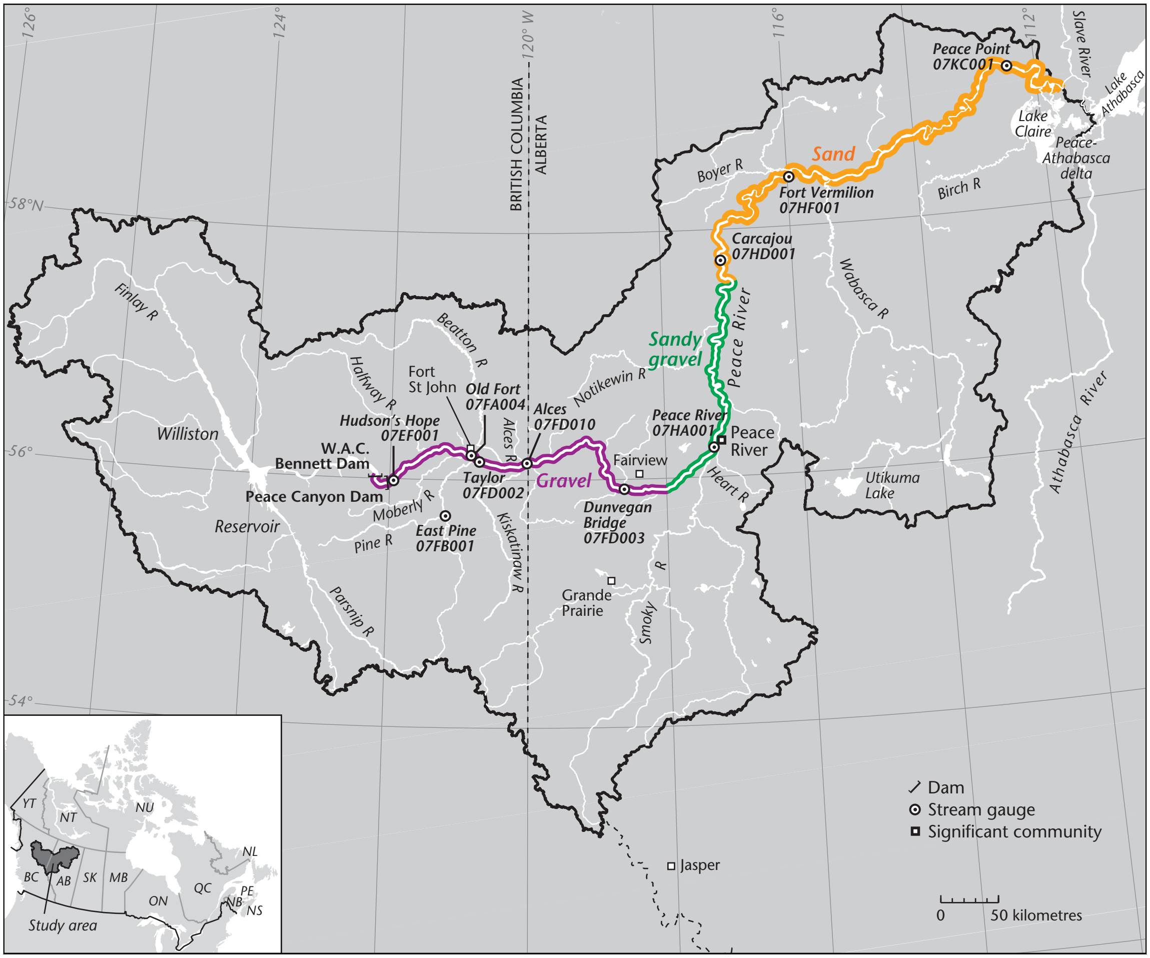

Figure 5.1 Map of Peace River drainage basin, showing the location of gauges discussed in this chapter.

the increasingly northerly tributaries and very limited runoff in the balance of the year.

There have been two extraordinary flows in the river within the period of regulation. In June 1990, the flood of record (stretching back to 1917) occurred on the river from the Smoky confluence down, reaching 16 500 m^3s^{-1} at TPR and 12 600 m^3s^{-1} at Peace Point (Chapter 10). It resulted from an intense rainstorm in the upper basin that produced the post-regulation flood of record on the upper river as well, 5190 m^3s^{-1} at the Taylor gauge. However, this flow was surpassed in the summer of 1996 when the need to do maintenance work at Bennett Dam led to the spillway being opened, so that flows exceeded 3000 m^3s^{-1} for 53 days, peaking at 6220 m^3s^{-1} at Taylor on July 19. The flow was managed to be just bankfull in terms of the old, pre-regulation floodplain in the upper river.

WSC stations studied in this report are located on the upper river at Hudson's Hope, at Taylor, immediately downstream from the Pine River confluence, and at Dunvegan Bridge, 275 km below the dams and below several moderate-sized tributaries that enter below Pine River. The gauge at TPR is immediately below the Smoky River confluence, but is located at a point where bedrock occurs in the river bed; hence the adjustment of the river here can be expected to have been mainly passive. The gauge at Fort Vermilion is about 175 km beyond the gravel–sand transition, hence, records channel form

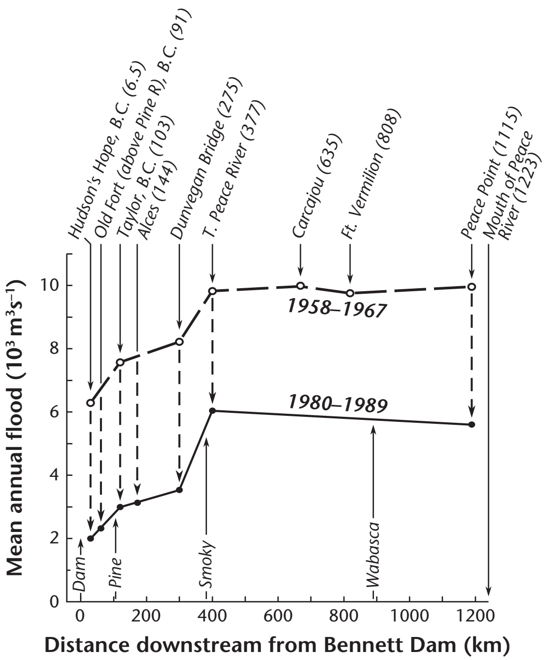

Figure 5.2 Mean annual flood in Peace River downstream from the dams before and after regulation.

in the sand-bed reach. The final gauge is at Peace Point, 1115 km below the dams in the Peace–Athabasca Lowland, where it records the river morphology in the low-gradient reach approaching the Peace–Athabasca delta (Figure 5.1). Additional data are studied from gauges at Alces River (post-regulation only), at the BC–Alberta border, and Carcajou (pre-regulation flows only), located in the vicinity of the gravel–sand transition. The gauges at Hudson's Hope and TPR, which are located on rock-controlled sections, and the gauge at Old Fort, British Columbia (named "Peace River above Pine River"), which has only brief records, are excluded from study.

5.2 Hydraulic geometry

The hydraulic geometry of river channels was introduced by Leopold and Maddock (1953) to describe the covariation of channel width, depth, and mean flow velocity with discharge. The concept is an extension of empirical "regime theory," a set of equations developed in the early twentieth century to describe the equilibrium geometry of unlined, sediment transporting irrigation canals in British India and in Egypt (Lindley, 1919; Lacey, 1930; Leliavsky, 1955; Blench, 1969). Lacey and Blench predicted general scaling relations of the form $w \propto Q^b$, $d \propto Q^f$, which compel a third relation, $v \propto Q^m$, with the exponents $b + f + m \equiv 1.0$. These simple relations have been applied in two contexts: (i) to describe the changes in width, depth, and velocity at a specific place along a channel as flow varies, known as "at-a-station hydraulic geometry," and (ii) to describe the changes in width, depth, and velocity as one proceeds downstream through a river system for flows of some fixed frequency, known as "downstream hydraulic geometry." (In the downstream context, Leopold and Maddock (1953) also introduced a relation $S \propto Q^t$, $t < 0$.) The at-a-station analysis is purely a descriptive device to represent the covariation of sectional hydraulic quantities as flow varies; most of the time, the river geometry remains unchanged and one simply records the effect of filling the channel with water. The downstream case, however, represents scaling relations for the effect of flow magnitude on alluvial channel form as one proceeds through the river system.

In fact, it is known from rational constructions of regime theory (e.g., Eaton *et al.*, 2004) that the equations of hydraulic geometry are incomplete scaling statements. An important missing factor is the effect of sediment properties, which influence sediment mobility and, critically, riverbank strength. Hence, we may expect systematically different hydraulic geometries for sandy, as opposed to gravelly, channels (Lane, 1957). Accordingly, we may expect changes in the controlling hydraulic geometry between the upper and lower reaches of Peace River.

Furthermore, the at-a-station relations are not constrained to be power functions (Ferguson, 1986a). The simple power function scaling relations are nevertheless good approximations, within the limits of precision of field measurements, and will be adopted for the present investigation. The downstream case, in which we typically find $b \approx 0.5$ and $0.3 < f < 0.4$ furthermore emphasizes the allometric character of river channels—that is, small channels are not simple scale models of larger ones. This is a consequence of the limited capacity of materials of any particular calibre to resist the erosive force of running water so that, as channels become larger, they tend to grow wider more rapidly than they deepen.

5.3 Methods

Copies were obtained from the WSC of the gauging notes for all stream gaugings at each of the gauging stations along Peace River for the period to 1995, from which data of channel width, mean water depth, mean flow velocity, cross-sectional area, and computed discharge were abstracted. After 1995, these data are available in summary files prepared by the WSC. Table 5.1 gives gauging station record periods and numbers of data.

Initially, mass plots of the data were used to identify coherent subsets of data, with special attention given to the periods before 1967 (inception of regulation), 1967 to May 1996 (period of normal regulated flows), June 1996 to present (drawdown flood and after). In addition, attention was given to the question whether the June 1990 flood of record may have affected stations on the lower river. However, data to engage this question are restricted to Peace Point, the extreme downstream station. Relations were calculated for coherent subsets of the data and reasons sought for the identified changes in hydraulic geometry. The hydraulic geometry for periods with ice cover was separately considered for the two stations with winter gaugings (Taylor, ice encountered only in the pre-regulation period, and Peace Point).

Figure 5.3 shows the initial data plots for Taylor, the most complex record in the set. The occurrence of distinct pre- and post-regulation regimes is clear. In particular, mean velocity exhibits separate, individually coherent regime relations for the open-water period. Channel depth and width, however, display a curious mixture of pre- and post-regulation values within one of two distinct data subsets. The evident regime changes were explored farther by the selection of temporally continuous subsets of the data sets that yield homogeneous relations.

Relations for identified subsets were estimated as power functions established by ordinary least squares regression performed as linear regression on log-transformed variates; hence the displayed equations are subject to a back-transform bias which means that they are, in effect, median regressions, not mean regressions. This relatively discounts the effect of high outliers in the data. A bias adjustment has been made according to the method of Miller (1984; see also Ferguson, 1986b). However, correlations are so high that the correction has made effectively no difference to the results.

A more subtle source of bias arises from the adoption of regression as the method of fitting a descriptive relation to the data. Regression assigns all residual error to the statistically dependent variate, which is appropriate when the goal is prediction of new values of that variate from arbitrary values of the statistically independent one. We are more interested, however, in the true underlying value of the exponents and coefficients of the relations. For that, functional analysis should be adopted, a technique that assigns the appropriate portion of the residual error to each variate (geometrically, this amounts to making an off-axis determination of the least squares minimization of residual variance: see Mark and Church, 1977 for a discussion of functional

Table 5.1 Data of WSC gauging stations

Station No.	Name (Peace River at)	Distance from dam[a]	Record			Number of observations	
			Start	End	Length (a)	Total	Ice affected
07FD002	Taylor	103	1944	2010	67	207	38[b]
07FD010	Alces River	143	1990	2010	21	45	0
07FD003	Dunvegan Bridge	275	1961	2007	47	77	0
07HD001	Carcajou	635	1961	1967	7	29	0
07HF001	Fort Vermilion	808	1961	2011	24[c]	112	25
07KC001	Peace Point	1115	1960	2011	52	430	255

[a]Distance in kilometers below Peace Canyon Dam.
[b]All before 1970.
[c]No measurements between 1979 and 2006, except a single gauging in 1990.

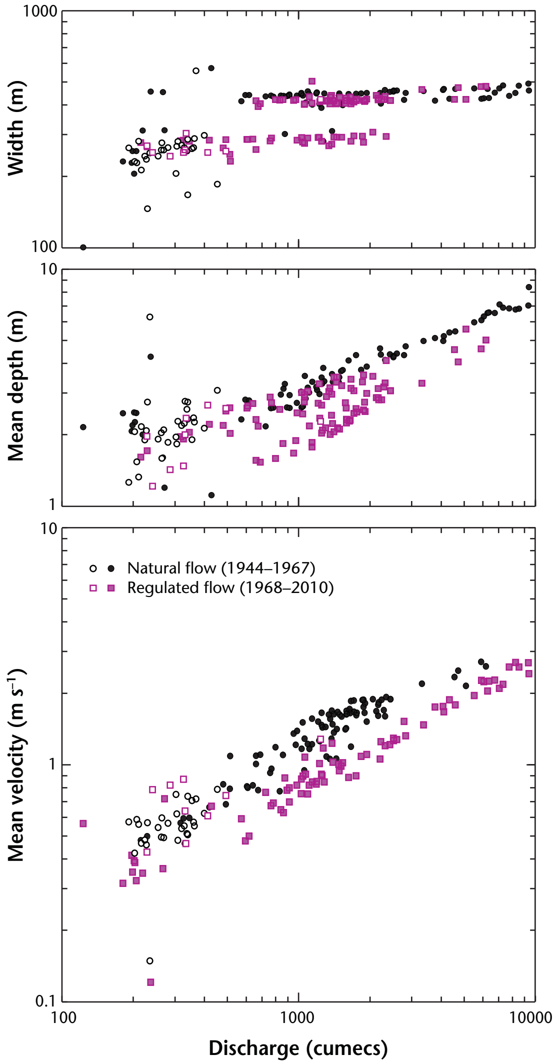

Figure 5.3 Initial data plots for WSC Stn. 07FD002, Peace River at Taylor: all data are displayed. Open symbol indicate ice-period gauging.

relations). We have in the present case, however, additional constraints in that the exponents $b + f + m \equiv 1.0$, and the coefficient, $ack \equiv 1.0$. Since the correlations are very high, these constraints are observed when the least squares minimization is performed in the y-axis direction (i.e., ordinary regression is applied) so that departures from perfect agreement between the dependent variate and Q are just offset over the product of the three dependent variates. (Note that many of the relations for width do not exhibit high correlation, but that is because there is little variation in channel width with stage change, not because the data are scattered.) Computation of the reduced major axis solution (a default method that assumes the error ratio of the variates is proportional to the ratio of their total variances, adopted since the true error ratio is unknown) produces results that do not obey the constraints imposed by the linkage of the equations. There remains a measure of bias in the adopted regressions, however, which appears when R^2 is calculated in the back-transformed (i.e., original) variates—in some cases this ${R_{bt}}^2 > 1$, by up to 5%, a situation that is possible only when R^2 is very high and the relation is biased with respect to the distribution of the data.

Some individual gaugings exhibit large discrepancies in comparison with the bulk of the data. Reasons for these discrepancies are not generally known and may or may not entail gauging or recording errors. Highly discrepant results have been deleted before computation of the hydraulic geometry relations.

5.4 At-a-station hydraulic geometry

Equations derived from the analysis are summarized in Table 5.2. The following text summarizes the results station-by-station.

5.4.1 Peace River at Taylor, British Columbia (WSC Stn. 07FD002)

WSC Stn. 07FD002 is located in a pier of the Alaska Highway Bridge crossing of Peace River, 103 km below Peace Canyon Dam. The site is immediately downstream from the confluence with Pine River (Figure 5.1), the second most important tributary of the system, so that, in the regulated regime, it records a weak spring freshet in addition to elevated winter flows. Records began in 1944, immediately following construction of the bridge, so that there is a 24-year record of natural flows at the station and the best available comparison, along Peace River, of the contrast between the natural and regulated hydraulic geometry. Following regulation, winter ice has virtually disappeared from the first 100 km of the river below the dams; hence observations of winter ice effects are restricted to the period of natural flows and a few records extending to 1974, during the period of reservoir filling and early operations. Very early, the

Table 5.2 Peace River at-a-station hydraulic geometry

Station	Width			Depth			Velocity				
	Coeff.	Exp.	R^2	Coeff.	Exp.	R^2	Coeff.	Exp.	R^2	*n*	Deletion[a]
Open water											
Taylor											
Non-regulated	360	0.027 ± 0.006	0.19	0.18	0.41 ± 0.022	0.96	0.016	0.56 ± 0.024	0.97	61	17
1968 to 1996	99	0.19 ± 0.036	0.43	0.41	0.25 ± 0.046	0.46	0.025	0.56 ± 0.056	0.85	62	2
1996 to 2010	217	0.039 ± 0.016	0.16	0.56	0.24 ± 0.060	0.67	0.0083	0.72 ± 0.086	0.92	21	2
Reg. *w* = 250 m	226	0.033 ± 0.018	0.14	0.33	0.31 ± 0.034	0.96	0.014	0.66 ± 0.070	0.96	13	
Reg. *w* = 400 m	381	0.014 ± 0.004	0.06	0.038	0.57 ± 0.058	0.89	0.070	0.42 ± 0.060	0.79	41	11
Alces											
Reg.—reduced set	102	0.11 ± 0.022	0.64	0.13	0.48 ± 0.070	0.80	0.076	0.41 ± 0.072	0.72	37	8
1990 to 1995 (pre-flood)	115	0.093 ± 0.034	0.57	0.21	0.40 ± 0.044	0.96	0.041	0.50 ± 0.074	0.93	13	1
1996 to 2010[b]	94	0.12 ± 0.026	0.69	0.14	0.48 ± 0.092	0.78	0.080	0.40 ± 0.094	0.68	24	7
Dunvegan Bridge											
Non-regulated	260	0.062 ± 0.012	0.83	0.051	0.56 ± 0.024	0.99	0.076	0.38 ± 0.020	0.99	17	5
1968 to 1996	70	0.23 ± 0.017	0.80	0.60	0.23 ± 0.046	0.63	0.024	0.54 ± 0.052	0.92	36	9
1996 to 2010	153	0.12 ± 0.036	0.80	0.075	0.51 ± 0.050	0.98	0.087	0.37±0.022	0.99	9	2
Carcajou											
Non-reg.—high flow	363	0.063 ± 0.012	0.83	0.051	0.57 ± 0.054	0.96	0.054	0.37 ± 0.052	0.92	17	1
Non-reg.—low flow	62	0.29 ± 0.088	0.81	0.25	0.36 ± 0.096	0.86	0.066	0.35 ± 0.086	0.88	8	3
Fort Vermilion											
All data	248	0.077 ± 0.012	0.52	0.53	0.33 ± 0.032	0.44	0.0059	0.63 ± 0.018	0.98	87	25
Non-regulated	263	0.073 ± 0.012	0.77	0.78	0.28 ± 0.024	0.94	0.0049	0.65 ± 0.024	0.99	35	13
1968 to 1990	277	0.061 ± 0.014	0.31	0.69	0.30 ± 0.034	0.84	0.0053	0.64 ± 0.022	0.99	46	0
2006 to 2008	303	0.046 ± 0.012	0.90	0.47	0.34 ± 0.020	0.99	0.0071	0.61 ± 0.028	1.00	6	12
Peace Point											
Non-regulated	430	0.044 ± 0.004	0.93	0.11	0.49 ± 0.036	0.95	0.021	0.47 ± 0.036	0.95	36	5
1968 to 1996	430	0.045 ± 0.008	0.31	0.047	0.58 ± 0.022	0.96	0.049	0.37 ± 0.028	0.84	111	14
1996 to 2011	531	0.015 ± 0.006	0.0027	0.18	0.42 ± 0.132	0.55	0.011	0.56 ± 0.112	0.82	18	2
Ice regime											
Taylor											
1945 to 1969	72	0.23 ± 0.074	0.39	0.089	0.56 ± 0.174	0.42	0.16	0.22 ± 0.082	0.15	24	7
Peace Point (1960 to 2011)											
w = 640 m	445	0.057 ± 0.006	0.44	0.022	0.72 ± 0.036	0.89	0.11	0.22 ± 0.026	0.39	169	13
w = 540 m	539	0.0008 ± 0.0002	0.00	0.21	0.43 ± 0.084	0.53	0.0091	0.57 ± 0.094	0.68	48	1

Equations are of the form $y = aQ^b$. The quoted errors for the exponents are two times the standard error. R^2 values are for the linearized logarithmic relations. R^2 for the width relation is often very low because of very low variation in channel width.

[a]Number of data deleted from the calculation of the relation.

[b]Includes the 1996 flood.

pattern of hydropower generation was adjusted to minimize ice problems on the river as far downstream as possible. The Taylor history, describing an alluvial section relatively close to the dams and immediately downstream of a large gravel-yielding tributary, is the most complex on the river.

Winter data and derived relations are displayed in Figure 5.4. Correlations are poor, which is not surprising given the variable conditions for water passage that must occur according to whether sheet ice covers the river or jammed ice or frazil ice constricts the section. Depth shows the greatest adjustment, consistent with the presence of ice promoting anomalously high stages to force water passage, while velocity and width contribute equally, on average, to the definition of the hydraulic section. The single 1974 observation—made after winter power generation was established—severely skews the results because the flow is much higher than

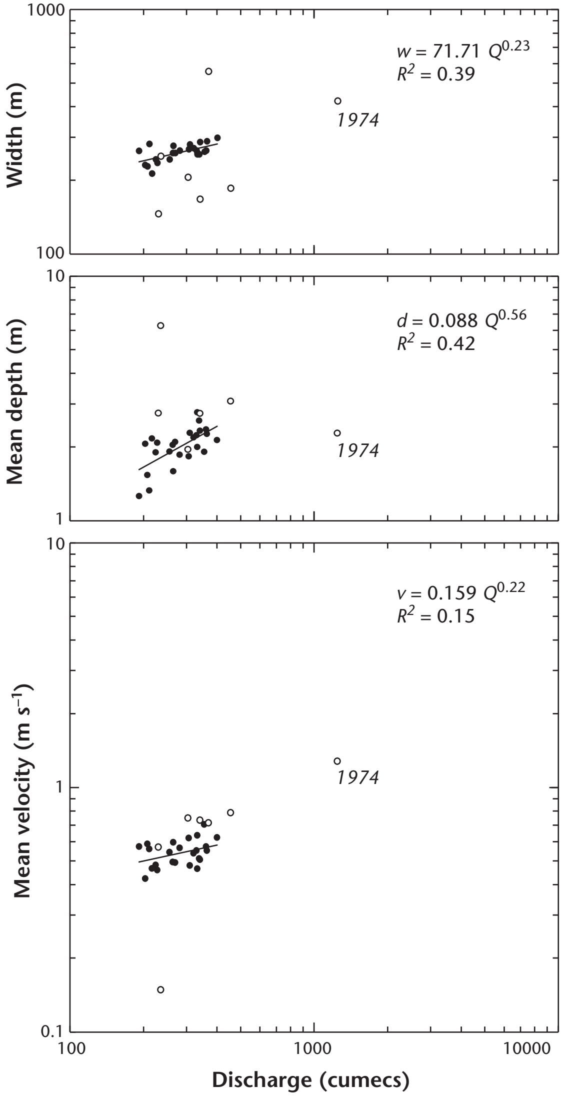

Figure 5.4 WSC Stn. 07FD002, Peace River at Taylor: hydraulic geometry with ice on the river, period 1945 to 1969, natural regime and the first two winters of flow regulation (reservoir filling; flows extremely low). Aberrant data are plotted (open symbols) but not included in the calculation of the best-fit function.

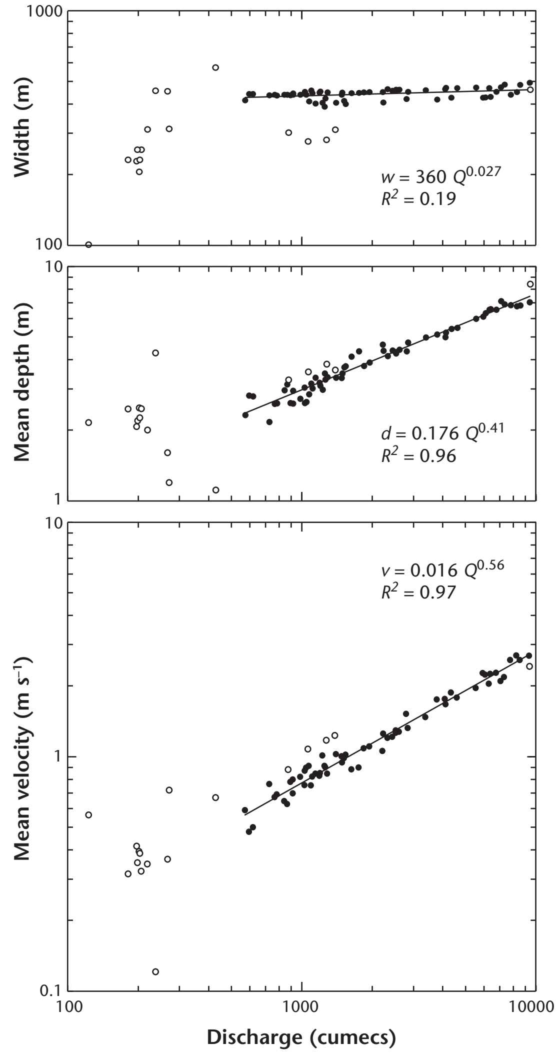

Figure 5.5 WSC Stn. 07FD002, Peace River at Taylor: hydraulic geometry for open water, period 1944 to 1967, natural regime. Aberrant data (open symbols) are plotted but not included in the calculation of the best-fit function. R^2 for width is poor because there is very little variation in width.

in any other observation; it has been removed from the calculation.

Figure 5.5 displays open-water conditions for the comparable period 1944 to 1967. With the removal of a number of outlying points, a well-defined hydraulic geometry emerges in which the variation of depth and velocity accommodate increased flows with relatively little adjustment of width. Whilst not an uncommon feature of at-a-station hydraulic geometries, the restricted width adjustment is rather unusual for a gravel-bedded river. At the gauging site (also a bridge site) both banks are relatively high, comprising a well-developed floodplain surface on the right bank and, on the left bank, artificial fill. Over most of the observed range, the river was between 400 and 450 m wide at the gauging section, the variation occurring mostly on the right bank. At flows less than 500 m^3s^{-1}, there is no coherent relation. The reason for this is not clear but may relate to talweg zone sedimentation from Pine River or to switching of channels in the mouth of Pine River. It might also relate to the need to find a section different than usual in order to obtain a reliable gauging at low flows. But all the winter gaugings, which return a roughly consistent record, fall within this range.

Hydraulic geometries for the periods 1968 to 1995 and 1996 to 2010 are displayed in Figure 5.6. The two periods are divided by the reservoir drawdown flood of 1996 and four measurements made during the flood flow are excluded from calculations. It is evident that reciprocal adjustments between width and depth define two distinct hydraulic geometries in the early period of "normal" regulated flows and that the post-1996 hydraulic geometry follows the high depth–low width variant. The two geometries are resolved in Figure 5.7 as a "250 m width" variant and a "400 m width"

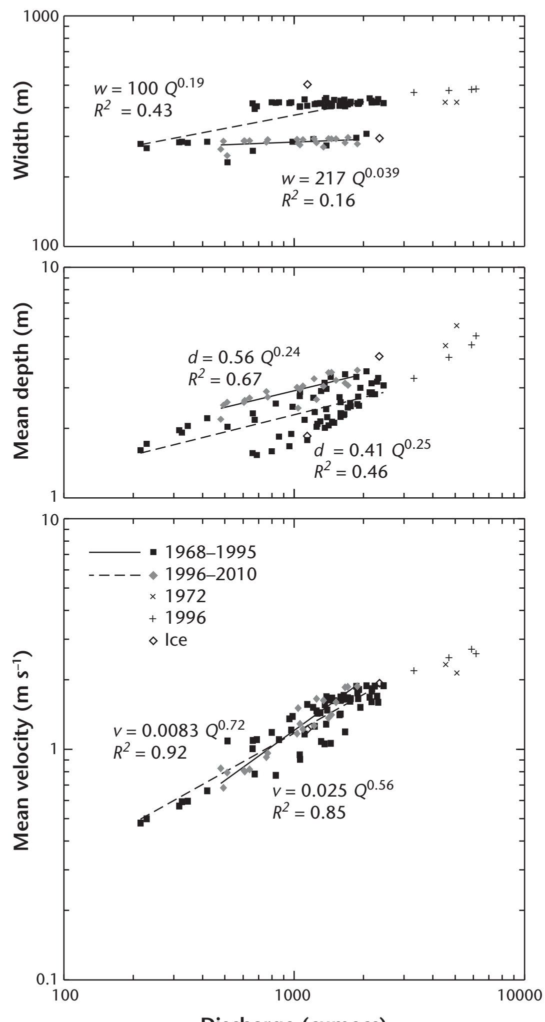

Figure 5.6 WSC Stn. 07FD002, Peace River at Taylor: hydraulic geometry for open water, periods 1968 to 1995 and 1996 to 2010. Aberrant data are plotted but not included in the calculation of the best-fit functions. It is evident that the early period presents two geometries: see figure 5.7 for further analysis.

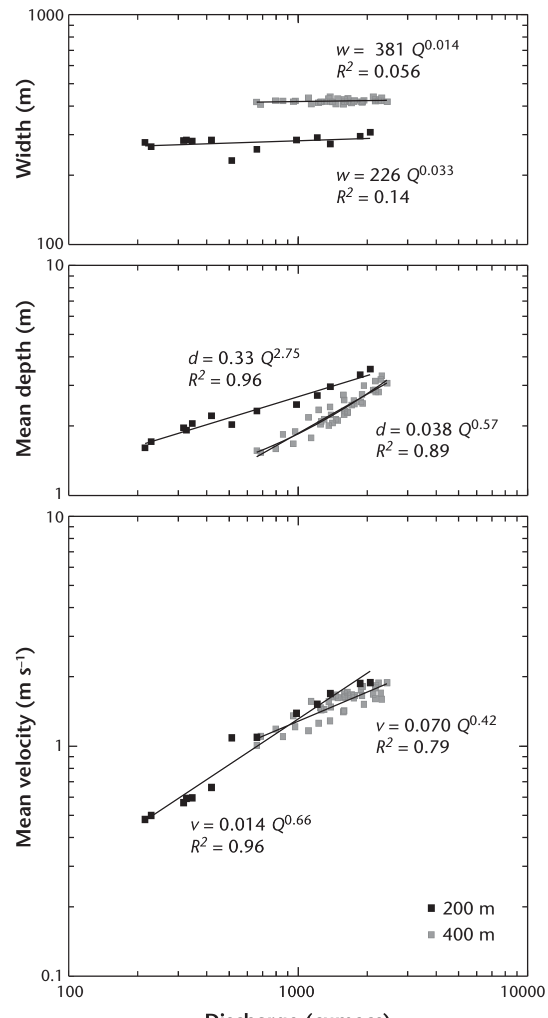

Figure 5.7 WSC Stn. 07FD002, Peace River at Taylor: hydraulic geometries for open water, period 1968 to 1995. Distinct geometries for a 250 m wide river and for a 400 m wide river are displayed. Two outlying data from the 1972 spillway flood are deleted.

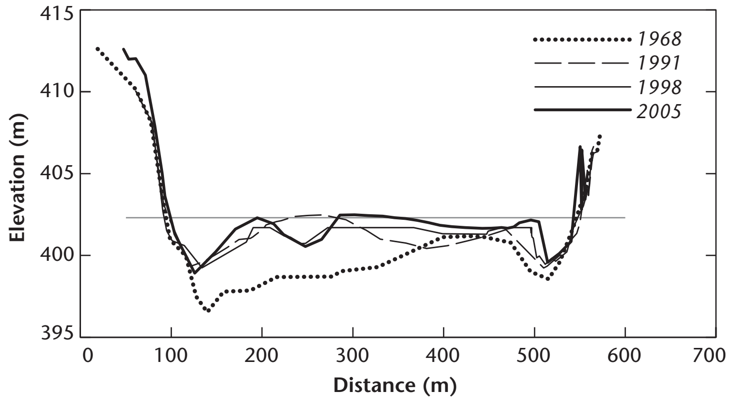

Figure 5.8 Section S-10, Taylor gauge section: surveys for 1968, 1991, 1998, and 2005.

variant. The 250 m variant comprises measurements taken in 1968 and in the period from 1992 on, with two additional measurements in late 1986 and early 1987. These measurements are, then, temporally grouped but not temporally isolated from 400 m ones. Discharge measurements have been made at various times at two principal positions in the river, upstream or downstream of the bridge. While this may very well influence results, the notes specifying the location of the measured section are incomplete. The data do not appear to correspond straightforwardly with available information of measurement position.

Survey section S-10 of this study corresponds with the upstream gauging section (it is about 30 m upstream of the bridge: see the illustration of the section in Figure 3.4). The surveyed section at key dates is illustrated in Figure 5.8. It is evident that a mid-channel bar has grown in the section since 1968, the product of gravel delivered from Pine River and deposited in the Peace River. It has extended under the bridge and for a considerable distance downstream, hence, has affected the entire vicinity of the gauge. It is likely that this bar, exposed at lower flows, has strongly influenced gauging practice and may represent the reason for the apparently varying geometry. Immediately upstream of S-10, there is a deep, semi-prismatic channel strongly conditioned by the Pine River outflow and it is possible that the narrow variant measurements have mainly been taken there. While the largest widths correspond with the highest flows, there is a large range of overlap in discharge between the two subsets of data. Overall, the gauging history at Taylor provides a strong cautionary example against over-interpreting the meaning of at-a-station hydraulic geometry.

5.4.2 Peace River at Alces River, British Columbia (WSC Stn. 07FD010)

This station is located about four kilometers from the British Columbia–Alberta border (Figure 5.1) immediately upstream from the small left-bank tributary Alces River, and on the upstream side of the Clayhurst Bridge. Records cover the period 1990 to present; hence the value of the station is to consider possible effects of the 1996 drawdown flood. A massed plot of data from this station is shown in Figure 5.9. There is no clear separation between pre- and post-flood data and a single set of equations (Table 5.2) describes the section well. The best equations, with aberrant points deleted from the calculation, are given in Figure 5.9; they are little different than the equations for the complete data set, but values of R^2 for depth and width are substantially improved. Separate calculations for the two periods reveal that the pre-flood correlations ($R^2 > 0.9$, except for width) are much tighter than those for the post-flood period ($R^2 < 0.8$), implying some instability in the section since the flood, but the variation is not systematic. The post-flood equations differ somewhat from the pre-flood ones, but do not produce any significant variations within the range of the data.

5.4.3 Peace River at Dunvegan Bridge (WSC Stn. 07FD003)

Dunvegan Bridge is located 275 km from the dams in a reach in which the river is confined within a young, postglacial valley. The gauge house is located immediately downstream from the bridge where the channel is additionally confined by the sediment fan of Hines Creek. The progradation of the fan has affected

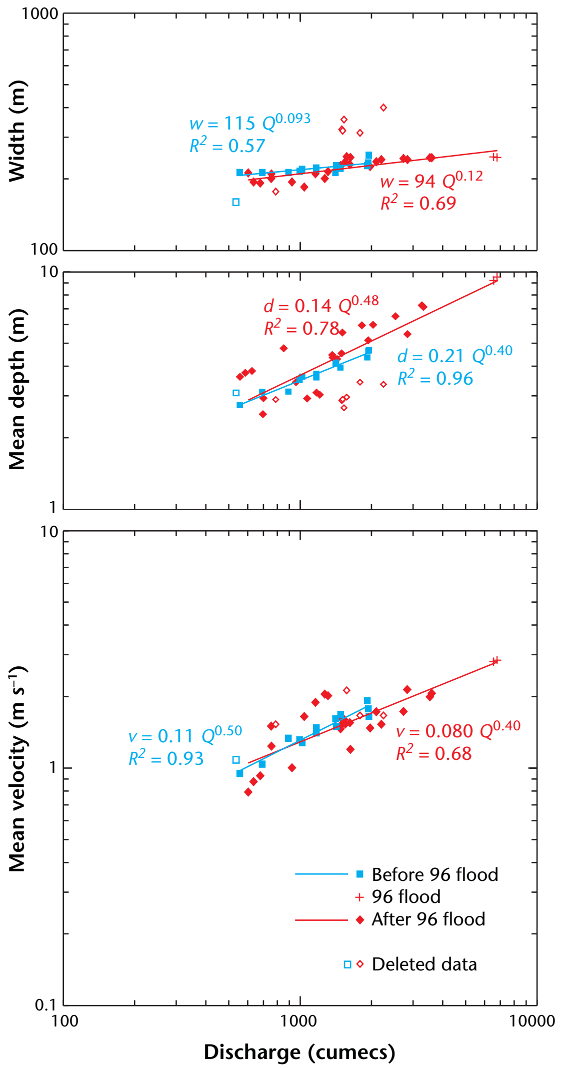

Figure 5.9 Data of WSC Stn. 07FD010, Peace River at Alces River, for the period 1990 to 2010. Aberrant data are plotted but not included in the calculation of the best-fit functions.

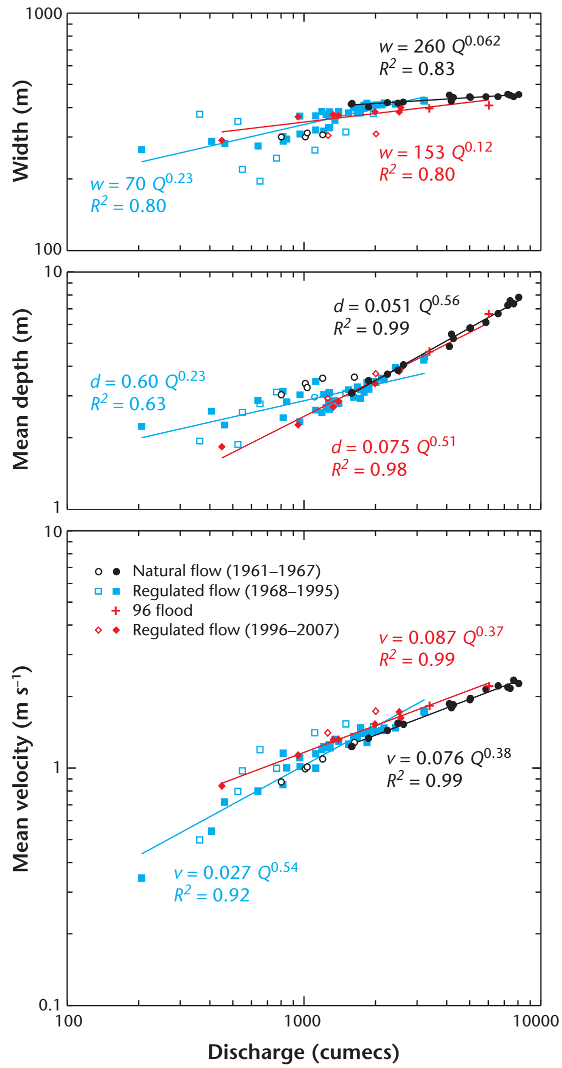

Figure 5.10 WSC Stn. 07FD003, Peace River at Dunvegan Bridge, for the period 1961 to 2007: mass plot of data and hydraulic geometry for three periods: aberrant data (open symbols) are plotted but not included in the calculation of the best-fit functions. Measurements taken during the 1996 flood are annotated.

the section. The gauge has been operated seasonally hence there are no winter measurements. Records began in 1961, yielding seven years of pre-regulation measurements during which there were 22 gaugings. Figure 5.10 shows a mass plot of the data. They are not widely scattered and an argument could be sustained that they represent a stable section, but it has been affected by deposition from Hines Creek (Figure 5.11).

Broken into regime periods, there is a clear distinction between the displayed hydraulic geometries for the period of natural flow (1961 to 1967) and the early period of "normal" regulated regime (1968 to 1996). In the period of early regulation, with mostly modest flows, depth became less variable and width more variable, reflecting the restriction of flows within the confines

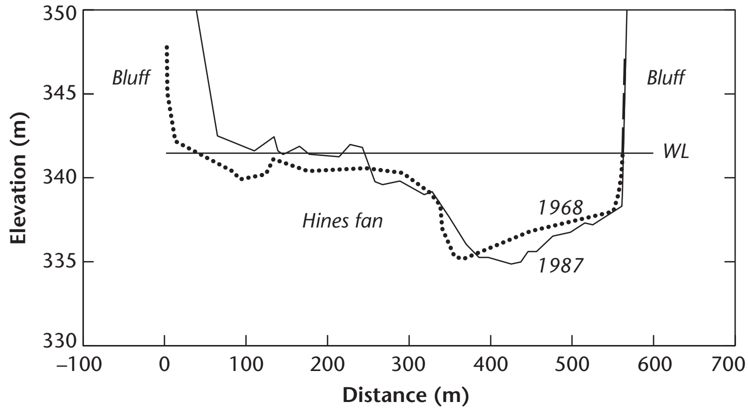

Figure 5.11 Surveys at section U (Peace River at Dunvegan Bridge). Sediment deposition from Hines Creek has forced the channel to the right during the period of record. It is doubtful that the same survey positions were occupied on the left bank.

of the low-water channel. After 1996, however, the hydraulic geometry reverted to one similar to that of the pre-regulation regime. There are indications from the number of outlying data points in the preceding period (eight points, all of them occurring after 1991) that the channel was already beginning to change before the 1996 flood. The shift is consistent with a reduction in channel width produced by Hines Creek sedimentation. Hence, the observed adjustments in hydraulic geometry at this section are subtle and possibly associated mainly with local effects.

5.4.4 Peace River at Carcajou (WSC Stn. 07HD001)

This station, located 635 km below the dams and close to the gravel–sand transition in the river, was operated only for the seven-year period 1961 to 1967 immediately before the closure of Bennett Dam. A coherent hydraulic geometry emerges from the measurements (Figure 5.12), with the exception of four highly eccentric points measured successively between June and October 1966. These are almost certainly measurement problems that may derive from using different gauging sections. The data can be decomposed, however, into a “high-flow” hydraulic geometry and a “low-flow” hydraulic geometry. The latter shows higher width variation and lower depth variation than the high-flow subset, lending additional weight to the interpretation put forward for the temporal change observed at Dunvegan, that low flows confined within the lower part of the channel section exhibit greater variability in width. In the period of natural flows at Dunvegan there are, unfortunately, almost no measurements below 1000 m^3s^{-1}, when this phenomenon might also have been observed there.

5.4.5 Peace River at Fort Vermilion (WSC Stn. 07HF001)

The station at Fort Vermilion, 808 km from the dams, was established in 1961 and measurements were taken until 1978. Apart from a single measurement in 1990, no further measurements were taken until 2006, since when 20 measurements have been taken, 12 of them during ice cover. A mass plot of the data is shown in Figure 5.13. All the post-2006 regulated regime measurements with ice cover have $Q > 1000$ m^3s^{-1} while, aside from one measurement taken in April 1965, all the natural regime ice measurements have $Q < 400$ m^3s^{-1}; hence they form two separate clusters of data neither of which is sufficient to bear close scrutiny. There are no ice cover measurements during the early period of flow regulation.

The open-water measurements (Figure 5.13) show little variation between periods. Nevertheless, differences in the derived relations are significant and vary significantly about the overall relation (Table 5.2), which describes the open-water data reasonably well. In detail, depth changes become steadily more sensitive (exponent increases from 0.28 to 0.34) while width becomes less sensitive (exponent decreases from 0.073 to 0.046). Velocity changes only slightly through the periods: the coefficient increases from 4.9×10^{-3} to 7.0×10^{-3}, reflecting a slight increase over all flows. These subtle changes are consistent with a channel that has become narrower over time; the change in velocity presumably being a consequence of the increased characteristic

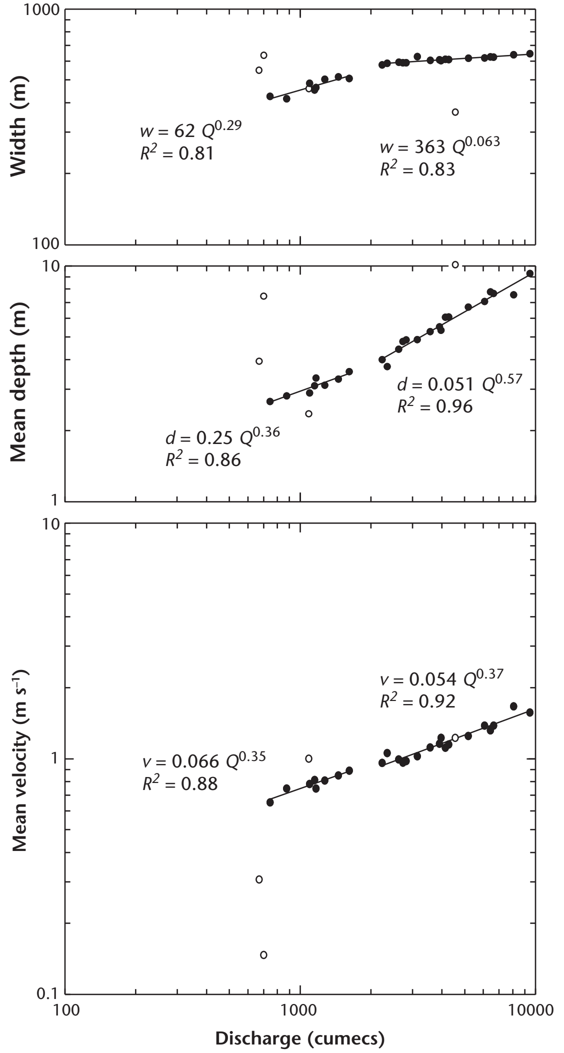

Figure 5.12 Open-water hydraulic geometry for WSC Stn. 07HD001, Peace River at Carcajou for the pre-regulation period 1961 to 1967, segmented into "high-flow" and "low-flow" subsets. Aberrant data (open symbols) are plotted but not included in the calculation of the best-fit functions.

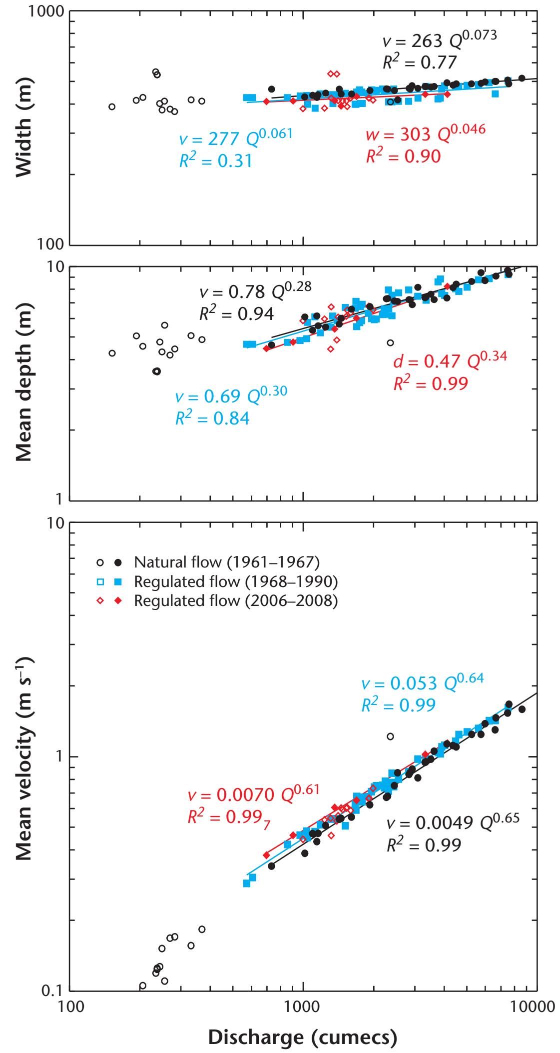

Figure 5.13 WSC Stn. 07HF001, Peace River at Fort Vermilion, data for 1961 to 2011. All data are shown: displayed equations are based on a subset excluding ice period measurements (open symbols) and one aberrant datum. Displayed equations describe open-water hydraulic geometry for Peace River at Fort Vermilion for three periods.

depth of flow. However, it must be realized that there are relatively few measurements after 1996.

5.4.6 Hydraulic geometry at WSC Stn. 07KC001, Peace River at Peace Point

Peace Point, 1115 km downstream from the dams, lies 90 km above the division of the river into the channels of the Peace–Athabasca delta (with Peace River substantially continuing as Slave River). It is located in the Peace–Athabasca Lowland, beyond the rock control of the river gradient at Vermilion Chutes and Boyer Rapids. The sand-bed river meanders between silty banks. The station has been operated continuously since 1960 with many measurements both during open water and ice cover. Figure 5.14 presents a mass plot of the data.

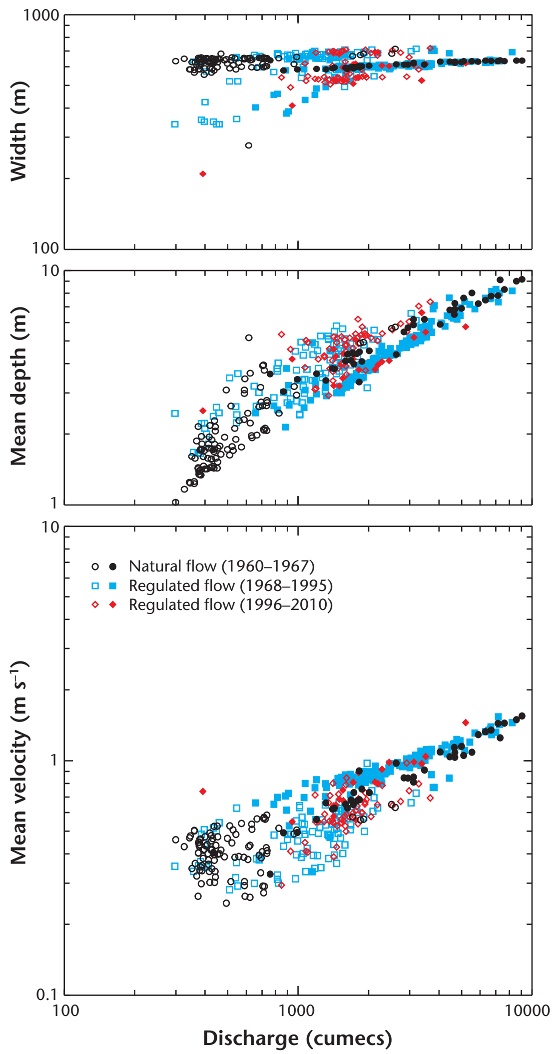

Figure 5.14 Peace River at Peace Point, WSC Stn. 07KC001: mass plot of data with three periods and ice-period measurements (open symbols) distinguished.

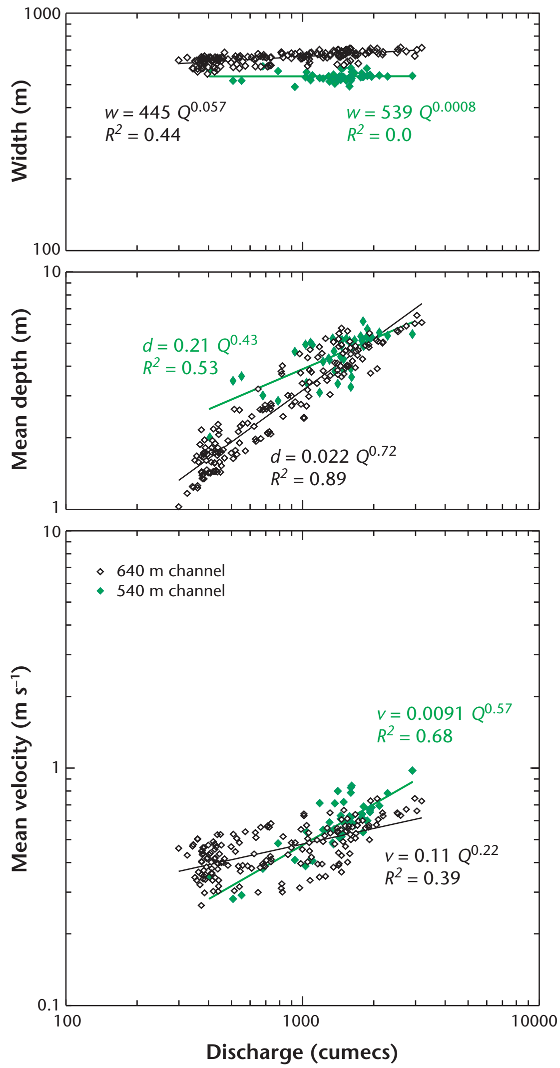

Figure 5.15 Ice-regime hydraulic geometry for Peace River at Peace Point: two regimes are evident, one reflecting river width, the other subject to ice build-up alongshore. Ten aberrant data points have been deleted in the pre-1967 period and one in the post-1996 period. The deleted points occur in clusters of adjacent measurements, suggesting that they are the result of unusual ice configurations.

Figure 5.15 presents a hydraulic geometry for the ice regime. Two clear relations for channel width are revealed, neither showing much variation. At an average of about 640 m, one relation approaches the river width; the other, at about 540 m, reflects the occurrence of a shore-fast zone of jammed ice. The data do not correspond with the identified "regime periods" for the river and many data do not follow either relation. The width effect is compensated in both depth and velocity, but not in a distinctly apportioned fashion. The state of the ice cover within the channel dictates variable depth and velocity effects.

Open-water hydraulic geometry is displayed in Figure 5.16: changes are subtle. After regulation, depth became rather more sensitive to changes in flow, and velocity correspondingly less so: the channel width

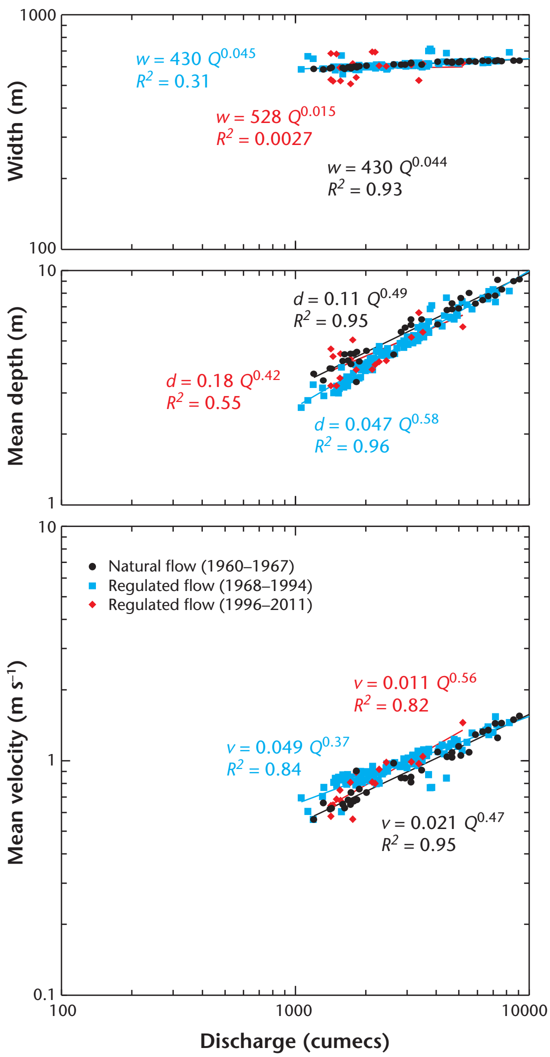

Figure 5.16 Open-water hydraulic geometry for Peace River at Peace Point. Significant change was induced by the moderate but long-sustained flood of 1996.

relation—very insensitive to flow variation—did not change. After the 1996 flood, however, width clearly increased, depth became considerably less sensitive and velocity much more so. This effect implies significant lateral erosion of the channel. In comparison, the flood of 1990 produced changes in the hydraulic geometry so small that they plausibly fall within the realm of sampling variation. The extended duration of the 1996 flood evidently was important in determining the significant change that occurred in that year.

5.4.7 Summary on at-a-station hydraulic geometry

The variation with discharge of width is generally low, exponents being typically <0.1 (Table 5.2). (For this reason R^2 in the relations for width are often very low: modest variations about the observed relations tend to be greater than the total variation observed over the range of flows.) However, in the early post-regulation period at the upstream, gravel-bed stations—Taylor and Dunvegan Bridge—width variation is more pronounced, with exponents near 0.2. This is the consequence of relatively low flows being restricted to the generally flat bottom of the channel, where stage variations significantly change the wetted perimeter (see Figure 5.17). The phenomenon is emphasized by the data of Carcajou, where high and low flows in the natural regime are segregated into less and more sensitive ranges of variation of width with discharge.

The Taylor situation is more complex as the data of the early regulated period segregate into two low-variation groups for the same range of flows, one for a 250 m wide channel, and one for a 400 m wide channel (Figure 5.7). The 250-m data derive from the period of reservoir filling (1968) and after 1990, apart from two 1986 data, while the 400-m data derive from the period 1972 to 1990. It appears that the 400-m relation is the representative one for the "early" period of regulated flows. It must be recognized that, to some degree, the apparent difference may have been induced by where the hydrometric technicians chose to make their boat-borne measurements of the river. At Dunvegan, on the other hand, the excursion in sensitivity of the width relation appears to have been real.

Depth variation is more nuanced. At the upstream, gravel-bed stations, depth variation in the natural regime exhibited exponents in the range 0.41 to 0.56, the relatively high sensitivity corresponding with low

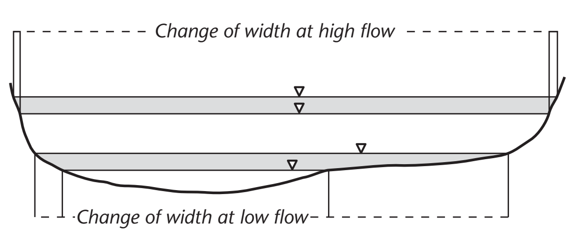

Figure 5.17 Sketch of width variation with stage at low and at high flow.

width sensitivity and implying flow within an approximately rectangular channel (Figure 5.17). With regulation, the exponents appear to have dropped to near 0.24, all data considered. The appearance is deceptive. For the dominant 400 m channel at Taylor, the exponent rose to 0.57. At Dunvegan Bridge, the drop appears to have been real but, after 1996, the channel had changed to yield a sensitive relation ($f = 0.51$) again. This result corresponds with the observed change in the width relation and is a plausible result of sedimentation in the gauge reach derived from the tributary Hines Creek. The gauge at Alces River, located between the two long-term sites, has exhibited relatively high sensitivity of depth since the inception of gauging in 1990. This station has high banks on either side of a broadly flat-bottomed channel. The downstream, sand-bed stations have presented more stable but quite distinct relations, with the Carcajou station exhibiting two regimes of depth variation corresponding with the two regimes of width variation.

Velocity variation with flow appears to fall into two groups. High variation (exponent $m \sim 0.6$ is observed at Taylor and Fort Vermilion, while lower (but still substantial) variation ($m \sim 0.4$ to 0.5) is observed at Alces (regulated flow only), Dunvegan Bridge, and Carcajou (natural flow only). Peace Point exhibits $m \sim 0.5$. At Dunvegan Bridge, the exponent increased in the early period of regulation, corresponding with the variation in the other exponents. At Taylor and Fort Vermilion, velocity absorbs a higher proportion of the variation in hydraulic geometry than does depth ($m > f$), whereas the reverse is the case at the other stations, except periodically at Dunvegan Bridge (1968 to 1996) and Peace Point (after 1996). The pattern for greater sensitivity of velocity than of depth is unusual and remarkable in that it is observed in both gravel- and sand-bed reaches along the river and both before and after regulation. The phenomenon previously has chiefly been observed in small and steep channels (see a data summary in Baki *et al.* (2012), Table 3). It implies a sharp decrease in resistance to flow as stage increases.

The variation in coefficients of the hydraulic geometry generally follows reciprocally the variation in exponents; that is, high exponents correspond with low coefficients. That is because, in all cases, flow values are much greater than one cumec so that, in effect, a higher exponent induces a rotation of the trend line about a mean value that has the effect of decreasing the coefficient in the relation. There is little independent information here. Somewhat surprisingly, there is no obvious correlation between at-a-station geometry and river boundary material properties. Gauging sites are deliberately chosen to be relatively simple and stable sections on the river (the three upstream gauge sites are also bridge sites, and Fort Vermilion is very close to a bridge); hence special properties of bed and banks may locally affect the observed geometry.

Taken overall, the pre- to post-regulation changes in open-water hydraulic geometry are not radical, as can best be seen graphically (Figures 5.5 through Figure 5.16). The largest changes occurred at Taylor, the station nearest the dams, but that probably has more to do with the effect of sedimentation from the nearby Pine River tributary than from proximity to the dams. There is some evidence that reduced flows after 1967 produced changes associated with the reduced cross-section that were beginning to be compensated after 1996 by a trend back toward the original channel form, which must be accomplished through dynamic changes in channel form.

5.5 Downstream hydraulic geometry

5.5.1 Formative flows

Rivers do the work of moving the sediments that form their bed and banks and consequently modifying their morphology over a range of flows. To index the conditions under which such modifications occur, geomorphologists have argued that most work is accomplished under some relatively frequently recurring competent flow. Mean annual flood has been proposed to be that flow (Wolman and Miller, 1960). Alternately, bankfull has been forwarded as the most relevant index since that flow brings large sediment-mobilizing stresses to bear on the channel boundaries that do not much increase beyond bankfull as additional water spills out of the confines of the channel. Bankfull has been shown to have a wide range of recurrence intervals in different rivers (Williams, 1978), so no simple correspondence occurs between these two concepts. A more rational approach to setting an index flow for channel modification would be to define that flow which, if sustained for some time, would move the same mass of bed-material sediments *of the same texture* as is actually moved by the varying flows in the river (Ferguson and Church, 2009). The specification of sediment texture jointly constrains the

Table 5.3 Estimated formative flows in Peace River

Station	Equation		Flow at return period			1990		1996		Record length (years)
	Q^b	R^2	2.33 years	10.0 years	100 years[a]	Flow[b]	r^b	Flow[b]	r^b	
Taylor										
Natural flow	$6060r^{0.20}$	0.94	7180	9600	15 200					23
Regulated[c]	$2300r^{0.25}$	0.98	2850	4100	7290	5190	26	6220	53	40
Alces										
Regulated	$2290r^{0.33}$	0.92	3020	4890	10 450	n.a.		7240	33	18
Dunvegan Bridge										
Natural flow	$6610r^{0.24}$	0.92	8100	11 490	19 960					8
Regulated[c]	$2500r^{0.32}$	0.98	3280	5220	10 900	7 600	32	7300	29	38
Carcajou										
Natural flow	$7550r^{0.25}$	0.85	9330	13 430	23 880					8
Fort Vermilion										
Natural flow	$7850r^{0.20}$	0.84	9300	12 450	19 720					13
Regulated[c]	$3540r^{0.34}$	0.91	4710	7740	16 920	n.a.	n.a.			15
Peace Point										
Natural flow	$8350r^{0.17}$	0.69	9650	12 350	18 270					9
Regulated[c]	$4200r^{0.32}$	0.96	5510	8780	18 340	12 600	31	9760	14	41

[a]Extrapolated figures.

[b]r = return period, in years; flow is given in m^3s^{-1}. All flows are rounded off to nearest 10 m^3s^{-1}.

[c]Excludes 1972 and 1996 reservoir spill floods.

magnitude and duration of the index flow. Unfortunately, we do not have information of bed-material movement in Peace River, so we must fall back on the cruder indices, amongst which, an index based on flow recurrence is most convenient both for computation and for comparison between natural and regulated flows.

Flow recurrence has customarily been based on the annual flood series. However, the partial duration series provides a more faithful reflection of the recurrence of competent flows in a river and is well represented as a power sequence (Malamud and Turcotte, 2003, 2006). Accordingly, partial duration sequences have been formed for Peace River gauges for the periods of natural flow and regulated flow in which *n*, the number of flows, is equal to the number of years of record. Results are given in Table 5.3 for flows with recurrence 2.33 years and 10 years. The notable flows of 1990 and 1996 are also reported for the stations where they were recorded. (The flows reported here are different than flood flows with putatively the same return period based on the conventional annual flood sequences reported in Chapters 2 and 6.)

It is interesting to note that, in the upper river—the gravel-bed reach—the 2.33-year flow in the natural regime is greater than the largest flow experienced since regulation and, in fact, comparable with the estimated 100-year regulated flow. At Peace Point, the only available comparison in the lower river, the pre-flood 2.33-year flow is comparable with the 1996 flow but smaller than the 1990 flood of record. The upper river, then, appears unlikely, in the regulated regime, to experience flows of the magnitude that may have determined the form of the pre-regulation channel, but the lower river—below the Smoky confluence—may still be subject to such flows, albeit at considerably reduced frequency.

5.5.2 Downstream changes

The downstream hydraulic geometry of Peace River broadly conforms with the expectation based on a mass plot of Alberta rivers (Figure 5.18). In Figures 5.18 and 5.19, regime dimensions are calculated for the flow with 2.33-year recurrence in the partial duration sequence using the at-a-station relations for the natural flow

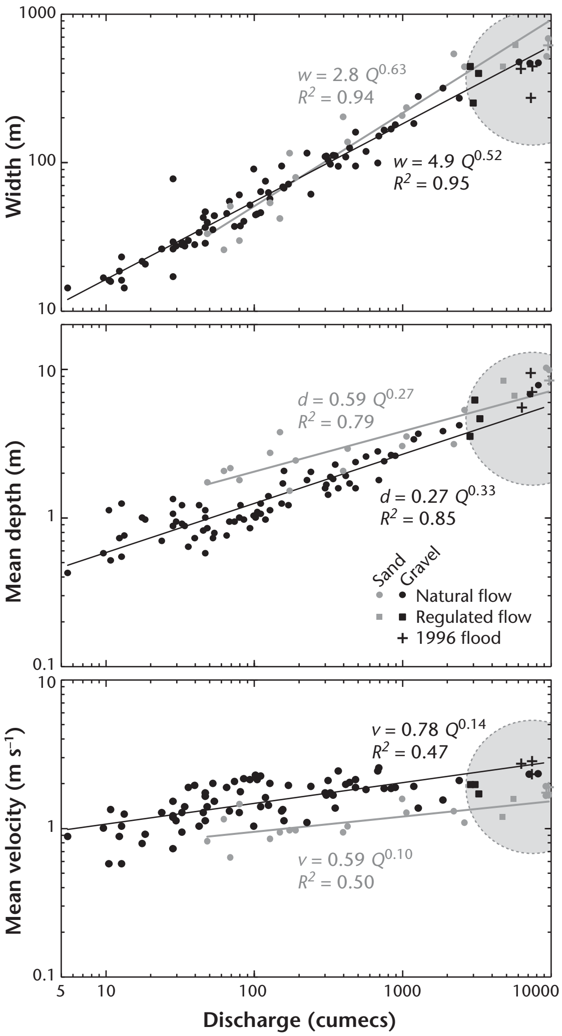

Figure 5.18 The hydraulic geometry of Albertan rivers (After Bray (1973) and Neill (1973)) showing Peace River data, which are inside the shaded circle. See text for details of the derivation of the Peace River data.

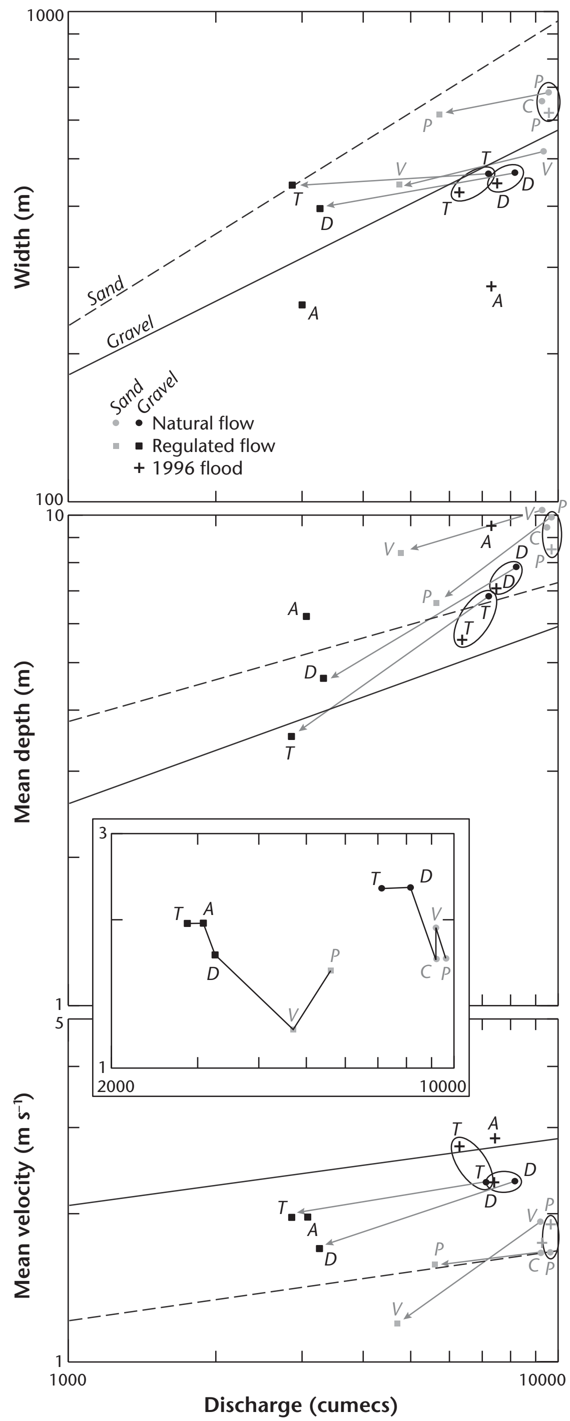

Figure 5.19 Changes in downstream hydraulic geometry of Peace River after regulation: lines are hydraulic geometry relations for Alberta Rivers (as in Figure 5.18). Arrows display the shift from natural regime to the regulated regime. See text for details of the derivation of the displayed data. The circles associate points representing natural flow and the 1996 flood flow at each station. *T*, Taylor; *A*, Alces; *D*, Dunvegan Bridge; *C*, Carcajou; *V*, Fort Vermilion; *P*, Peace Point. The inset shows the pattern of change in velocity downstream, before and after regulation.

regime, the $w = 400$ m relations at Taylor for regulated flow and the 1996 to 2010 relations for the other stations. Data vary about the mean relations, but by no more than might be expected from the overall scatter of data. Much of the overall variability seen in Figure 5.18 is induced by the indiscriminate plotting of data from rivers with varying bank conditions—only "sand" and "gravel" bed conditions are discriminated.

Following regulation, we expect the channels to change along a trajectory parallel to the appropriate regime relation. Figure 5.19 demonstrates that this has not happened. Channel width has varied relatively little so that the locus of change is almost flat in the downstream plot. This is consistent with the insensitivity of the at-a-station relations for width. On the other hand, depth has decreased more drastically than the regime relation would suggest, while changes in velocity more or less follow the expected trajectory. Noting that velocity is expected to be the least variable quantity in downstream relations, these observations suggest that, to this point, the reduced flows have been accommodated mainly by a change in flow depths along the length of the river, a passive outcome.

Fort Vermilion is an exception. Here depth has changed approximately as expected and velocity has been greatly reduced. This outcome may be conditioned by a change in sand transport and an adjustment of sand dune dimensions, which are known to be present in the Fort Vermilion reach (McLean and Anderson, 1980), hence, a significant change in flow resistance.

The actual downstream hydraulic geometry of the river does not present a coherent picture. We have two (three after regulation) stations in the gravel-bed reach and three (two after regulation) in the sand-bed reach. Of these, the channels at Dunvegan Bridge (gravel) and Fort Vermilion (sand) are essentially confined, while the station at Peace Point has notably finer bank sediments. These circumstances underlie the variability seen in the regional relations, but constitute too few stations to extract meaningful relations for the single river.

One result is generally consistent, however: velocity decreases downstream (Figure 5.19, inset). This is, at least in part, a reflection of the gravel-to-sand transition. However, it also suggests that gradient, essentially imposed by regional geology and the partially confined nature of the channel, exercises an important independent control over the hydraulic geometry of the river.

5.6 Resistance to flow

Despite more than two centuries of study, there is no universal, theoretically-based formulation of the resistance to flow in an open channel. A part of the reason is the multiple and irregularly varying sources of resistance, from grain-scale roughness at the bed, through bedforms and bars, to the shape and curvature of the channel itself. The classical equations all contain an empirically evaluated "resistance coefficient" that is meant to subsume the sum of sources of flow resistance.

Changes in flow resistance at Peace River gauging stations can be indexed using the classical Manning equation, $n = R^{2/3}S^{1/2}/v$, in which n is the Manning flow resistance coefficient. To assess n, hydraulic mean flow depth, $d = A/w$, is used as a satisfactory approximation of hydraulic radius, R. In the limit that only grain resistance is present, n is approximated for gravels by the Strickler equation as $n = 0.047D_{50}{}^{1/6}$, in which D_{50} is the median diameter of bed-surface material. These equations are used to construct the patterns of variation with flow of n at the gauging stations along Peace River, for various epochs and conditions. The results portrayed in Figure 5.20 are only approximate, for they are based on a fixed value of S for each station (surveyed and reported by Kellerhals *et al.* [(1972), and recorded in Table 5.4), and for a fixed value of bed grain size (also reported by Kellerhals *et al.*, Table 5.4). Further, the Strickler equation is not intended for use with sand-size sediments, but is applied here for want of another means of estimation. In fact, the pervasive presence of sand waves on sandy beds probably raises the actual limit value of n in sands.

Two patterns of variation stand out. In one, n declines from relatively high values (0.06 to 0.08) at low flows to become asymptotic to the grain-dictated lower limit at high flows—generally, flows >4000 m^3s^{-1}, which are still experienced in the regulated regime. Taylor (gravel-bed reach) and Fort Vermilion (sand-bed reach) demonstrate this pattern, and there is a hint of it at Alces River. The second pattern is for a consistent value of n, either at the grain limit (Dunvegan Bridge, for the most part; Carcajou) or slightly above the grain limit (Peace Point). This pattern implies fixed and persistent sources of flow resistance, whereas the former implies steady erosion or drowning of low-flow form resistance as flows increase. It is notable also that the limit value of n in the sand-bed reaches is indeed higher than the value estimated from grain size.

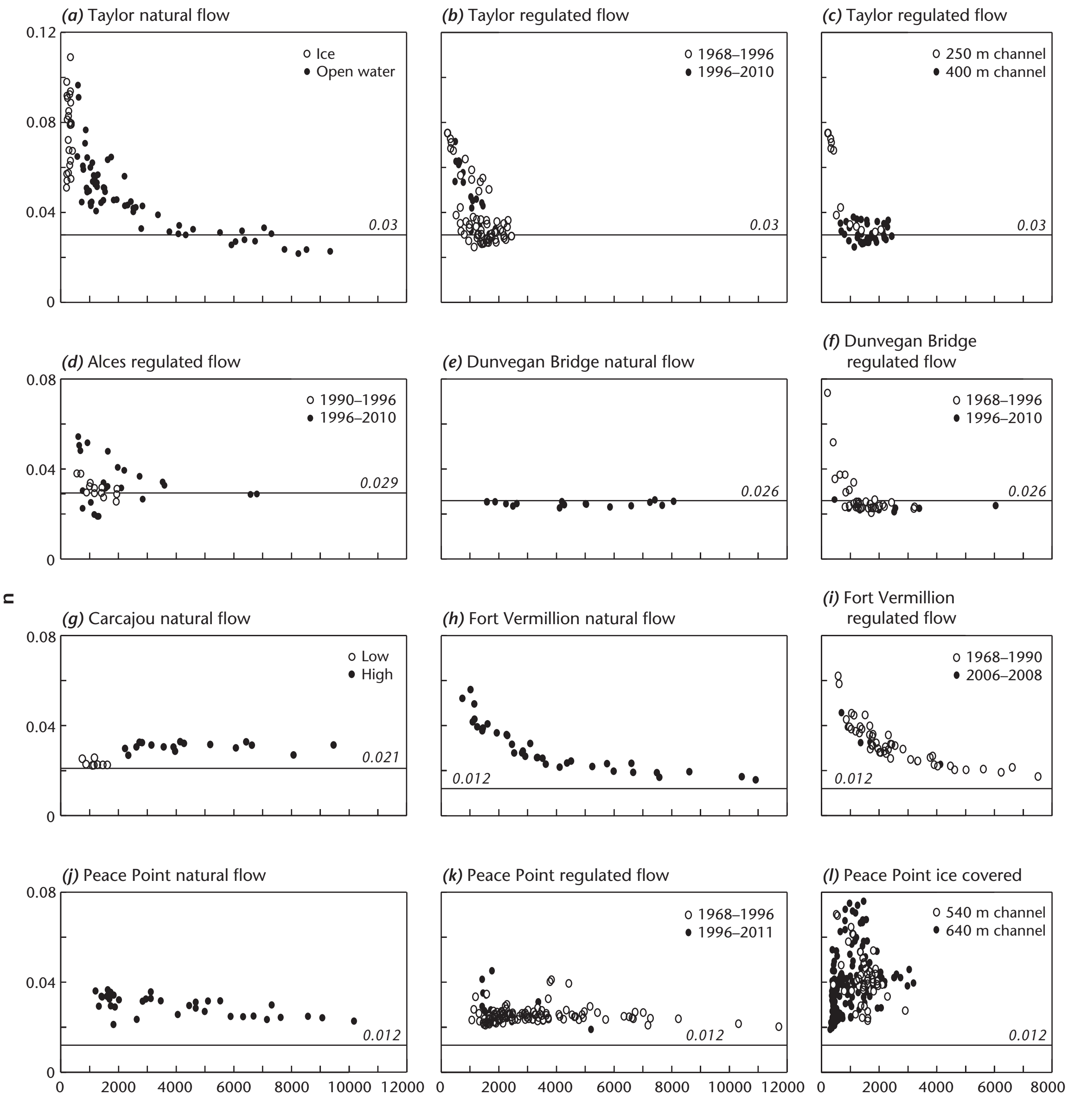

Figure 5.20 Pattern of variation of Manning's *n* at gauging stations on Peace River. In each panel, the annotated horizontal line indicates the lower limit dictated by grain size using Strickler's relation.

At Taylor, the transient form resistance probably is bar resistance presented by the medial bar in the gauge section, while at Fort Vermilion it is likely to be transient bedforms. Dunes are known to form on the bed (McLean and Anderson, 1980). Those observers estimated that, at high flows, resistance to flow was partitioned approximately evenly between bedforms and grain resistance while, at lower flows, bedform resistance was dominant. At Peace Point, channel sinuosity provides an enduring measure of form resistance.

Table 5.4 Critical index values for flow resistance and for braided versus meandered channel

			2.3-year flow					10-year flow				
Station	S	D_{50}	Q	w/d^a	$Q^{0.4}/d^b$	S_{crit}	F/S^c	Q	w/d^a	$Q^{0.4}/d^b$	S_{crit}	F/S^c
Natural flow												
Taylor	0.00069	0.064	7180	66	5.1	0.00083	405	9600	60	5.1	0.00074	450
Dunvegan Bridge	0.00022	0.053	8100	57	5.4	*0.00018*	1187	11 490	48	4.3	*0.00015*	1264
Carcajou	0.000074	0.007	9330	70	4.2	*0.000069*	2261	13 430	57	3.9	*0.000037*	2286
Fort Vermilion	0.000041	0.00026	9300	51	3.8		3663	12 450	48	4.0		4079
Peace Point	0.000074	0.00022	9700	65	4.0		2190	12 550	58	3.9		2320
Regulated												
Taylor	0.00069	0.064	2850	*121*	6.9	0.0012	495	4100	97	6.33	0.0011	507
Alces River	0.00034	0.032	3020	40	4.0	0.0019	760	4890	34	3.9	0.00075	846
Dunvegan Bridge	0.00022	0.053	3280	86	5.4	*0.00016*	1137	5220	72	5.2	*0.00022*	1254
Fort Vermilion	0.000041	0.00026	4710	54	3.5		2545	7740	46	3.6		3213
Peace Point	0.000074	0.00022	5510	90	4.7		2330	8780	74	4.6		2712

Surveyed slope data and D_{50} values from Kellerhals *et al.* (1972).

[a]Critical value is 110 (Xu, 2004) or 50 (Fredsoe, 1978). Critical values (italic) follow Xu's value.

[b]Critical value is 6.4.

[c]*w/d* must exceed this value for the braided state.

Ferguson (2007) collated flow resistance formulations for shallow and deep flows in channels with low form resistance and proposed a hybrid "variable power equation" that subsumes all flows and appears to be robust. He also reviewed a history of representation of flow resistance in the form of hydraulic geometry equations. This approach makes sense because, ultimately, the velocity of flow and the wetted dimensions of the channel are determined by the balance of the forces driving and resisting the flow, the condition formulated in a flow resistance equation. For "deep" channels ($d/D > 10$), the end-member form of Ferguson's equation, expressed in hydraulic geometry terms, can be represented as

$$v^* = a^{0.6} q^{*0.4} S^{0.3}, \tag{5.1}$$

which is cast in nondimensional form using the scaled velocity $v^* = v/(gD_{84})^{1/2}$ and discharge $q^* = q/(gD_{84}^3)^{1/2}$. This result is equivalent to the classical Manning–Strickler equation (which combines the Manning and Strickler equations), signifying the dominance of grain resistance, and can be developed directly from that equation. Ferguson (2013) has shown that sand-bed channels conform to a similar equation and Rickenmann and Recking (2011) found that redefinition of $v^* = v/(gSD_{84})^{1/2}$ and $q^* = q/(gSD_{84}^3)^{1/2}$ effected a general collapse of data.

The data of hydraulic geometry introduced in the preceding section are used to calculate v^* and q^* and to compare the results with the general collapse achieved by the results of Ferguson and of Rickenmann and Recking. River gradients surveyed at gauge points (Kellerhals *et al.*, 1972) are once more adopted. Since the surveys were done at the inception of regulation, contemporary gradients may have changed by a few percent. Only the Taylor gauge section shows evidence of substantial morphological change since regulation: It has become less steep immediately upstream and steeper immediately downstream. Sediment texture at the gauge sites is also adopted from Kellerhals *et al.*

Figure 5.21 demonstrates the general conformity of the gravel reach data of Alces and Dunvegan Bridge—stations that exhibit no trend in values of n—with the general relation. The results are notably consistent through the variations in flow regime that have occurred, including changes in the conventional hydraulic geometry. Taylor data and Fort Vermilion data depart on the side of low velocities and show a definite oblique trend, presumably because of significant form resistance that becomes drowned or attenuated at high

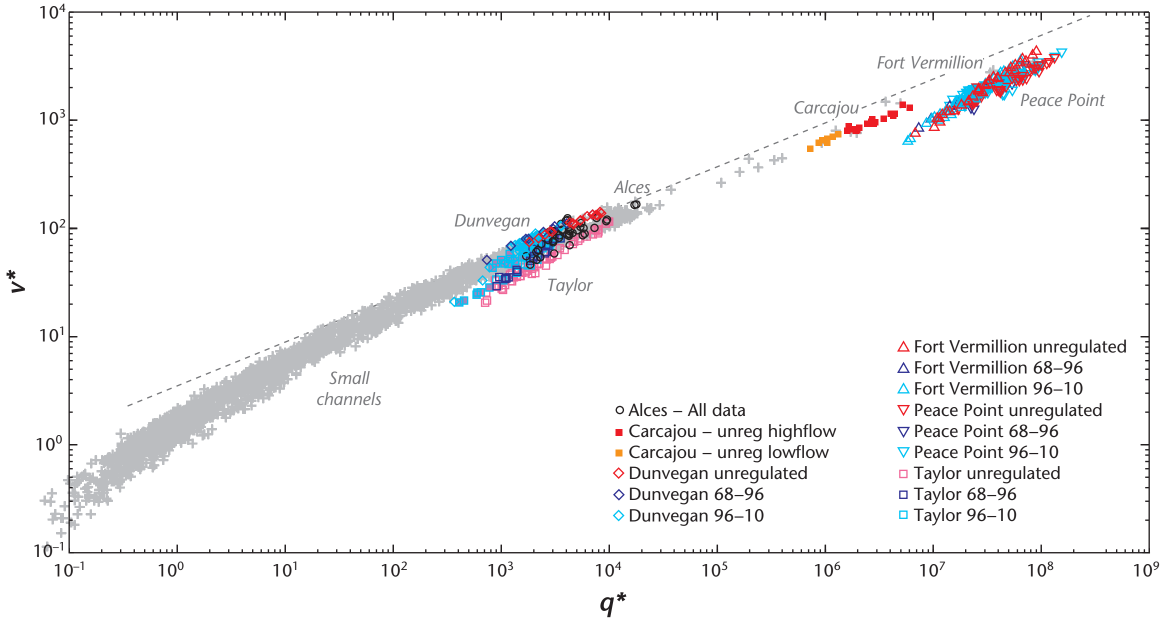

Figure 5.21 Dimensionless hydraulic geometry to demonstrate the coherence of flow resistance along Peace River. Range of data plotted by Rickenmann and Recking (2011) is shown as gray spots; Peace River stations are individually distinguished for individual periods before and after regulation. The dashed line is Ferguson's deepwater limit equation, based on the Manning–Strickler relation.

flows. Data of Carcajou and Peace Point also plot low but parallel with the limit trend, presumably indicating persistent, significant form resistance in these reaches, including sand dunes and significant channel curvature at Carcajou.

Those stations exhibiting trends in flow resistance that converge toward the general relation are those that exhibit unusual sectional hydraulic geometry ($m > f$), with values $1.3 < m/f \leq 3.0$ (velocity increases more rapidly than depth with increasing flow). Peace Point has lower values, varying from 0.64 to 1.3. In contrast, stations with trends parallel to the general relation show the more usual range $0.65 \leq m/f < 1.0$. Dunvegan Bridge provides an interesting history in that values of m/f there jumped from 0.68 before regulation to 2.3, and then returned to 0.73 after the 1996 high flow. At the same time, the behavior on n shifted from consistent limit values to one of n varying with flow (Figure 5.20e,f). A reasonable interpretation of these appearances is that those stations exhibiting high ratios of m/f are subject to significant form resistance in the low flow channel, probably in the form of bar features as is clearly evident at Taylor. At higher flow these features are drowned, leading to the rapid increase in velocity and closer approach to the grain resistance limit. For strict conformity with the Manning–Strickler relation, and at constant gradient and grain size, $m/f \equiv 0.60$. It is probable that, as bedform resistance is overcome, gradient changes as well. At Dunvegan Bridge it appears that form resistance in the low flow channel following regulation was reduced in effect by channel changes (Figure 5.11) that eventually produced a narrower, deeper channel.

The deep water arm of Ferguson's variable power flow resistance equation, appears to be suitable, then, for estimating mean velocity or geometry in (frequently occurring) simple sections at high flows in the gravel-bed reach of Peace River. Exception must be recognized for multi-thread and sharply curved reaches, such as the British Columbia reach downstream from Taylor, or the Alberta reach downstream from TPR. The equation is convenient because slope, which must be known, is the least temporally variable of the geometrical quantities associated with channel form, nor are wholesale adjustments of grain size quickly achieved except in the case of sand advected into a gravel reach. The sand-bed reach may be more difficult to predict, in general, because of the pervasive occurrence of additional sources of flow resistance in the form of bedforms and channel deformation.

5.7 Some tests for channel pattern

River channel pattern is an aspect of an extended concept of hydraulic geometry that is rarely considered as such. Peace River presents a wandering channel aspect in much of the British Columbia reach, with channel islands more prominent than transient bars. The channel pattern could be qualified as a low-order anabranched pattern (Type 5 channels in the anabranched channel typology of Nanson and Knighton (1996)). Downstream, the river is largely confined to a single thread in Alberta Reach 1, but "crescent" islands are common in channel bends in Alberta Reaches 2 and 3, becoming quite broad in Reach 3. The upper part of Reach 4 shares the anastomosed aspect of the BC reach while the lower part is highly sinuous with one prominent subreach divided into two meandered channels. How well do the available criteria for channel pattern predict these characters?

Studies of channel patterns (Mollard, 1973; Schumm, 1985) imply that the pattern is influenced by discharge, bed material sediment load and calibre, and by river gradient. Discharge and sediment load jointly determine sediment concentration or transport intensity necessary to continue to pass the load. Discharge and topographic gradient determine the stream power available to transport the load. Critically, sediment calibre influences not only the competence of the stream to move the sediment, but also indexes bank strength in alluvial channels, which has a major influence over channel shape, hence flow depth and velocity, and the shear force that can be brought to bear on the bed sediments to move them. If bank strength is sufficiently low (as in noncohesive gravels) the channel may become relatively wide and shallow, shear forces become low, bed material cannot be transported, and the channel splits about bar deposits and takes on a multichannel aspect. Individual channel threads are narrower and relatively deep, hence, are able to transport the load that cannot be passed through a single wide and shallow channel.

Most criteria for channel pattern make a simple distinction between classically defined single-thread and braided channels and most focus on some aspect of channel shape and its relation to discharge or to channel gradient. Only rarely has the critical factor of bank strength been directly studied. Xu (2004) investigated a range of simple, mainly geometric, indices using a large sample of rivers (150 to 196), both meandered and braided, and flowing in sand or gravel. Amongst a range of simple criteria he found that relations between depth and bankfull discharge, width/depth ratio and discharge, and stream power and bed material size provided the best discrimination. Each of these criteria misclassified less than 10% of his sample. Remarkably, a fixed value of width/depth ratio, $w/d = 110$ misclassified only 8.7% of the sample. Fredsoe (1978), in an early stability analysis of alluvial channels, had found a result that suggested a discriminant value of about 50 (pointed out by Millar (2012)). Similarly, Eaton *et al.* (2010) found a simple discriminating value of 60.

Another of Xu's effective discriminators is

$$d = 0.156Q_{bf}^{0.4},$$

which is equivalent to $Q^{0.4}/d = 6.41$.

More nearly physically based criteria have been suggested, beginning with the early proposal by Parker (1976) that braided and meandered channels are discriminated by the criterion

$$w/d = F/S$$

in which F is the Froude number. Recently, Millar (2012) has proposed a formula based in rational regime theory:

$$w/d = 155Q^{*0.53}S^{1.23}\mu^{-1.74}$$

in which $Q^* = Q/D_{50}{}^2\sqrt{(gD_{50}(s-1))}$ is the nondimensioned discharge and μ is the relative strength of the channel bank versus the bed. Assuming that $\mu = 1$ (i.e., banks are loose, non-cohesive gravel) and adopting Fredsoe's value for the limit w/d, Millar found that the critical value of gradient, $S_{\text{crit}} = 0.40Q^{*-0.43}$. If Xu's critical value be adopted, the coefficient becomes 0.76. Either way, the criterion is ultimately empirical. It is interesting, however, that, apart from a difference in coefficient value that appears to depend on the data set used to determine the critical ratio w/d, and which in turn depends on one's definition of what constitutes a braided or a meandered stream, the criterion is very similar to pioneering discriminant criteria presented by Leopold and Wolman (1957) and by Henderson (1963).

Here the simple geometrical criteria of Xu, and the criteria of Parker and Millar are tested against data of the Peace River gauging stations. The bankfull flow is not used since there is substantial evidence for ice effects influencing the overall channel shape (Uunila and Church, Chapter 6). Instead, channel geometry is computed from the at-a-station hydraulic geometries for the 2.3- and 10-year recurring floods in the partial duration sequence for both unregulated and regulated flow. We use two flows because it appears that—especially in the regulated regime—a flow with return period longer than the frequently quoted two-year level may be the more effective flow in determining channel form. Even at 10 years, flows are only marginally competent in the upper river. The equations used were those selected to compute values to study the downstream hydraulic geometry. Pertinent results are given in Table 5.4. Once again, river gradients and grain size surveyed at the gauge points by Kellerhals *et al.* (1972) are adopted.

The empirical indices of Xu (2004), which are based purely on channel geometry and flow, indicate that the river should have a single-thread habit, except that the Taylor gauge is indicated to have become marginally braided ($w/d = 121$; $Q^{0.4}/d = 6.33$) at the two-year flow level after regulation; at the 10-year flow, the river is indicated to be marginally single-thread. In fact, in substantial reaches both upstream and downstream from Taylor the river exhibits a wandering habit, with channel islands more prominent than transient bars.

Millar's (2012) critical gradient criterion, which incorporates a bed grain size, indicates that the river at Dunvegan Bridge and Carcajou should be braided. The D_{50} grain size at Dunvegan Bridge is based on a field sample taken nearby but, at 16 mm, appears to be anomalously small for this location along the river. Interpolating a value of 32 mm from the longitudinal trend of grain size, Dunvegan is no longer indicated to be braided, though it is on the margin (S_{crit} = 0.00032, the actual river gradient) for the two-year flow in the natural regime. In fact, the river is confined, but at nearby locations (Many Islands; Montagneuse River) where there is lateral room, the river does divide about channel bars and islands. Miller's criterion was computed for gravel-bed rivers; hence, it is not clear that it should apply at the distal stations, including Carcajou. But it is also based on Fredsoe's (1978) low value for critical channel aspect ratio, which was derived on the basis of sand-bed channels, some of them experimental stream tray results. Substituting Xu's value (110), based on extensive field data and seemingly more appropriate, yields critical gradients that indicate a single-thread condition, though again on the margin at Dunvegan Bridge for the two-year flow in the regulated regime. None of the values returned by Parker's (1976) index is anywhere near critical: according to this criterion, the river should be single-thread.

The river in the natural regime exhibited a wandering habit in the British Columbia reach and in part of Alberta Reach 4 (Peace–Athabasca Lowland), and has frequent "crescent islands" in channel bends through Alberta Reaches 2 and 3. This wandering style has been shown by Millar (2012) and others to straddle the boundary of most criteria for discriminating multiple-thread from single-thread channels; hence, it is perhaps not surprising that some ambiguous results are returned from the present exercise. What is more interesting is that, except at Taylor, the indices do not change much from the natural to the regulated state, suggesting—insofar as the indices have validity—that the regulation has not severely perturbed the channel planform habit. It is also interesting that, if (as is likely) a flow nearer 10-year recurrence or higher, is the effective channel-forming flow, the river should more robustly maintain single-thread status than if a more frequently recurring flow dominates. This will certainly be the case in the upper river, where the two-year flow is not competent, in the regulated regime, to move the bed material.

5.8 Discussion

The at-a-station hydraulic geometries indicate modest variations since regulation, with flow variations being taken up mainly by velocity and depth variations, consistent with flow within a more or less rectangular channel. Width has become more variable since regulation at some stations as flows have declined into the nearly flat bottom of the pre-regulation channel. At Taylor and Fort Vermilion, velocity variations are particularly important. In the former case, the complex channel bottom created by the deposition in the section of a substantial medial bar composed of gravel delivered by Pine River is probably an important factor affecting resistance to flow. At higher flows, this feature is progressively drowned. At Fort Vermilion, the evolution with the flow of a dune bed is a possible source of the high variability of velocity.

The overall picture from the downstream hydraulic geometry suggests that the channel has not established a new equilibrium with the current, regulated flow regime. Church (1995) produced predictions for the ultimate equilibrium geometry of the channel at each of the gauge points on the basis of the Alberta hydraulic geometry relations displayed in Figure 5.18, assuming that stations would not experience a change in regime type (i.e, gravel-bed reaches will continue to be gravel-bedded, and similarly for sand-bed reaches). The relations reduce to

$$w_r/w_n = (Q_r/Q_n)^b$$

and, similarly, for depth and velocity. A similar exercise is presented in Table 5.5, based on the estimated 2.33-year flow in the partial duration sequence and the actual at-a-station hydraulic geometry of each station (hence the results vary from the earlier presentation). We observe that the contraction in river width has been less than expected ($w/w_r > 1.0$) from the empirical relations of hydraulic geometry everywhere along the river. Depth, on the other hand, has contracted by more than the expected amount everywhere except at Fort Vermilion. These results point again to a passive adaptation to the generally reduced flows in the channel. Consequently, the channel still possessed the capacity to pass the 1996 high flow which, at stations for which comparative data are available, was comparable with or smaller than the 2.33-year partial duration flow in the natural regime.

Width adjustment is more nearly complete (at the gauge sites, at least) as one moves downriver, but adjustments in the other quantities, depth and velocity, show no consistent pattern beyond the fact of uniformly lower than expected values, again excepting depth at Fort Vermilion. This is expected in view of the larger than expected width.

The results are not surprising given the limited competence of the river since regulation, nor is it surprising that the major adjustment in width is least realized in the upper river. Here, flows are more highly regulated and bed sediments are coarser, hence, more difficult to move. Only on a very small fraction of days since regulation has the river passed flows competent to move the bed material (Chapter 2). Farther downstream, sand is more readily moved and is contributed in abundance by Smoky River; hence, one expects adjustments to have proceeded farther toward completion.

Finally, we may remind ourselves that the expected change in riffle spacing along the river should correspond with that of width, in view of the commonly observed relation $\lambda \sim w$. Riffle spacing is accordingly expected to become shorter by values varying between approximately 0.6 (upper river) and 0.70 (distal reaches). This adjustment may be accompanied by

Table 5.5 Change in channel dimensions in Peace River predicted from empirical hydraulic geometry

Station	Q_r/Q_n	w_r/w_n	w/w_r	d_r/d_n	d/d_r	v_r/v_n	v/v_r
Gravel-bed reach							
Exponent		0.52		0.33		0.14	
Taylor	0.40	0.62	1.50	0.74	0.69	0.88	0.99
Dunvegan Bridge	0.40	0.62	1.42	0.74	0.80	0.88	0.84
Transition							
Exponent		0.63		0.27		0.10	
Carcajou	~0.50	0.65	–	0.83	–	0.93	–
Sand-bed reach							
Exponent		0.63		0.27		0.10	
Fort Vermilion	0.51	0.65	1.34	0.83	0.99	0.93	0.68
Peace Point	0.57	0.70	1.33	0.86	0.79	0.95	0.92

Subscripts "n" indicate natural flow condition; subscripts "r" indicate expected equilibrium regulated flow conditions; unsubscripted symbols indicate present channel dimensions. All dimensions calculated from at-a-station hydraulic geometry equations.

an increasing propensity to meander and a corresponding reduction in gradient. The latter, however, would be offset by increased gradient below prominent tributary junctions, where sediment is accumulating in the channel. Alternatively, additional riffles may form within the confines of the present channel configuration. There are, at present, no observations against which to compare these predictions.

A universal form of the flow resistance equation for channels lacking significant form resistance is approximately matched in the gravel-bed reaches of Peace River and, expressed in terms of hydraulic geometry, provides a general means to predict flow velocity, followed by aspects of channel geometry. At Taylor and Fort Vermilion there are systematic changes in the resistance coefficient with flow, while in the sand-bed reaches there are systematic departures in the direction of additional resistance to flow, probably mainly in consequence of the occurrence of systematic sinuosity and/or the presence of sandy bedforms. Flow resistance is not observed to have changed in a significant way from natural to regulated state (Figure 5.21), which is consistent with the appearance, from the indices of planform habit, that the regulation has not significantly altered the planform morphological tendency of the river. The only notable differentiation of unregulated/regulated data in Figure 5.21 is at Taylor, the single station on the river that gives some indication of a post-regulation tendency to change its habit. This outcome is no doubt conditioned by the growth of a significant medial bar through the gauging section, immediately downstream from the Pine River confluence. This has probably reduced the gradient in the approach to the gauge section, as well, a circumstance that would strengthen the indication for a multi-thread channel here.

5.9 Conclusions

At-a-station hydraulic geometry has been constructed at six stations along Peace River from gauging data. Periods of observation vary from 7 to 64 years and numbers of gaugings from 29 to 430 (of which 255 for ice conditions). There are significant differences in open-water geometry between the natural and regulated regimes at all stations, but these largely reflect the passive adjustment of flows so that post-regulation flows are more sensitive to width variations in the lower part of an essentially unchanged channel. Changes in the channel bed at Taylor and Fort Vermilion have produced variable adjustments between flow depth and velocity.

The downstream hydraulic geometry corresponds with regional relations for Alberta gravel-bed and sand-bed rivers. Accordingly, predictions may be made of the expected equilibrium adjustment to regulation at each station. These adjustments have not been completed, a consequence of the limited competence of the post-regulation channel and the slow progradation of riparian vegetation down river banks that are now customarily exposed. Ice may be a factor in this latter circumstance below Dunvegan (Chapter 6).

The actual downstream hydraulic geometry of the river is complex, the consequence of changing bed and bank materials, partial confinement and, in all likelihood, the special character of sites chosen for gauging. One unusual feature stands out, however, the consistent downstream decrease in velocity. This arises in part from the gravel–sand transition and, in part, from the independent control of gradient over the hydraulic character of the river. A universal formulation of flow resistance for channels dominated by grain resistance is shown to describe conditions in the gravel reach of Peace River at high flows reasonably well. Geometrical and semi-rational tests for river planform habit suggest that flow regulation has not created a strong tendency for the river to change habit, except perhaps at Taylor, where local effects associated with the Pine River confluence are important.

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References

Baki, A. B. M., Zhu, D. Z. and Courtice, G. (2012) Hydraulic geometry and resistance to flow in headwater streams in the Northwest Territories, Canada. *Canadian Journal of Civil Engineering*, 39, 1252–1263. doi:10.1139/12012-113

Blench, T. (1969) *Mobile-Bed Fluviology*, The University of Alberta Press, Edmonton, Canada.

Church, M. (1995) Geomorphic response to river flow regulation: case studies and time scales. *Regulated Rivers: Research and Management*, 11, 3–22.

Eaton, B. C., Church, M. and Millar, R. G. (2004) Rational regime model of alluvial channel morphology and response. *Earth Surface Processes and Landforms*, 29, 511–529. doi:10.1002/esp.1062

Eaton, B. C., Millar, R. G. and Davidson, S. (2010) Channel patterns: braided, anabranching, and single-thread. *Geomorphology*, 120, 353–364.

Ferguson, R. I. (1986a) Hydraulics and hydraulic geometry. *Progress in Physical Geography*, 10, 1–31.

Ferguson, R. I. (1986b) River loads underestimated by rating curves. *Water Resources Research*, 22, 74–76.

Ferguson, R. I. (2007) Flow resistance equations for gravel- and boulder-bed streams. *Water Resources Research* 43, W05427, 12 p. doi:10.1029/2006WR005422.

Ferguson, R. I. (2013) Reach-scale flow resistance [Chapter 9.5], in *Treatise on Geomorphology*, edited by J. F. Shroder. Vol. 9: Fluvial Geomorphology, edited by E. Wohl. Academic Press, San Diego, CA 50–68.

Ferguson, R. I. and Church, M. (2009) A critical perspective on 1-D modeling of river processes: gravel load and aggradation in lower Fraser River, *Water Resources Research*, 45, W11424, 15 p. doi:10.1029/2009WR007740

Fredsøe, J. (1978) Meandering and braiding of rivers. *Journal of Fluid Mechanics*, 84, 609–624.

Henderson, F. M. (1963) Stability of alluvial channels. *Transactions of the American Society of Civil Engineers*, 128, Part 1, 657–754 (with discussion).

Kellerhals, R., Neill, C. R., and Bray, D. I. (1972) Hydraulic and geomorphic characteristics of rivers in Alberta. *River Engineering and Surface Hydrology Report* 72-1, 48 p. Research Council of Alberta, Edmonton, Canada.

Lacey, G. (1930) Stable channels in alluvium. *Proceedings of the Institution of Civil Engineers*, 229, 259–384.

Lane, E. W. (1957) *A Study of the Shape of Channels Formed by Natural Streams Flowing in Erodible Material*. Sediment Series No. 9. United States Army Engineer Division, Missouri River Division.

Leliavsky, S. (1955) *An Introduction to Fluvial Hydraulics*. Constable, London.

Leopold, L. B. and Maddock, T. (1953) The hydraulic geometry of stream channels and some physiographic implications. *United States Geological Survey, Professional Paper*, 252. 57 p.

Leopold, L. B. and Wolman, M. G. (1957) River channel patterns: braiding, meandering and straight. *United States Geological Survey, Professional Paper*, 282-B. pp. 39–85.

Lindley, E. S. (1919) Regime canals. *Proceedings of the Punjab Engineering Congress* 7, 63–74.

Malamud, B. D. and Turcotte, D. L. (2003) Shelf record of climatic changes in flood magnitude and frequency, north-coastal California [Comment]. *Geology*, 31, p. 288. doi:10.1130/0091-7613(2003)031<0288:SROCCI>2.0.CO;2

Malamud, B. D. and Turcotte, D. L. (2006) The applicability of power-law frequency statistics to floods. *Journal of Hydrology*, 322, 168–180. doi:10.1016/j.jhydrol.2005.02.032

Mark, D. M. and Church, M. (1977) On the misuse of regression in Earth science. *Mathematical Geology*, 9, 63–75.

McLean, D. G. and Anderson, M. D. (1980) Hydraulic and morphological processes on the Peace River near Fort Vermilion. *Report*, SWE 80-2. Alberta Research Council, Transportation and Surface Water Engineering Department, Edmonton, Canada.

Miller, D. M. (1984) Reducing transformation bias in curve fitting. *The American Statistician*, 38, 124–126.

Millar, R. G. (2012) Morphodynamics of bars in gravel-bed rivers: coupling hydraulic geometry and analytical models, in *Gravel-Bed Rivers: Processes, Tools, Environments*, edited by M. Church, P. Biron, and A. G. Roy. John Wiley & Sons, Ltd, Chichester, UK. pp. 96–100.

Mollard, J. D. (1973) Air photo interpretation of fluvial features, in *Fluvial Processes and Sedimentation, Proceedings of the 9th Canadian Hydrology Symposium*, May 8–9, Edmonton, Canada. National Research Council of Canada, Ottawa, Canada. pp. 341–380.

Nanson, G. C. and Knighton, A D. (1996) Anabranching rivers: their cause, character and classification. *Earth Surface Processes and Landforms*, 21, 217–239.

Parker, G. (1976) On the cause and characteristic scales of meandering and braiding in rivers. *Journal of Fluid Mechanics*, 76, 457–478.

Rickenmann, D. and Recking, A. (2011) Evaluation of flow resistance in gravel-bed rivers through a large field data set. *Water Resources Research*, 47, W07538, 22 p. doi:10.1029/2010WR009793

Schumm, S. A. (1985) Patterns of alluvial rivers. *Annual Review of Earth and Planetary Sciences*, 13, 5–27.

Wolman, M. G. and Miller, J. P. (1960) Magnitude and frequency of forces in geomorphic processes. *Journal of Geology*, 68, 54–74.

Williams, G. P. (1978) Bankfull discharge of rivers. *Water Resources Research*, 14, 1141–1154. doi:10.1029/WR014i006p01141.

Xu, J. (2004) Comparison of hydraulic geometry between sand- and gravel-bed rivers in relation to channel pattern discrimination. *Earth Surface Processes and Landforms*, 29, 645–657.

CHAPTER 6

Ice on Peace River: effects on bank morphology and riparian vegetation

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6.1 Introduction

Peace River is a boreal river. In its natural (i.e., pre-regulation) regime it carried an ice cover for roughly four (upper river) to more than five (lower river) months of the year. Because it is a northward flowing river, ice forms earlier and remains longer as one proceeds downstream. Typically, freeze-up progresses upstream while breakup proceeds downstream. As a result, there is a high likelihood for floating ice to develop jams during both freeze-up and breakup periods. Ice jams, and the ice runs that occur when a jam breaks, create high water levels and may pile ice up to several meters above the water surface. On Peace River, ice-induced water stages may increase rapidly and may substantially exceed levels reached by open-water floods (Gerard and Karpuk, 1979; NRCC, 1989; Prowse, 1994).

Reviews on ice jams and ice-jam flooding in the Canadian context have been given by Beltaos (1995, 2008). High water and ice levels combined with high velocities in ice runs exert tremendous forces on the river bed and banks. These forces can be responsible for increased sediment mobilization (Beltaos, 1993; Milburn and Prowse, 2000), for bank scour, for the production of distinctive erosional and sedimentary features (Smith, 1980; Prowse, 2001), and for damage to or destruction of riparian vegetation (Mackay and MacKay, 1977; Koutaniemi, 1984; Uunila, 1997). Redirection of flow at ice jams can cause unusual erosion, both in magnitude and in location, and may lead to channel cutoffs or avulsions (Williams, 1973; MacKay *et al.*, 1974; Doyle, 1988), or scour holes, particularly at sites of repeated ice-jam formation (Melin, 1954; Mercer and Cooper, 1977).

Conversely, sedimentation associated with water levels induced by ice jams is a major factor in the construction of the floodplain (Eardley, 1938; Mackay, 1958) and in the exchange of nutrients between the channel and the floodplain (Scrimgeour *et al.*, 1994). Ice jams are also a major factor responsible for maintaining primary successional plant species along northern river margins. Ice-jam flooding and associated effects may in fact be essential to the integrity of some components of northern lotic systems, such as side channels with high entrances and delta lakes—as in the Peace–Athabasca Delta (Prowse and Lalonde, 1996).

Altogether, river environments that experience annual ice cover are adapted to and maintained by the ice regime, particularly through the effects of ice jamming and associated water levels during freeze-up and breakup. Knowledge of processes operating during the ice period, particularly during freeze-up and breakup, is essential to understand the river morphology and riparian vegetation dynamics on boreal rivers. The purpose of this paper is to characterize the effects of river ice, and especially of ice jams, on the morphology and riparian vegetation of Peace River, which has been regulated for hydroelectric power production at W.A.C. Bennett Dam since late 1967. Attention will be focused on the 800 km reach between the Peace Canyon Dam and Fort Vermilion, Alberta (Figure 6.1), with main attention directed to the Alberta Peace River, beginning 148 km below the dam since ice cover has become

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The Regulation of Peace River: A Case Study for River Management, First Edition. Michael Church.

Companion website: www.wiley.com/go/church/peaceriver

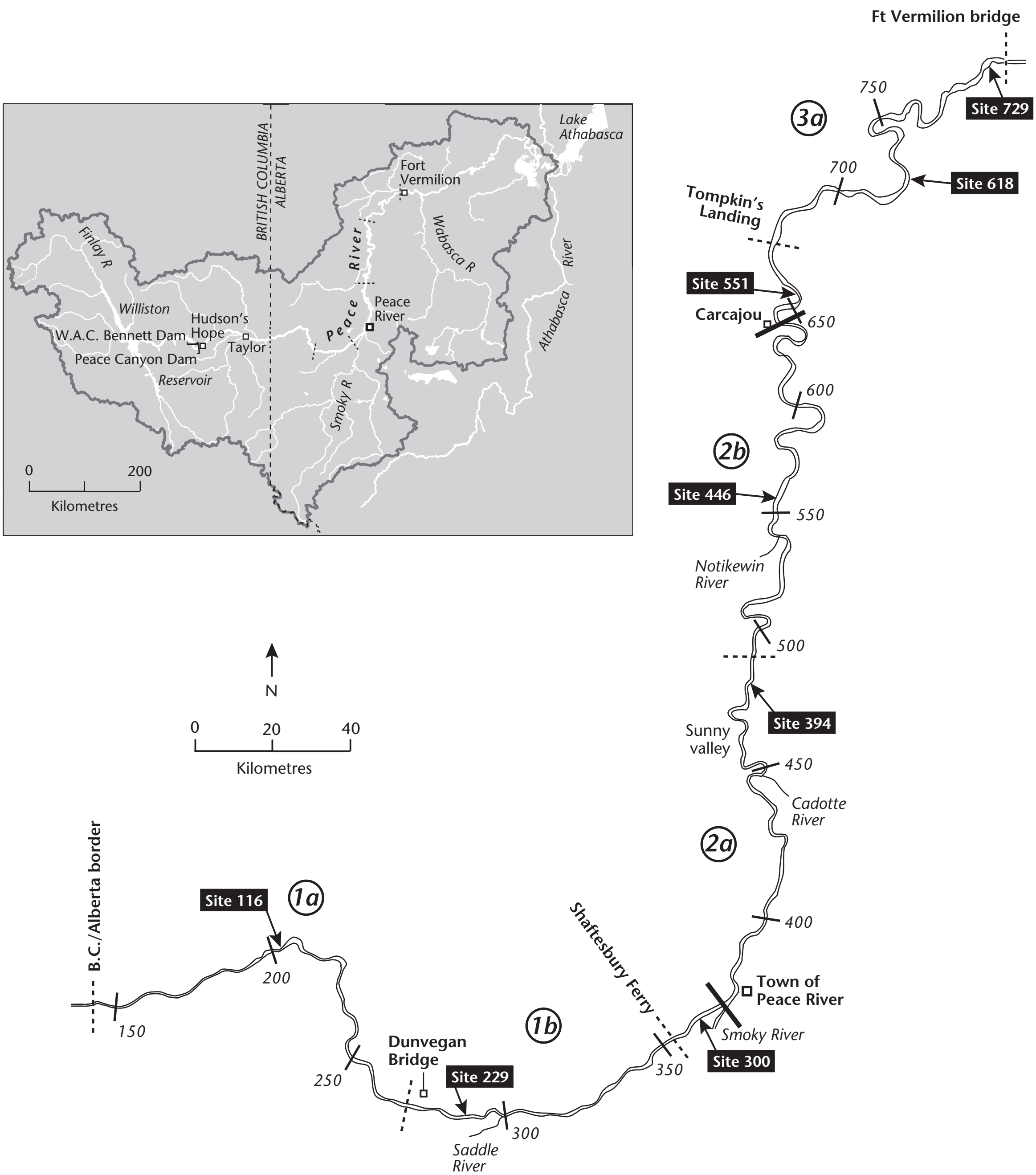


Figure 6.1 Map of Peace River in Alberta, showing the reaches established for analysis of the ice regime and the location of bank profiles illustrated in Figure 6.14 and data plotted in Figure 6.17. Numbers along the river are distance in kilometers below the Peace Canyon Dam. Bold lines mark the limits of the cobble-gravel and sandy gravel reaches. Inset: Peace River basin.

limited in the British Columbia reach. Shortly downstream of Fort Vermilion, the river flows over Vermilion Chutes and into the Peace–Athabasca Lowland and the Peace–Athabasca delta. The ice regime in these areas has been extensively studied (Prowse and Lalonde, 1996; Prowse and Conly, 1998; Beltaos *et al.*, 2006; Beltaos and Carter, 2009).

Ice-related processes, as well as the hydrological regime, are affected by flow regulation (Keenhan *et al.*, 1982; Beltaos, 1995). Since the regulation of Peace River, the magnitude of the mean annual flood has been reduced by 60% at Taylor, British Columbia, immediately downstream from the first large tributary confluence, and has been reduced by 42% at Peace Point, immediately upstream of the Peace–Athabasca delta. In contrast, winter flows have been increased by 500% immediately below the dams (averaging 1073 m^3s^{-1}) and by 300% at Peace Point (averaging 1082 m^3s^{-1}). Because reservoir releases are manipulated in response to hydroelectric power demands, which peak in winter, there is the potential to cause ice jams and associated effects by the imposition of sudden flow changes. Unfortunately, detailed observations of the ice regime on the river have been made only since 1972, when such effects began to be experienced, so that comparisons with the former natural ice regime are limited to inferences that can be made from surviving morphological evidence of the pre-1967 period and to partial records and anecdotal reports, almost entirely from the Town of Peace River (TPR) and from Fort Vermilion.

For this study, the river is divided into three reaches (Figure 6.1), the cobble-gravel upper river extending from the dams to the Smoky River confluence, immediately upstream of TPR; a sandy gravel reach extending downstream from there to the vicinity of Tompkins Landing; and a sand-bed reach beyond. While the bed and banks of the distal reach are primarily sand, one finds considerable gravel on the bed and lower banks in places. Some of it is ice-rafted from farther upstream but most of it is derived from erosion of glacial deposits along the valley side, which continues to partially confine the river in this reach. Although dispersive effects dampen the downstream character of varying reservoir releases, winter flows along the length of the river are relatively similar due to low tributary inflow. Nevertheless, ice effects are somewhat distinctive in each of the three reaches, partly because of the changing length and severity of the winter season, and partly because of the changing sedimentary morphology of the river. In the first 100 to 175 km below the dams there may be no ice formation at all, depending on the severity of the winter weather, because of the positive temperature of water released from the dams. An important change in the ice regime occurs at TPR, where Smoky River enters Peace River. Its early breakup and large flow have a significant effect on spring breakup phenomena at TPR and downstream.

Prior to this study, no systematic work had been carried out on the morphological effects of ice along Peace River. Elsewhere, distinctive boulder pavements were observed along the more northerly Mackenzie River (to which Peace River is tributary) by Kindle (1918), work followed up in the 1970s by Mackay and MacKay, 1977, who also described ice-push ridges, boulder ridges, and extensive vegetation damage. Similar observations were reported on Liard River (a Mackenzie River tributary north of Peace River) by Parker and Josza (1973). Early observations were made along Yukon River in Alaska (Wentworth, 1932) while there is a long history of reports from Siberian rivers (see Hamelin, 1972). In some of these studies, permafrost in the river banks is a significant factor not present on Peace River. Ettema (2002) has given a general review of the effects of river ice in alluvial channels with substantial emphasis on transient hydraulic effects.

In the absence of documentation of effects along Peace River, the principal objectives of this study are:

i. to map the incidence and severity of ice jamming along Peace River by recording the position and elevation of ice-scarred trees and other indicators of high ice-jam stages along the river, and by dating the events by dendrochronology;

ii. to document the morphological and sedimentary features related to river ice along the channel margins and to determine whether they have any overall effect on river hydraulics and channel-scale morphology.

iii. to characterize the response of riparian vegetation to ice jams on Peace River; in particular, to characterize the influence of ice jams in modifying successional trends in the riparian zone of a regulated boreal river by determining the elevation, age, species and degree of ice damage within distinct riparian vegetation galleries.

6.2 The ice regime

6.2.1 An introduction to river ice

The ice regime of a river is comprised of three periods: (i) freeze-up, (ii) mid-winter, and (iii) breakup. Freeze-up and breakup are relatively short periods that can, nevertheless, produce significant geomorphological effects and riparian damage due to the effects of moving ice and fluctuating water levels. In comparison, mid-winter tends to be a time of relatively stable low flows and stable ice cover. On regulated rivers, however, fluctuating flows may destabilize the ice cover, producing damaging mid-winter ice runs.

Freeze-up begins with the formation of frazil ice in the water, disc-shaped millimeter scale ice crystals that grow and stick together to form slush pans. Frazil ice may also stick to the river bed and banks, forming anchor ice. As slush pans grow, they agglomerate into larger units that grow out from the channel edge to the point that they lodge across the channel and bridge it. With continued cooling this ice may develop what is known as a juxtaposed ice cover. Such an ice cover grows in an upstream direction with the attachment and freezing of downstream floating ice pans. This process is relatively uneventful and produces only a modest stage rise as the flowing water encounters the increased flow resistance imposed by the new ice cover. In fast water, however, frazil ice and slush may be drawn under the edge of the cover where it sticks in a downward growing hanging ice dam that interferes with water conveyance and can create significant water level increases. This, in turn, may break up the developing cover, which then runs into a larger jam downstream. This "consolidated" ice cover can cause significant flooding and damage along the channel margins.

At breakup, there are similarly two scenarios. A thermal breakup occurs when ice melts *in situ* and remaining ice floats out without obstruction. Little damage is done. Thermal breakups occur when warm weather melts ice before the spring freshet. If, however, rising flows break a still competent ice cover, slabs of ice may pile up or jam, triggering rapid water level increases. Jams eventually break under the force of oncoming water and ice causing a downstream surge of ice and water known as an ice run or ice drive. Such a mechanical or dynamic ice breakup usually entails a series of damaging jams and surges downstream, the jams occurring at similar places each year where the river geometry makes ice passage more difficult. Hence, the most extreme damage may be quite localized.

6.2.2 Ice on Peace River

Before regulation, early winter flows on Peace River were well below 1000 m^3s^{-1} and water temperatures declined in response to decreasing air temperatures. This produced ice floes at nearly the same time all along the river that bridged the river at various locations to initiate a continuous ice cover. This sometimes led to freeze-up in the upper river first, but the ice cover generally progressed upstream from Fort Vermilion to reach TPR in late November or early December and Hudson's Hope by early to mid-December (see Figure 6.2). The ice cover usually formed by simple juxtaposition and caused water levels to rise by about one meter at TPR.

Since regulation, the release of relatively warm water (typically 0.5 to 4.0°C; Keenhan *et al*., 1982) from the reservoir has eliminated winter ice from most or all of the British Columbia reach (Figure 6.2). The mean date of freeze-up is now later all along the river—by as much as five weeks at TPR—while breakup occurs about a week earlier (Andres, 1996). The shift in breakup time might wholly or in part be ascribed to warmer winters in the last decades of the twentieth century; de Rahm *et al*. (2008a) identify a steady retrogression of the time of peak breakup associated water level between 1970 and 2002. The duration of ice cover at TPR has declined by an average of 24 days, and there are a few winters when a static ice cover has failed to form at Dunvegan Bridge. With increased autumn flows and flow velocities, ice formation along the steeper upper river is now more frequent by consolidation, producing a thicker cover and rough undersurface that causes water levels to rise on the order of two to three meters, or even more. In most years, the stage rise at freeze-up now exceeds the breakup rise at TPR (Andres, 1996). Stage rises produced by a consolidated ice cover may persist through the winter, a duration far longer than that of any open-water flood. Consolidating ice covers involve substantial ice shove, creating ice piles at the bank and an offshore shear wall of ice. Channel geometry and the history of water level increases influence how severe the ice/bank contact is. A notable series of such jams occurred at Taylor, British Columbia, in 1979 during an unusually cold winter, producing river stage rises of up to four meters and water levels that had been exceeded by only two open-water flood stages (Keenhan

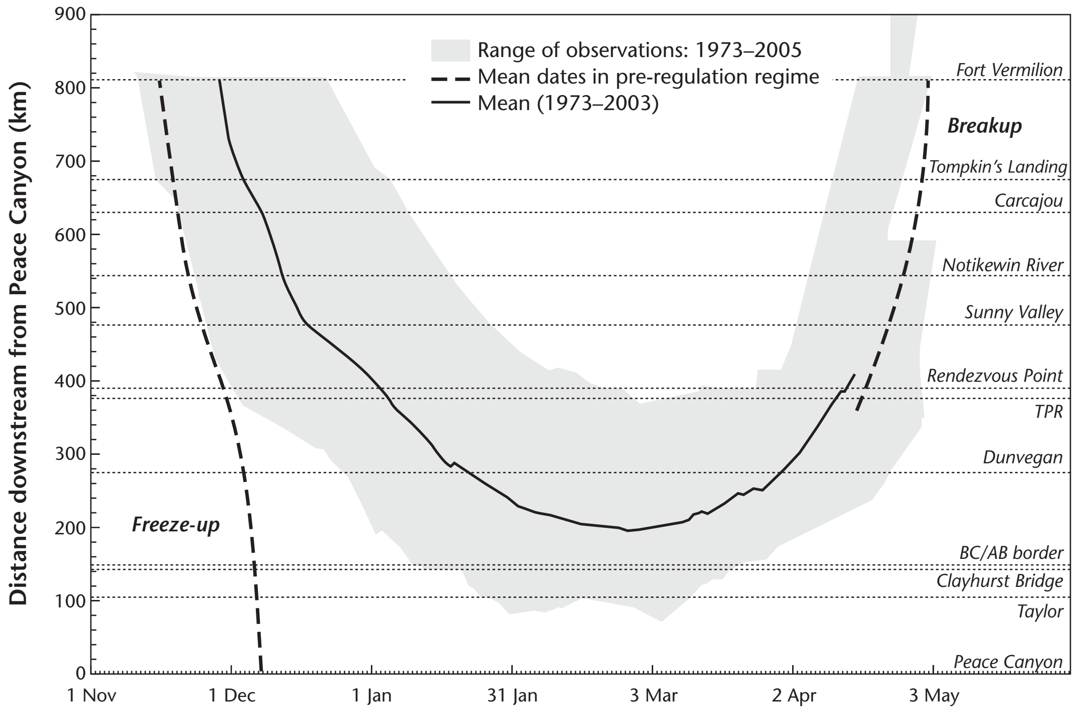


Figure 6.2 Location and date of the ice front on Peace River (the mean and range of dates for 1973 to 2005 are from Jasek *et al.*, 2007), from which the diagram is adapted).

et al., 1982). With warmer winters and warmer water, mid-winter breakups and ice drives on the river are now more frequent than in the past as well.

The pattern of breakup on the upper river has also changed since regulation. High flows deliberately maintained during the freeze-up period (by manipulation of reservoir releases) create a relatively high-stage ice cover with significant sub-ice conveyance. Hence, late winter flows are accommodated and breakup is mainly thermal. However, Smoky River, which enters Peace River immediately upstream of TPR, drains the southernmost part of the Peace River basin so that its breakup—often with significant ice drives and water surges—and peak flows commonly precede Peace River breakup. The Smoky River breakup may produce ice jamming and serious flooding at TPR. A graphical comparison of open-water and breakup water levels is shown in Figure 6.3. It is notable that the most severe breakup floods have exceeded the open-water flood of record by two meters. Since regulation, freeze-up period water releases (increased flows to encourage ice formation at a relatively high level) and breakup period releases (reduced flows as necessary) from the reservoir have been manipulated to attempt to minimize the flood hazard at TPR, the principal river-level settlement along the entire river.

In comparison, the dominantly thermal breakups at Dunvegan have created relatively few significant high stages (Figure 6.4a), but consolidated freeze-up jams, though infrequent, are dangerous. The 1987 event, four meters above the open-water flood of record, occurred in the first days of March during a late-winter freeze-up event.

Below TPR, decreasing channel gradient, a sinuous river course for about 250 km, the effect of the early Smoky River spring breakup, and the increasingly northern location combine to create characteristically dynamic breakups with major jams and ice drives. Significant morphological effects and riparian damage may be expected in this reach. At Fort Vermilion, maximum breakup stage has exceeded the flood of record by as much as five meters, though no such extraordinary jam has occurred in more than half a century (Figure 6.4b).

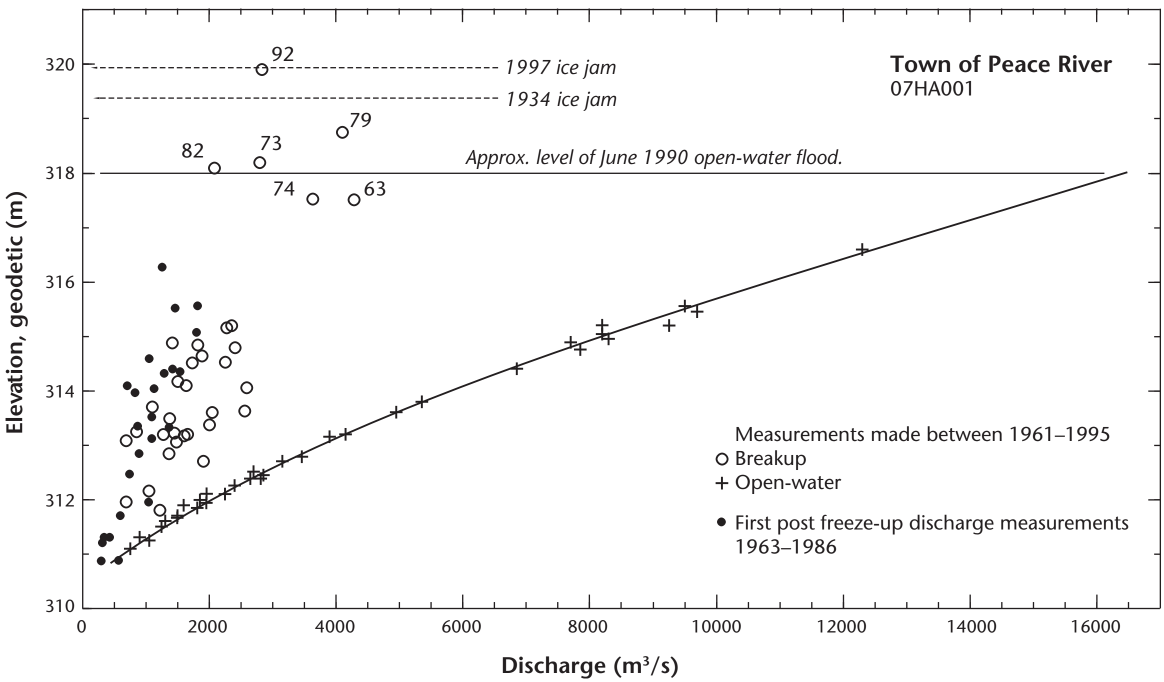


Figure 6.3 Ice affected stages at TPR in comparison with open-water stages. The ice stages are treated as a single sequence before and after regulation. Freeze-up data from Andres (1995).

de Rahm *et al*. (2008b) report a systematic analysis of gauging stations in the Peace–Mackenzie river system to determine whether ice-induced stage or open-water floods produce the highest water levels. They found that the highest water levels at all stations on the mainstem river from TPR down were caused by ice. While the upper Peace River would formerly have been dominated by open-water floods, as are the southern and western tributaries that carry snowmelt runoff from the mountains, the result of regulation is to have created a regime of mixed high water levels.

6.3 Methods

Field observations were made during a three-month, 665 km traverse of the river from Clayhurst, British Columbia to Fort Vermilion, Alberta, in the summer of 1995. Supplementary observations were gathered in June 1996, and during frequent traverses along the British Columbia reach of the river over many years. Winter observations were made in December 1994, and February 1996, and the 1996 breakup was observed between Shaftesbury Ferry and Notikewin River (Alberta) by air and on the ground. Because of the limited intrusion of river ice into the British Columbia reach since regulation, the main focus of attention is the Alberta reach of the river traversed in 1995.

6.3.1 River datum

Because the elevation of ice damage relative to normal water levels is a key observation, some consistent datum was required along the river. It was not possible to carry an absolute datum along the river and, in any case, the river gradient dictates a changing reference elevation as one proceeds downstream. A reference water surface elevation is desirable, but flows and water levels changed continually during the survey and it was not practical to transfer gauge levels along the river. Elevations were therefore referred to the lowermost edge of continuous vegetation taller than 0.25 m. This datum is surprisingly clearly defined along most of the river (Figure 6.5), not only by the vegetation, but also by a boundary between recently washed sediments (below) and deposited fine sediments (above). It represents a coherent water plane that reflects normal high

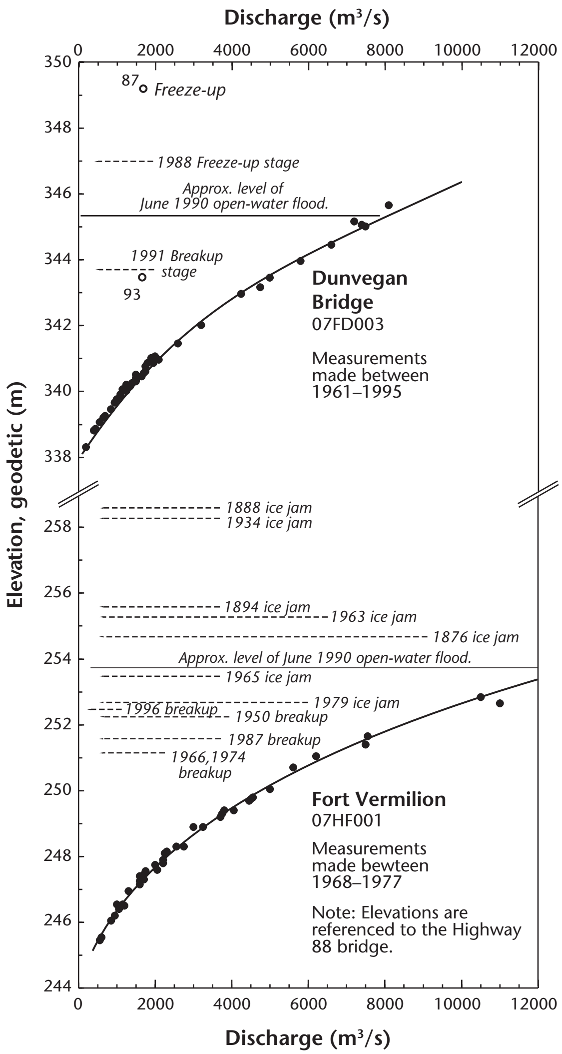
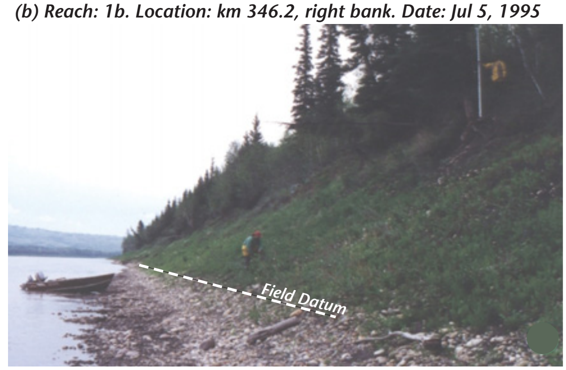


Figure 6.4 Ice-induced stages in comparison with open-water stages at (a) Dunvegan and (b) Fort Vermilion.

(a) Reach: 1a. Location: km 176.7, right bank. Date: Jul 5, 1995

(b) Reach: 1b. Location: km 346.2, right bank. Date: Jul 5, 1995



(c) Reach: 2b. Location: km 662.5, left bank. Date: Jul 23, 1995

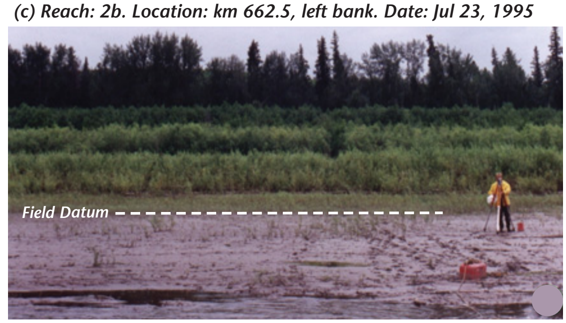


Figure 6.5 Views of the lower vegetation limit used as field datum along Peace River. (a) Upper river about 35 km below the British Columbia border (km 176.7). (b) Ice-scoured bank on a straight reach of the upper river (km 346.2). (c) Field datum and vegetation galleries at Keg River (lower river; km 662.5).

water; hence it is a useful datum from which to measure the height of riparian damage and, by inference, the elevations reached by ice. Figure 6.6 shows the relation between the field datum and river water levels during the summer of 1995. The field river datum approximates the level of mean monthly post-regulation flow for June—the month of highest flow from Pine River confluence downstream due to the spring snowmelt runoff from the unregulated portion of the drainage basin.

6.3.2 Vegetation damage

Corrasion scars have been widely used to date the magnitude and frequency of riparian disturbance events such as floods (Sigafoos, 1964) and ice jams (Gerard, 1981; Smith and Reynolds, 1983). On northern rivers, damage to riparian vegetation usually offers the only available evidence of past ice-jam stages. Ice forced

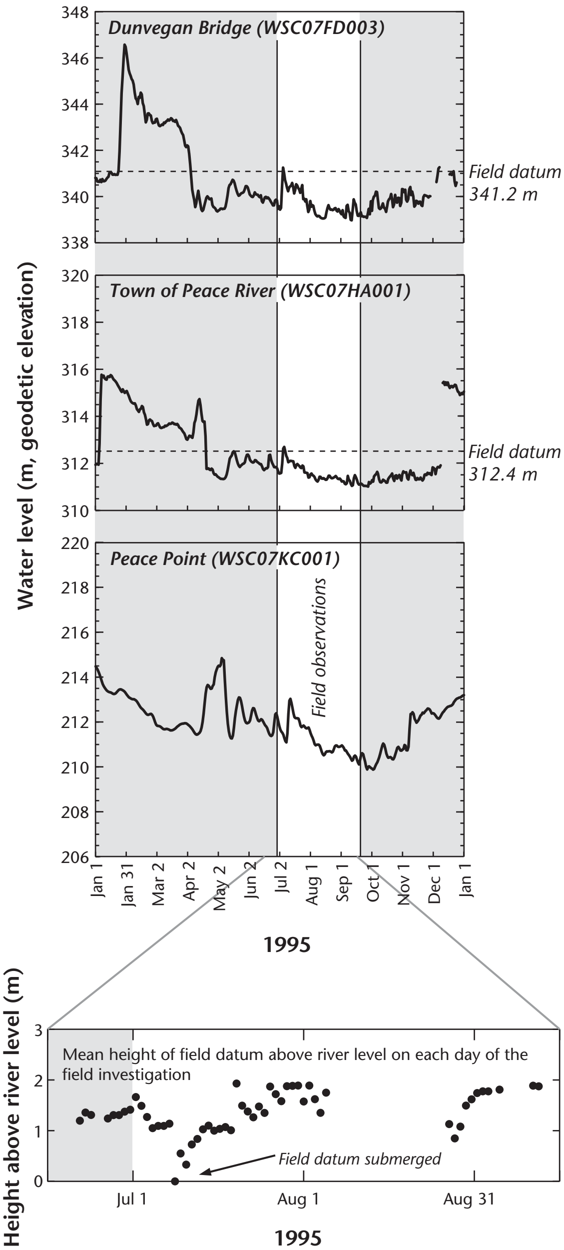


Figure 6.6 Water level variations at Dunvegan and TPR gauges during the field survey and the elevation of field datum above river level. Data for Peace Point are also shown as the Carcajou and Fort Vermilion gauges were inactive in 1995.

against trees scrapes off bark and damages the underlying cambial layer. The bark is not replaced but, if the tree survives, it produces scar-wood around the wound, slowly growing over it. The age of an event can be determined by counting the number of growth rings over the scar in a wedge cut from the tree[1]. In the case of ice scars, the date will determine the winter of occurrence, but the method cannot discriminate between a freeze-up event in early winter and a breakup event in the following spring (and year). Hence, there is usually ±1 year of uncertainty.

Field observations were made every one to two kilometers along the river, extending to 10 km in reaches with limited evidence of ice damage. Deliberate efforts were made to distribute sampling over both banks and over all principal reach morphologies, in straight reaches and bends, on cut banks and point bars, on islands and near tributary junctions.

Corrasion scars on mature trees are ubiquitous along Peace River and their association with ice impact was directly substantiated during winter observations. However, driftwood in high water may also damage trees. Damage by this means is, however, quite localized to island heads and locations where the maximum current impinges on the shore, and is often accompanied by driftwood accumulations. In comparison, ice damage is pervasive along the river banks. In this study, scars were dated only if they were located on the channel-side of a living tree (i.e., in the likely path of ice movement) and clearly were not caused by animals, disease, wind throw, slope instability, driftwood, fire, lightning, or human activity. Scars were measured only when located in an area exhibiting a number of scars or other morphological evidence of ice action. Areas easily accessed from settlements were avoided.

Scars provide evidence of the limit of ice shove, not the associated water level. Locally, ice may be pushed to anomalously high levels. Ice shove potential is high at the head of islands, on the outside of bends, and at channel constrictions. It is low on lee shores and long, straight reaches. Gerard (1981) reported that scars on Smoky River overestimated ice-jam water levels by 0.5 m on average while Smith and Reynolds (1983) found that, over 41 years, recorded peak stages of ice-jam floods on Red Deer River averaged 1.4 m below maximum

[1]The cutting of wedges and sections is destructive. In this study the practice was restricted to significantly damaged or moribund trees and immature specimens of common forest species. In the case of mature trees, incision was restricted to the scar wood.

tree scar elevations (range 0.15 to 3.4 m). However, the largest events returned the more concordant elevations.

Scar evidence is also incomplete: there are sites along the river where ice damage tends to be minimal. Trees are eventually lost to bank failure, beaver activity, disease, windthrow, or severe ice impact. Furthermore, very old scars may be completely grown over and not easily noticed in a reconnaissance survey. The overwhelming majority of scars identified in the study post-date the inception of river regulation.

At each site identified as having been scarred by ice, elevation relative to river datum was determined for the upper and lower edge of the highest visible scars. A "trim-line" elevation—the upper limit of all visible vegetation disturbances, including trimmed branches and roughened bark—was also recorded. The trim line results from ice damage during ice drives and indicates the long-term upper limit of ice disturbance. On the lower river, the trim line was often obscured by dense shrub galleries within which damage was apparent but no clear limit could be identified.

About 300 scars were dated for this study. About one-third of the sample was dateable in the field; the balance was returned to the laboratory and prepared and counted by standard methods using magnification of up to 40×. The minimum and maximum scar elevations measured in the field were reduced to mean values following Smith and Reynolds, 1983. Data were grouped into five morphologically identified reaches (Figure 6.1) (and 34 subreaches) of the river. Sub-reach length varied from 6 to 55 km (mean length, 21.9 km, standard deviation ±11.0 km). The highest scars in each sub-reach and for each year were extracted to study magnitude–frequency aspects of ice jamming. Results were compared with historical data available at Dunvegan, TPR, and Fort Vermilion.

6.3.3 Riparian vegetation

Riparian vegetation carries additional evidence of ice disturbance. Along the edges of Peace River, vegetation is grouped into distinct linear galleries that occupy recent and relict alluvial surfaces. The vegetation patterns are a result of factors imposed by the river, including past ice activity. Event frequencies may be established by dating post-disturbance communities using tree ages while magnitudes may be measured by identifying the areal extent of damage or vegetation removal. Riparian vegetation is, of course, also affected by channel instability.

At about 270 sites, transects were conducted from waterline into the mature forest to observe bank morphology and vegetation conditions (communities, stand height, elevation above river datum). The presence/absence of riparian species (Table 6.1) was noted within each community. Stand heights were classified as in Table 6.2. Minimum ages of stands were determined by counting tree rings from *Salix* sp. (willow), *Alnus incana* ssp. *tenuifolia* (mountain alder), and *Populus balsamifera* (balsam poplar). The ecesis period for these species is often 3 to 12 months after a major ice-jam event (Scrimgeour *et al*., 1994). In many cases, ice-mown trees sprout new vertical shoots that date the event. In each stand, 5 to 10 sections were cut from the largest and presumed oldest shrubs and trees to date ecesis or scarring. Most dates were determined in the field.

Elevations above river datum and ages of riparian communities were filtered by 20-km running means with a step length of five kilometers and plotted for comparison with the scar record. However, riparian community structure may reflect not only major ice jams but also ice shove in lesser events and effects of open-water floods. Return periods of ice disturbance were estimated for each sub-reach on the assumption, following Eggington (1980), that tree age in the lower riparian zone represents time since the last significant disturbance.

6.3.4 Bank morphology and sedimentary features

Bank profiles were surveyed at each site where vegetation communities were investigated to determine the elevation and downstream trend of several alluvial surfaces along the river. These surveys were employed to identify characteristics of the bank zone and to speculate on the possible influence of ice, and of flow regulation, on their formation. In addition, ice-related sedimentary features were recorded and measured to gain insight into the direct morphological effects of ice shove against the channel bed and banks. Locations of ice-scoured features were plotted on maps to determine whether they were widespread or localized and to identify any systematic association with other river features.

6.4 Ice-jam location, magnitude, and frequency from the scar record

Most previous studies of ice-jam events have investigated single sites or short reaches. In this study we seek

Table 6.1 List of species identified within riparian communities

Trees
Betula papyrifera var. papyrifera (white birch, paper birch, canoe birch)
Picea glauca (white spruce)
Picea mariana (black spruce)
Populus balsamifera (balsam (black) poplar)
Populus tremuloides (trembling aspen, white popular)
Shrubs
Amelanchier alnifolia (saskatoon, serviceberry, juneberry)
Alnus incana ssp.tenuifolia (mountain alder)
Arctostaphylos uva-ursi (common bearberry, kinnikinnick)
Cornus stolonifera (red-osier dogwood, red willow)
Elaeagnus commutata (silver berry, wolf willow)
Juniperus communis (common juniper)
Lonicera involucrata (bracted honeysuckle, black twinberry)
Prunus virginiana (chokecherry)
Ribes sp. (currants and gooseberries)
Rosa acicularis (prickly wild rose)
Rubus idaeus (wild red raspberry)
Salix exigua (coyote willow)
Salix prolixa (Mackenzie's willow)
Shepherdia canadensis (Canada buffaloberry, soopolallie, soapberry)
Symphoricarpos albus (common snowberry, few-flowered snowberry)
Vaccinium sp. (blueberry)
Viburnum edule (lowbush cranberry, squashberry, mooseberry)
Herbaceous
Fragaria sp. (woodland strawberry, wild strawberry)
Potentilla sp. (cinquefoil)
Vicia americana (wild vetch, american vetch)
Trifolium hybridum (alsike clover)
Melilotus alba (white sweet clover)
Melilotus officinalis (yellow sweet clover)
Viola sp. (violets)
Epilobium angustifolium (fireweed)
Taraxacum officinale (common dandelion)
Sonchus arvensis (Canada thistle, perennial sow thistle)
Achillea millefolium (common yarrow, milfoil)
Aster sp. (aster)
Solidago canadensis (Canada goldenrod)
Cornus canadensis (bunchberry)
Plantago major (common plantain, whiteman's foot)
Galium sp. (bedstraw)
Linnaea borealis (twinflower)
Heracleum lanatum (cow parsnip)
Cicuta douglasii (water hemlock)
Medicago sativa (alfalfa)
Smilacina racemosa (false solomon's seal)
Maianthemum canadense (wild lily of the valley)
Rubus pedatus (creeping raspberry, five-leaved bramble)
Mentha arvensis (mint)
Other
Cyperaceae (Sedge family) (sedges)
Equisetum sp. (horsetails)
Juncaceae (Rush family) (rushes)
Poaceae (Grass family) (grasses)

Table 6.2 Vegetation stand height classification

Class	Height range	Indication
0	<0.25 m	Seedlings
1	0.25 to 0.9 m	Below waist high, annuals and low shrub vegetation
2	1.0 to 1.9 m	Waist to head high, intermediate shrub vegetation
3	2.0 to 4.9 m	Above head, below stadia height; high shrub and young trees
4	5.0 to 15 m	Above stadia; young forest, shrub understorey
5	>15 m	Mature forest

to determine the magnitude and frequency of ice jamming at river length scale. While it is clear from winter observations that ice can abrade and even uproot trees, it is also evident that moving ice can flow within the confines of ice stranded along the banks. This phenomenon is particularly evident on falling stage, a common situation in the upper river where flow releases early in winter result in freeze-up occurring at elevated levels. Along upper Peace River, particularly in the British Columbia reach, stranded ice is common and damage is limited.

Below Smoky River, the situation differs: severely damaging jams are much more common. Between 1960 and 2000 there were six major ice-jam floods at TPR, all but one generated by breakup in Smoky River. There is little synoptic information available about ice jams at other locations along the river.

6.4.1 Location and magnitude of ice jams

The location of the highest measured scars along the river (about half of all measured scars) is mapped in Figure 6.7. On the upper river, most jam sites exhibit scars up to 7.0 m above field river datum, no doubt related to the occurrence of stage increases created by ice consolidation during freeze-up on the order of five meters (Andres, 1996). Three sites with higher jams occur at classic jam locations; in order downstream, a 90° left-bend, at the tributary Saddle River confluence, and upstream of Smoky River confluence. The highest jam elevations on the river occur in the middle reach between TPR and Carcajou. Here the river flows through confined tight bends, often with islands in the bends. Near Carcajou, an extensive left-bank floodplain provides escape for floodwaters and scars are not as high as

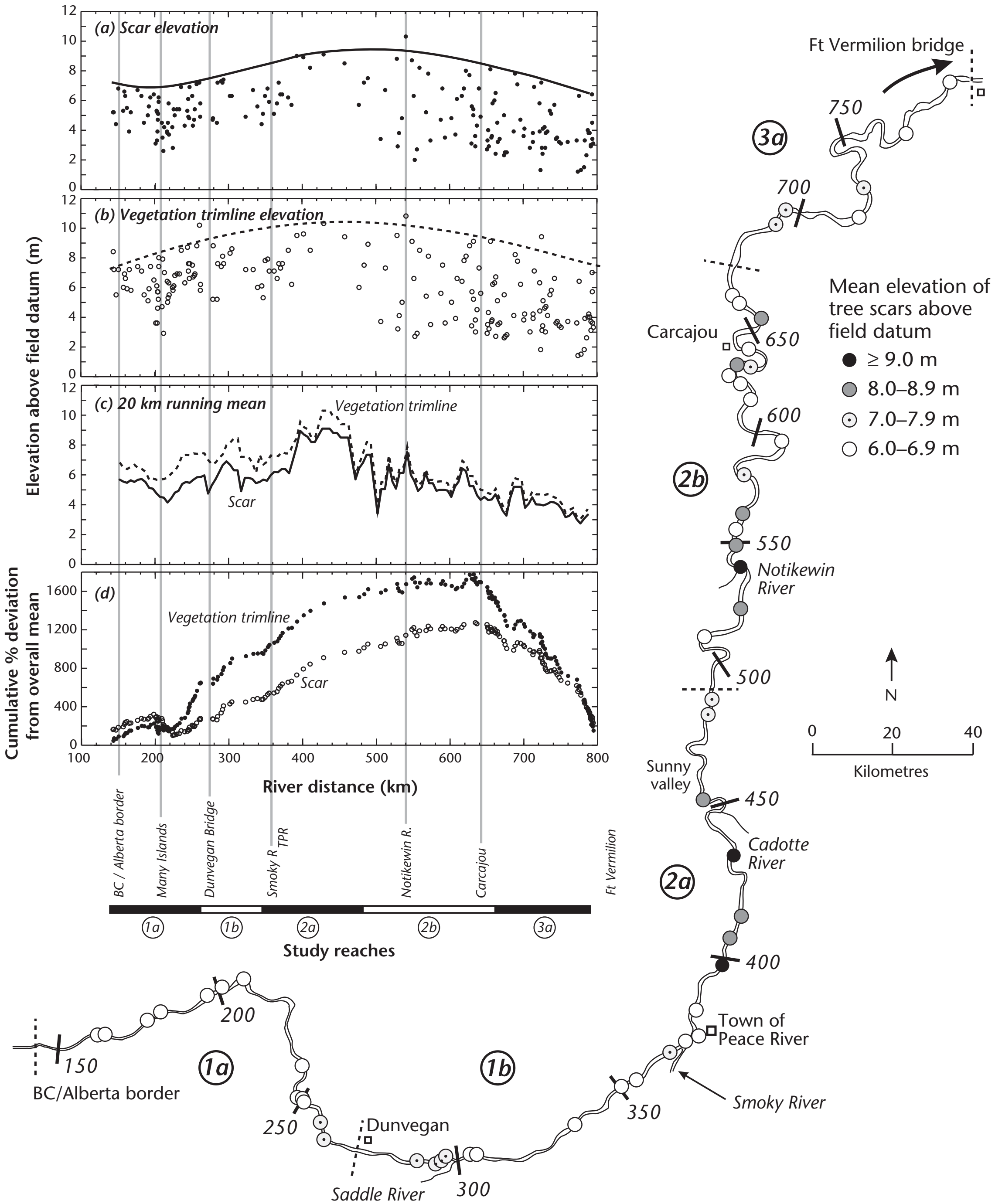


Figure 6.7 Locations of trees with ice scars >6 m above field river datum. Numbers along the river are distance in kilometers below the Peace Canyon Dam. Insets: (a) envelope of ice scar elevations along Peace River: one very high site exceeds the envelope; (b) same for trim-line elevation. A few very high sites exceed the displayed general envelope; (c) 20 km running mean calculated every five kilometers of all ice scars on mature trees and of trim-line elevation; (d) cumulative percent deviations from the overall mean scar elevation (5.0 m) and overall mean trim-line elevation (5.8 m). Where the plot rises, mean feature elevations are above the river-length mean and where it declines they are below the river-length mean.

upstream. Below Carcajou, the channel is not confined and scar elevations are lower than eight meters above river datum.

Figure 6.7, inset (a) plots all scar elevations, demonstrating a rather regular variation in highest elevation along the river, peaking between km 420 and km 540 in the confined, sinuous reach below TPR. The distribution of trim-line elevations (bruising and branch trimming) (Figure 6.7, inset (b)) mirrors the scar record, but about 0.5 m higher, with a peak at 10 m. There are, however, some notable outliers in the trim-line plot, emphasizing the significance of local river morphology in determining the most severe jamming locations. Running means of disturbance elevations (Figure 6.7, inset c) shift the location of peak elevations upstream to the reach between km 400 and km 470, immediately downstream from TPR. The high average elevation of sites in this reach conditions the outcome.

Cumulative departures from the overall mean elevation (5.0 m for scars; 5.8 m for trim lines) reveal a more nuanced picture (Figure 6.7, inset (d)). Elevations exceed the means from the British Columbia–Alberta border to as far as Many Islands (km 206), a place where the river is notably divided into several channels. They are then low as far as Montagneuse River (km 222). There is then a long sequence of above-average elevations extending to the Notikewin River confluence (km 543), with a notable "bump" at km 287 between Dunvegan and Saddle River. Elevations are approximately average to km 632 (Carcajou). The trend reverses immediately downstream from Carcajou. Altogether, 70% of the study reach experiences ice disturbance to elevations equal to or greater than the overall mean.

The river-length trends emphasize the significance of tributary confluences and river morphology in localizing ice jams. The geographical distribution also emphasizes the relatively low level of disturbance in the upper river, which has only transient ice in many winters, and in the unconfined lower river. However, extraordinary floods have been experienced at Fort Vermilion (Figure 6.4b), where the river is, again, locally confined.

6.4.2 Frequency of ice jams

A total of 188 scars on mature trees were measured and dated. For frequency analysis, information was compiled into major reaches. Because ice-jam frequency is known to have been affected by regulation, especially in the

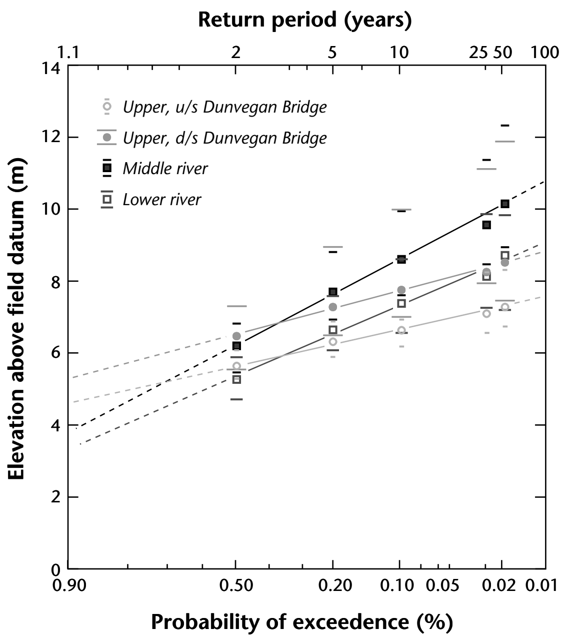


Figure 6.8 Elevation-frequency plots for ice-jam stages in major reaches of Peace River. The upper river is represented by two plots because of the noted relatively low elevations and transient freezing above Dunvegan. Error bars represent 5% and 95% confidence limits on the estimated elevations.

upper river, frequency analysis was limited to the period 1973–1995, that is, to the "early" period of normal regulated operation before the 1996 reservoir drawdown flood. The analysis is not statistically robust insofar as freeze-up and breakup events are not distinguished by the scar record, so the sequence may not be homogeneous. The sequence also may not be stationary inasmuch as winter climate has fluctuated over the 25-year period, with a sequence of notably mild winters in the 1970s, and events may not be entirely random due to flow regulation. Perhaps most serious, though, is that the sampled record certainly is not complete.

Nevertheless, a clear pattern emerges (Figure 6.8). The upper river is represented by two plots, the dividing point being Dunvegan. There is about one meter difference between them across the domain of return periods, but the error ranges of the two sets of estimates overlap everywhere, chiefly because of the very wide range of variation in the reach between Dunvegan and TPR. The frequency plot is steeper and higher in the middle river, in keeping with the demonstrated occurrence there of

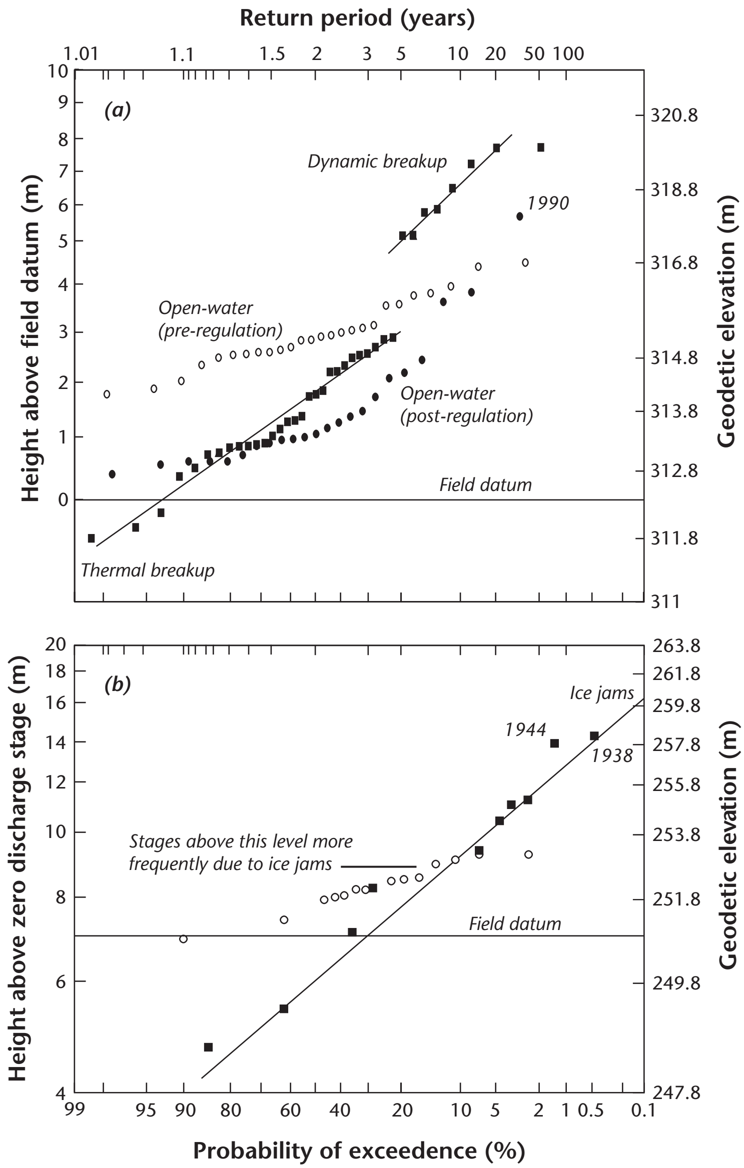


Figure 6.9 Historical ice-jam stages in comparison with open-water stages at (a) Town of Peace River and (b) Fort Vermilion. The Fort Vermilion record is for the pre-regulation period. The gauging record extends from 1917 to 1922 and from 1961 to 1968. The ice-jam record extends back to 1920, but includes records from only some years. The ice stage records at TPR include all available data, before and after regulation.

elevated disturbances. However, very high disturbance occurs relatively infrequently: back-extrapolation suggests that jams with near-annual recurrence are actually lower in this part of the river than upstream. This might reflect the fact that a persistent, solid ice cover is more common in this part of the river than above TPR and that in some years, thermal breakup occurs with little ice movement and little jam activity. But it may also reflect lack of complete data. In the lower river, the magnitude–frequency plot is similar to that of the upper river, but steeper, reflecting the known fact that severe jams occasionally occur in the vicinity of Fort Vermilion.

A continuous modern historical record is available at TPR (Figure 6.9a) in which dynamic and thermal breakups are distinguished. Analysis of all available data shows that thermal breakups produce stage rises similar to post-regulation open-water flood stages, but that dynamic breakups may exceed the highest open-water stages recorded and much more frequently give rise to high stage. The range of ice-jam floods—about 7.5 m—is lower than the range for the middle river but consistent with the position of TPR on the river.

Gerard and Karpuk (1979) conducted a study of tree scar evidence at Fort Vermilion and also incorporated other historical information into their record. Their plot is based on "perception stage"—the stage above which an event is apt to be recorded as significant—to overcome the bias that would otherwise exist because of the non-record of lower events. Their results are reproduced as Figure 6.9b. Their results extend back to 1920 and cover only the pre-regulation period. Their record can be approximately compared with the reach-wide plot if a common datum can be established. We do not have such a datum but, if we assume that field river datum at Fort Vermilion has the same stage frequency as at TPR, we can estimate field datum as 250.4 m (geodetic). Then the range of Gerard and Karpuk's ice-jam evidence extends to eight meters above field datum, which is comparable to our result for the lower river at 25 to 50 years return period (Figure 6.8). It is also comparable with the earliest records from the community (Figure 6.4b). Fort Vermilion is more than 800 km below the dams and a long way "down north," so that winter ice conditions have been changed here to a much lesser degree than on the upper river and remain under the dominant influences of the Smoky River spring breakup and regional weather. The data of Figure 6.9b probably remain relevant in the regulated regime.

6.5 Sediment scour and deposition by ice

In this section, we describe the types and distributions of the principal ice-related channel margin and bank features. We have grouped the effects as erosional features, depositional features, and features modifying overall bank morphology. In fact, it is difficult to separate erosional and depositional features. Since sediments are usually disturbed only locally, erosion must be associated with nearby sediment deposition, while some important features (e.g., stone pavements) may amount to modification of the sedimentary surface *in situ*. It is important as well to recognize that, whilst ice may often rework sediments along channel margins, it may also play a protective role when it is stable and grounded along the banks. An offshore shear line then separates moving from static ice.

Figure 6.10 presents the distribution of the common ice-related morphological features along Peace River. Depositional features appear to have a higher incidence than erosional features, in large measure probably because erosional scrapes associated with the deposition of ice-pushed ridges are often under water and out of sight.

6.5.1 Bar and bank scour

Scour by ice jams and ice drives leaves a wide range of small-scale disturbances in the shore zone and on the banks (cf. Wentworth, 1932). Keel marks and grooves indicate shove by grounded ice. Features identified on Peace River varied from centimeters to two meters in depth. Widths were the order of one meter and lengths varied from 1 to 20 m. Bank scour is usually associated with evidence of vegetation damage.

Small-scale scour features are well distributed along Peace River except in the most distal study reach, below Tompkin's Landing, where near-vertical silt/sand banks do not favor the preservation of scour evidence. The greatest concentration and largest features are found in the upper river and in the vicinity of Carcajou. In the upper river the prevalence of mobile ice, freeze-up consolidation, and significant stage fluctuations likely cause frequent grounding of ice along channel margins and bars. In addition, large discharges at freeze-up may cause fluvial scour beneath a confining ice accumulation. Large scour troughs are often located on gravel bars at the heads of islands (Figure 6.11a), and might be up to 20 m long, 10 m wide, and 2 m deep. There is commonly an ice push deposit immediately downstream. Though mostly oriented parallel to the thalweg, they might deviate by up to 45°. A relatively large scour feature and associated ice-push ridge (Figure 6.11b) discovered near Saddle River is known to have formed near freeze-up in 1993 (J. Chalmers, personal communication, 1995). Only six features on this scale were found, four of them in the upper river. Other features were minor and apt to be quickly obliterated.

Bank scour is widespread but sediment scour attributable to ice is difficult to ascertain. Ice scour was inferred if ice-scarred trees or shoved sediment was found (Figure 6.11c). Ice-scoured banks were confirmed at only 11 sites, mainly in the lower middle reach where the river flows through a series of tortuous confined bends.

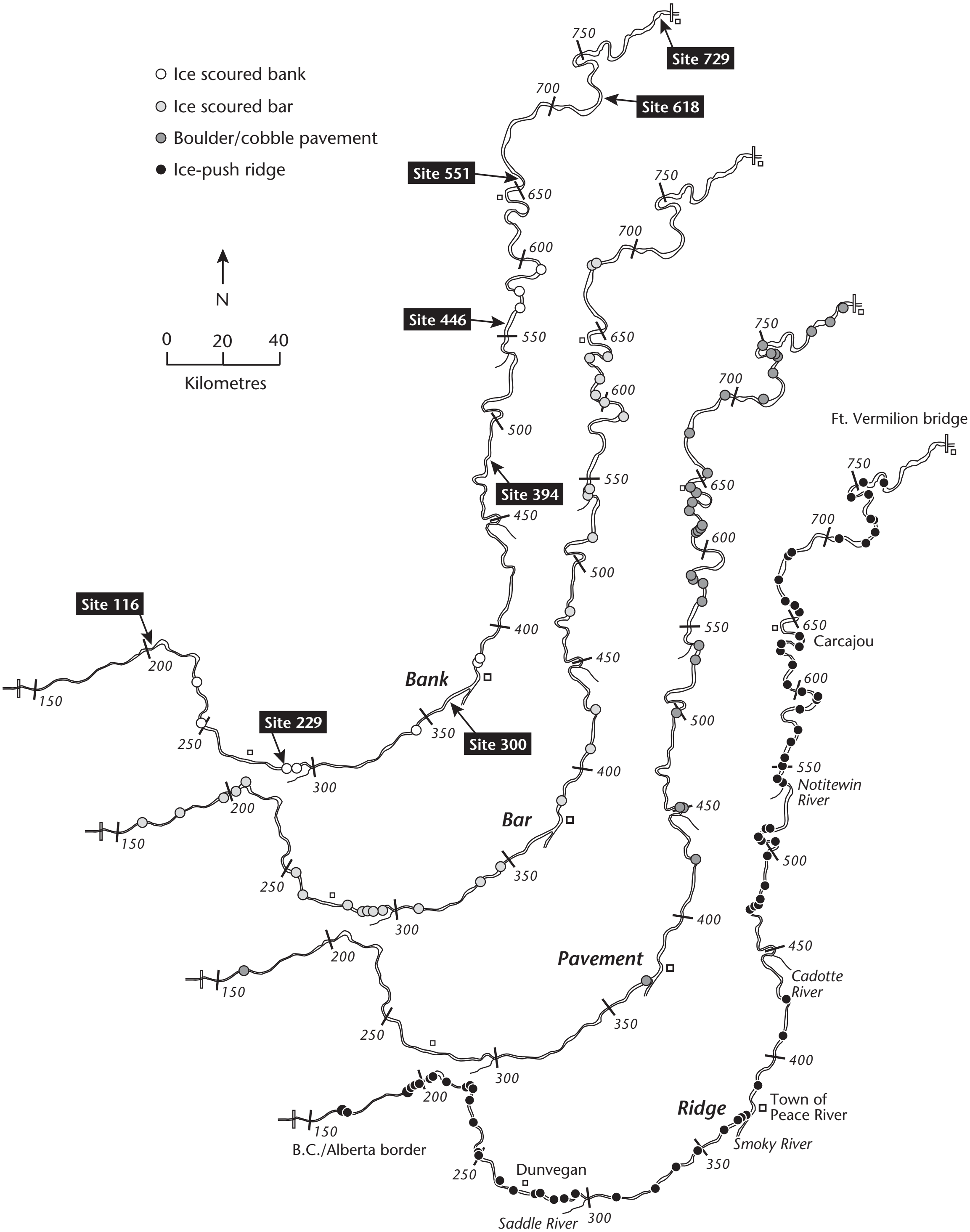


Figure 6.10 Distribution of ice-associated sedimentary features along Peace River. Features mapped have a characteristic dimension of one meter or greater. Also shown, the location of bank profiles illustrated in Figure 6.14 and additional sites with data in Figure 6.12.

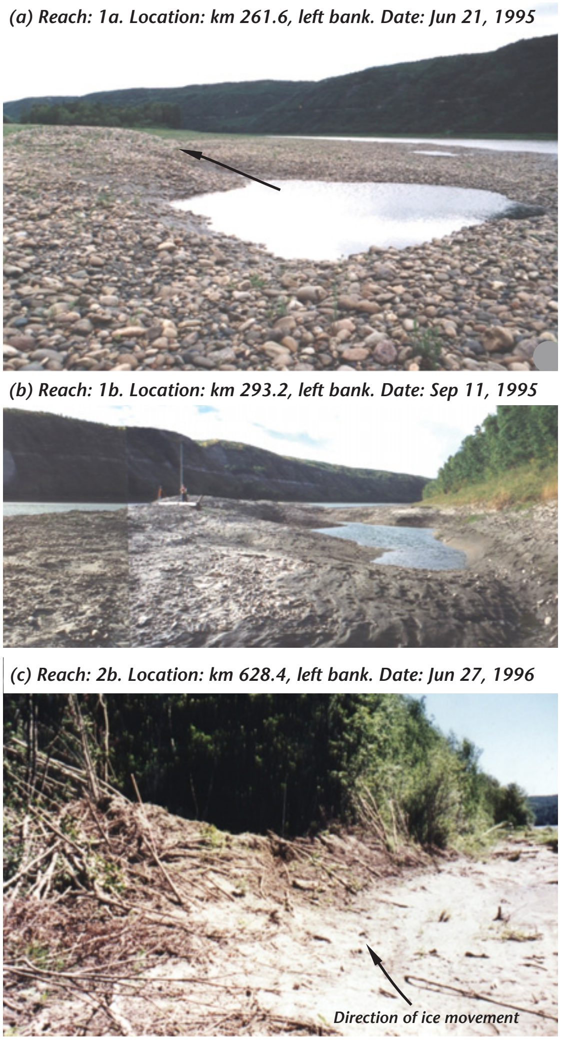


Figure 6.11 Evidences of ice scour along Peace River. (a) Ice-scoured bar at the head of an island in the upper river (km 261.6). Note the ice-pushed ridge beyond. (b) Large ice-scour and ice pushed gravel ridge on a tight meander bend near Saddle River (km 293.2; view upstream), likely formed during a freeze-up jam in late 1993 (photo taken in September 1995). (c) Ice-pushed alluvium and damaged Alnus near Carcajou (km 628.4) caused by a breakup jam.

At Carcajou, a series of tight bends had evidence of severe ice shove toward the outer bank during breakup. Water seeking a way around the jam often follows the inside of the bend (the steepest route) or a secondary channel behind an island. Ice jam–induced flow through secondary channels is responsible for maintaining many of the secondary channels since regulation along the middle and lower river.

Ice may become frozen to the bank so that, when remobilized, it tears off a layer of frozen soil the order of centimeters in thickness. This action appears to be more common if a fall in river stage causes the ice to topple away from the bank, pulling the soil with it, than on a rising stage, which causes ice to float free after melt at the ice-soil interface. Falling stage remobilization is most common in the upper river, where the effects of varying regulated flow are strongest.

6.5.2 Depositional features

Ice-pushed ridges are the most common feature observed along the river (Figure 6.10). Although features of over five meters height have been reported along subarctic rivers (Hamelin, 1972; Dionne, 1976), Peace River features (Figure 6.12a) rarely exceed two

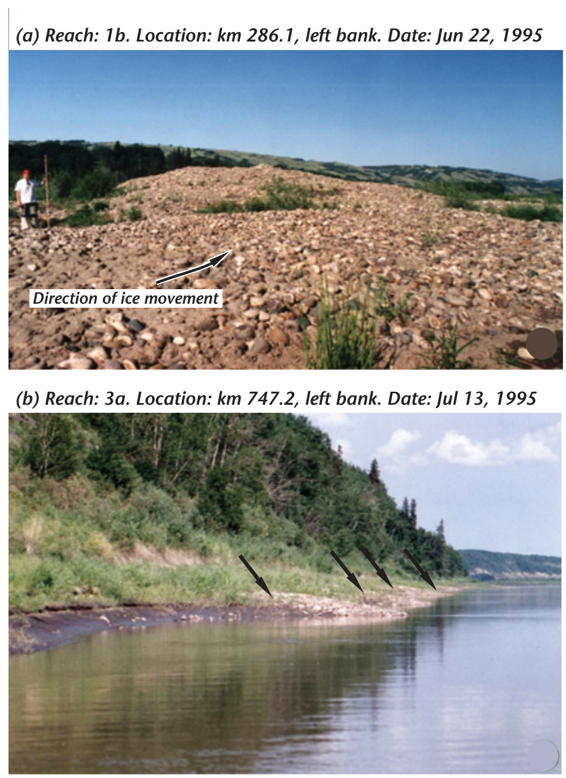


Figure 6.12 Ice-pushed features along Peace River. (a) Gravel ridge on a large bar near Fairview, km 286.1. (b) Characteristic sequence of ice-pushed cobble deposits on the left bank at km 747.2: view upstream. Notice the ice-scoured shrub zone behind.

meters. They are formed of silty gravel and usually armored by cobbles. Individual stones sometimes have aligned striations and may be polished, presumably from planing by sediment frozen to the ice. Downstream features are larger. Ridge orientation depends on the trajectory of moving ice floes, which chiefly is controlled by bank configuration.

The often jerky downstream progression of jammed ice has resulted in discrete, rhythmically spaced ridges (Figure 6.12b), with spacing of 50 to 150 m over distances up to 600 m. Rhythmic ridges often have the appearance of cobble dunes moving onto the bank of the river, but they mostly emerge only a meter or less above summer stage. Their position with respect to obvious sources of cobbles gives the appearance that they migrate downstream. These features have been observed within 50 km of the Peace Canyon Dam but, as the post-regulation river bed there is effectively static and significant ice extremely rare, it is likely that these are relicts of the pre-regulation era. Ice-pushed deposits occasionally are seen to extend into the river, forming a hook-like feature (cf. Wentworth, 1932) (Figure 6.13a).

Cobble-boulder pavements are sedimentologically similar to ice-pushed ridges except that they are smoothly planed rather than shoved up. They occupy positions well below high water and were observed only during low flows. The surface consists of sub-rounded cobbles and boulders embedded in a silty or fine sand matrix (Figure 6.13b). The cobbles are loosely packed and grain size often decreases downstream. They are found in the middle and lower river in the proximity of gravel deposits, usually relict glacial deposits. The larger ones are up to 100 m long and 15 m wide and located on the heads of islands.

Disorganized patches of clay to cobbles, found on the lower banks and bar surfaces, are widely distributed along the river, though not common. They are attributed to meltout from stranded ice floes since they are often found near ice-damaged shrubs. In some instances, deposits were found more than 100 m from the summer waterline.

Since regulation, ice-jam floods provide the primary means for supplying sediment to the upper river banks and floodplain. At sites between Sunny Valley and Fort Vermilion pre- and post-ice-jam observations in 1996 showed that overbank silt deposits averaged 10 mm in depth, with a range between 5 and 100 mm. Shrub galleries enhance deposition by checking currents and

(a) Reach: 3a. Location: km 723.5, right bank. Date: Jul 16, 1995

(b) Reach: 2b. Location: km 653.3, right bank. Date: Jul 24, 1995

Figure 6.13 Ice-pushed and ice-planed features. (a) An ice-pushed cobble hook at km 723.5 (near La Crete). These features were rarely seen. (b) A typical boulder pavement on the lower river (km 653.3), in the vicinity of the gravel/sand transition.

here the thickest deposits were found. Deposits were concentrated on a shelf—the so-called “active channel shelf” (Osterkamp and Hupp, 1984)—between the pre-regulation floodplain and the summer waterline (further discussion below). This level represents a developing, albeit confined post-regulation floodplain level, determined mainly by ice.

Tributary confluences have conspicuous deposits of silt following breakup. Silt is deposited when the tributary breakup precedes that on Peace River so that tributary waters pond along the river ice margin at the confluence. Such deposits do not persist along the channel though they constitute significant additions to floodplain surfaces. Hence most ice-associated sedimentary features along the channel are found at sites with abundant coarse sediment. Since regulation, these materials tend to remain at or near their point of entry into the river. Therefore, the density of ice-associated sedimentation is

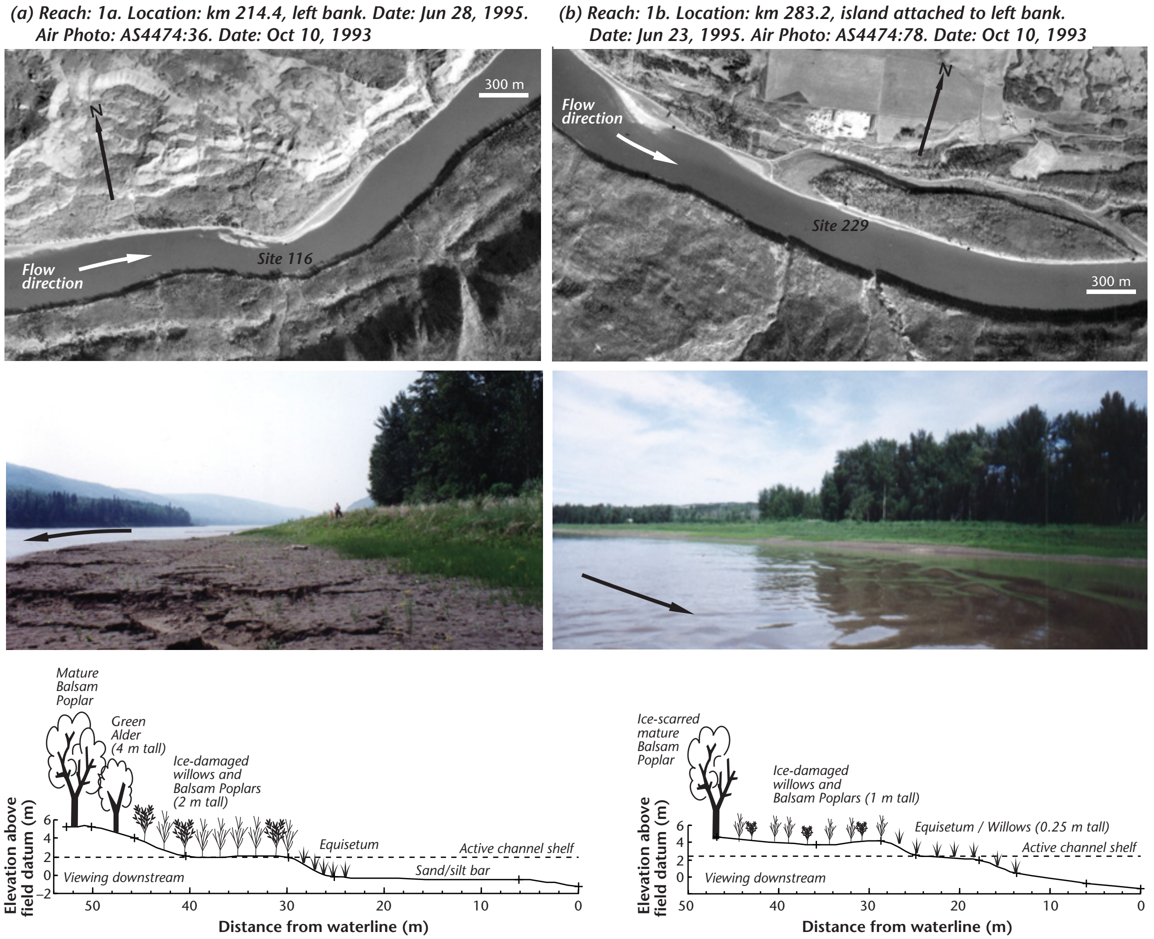


Figure 6.14 Bank profiles in typical depositional environments along Peace River, that is, moderate- to low-exposure sites. See Figure 6.1 and Figure 6.10 for locations.

not a satisfactory indicator of the severity of ice disturbance along the river, but it certainly is corroborating evidence of ice activity. In many instances ice-worked cobble deposits are found well beyond the vicinity of the gravel–sand transition (Figures 6.12b; 6.13a). In the sand-bed reach, cobbles arrive by transport in ice, by erosion from glacial deposits in the valley sides, or by transport beyond the point of the evident transition.

6.6 Bank morphology

It has been proposed that icy rivers, especially those experiencing severe ice jams and ice drives, have a unique bank morphology in response to ice scour and ice-associated sedimentation. (Marusenko, 1956; Hamelin, 1972; Smith, 1979, 1980; Boucher *et al.*, 2012). The objective of the bank investigations is to document further the impacts of ice on Peace River and to determine whether it has any overall effects on channel morphology, such as enlarging the channel beyond the regime expectation for the flows carried by the river.

Eight representative bank profiles, selected from the 270 surveyed, are illustrated (Figure 6.14) to represent depositional environments along the study reach. They represent somewhat protected straight channel and island shores, and point bar sites. All present a more or less well-developed active channel shelf. Banks in high exposure sites, in contrast, are scoured clean or relatively undisturbed (see Figure 6.5b), a common

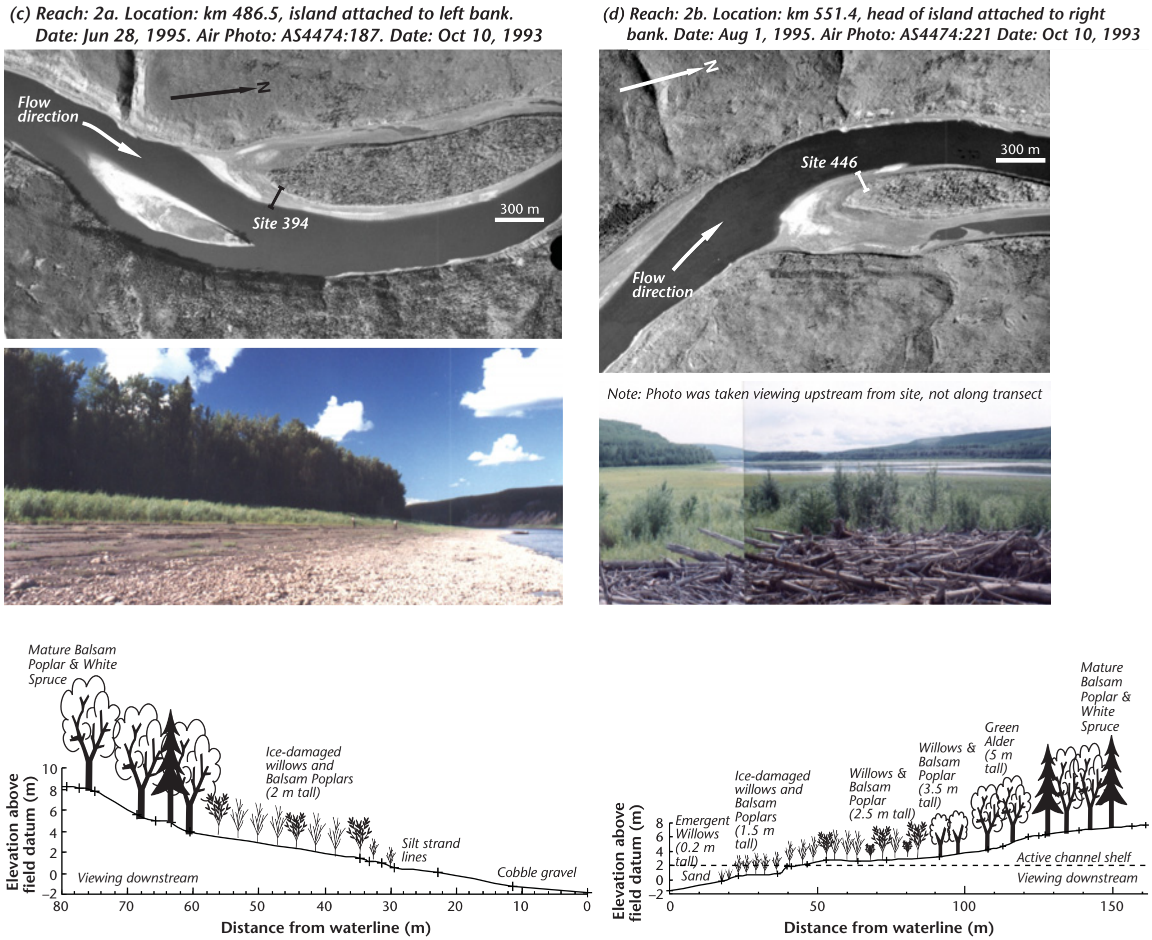


Figure 6.14 (*Continued*)

circumstance along icy rivers. At most depositional sites the active channel shelf is located at two to four meters above field datum (see Figure 6.14) and is composed of sand or silty sand. On average, this range is surprisingly consistent along the river despite trends in hydrology and sediment texture, and variations in the intensity of ice action. Local variations in exposure are more significant than river-length differences in controlling the variation in shelf elevation. The main difference between profiles is simply bank steepness, which is a function of exposure and sediment texture. At some locations on the upper river (e.g., Dunvegan) the "shelf" presents a strongly disturbed, ice-gouged surface, with significant erosion on the uppermost bank, behind the shelf, reminiscent of descriptions in Boucher *et al*. (2012, Figure 39.3). On the lower river both shelf and floodplain tend to be wider and vertical steps in silt or fine sand separate each level on the bank. As a result, ice damage is more restricted on the shelves and shrub communities are more mature than upstream. On the upper river, the vegetation condition suggests that the shelves are disturbed frequently, even annually in some places. This is likely due to ice-shove during freeze-up consolidation producing a significant stage rise.

The genesis of active channel shelves can be entirely fluvial (cf. Hupp and Osterkamp, 1985). On non-icy rivers Hupp and Osterkamp report that active channel shelves may be inundated for between 5% and 25% of the time. Marusenko, 1956 concluded that similar features in Russia—termed *becevnik* (Hamelin, 1972; the term means "tow path")—were formed by ice scour followed by bank slumping (and, accordingly, the term has

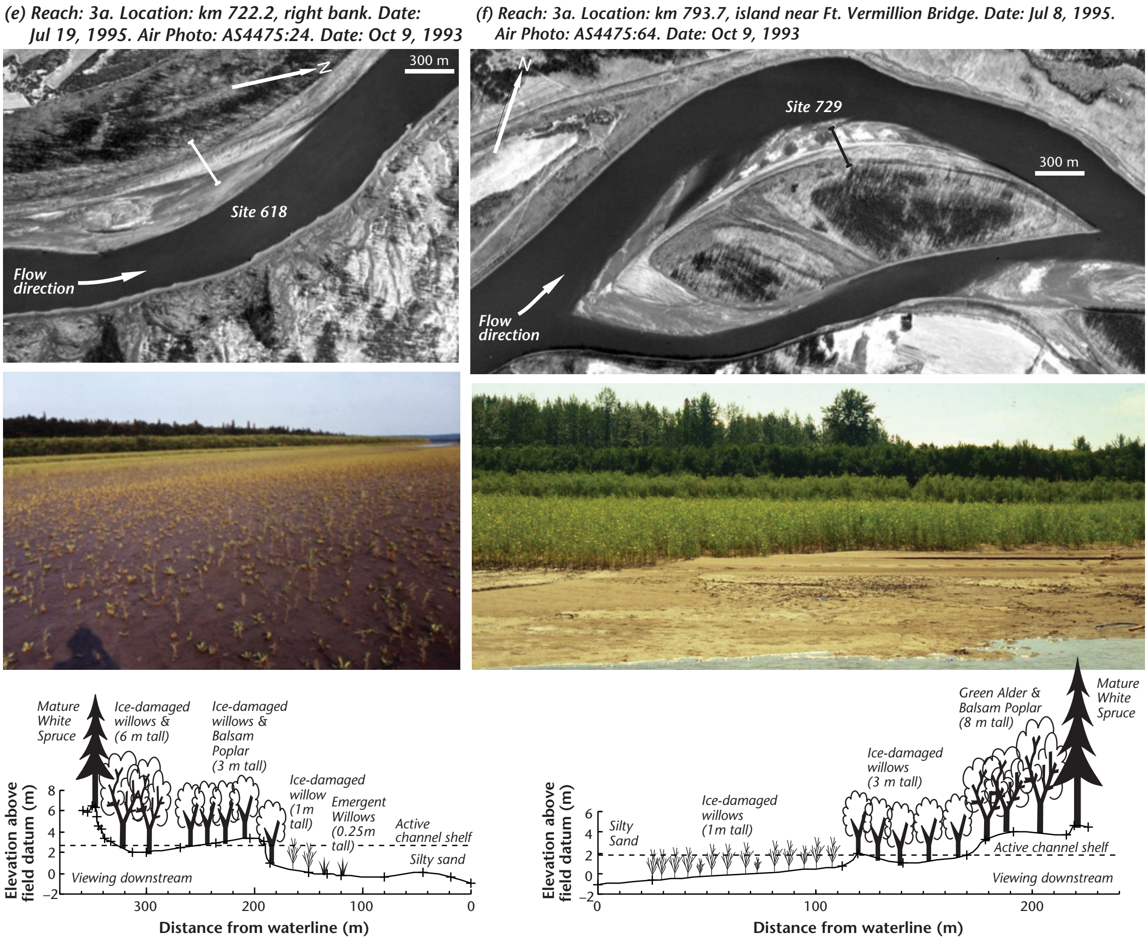


Figure 6.14 (*Continued*)

been applied to both scoured and depositional banks where ice activity is implicated). On Peace River they give the appearance of a post-regulation floodplain element inset into the pre-regulation channel zone but there is no doubt that, on the upper river at least, they are associated with ice scour and ice-mediated sedimentation. They are observed even in the British Columbia reach below Pine River, where contemporary ice action is quite limited. Ice scour and flooding of these surfaces in the Alberta reaches has occurred in between 27% and 86% of post-regulation years depending on location. Observations during and following ice jams show that ice action does play a role in maintenance of these shelves, both in episodically "resetting" the shrub vegetation succession and in promoting sedimentation when water moves over the shelves in early spring, outside the limit of fast or jammed ice in the main channel. Visible evidence of ice scour on the shelves is not prominent, but it has a relatively low chance of preservation in fine-grained sediments. In comparison, ice damage is much more restricted on upper floodplains; on Peace River these may either be pre-regulation flood levels, not now frequently broached, or a flood surface built to an unusually high level by deposition from floods associated with ice-jam water levels. As ice activity in the middle and lower river appears to have been relatively little affected by regulation and ice-associated flooding of the upper surface has been directly observed, the latter possibility appears very likely.

The question arises "is the overall channel geometry specially affected in icy rivers?" Smith (1979; 1980) has put forward the hypothesis that scour during ice drives has systematically enlarged channels in ice-infested rivers so that their equivalent bankfull open-water discharge (which is not the actual formative discharge, in the usual fluvial sense) would be up to 4.7 times larger than the usually quoted mean annual flood discharge. Boucher *et al.*, 2012 suggest 1.5 to 2 times enlargement. Smith's evidence is based on the widespread occurrence of a channel shelf in Albertan rivers, the seeming correspondence of shelf elevation with mean annual flood level, and the occurrence of a threshold in channel size below which neither ice drives nor channel shelves apparently occur. The argument has met substantial scepticism, but is difficult to adjudicate, one way or the other. Kellerhals and Church (1980) pointed out that Albertan alluvial rivers in general exhibit a suite of terrace levels in addition to a contemporary floodplain because the Holocene history of the rivers has generally been degradational, so that the occurrence of a "channel shelf" is not surprising. Furthermore, it is distinctly possible that the deposition of overbank sediment during ice-jam associated flooding builds the outer floodplain surface to unusually great height above the river (hence giving rise to the exaggerated open-water "bankfull" discharge estimates).

Neill (1973) and Bray (1973) have examined the hydraulic geometry of Albertan sand-bed and gravel-bed rivers, respectively, including Peace River gauging stations, and found them to be entirely consistent with regime relations derived elsewhere, including, in Neill's case, the Indian regime canals that gave rise to the regime "theory." Smith's (1980) own plot of bankfull hydraulic geometry is as coherent as any regime relation for natural rivers; a coherence that would seem rather unlikely for a group of rivers variously disturbed by ice action. But all of the rivers in these examples are, to some degree, subject to ice effects. A more critical test would compare the hydraulic geometry of Albertan rivers against that of sedimentologically similar rivers (i.e., ones in a similar regime group) in an ice-free environment.

Such a comparison is shown in Figure 6.15, using the width-discharge scaling relation. The relations derived for ice-free rivers, presented by Hey and Thorne (1986), are from British rivers with gravel-bed, sandy upper bank and bank vegetation condition varying from "heavy" (dense forest cover) to "light" (scattered shrub, sod, or little vegetation). The data for upper Peace River lie on an extension of the relation for "light vegetation"

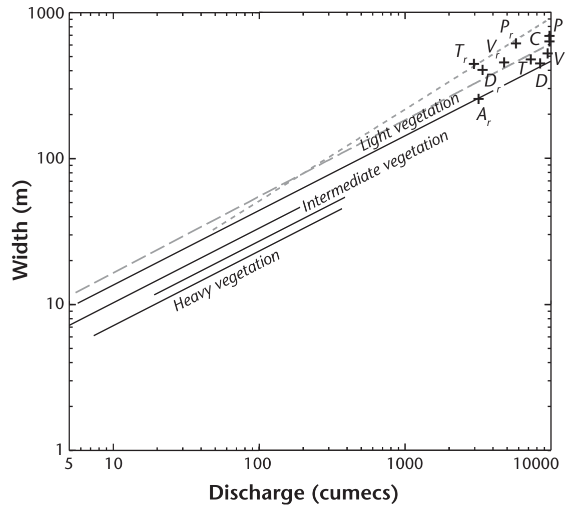


Figure 6.15 Width-discharge relations at bankfull for ice-free gravel-bed rivers with "heavy" bank vegetation and with "light" bank vegetation (data of Hey and Thorne (1986)); also shown, mean relations for Albertan gravel-bed (long dashed line, Bray, 1973) and sand-bed rivers (short dashed line, Neill, 1973). Data of Peace River stations are indicated by letter codes: *HH* = Hudson Hope; *T* = Taylor; *A* = Alces; D = Dunvegan Bridge; *C* = Carcajou; *V* = Fort Vermilion; *P* = Peace Point; subscript *r* indicates regulated flow.

in the British rivers, but data from the lower (sand bed) river fall above the relation. That may be the simple consequence of the different regime group to which the lower channel belongs. Peace River is much deeper than the rooting depth of floodplain trees on cut banks, but many banks along the river have the form of those illustrated in Figure 6.14, with shrubs and young trees growing to within two to three meters of our water datum (see Section 6.7), well below the level of the active shelf. On balance this evidence is equivocal; it is by no means clear, on either the field evidence of recent ice effects or the overall geometry of the Peace River channel, that ice has any major effect on the overall channel form. The topic deserves further study (Chapters 7 and 11).

6.7 Effects of ice on riparian vegetation

Riparian vegetation grows under edaphic conditions that are strongly influenced by the flood regime and associated sedimentation and scour. Riparian succession is made complex due to additional factors such as variable seed sources and diffusion mechanisms, diseases, variations in species' lifespans, and unpredictable extreme events, including fire. On boreal and subarctic rivers, ice drives and ice jams represent event disturbances along channel margins that redistribute litter, sediments, and nutrients and directly impact the standing vegetation (Scrimgeour *et al.*, 1994), hence impact community and ecosystem functioning.

Vegetation galleries reflect unit successions or seres. In riparian zones, they are organized by elevation above the river. With increasing elevation, vegetation becomes older and taller, reflecting the gradient in frequency of flood and ice-related disturbance. Following regulation of Peace River, reduced summer water levels have resulted in extensive secondary succession within existing floodplain communities and primary succession on bars and in secondary channels (Figure 6.14). Riparian species found along the river are listed in Table 6.1. Ice jams remain the dominant form of physical disturbance and only rare summer floods below the Smoky confluence are effective in impacting riparian communities. The distribution of disturbance is not uniform along the river. At highly exposed locations, such as cut banks and island heads, annual ice shove scours the surface and restricts vegetation to interrupted, very early primary succession. In low-exposure sites, such as secondary channels, ice effects are less conspicuous and may be limited to the promotion of sedimentation associated with ice jam–related water levels.

Figure 6.16 displays the lower bounding elevation of five riparian communities (Table 6.2), generally corresponding with seres, plotted as sub-reach means. Elevations are seen to vary significantly along the reach. Mature forest (Class 5) varies from four to nine meters above field datum, young trees and very tall shrubs (Class 4) vary from two to five meters, while shrubs of Classes 2 and 3 occupy positions between zero and four meters above field datum. Herbaceous species in Class 1 are generally below 0.5 m. The episodic removal of the lower, younger shrub communities precludes their use as a long-term indicator of ice disturbance, but forest trees and tall shrubs (Classes 4 and 5) provide an index of the downstream local severity of ice disturbance.

Elevations of the edge of mature forest (Class 5) are moderately well correlated with the scar record (R^2 = 0.61), suggesting that the elevation of the forest edge

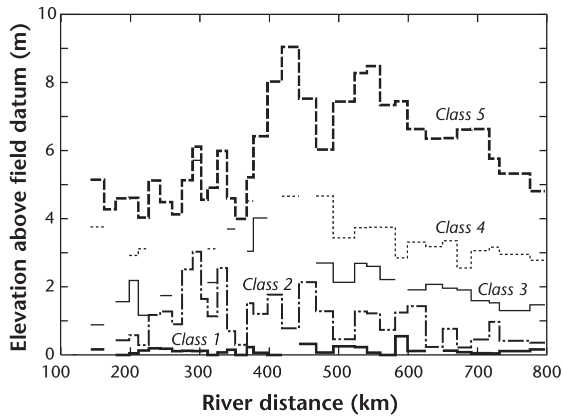


Figure 6.16 Lower bound of riparian vegetation communities along Peace River, plotted as sub-reach means. Reference elevation is field river datum. Community definitions as in Table 6.2. Discontinuities indicate absence of the type at most sites within the reach or too small a sample size.

provides a comparable index of the limit of ice disturbance. However, the difference between the elevation of the forest edge and the elevation of scar/trim-line elevations is not consistent along the river. Upstream of Smoky River, the heights of scars are on average one meter above the base of mature trees, but above Dunvegan Bridge scars are up to three meters above the base of trees. Above Dunvegan Bridge, as well, the elevation of shrub communities is notably variable. These factors point to the effect of freeze-up consolidation jams in this part of the river, when ice may reach relatively high elevations but be sufficiently weak not to shove trees over, and to the greater prevalence of thermal breakup along this east–west oriented and southernmost portion of the river.

Downstream from Smoky River, the elevation of the forest edge points to the most severe ice disturbances occurring near km 437, 537, and 680. The downstream limit of the reaches near km 437 and 537 are marked by highly sinuous and confined meanders where ice frequently jams. Near km 680 ice is apt to jam upstream of wide point bars that constrict ice passage. Along the lower river, ice-jam flooding is relieved in most sites by secondary channels and an increasingly wide floodplain so that running average scar heights fall within Class 4 vegetation on the lower river.

Since many riparian communities recover rapidly after scour or "mowing down," (e.g., *Salix*, *Alnus*, and *Populus* will resprout from roots, stumps, or flattened but still viable stems), measurements of the age and elevation of erect stems provides an estimate of the date and stage of former ice disturbance events. Assuming that the maximum age of woody vegetation on a transect approximates the return period for ice scouring events of a magnitude sufficient to uproot or crush vegetation at and below its elevation, we may construct return period plots for ice disturbance at various elevations above field datum. The results on age-elevation are remarkably consistent (Figure 6.17a), indicating that community age for sites in the zone of the active shelf vary between 5 and 30 years, whereas higher sites on the now abandoned floodplain are much older. We may therefore assume that the former flood surface is now rarely disturbed by ice activity. Data on return periods exhibit a consistent overall trend (Figure 6.17b) but are more scattered by virtue of the influence of local site effects on the frequency of ice disturbance. Plots for individual sites are quite coherent. Furthermore, sites on the upper river (e.g., sites 116 and 229) exhibit the highest elevations for a given return period, whilst sites on the lower river (e.g., sites 618 and 729) exhibit the steepest trends. The indication for the lower river sites is consistent with what we have learned from the scar data. We may, again, ascribe the differences to the dominant effect of freeze-up jams on the upper river, and occasionally severe breakup jams on the middle and lower river.

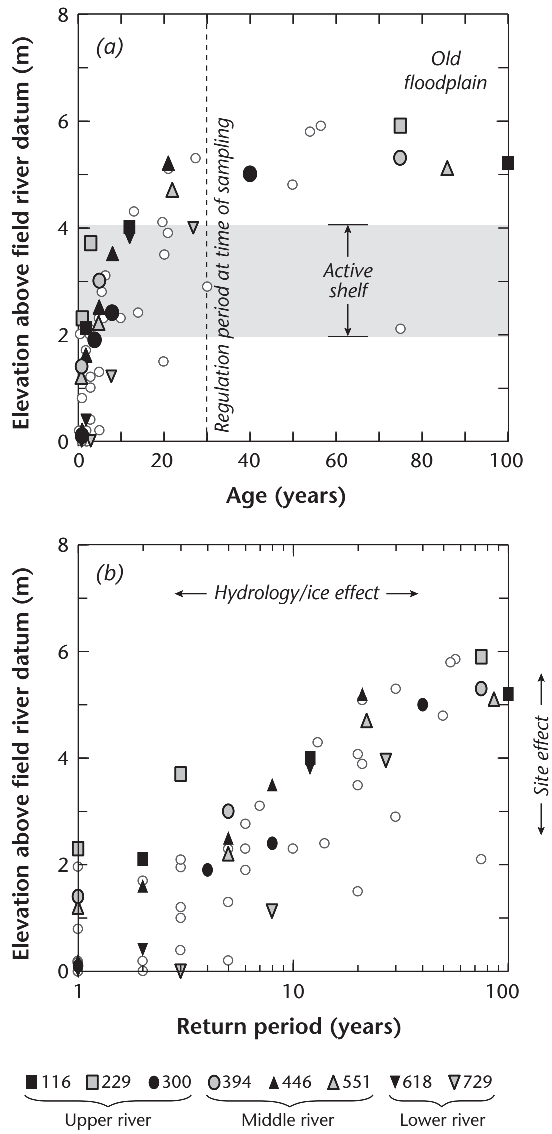


Figure 6.17 (a) Age-elevation plots for vegetation sampled on the bank profiles of Figure 6.14 (with additional sites) and (b) derived return period plots for ice disturbance at elevations above river field datum. Locations of plotted sites are shown in Figure 6.1 and Figure 6.10. Open circles are data from additional sites along the river.

6.8 Conclusions

Insight into the incidence and severity of ice jams along Peace River is gained by recording the position and elevation of ice-scarred trees and other vegetation disturbance along the river. One learns that the most severe disturbances are experienced in the middle river, downstream from the Smoky River confluence, but that extreme events are relatively infrequent. Indeed, it is possible to construct magnitude–frequency plots (Figures 6.8 and 6.17) for ice-jam effects in the regulated regime at various sites or sub-reaches along the river. The reader is strongly advised, however, that these plots remain tentative because the data on which they are erected derive from a reconnaissance study along the river and certainly remain incomplete.

Ice jams and ice drives are found to affect trends of vegetation succession in the riparian zone, particularly in the lower communities (class 0 and class 1) where scour frequently resets succession to the initial point. Classes 2 and 3—intermediate and high shrub communities—are more persistent but experience frequent damage that may or may not reset the succession. Classes 4 and 5 are persistent but exhibit ice scars and other damage that record the highest levels reached by ice. Given that associated flood water levels may be 0.5 to 1.5 m lower than the limit of ice damage and the restriction of damage in Class 5 (mature forest, characteristic of the pre-regulation floodplain) at the stand edge, it appears that the former floodplain is no longer frequently or severely disturbed by direct ice action, though floodwaters may escape jams via the floodplain on the lower middle and lower river.

Morphological and sedimentary features related to river ice activity are pervasive along the river but are of small scale in comparison with the channel scale of some 500 m (width). Some of these features are singular in character. Altogether, the features attest to the widespread occurrence of ice activity but they do not suggest that the overall river morphology is significantly affected by it. A comparison between the hydraulic geometry of Peace River and that of ice-free rivers in an ostensibly similar regime group to determine whether ice has any overall effect on river hydraulics and channel-scale morphology is not conclusive.

The major reaches of the river identified in this study exhibit distinctive regimes of ice activity. In the proximal—British Columbia—reach of the river, ice effects are restricted to local scour features since ice is absent or transient. In the Alberta reach of the upper river, the length of the ice season has been substantially reduced by the release of relatively warm water from the upstream reservoirs. In some winters ice is transient in the reach. The most severe ice-jam activity is associated with freeze-up ice consolidation events and with mid-winter thaw and refreeze events. In comparison, the southern location and east–west orientation of this part of the river, and the relatively limited thickness of the ice cover encourage thermal breakup before the spring freshet from Pine River—the principal upstream tributary—arrives. Local morphology and downstream position create effects that are, on average, more severe in the vicinity of and downstream from Dunvegan Bridge than farther upstream. These effects are influenced by the flow regime imposed by the upstream dams and are likely quite different than in the pre-regulation regime, but we have no corroborating evidence of comparable quality.

The northerly flowing middle reach of the river, downstream from the Smoky confluence, has subreaches with tortuous confined meanders, including ones with channel islands in the bends. These form constrictions in the river where the most severe ice jams are experienced. Comparisons with historical records of ice-jam effects at TPR and Fort Vermilion indicate that the post-regulation magnitude and frequency of ice effects below the Smoky River confluence are consistent with what is known about pre-regulation effects. This suggests that the northerly course of the river and the dominant effect of the timing and magnitude of the Smoky River spring flood remain the main controls over the occurrence of ice jams in this part of the river and that regulation has not changed the pattern in major degree. But, again, the reader must be cautioned that the historical comparison is based on just two sites and that no direct "on site" comparison is possible except at TPR.

The lower river, below Carcajou, becomes a sand-bed river with a wider channel and much less confinement. Here, ice-jam effects are again less severe, on average. Nevertheless, there are still bend sequence and channel islands that can constrict mobile ice passage. The long-term record at Fort Vermilion indicates that very severe events may occur there, but much less frequently than upstream. Over the length of the river, there is a striking correspondence between river morphology and the frequency and magnitude of ice jams that has not been obscured by the effects of regulation.

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References

Andres, D. (1995) A case study: freeze-up and jamming on the Peace River at Peace River, in *River Ice Jams*, edited by S. Beltaos. Water Resources Publications, Highlands Ranch, CO. pp. 287–308.

Andres, D. (1996) The effects of flow regulation on freeze-up regime: Peace River, Taylor to Slave River. *NRBS Study, Project Report* 122. Northern River Basins Study, Edmonton, Canada. 84 p.

Beltaos, S. (1993) Transport and mixing processes. *Environmental Aspects of River Ice*, *NHRI Science Report*, 5. National Hydrological Research Institute, Saskatoon, Canada, pp. 31–42.

Beltaos, S. (editor). (1995) *River Ice Jams*, Water Resources Publications, Highlands Ranch, CO. 327 p.

Beltaos, S. (2008) Progress in the study and management of river ice jams. *Cold Regions Science and Technology*, 51, 2–19. doi:10.1016/j.coldregions.2007.09.01

Beltaos, S. and Carter, T. (2009) Field studies of ice breakup and jamming in lower Peace River, Canada. *Cold Regions Science and Technology*, 56, 102–114. doi:10.1016/j.coldregions.2008.11.12

Beltaos, S., Prowse, T. D., and Carter, T. (2006) Ice regime of the lower Peace River and ice-jam flooding of the Peace–Athabasca Delta. *Hydrological Processes*, 20, 4009–4029. doi:10.1002/hyp.6417

Boucher, E., Bégin, Y., Arsenault, D., and Taha, B. M. J. (2012) Long-term and large-scale river-ice processes in cold-region watersheds, in *Gravel-Bed Rivers: Processes, Tools, Environments*, edited by M. Church, P. Biron, and A. Roy, John Wiley & Sons, Ltd, Chichester, UK. pp. 546–554.

Bray, D. I. (1973) Regime relations for Alberta gravel-bed rivers, in *Fluvial Processes and Sedimentation, Proceedings of the 9th Canadian Hydrology Symposium*, May 8–9, Edmonton, Canada. National Research Council of Canada, Subcommittee on Hydrology, Ottawa, Canada. pp. 440–452.

de Rahm, L. P., Prowse, T. D., and Bonsal, B. R. (2008a) Temporal variations in river-ice break-up over the Mackenzie River Basin, Canada. *Journal of Hydrology*, 349, 441–454. doi:10.1016/j.hydrol.11.018

de Rahm, L. P., Prowse, T. D., Beltaos, S., and Lacroix, M. P. (2008b) Assessment of annual high-water events for the Mackenzie River basin, Canada. *Hydrological Processes*, 22, 3864–3880. doi:10.1002/hyp.7016

Dionne, J. C. (1976) L'action glacielle dans les schores du littoral oriental de la Baie de James. *Canadian Geographical Journal*, 88(2), 4–9.

Doyle, P. F. (1988) Damage resulting from a sudden river ice break-up. *Canadian Journal of Civil Engineering*, 15, 609–615. doi:10.1139/l88-082

Eardley, A. J. (1938) Yukon channel shifting. *Geological Society of America Bulletin*, 49, 343–358.

Eggington, P. A. (1980) Determining river ice frequency from the tree record. *Current Research, Part A*, Geological Survey of Canada, Paper 80-1A, 265–270.

Ettema, R. (2002) Review of alluvial-channel responses to river ice. *Journal of Cold Regions Engineering*, 16, 191–217. doi:10.1061/(ASCE)0887-381X(2002)16:4(191)

Gerard, R. (1981) Ice scars: are they reliable indicators of past ice break-up water levels? *Proceedings of the 6th International Association for Hydraulic Research International Symposium on Ice*, Jul 27–31, Quebec City, Canada. pp. 847–859.

Gerard, R. and Karpuk, E. W. (1979) Probability analysis of historical flood data. *Journal of the Hydraulics Division* [American Society of Civil Engineers], 105, 1153–1165.

Hamelin, L.-E. (1972) Le glaciel de Iakoutie en Siberie Nordique. *Biuletyn Periglacjalny*, 21, 75–86.

Hey, R.D. and Thorne, C.R. (1986) Stable channels with mobile gravel beds. *Journal of the Hydraulics Division* [American Society of Civil Engineers], 112, 671–689.

Hupp, C. R. and Osterkamp, W. R. (1985) Bottomland vegetation distribution along Passage Creek, Virginia, in relation to fluvial landforms. *Ecology*, 66, 670–681.

Jasek, M., Friensenhan, E., and Granson, W. (2007) Operational ice forecasting on the Peace River—managing flood risk and hydropower production. *14th Workshop on the Hydraulics of Ice Covered Rivers*, Jun 19–22, Quebec City, Canada. Canadian Geophysical Union, Hydrology Section, Committee on River Ice Processes and the Environment, http://cripe.civil.ualberta.ca/proceedings/cripe-workshop14.html (last accessed Mar 15, 2010).

Keenhan, T., Panu, U. S., and Kartha, V. C. (1982) Analysis of freeze-up ice jams on the Peace River near Taylor, British Columbia. *Canadian Journal of Civil Engineering*, 9, 176–188. doi:10.1139/l82-021

Kellerhals, R. and Church, M. (1980) Comment on 'Effects of channel enlargement by river ice processes on bankfull discharge in Alberta, Canada' by D. G. Smith. *Water Resources Research*, 16, 1131–1134. doi:10.1029/WR016i006p01131

Kindle, E. M. (1918) Notes on sedimentation in the Mackenzie River basin. *Journal of Geology*, 26, 341–360.

Koutaniemi, L. (1984) The role of ground frost, snow cover, ice break-up and flooding in the fluvial processes of the Oulanka River, NE Finland. *Fennia*, 162, 127–161.

MacKay, D. K., Sherstone, D. E., and Arnold, K. C. (1974) Channel ice effects and surface water velocities from aerial photography of Mackenzie River break-up, in *Hydrological Aspects of Northern Pipeline Development*, Environmental Social Committee, Northern Pipelines, Task Force on Northern Oil Development, Ottawa Canada. Report 74-12, pp. 233–257.

Mackay, J. R. (1958) The valley of the lower Anderson River, N.W.T. *Geographical Bulletin*, 11, 37–56.

Mackay, J. R. and MacKay, D. K. (1977) The stability of ice-push features, Mackenzie River, Canada. *Canadian Journal of Earth Sciences*, 14, 2213–2225. doi:10.1139/e77-190

Marusenko, Y. I. (1956) Deyatel 'nost' l'da na beregakh rek [Ice action on river banks]. *Priroda*, 12, 91–93.

Melin, R. (1954) Stream erosion and sedimentation at low water in winter, *Proceedings of the International Association of Scientific Hydrology*, General Assembly at Rome, 3, 257–260.

Mercer, A. G. and Cooper, R. H. (1977) River bed scour related to the growth of a major ice jam, *Proceedings of the 3rd Canadian Hydrotechnical Conference*, Quebec, Canada. Canadian Society for Civil Engineering, Montreal, Quebec, pp. 291–308.

Milburn, D. and Prowse, T. D. (2000) Observations on some physical-chemical characteristics of river-ice breakup. *Journal of Cold Regions Engineering*, 14, 214–223. doi:10.1061/(ASCE)0887-381X(2000)14:4(214)

National Research Council of Canada [NRCC]. (1989) Ice jam floods, in *Hydrology of Floods in Canada: A Guide to Planning and*

Design, edited by W. E. Watt. NRCC, Ottawa, Canada. pp. 169–183.

Neill, C. R. (1973) Hydraulic geometry of sand rivers in Alberta, in *Fluvial Processes and Sedimentation: Proceedings of the 9th Canadian Hydrology Symposium*, May 8–9, Edmonton, Canada. National Research Council of Canada, Subcommittee on Hydrology, Ottawa, Canada. pp. 453–461.

Osterkamp, W. R. and Hupp, C. R. (1984) Geomorphic and vegetative characteristics along three northern Virginia streams. *Geological Society of America Bulletin*, 95, 1093–1101. doi:10.1130/0016-7606(1984)95<1093:GAVCAT>2.0.CO;2

Parker, M. L. and Josza, L. A. (1973) Dendrochronological investigations along the Mackenzie, Liard, and South Nahanni Rivers, N.W.T., Technical Report No. 10, Glaciology Division, Water Resources Branch, Department of the Environment, Canada. 187 p.

Prowse, T. D. (1994) Environmental significance of ice to streamflow in cold regions. *Freshwater Biology*, 32, 241–259.

Prowse, T. D. (2001) River ice ecology I: hydrologic, geomorphic, and water-quality aspects. *Journal of Cold Regions Engineering*, 15, 1–16. doi:10.1061/(ASCE)0887-381X(2001)15:1(1)

Prowse, T. D. and Conly, F. M. (1998) Effects of climate variability and flow regulation on ice-jam flooding of a northern delta. *Hydrological Processes*, 12, 1589–1610.

Prowse, T. D. and Lalonde, V. (1996) Open-water and ice-jam flooding of a northern delta. *Nordic Hydrology*, 27, 85–100.

Scrimgeour, G. J., Prowse, T. D., Culp, J. M., and Chambers, P. A. (1994) Ecological effects of river ice break-up: a review and perspective. *Freshwater Biology*, 32, 261–275, doi:10.1111/j.1365-2427.1994.tb01125.x.

Sigafoos, R. S. (1964) Botanical evidence of floods and flood-plain deposition. *United States Geological Survey. Professional Paper*, 485-A, 35 p.

Smith, D. G., (1979) Effects of channel enlargement by river ice processes on bankfull discharge in Alberta, Canada. *Water Resources Research*, 15, 469–475. doi:10.1029/WR015i002p00469

Smith, D. G. (1980) River ice processes: thresholds and geomorphic effects in northern and mountain rivers, in *Thresholds in Geomorphology*, edited by D. R. Coates and J.D. Vitek. George Allen and Unwin, London. pp. 323–345.

Smith, D. G. and Reynolds, D. M. (1983) Tree scars to determine the frequency and stage of high magnitude river ice drives and jams, Red Deer, Alberta, *Canadian Water Resources Journal*, 8(3), 77–94. doi:10.4296/cwrj0803077

Uunila, L. S. (1997) Effects of Peace River ice on bank morphology and riparian vegetation along Peace River, Clayhurst to Fort Vermilion, in *Proceedings of the 9th Workshop on River Ice*, edited by S. Ismail. Sept 24–26, Fredericton, Canada. National Research Council of Canada, Ottawa, Canada. pp. 315–334.

Wentworth, C. K. (1932) The geological work of ice jams in Sub-Arctic rivers, in *Contributions on Geology and Geography*, edited by L. F. Thomas. Washington University Studies, Science and Technology No. 7. Washington University, St. Louis, MO. pp. 64–67, 49–80.

Williams, G. P. (1973) Seminar on ice jams in Canada, *Technical Memorandum*, 107, 182 p. National Research Council of Canada, Ottawa, Canada.

CHAPTER 7

Post-regulation morphological change on Peace River

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7.1 Introduction

Flow regulation changes at least one—usually both—of the principal conditions that govern the morphology of alluvial rivers. Modification of the flow regime initiates downstream changes by which the channel seeks to become adjusted to the new frequency distribution of regulated flows (Petts, 1984; Andrews, 1986; Grant *et al.*, 2003). Usually, sediment transfer along the channel is more or less completely interrupted as well, so adaptation also occurs to the changed regime of sediment supply downstream. A common response is channel degradation below the point of flow regulation (Galay, 1983; Williams and Wolman, 1984). Petts (1984), in a comprehensive review of the effects of river regulation, listed three principal responses that might occur: passive response, in which mainstem flows are reduced below the level of competence to move the river-bed sediments so that the active channel simply shrinks within the pre-existing channelway; degradation, due to sediment starvation downstream of the dam and active erosion by the clear water; or aggradation, due to sediment inputs which the river is no longer competent to move farther on, the most common source being tributaries. Brandt (2000) has further specified the morphological response in terms of varying channel cross-sectional adjustments, the nature of which depend on the character of riverine sediments. Gaeuman *et al.* (2005) have presented an example of primarily vertical adjustments of the channel bed in sand-bed reaches, contrasted with primarily lateral adjustments in gravel-bed reaches.

In Peace River, British Columbia, regulation at W.A.C. Bennett Dam and Peace Canyon Dam has reduced flows below the level of competence in the cobble-gravel channel immediately downstream, producing a passive to aggradational response in the first 300 km of the river, demonstrated by survey (Chapter 3). This response prospectively extends 390 km below the dams, to the confluence with Smoky River where Peace River, in any case, encounters bedrock control. Beyond that point, the channel response has not been surveyed, but there is the possibility for a major change in the style of adjustment.

Smoky River is the major tributary of Peace River. In the regulated regime, the mean annual flood is increased by 65% at this confluence and a large sand and silt load—the order of 10^7 to 10^8 tonnes a^{-1}—is delivered to the river. We hypothesize that the river adjustment downstream will exhibit three distinct phases:

- initial, mainly passive adjustment to the reduced flood flows;
- vegetation progradation onto abandoned bar surfaces and channel edges, leading to an increase in flow resistance during high flow and fine-sediment trapping;
- aggradational response due to sand deposition in the reduced channel, becoming stronger downstream as gradient declines.

In fact, aggradation appears to have commenced in a more distal reach but not yet to have significantly changed the character of the channel. This response is different than in the upper river, where the reduction of post-regulation flows below the competence limit to transport the bed gravel, and the relatively small sand load, have combined to create a truly passive response in long stretches of channel, with aggradation close to tributary junctions and sites of landslide sediment inputs.

The Regulation of Peace River: A Case Study for River Management, First Edition. Michael Church.

Companion website: www.wiley.com/go/church/peaceriver

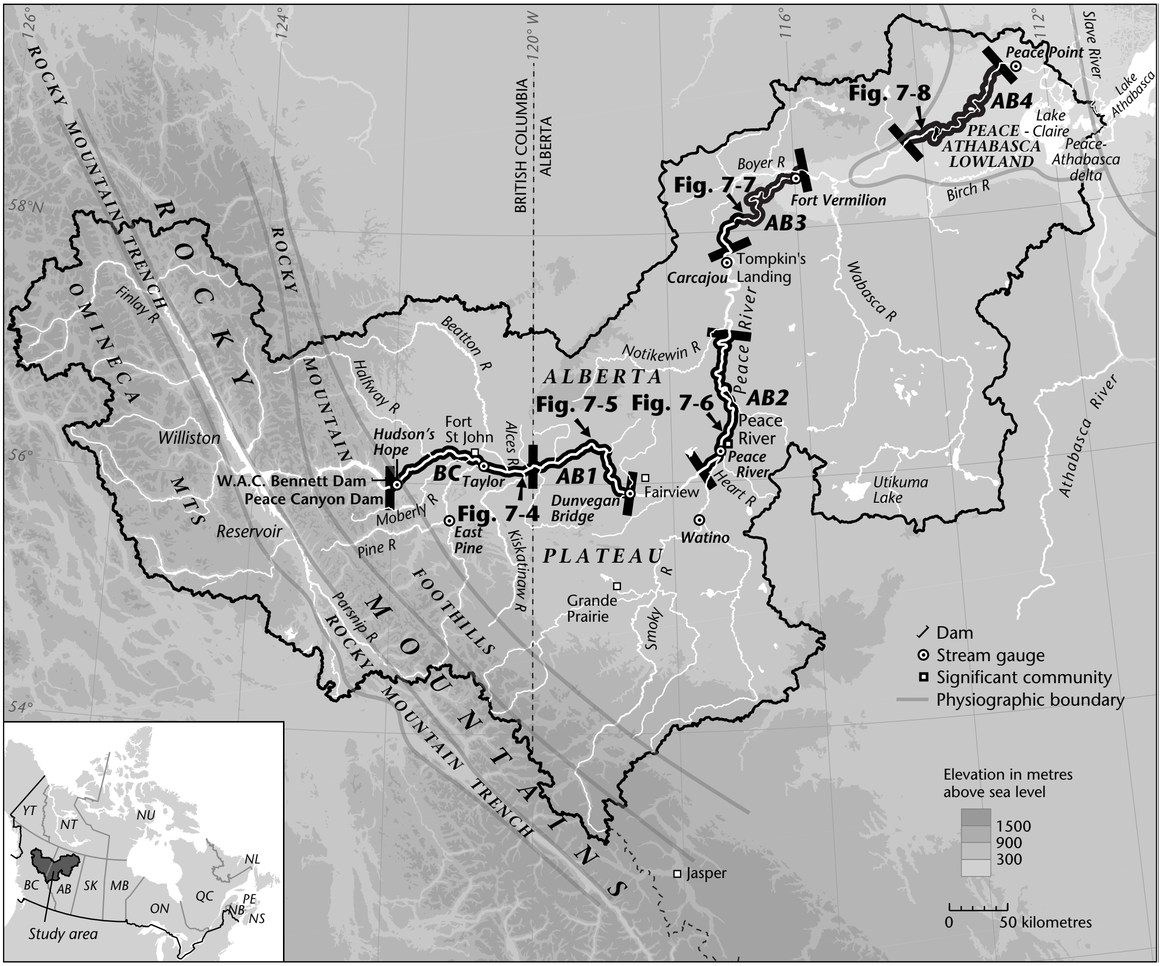

Figure 7.1 Map of Peace River basin showing the study reaches and gauges referred to in this chapter. Locations of morphological change maps illustrated in Figures 7.4 to 7.8 are indicated.

The aggradational adjustments have entailed vertical accretion in both the gravel-bed and sand-bed reaches, although overall shrinkage of the channels is also associated with lateral accretion.

In this chapter, we describe morphological evidence of the river's response to regulation obtained from air photo-based mapping exercises and field reconnaissance. Channel gradation is inferred from this evidence. The river is examined over the entire 1220 km course from Peace Canyon Dam to its confluence with Lake Athabasca outflow to form Slave River (Figure 7.1). Evidence gained by the methods used in this paper can be compared directly with field evidence reported in Chapter 3 for gradation in the upper river (i.e., above the Smoky confluence), and a comparison between the two major divisions of the river can be made using comparable evidence.

7.2 Study reaches

Peace River rises in the northern Rocky Mountains of British Columbia and flows 500 km east to its confluence with Smoky River, its principal tributary, at the Town of Peace River (TPR), Alberta. There it turns north and northeast to flow another 855 km to the Peace–Athabasca delta. The river is regulated by two dams near Hudson's Hope, at the eastern edge of the mountains. Drainage area at the point of regulation is 69 900 km^2

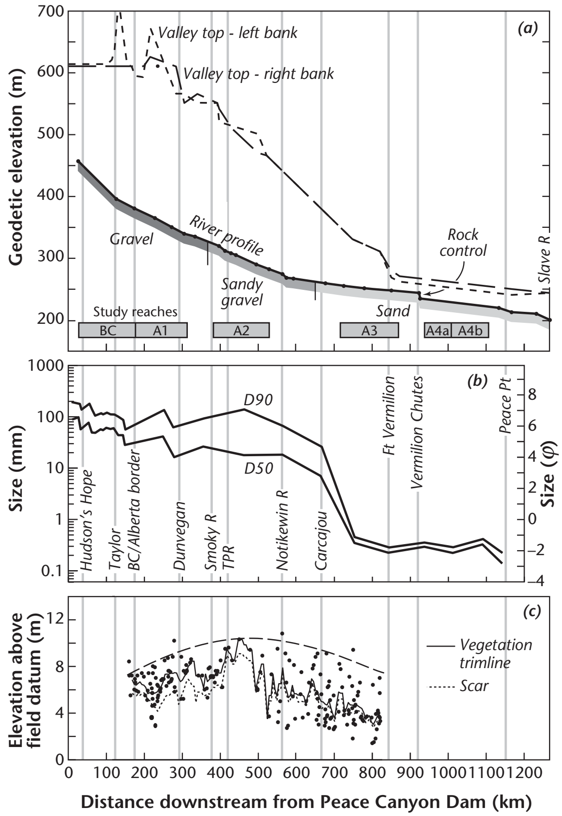

Figure 7.2 Long profile of Peace River, showing (a) the river entrenchment, (b) surface bed material grain size, and (c) the upper envelopes of ice damage (upper limit of damaged trees) and 20-km running averages of tree damage and of scar tissue (Chapter 6). The location of the study reaches is also shown.

and the regulated mean flow is 1135 m^3s^{-1}. At TPR the regulated fraction of drainage area is 38%, and at Peace Point it is 24%. Nevertheless, more than 50% of the river flow at Peace Point derives from the regulated mountain headwaters, which are considerably more humid than the Alberta Plateau to the east. On the other hand, nearly all of the river's sediment load derives from the Alberta Plateau and from the valley sides immediately adjacent to the river, a legacy both of Quaternary history and bedrock geology (see Chapter 2 for additional details).

The river is entrenched into the Alberta Plateau for about 830 km (Figure 7.2) and is sometimes confined. The river valley is cut into a succession of Cretaceous sediments with a shallow northeast dip. Most formations are poorly lithified and, since the valley depth is much greater than water table depths on the plateau, they are prone to deep-seated landsliding at seepage zones along the valley sides.

The entire river, apart from alpine headwaters, lies in Canada's boreal zone. The climax floodplain vegetation is *Picea glauca* (white spruce) with *Populus tremuloides* (trembling aspen). *Betula papyrifera* (white birch) occurs on well-drained sites and *Picea mariana* (black spruce) dominates wet sites, while *Pinus contorta/Pinus banksiana* (Lodgepole/Jack pine complex) is the major fire succession species. An important floodplain seral species is *Populus balsamifera* ssp. *balsamifera* (balsam poplar), which becomes senescent at about 150 years. Gallery forests of *Alnus incana* ssp. *tenuifolia* (mountain alder) and *Salix* spp. (willows) occur on increasingly wet sites with fine soils along the river margin, while *P. balsamifera* colonizes gravelly sites. These species can withstand seasonal inundation and can survive repeated flood and ice damage. All are shallow rooting species which do not provide deep bank reinforcement along the river (see Chapter 8 for further details on riparian vegetation).

Bed material size (Figure 7.2) declines from cobble gravel ($D_{90} \approx 120$ mm; $D_{50} \approx 38$ mm) below the dams to pebble gravel ($D_{90} \approx 40$ mm; $D_{50} \approx 8$ mm) at the Smoky confluence. The gravel–sand transition occurs near km 675 below the dams. The sedimentary style of the upper river floodplain is cobble gravel overlain by 0.5 to 2 m of upwardly fining sands and a silty floodplain soil, a common alluvial succession along rivers of the Cordilleran valleys and forelands (Desloges and Church, 1989). The gravels are laid down in mid-channel and lateral bars, while the overlying sands represent flood deposits. The sandy upper member becomes steadily more prominent downstream and, beyond Carcajou, the river banks become composed entirely of sand, except where ice-rafted gravels and lag gravels eroded from non-alluvial river banks occur. With the prominence of landsliding all along the incised reaches of the river, delivery of rock to the river is not unusual, but most of the lithologies are friable and quickly broken down in the northern freeze–thaw environment.

Because of its northern position and northward flow, the river is subject to major ice jams (Chapter 6), indeed the highest water stages are due to dynamic breakup jams (Gerard and Karpuk, 1979). Figure 7.2 shows the upper envelope of ice trim lines and scarred trees along Peace River in comparison with the positions of the study reaches. Ice scour is an important erosive agent

Table 7.1 Summary on the study reaches and associated gauges

Reach	km blw. dam	Gauge (WSC[a] no.)	km blw. dam	Drainage area (km^2)	Mean annual flow (m^3s^{-1})		Mean annual flood (m^3s^{-1})		River gradient[d]
					Pre-reg.[2]	Post-reg.[c]	Pre-reg.[b]	Post-reg.[c]	
BC	0 to 142.7	Hudson's Hope (07EF001)	6.5	69 900	1198_{1949+}	1135	5843	1927	0.00062
		Taylor (07FD002)	103	97 100	1560_{1945+}	1456	7213	2837	0.00062
AB1	142.7 to 276.8	Dunvegan (07FD003)	275	130 000	*	*	8275_{1960+}	3379	0.00033
AB2	351.3 to 496.1	Town Peace River (07HA001)	377	186 000	1919_{1957+}	1883	9700	5564	0.00030
AB3	670.5 to 828.9	Fort Vermilion (07HF001)	808	223 000	2357_{1961+}	*	9577	4894_{1978-}	0.000070
AB4	872.0 to 1055.2	Peace Point (07KC001)	1115	293 000	2327_{1959+}	2100	9817	5691	0.000012

[a]Water Survey of Canada

[b]From the year indicated by subscript (under mean annual flow) through 1967.

[c]1973 to 2010, excluding 1996, except where a later start date (+) or earlier end date (–) is noted by subscript.

[d]Reach average.

*Station operated seasonally: mean annual flow not available.

along the river banks, especially in the northward flowing reach downstream of TPR.

The data for this paper were measured on maps of interpreted river morphology constructed photogrammetrically for several dates from medium- to large-scale air photos (see "Methods," below). This is a laborious process, so not all the river has been mapped. Study reaches have been chosen to reflect the principal valley settings of the river and each study reach is associated with one or more stream gauges (see Table 7.1). In total about 763 km (62%) of the 1223 km course below the dams have been mapped.

Mapping is continuous for the first 277 km below Peace Canyon Dam, comprising two distinct reaches. In the British Columbia reach (147 km; designated in what follows as "BC"), the river flows in a relatively broad, preglacial valley about 250 m below the surrounding plateau. Major landslides, some of them chronically active, are common along the valley sides (Severin, 2004) and, where the river impinges on the valley wall, river action promotes slope instability. The most recent major landslide occurred at Attachie, immediately upstream of the Halfway River confluence, in 1973 and blocked the river for several days (Evans *et al.*, 1996). Immediately below the dams, the river is entrenched by some 30 m into and flows on bedrock but, from Lynx Creek (approximately 14 km below Peace Canyon Dam), there are floodplains or terrace surfaces along one or both sides of the river and it flows on a cobble-gravel bed. The channel has a wandering habit with exposed gravel bars and mostly nonoverlapping channel islands (but see Figure 7.4), while sinuosity is low, averaging only about 1.04. Average gradient in the British Columbia reach is 6.2×10^{-4} while average channel zone width is about 550 m, though it may expand to a kilometer in multithread sections. Since regulation, seasonal ice cover has not formed in the reach upstream of Taylor (km 110); frazil ice and pan ice have developed under some dam-operating regimes and ice jams have occurred, but dam-operating policy has discouraged these phenomena in recent years. The first major tributary, Pine River, enters in this reach 101 km below Peace Canyon Dam. The reach is subdivided into six subreaches according to details of the channel habit and the confluence of tributaries (Table 7.2).

At the British Columbia–Alberta border the river enters a confined, canyon-like reach, a postglacial valley, that extends for 134 km to Dunvegan and is defined as Reach AB1. The river lies 200 to 250 m below the adjacent plateau and the valley flat is restricted to narrow and discontinuous terraces and floodplain. Slumping of the valley walls is common (Cruden *et al.*, 1990). The channel is about 500 m wide and dominantly single thread. Island groups occur where the river executes

Table 7.2 Location and summary character of study sub-reaches

Sub-reach	River km	Morphological character
British Columbia (BC)		
1. Hudson Hope	0–17.8	Rockbound, includes rocky channel islands
2. Farrell Creek	–39.9	CGr, nonoverlapping islands
3. Halfway River	–83.7	CGr, nonoverlapping islands
4. Moberly River	–100.8	CGr, occasional islands
5. Pine River	–121.0	Gr, low-order anabranches
6. Beatton River	–147.7	Gr, low-order anabranches
Alberta		
AB1		
1.1 Pouce Coupe River	147.7–168.1	Gr, confined
1.2 Clear River	–183.3	Gr, confined
1.3 Campbell's Lease	–202.2	Gr, mainly confined
1.4 Many Islands	–214.1	Gr, locally anabranched
1.5 Montagneuse Islands	–228.5	Gr, locally anabranched
1.6 Highland Park	–243.6	Gr, confined
1.7 Pratt's Landing	–259.6	Gr, confined
1.8 Dunvegan	–276.2	Gr, confined
AB2		
2.1 Shaftesbury Ferry	348.1–365.3	Gr, nonoverlapping islands
2.2 Smoky confluence	–373.8	Rock control, some islands
2.3 (Town of)Peace River	–394.7	SaGr, sinuous, some islands
2.4 Carmon Creek	–415.4	SaGr, occasional islands
2.5 Whitemud River	–439.2	SaGr, sinuous, occasional islands
2.6 Cadotte River	–464.2	SaGr, highly sinuous, occasional islands
2.7 Sunny Valley	–492.8	SaGr, sinuous, nonoverlapping islands
AB 3		
3.1 Tompkins Landing	674.7–694.6	Sa, sinuous, islands in bends
3.2 Moose Island	–721.6	Sa, sinuous, islands in bends
3.3 La Crete	–737.3	Sa, sinuous, islands in bends
3.4 Prairie Point	–780.6	Sa, highly sinuous, islands in bends
3.5 Blumenort	–806.5	Sa, sinuous, islands in bends
3.6 Fort Vermilion	–833.6	Sa, low-order anabranches
AB4A		
4A.1 Little Red River	896.0–920.3	Sa, minor islands
4A.2 Fox Lake	–941.2	Sa, low-order anabranches
4A.3 Fifth Meridian	–961.3	Sa, low-order anabranches
AB4B		
4B.1 Garden Creek	961.3–970.3	Sa, low-order anabranches
4B.2 Big Island	–988.6	Sa, sinuous, bifurcated channel
4B.3 Little Fishery	–1001.8	Sa, sinuous, islands in some bends
4B.4 Gambling Point	–1024.5	Sa, sinuous, islands in bends
4B.5 Big Slough	–1044.2	Sa, mildly sinuous
4B.6 Portage Lake	–1060.7	Sa, sinuous
4B.7 Jackfish River	–1076.6	Sa, overlapping islands

CGr, cobble-gravel channel bed; Gr, gravel bed; SaGr, sandy gravel bed; Sa, sand bed sharp bends at Many Islands (see Figure 7.5) and at Montagneuse River. The river bed is cobble gravel and average gradient is 3.3×10^{-4}. Seasonal ice develops in this reach, though it may not consolidate in all years, and significant ice jams may develop in some years. The reach is subdivided into eight sub-reaches (Table 7.2).

Reach AB2 begins at the Shaftesbury Ferry 18 km upstream of the Smoky River confluence, at the limit of the Smoky backwater. It extends for 145 km and ends at Sunny Valley, near Manning. In this reach the river flows through a sequence of incised (150 to 200 m) valley meanders and is partly bedrock controlled, so that there is limited possibility for degradation. A narrow valley flat in a valley bottom that varies between one and two kilometers width also leaves limited room for the river to move laterally. Channel width varies from more than 800 m upstream of the Smoky confluence to 550 m downstream and sinuosity increases to nearly two in the confined meanders. Gradient in this reach averages 3.0×10^{-4}. The river carries a substantial sand load, gained from Smoky River, and the bed is sandy pebble gravel. Ice scars occur up to 10 m above the normally wetted channel along this reach and ice scour lines are found up to 11.5 m above the river (Chapter 6). The reach immediately downstream from Sunny Valley is well represented by this reach; together, they experience the most severe ice action along the river. There are seven sub-reaches (Table 7.2).

Reach AB3 begins upstream of Tompkins Landing (a ferry crossing point also known as La Crete Ferry) and runs for 158 km to below Fort Vermilion. The gravel/sand transition in the river occurs in the vicinity of Tompkins Landing (Shaw and Kellerhals, 1982) so this is a sand-bed reach, although gravel can be observed on channel edges and bar tops. Ice-scoured cobble pavements are common. The valley is only 50 to 100 m deep here, and the valley sides begin to fall back from the river so that it is much less confined. The river increases in width downstream from 750 to over 900 m, and the gradient averages 7.0×10^{-5}, substantially lower than upstream. The river forms a sequence of open meanders with islands or overlapping island groups in the bends. Sinuosity is generally about 1.2. At Fort Vermilion, the river exhibits low-order anastomosis about a major channel island. There are six sub-reaches (Table 7.2).

Below Fort Vermilion, the river encounters a significant knickpoint on bedrock at Vermilion Chutes and then flows into the Slave Lowland, a glaciolacustrine plain, where it is completely unconfined. It has a sand bed and silty sand banks. Reach AB4 runs from Boyer Rapids (rock controlled) to Jackfish River. The first 75 km (Reach AB4a; to Fifth Meridian) exhibits low-order anabranches about frequent islands. The following 108 km (Reach AB4b) are strongly meandered in loop-extension style with islands in the bends. Near km 970 the river splits into two channels about a large island. The principal channel division is 17 km in length while the major secondary channel length is 27 km. River width averages 1200 m in the upstream part of the reach, but varies substantially, and is about 1000 m in the longer downstream part. The gradient through this reach averages 1.2×10^{-5}. There are 10 sub-reaches, three of them in the AB4a Reach.

7.3 Methods

The morphology of the river has been photogrammetrically mapped from provincial and federal vertical air photography at several dates using a computer-linked Carto® AP190 analytical stereoplotter in planimetric mapping mode. Reference points for mapping were control points in the Geodetic Survey of Canada national network located on 1:80 000 diapositives. Additional "soft" control points were selected for bridging between photos so that rectification was typically based on about eight points. (It must be appreciated that much of the course of the river lies in completely unsettled territory, so that there are few fixed geodetic points and the identification of features suitable to act as control points in unbroken wildland was, in places, difficult.)

The plotter is designed to measure the position of objects to within ±60 cm from 1:30 000 scale photos obtained with metric cameras but, in practice, control point transfer and photo resolution degrade horizontal precision by a factor of 5 to 10 (cf. Walstra *et al.*, 2011). Hence, errors the order of three to five meters in boundary placements are to be expected at this scale (compare Winterbottom, 2000; Hughes *et al.*, 2006). Data were orthorectified in Carto software and imported into Arc/INFO®, a vector-based GIS operating in an X-Windows graphic environment, adjusted to reconcile mapped unit boundaries, and displayed. Details of the mapping procedures are given in Church *et al.* (1997). Examples of the mapping are shown as illustrations in this chapter and the complete suite of maps is available online (see Appendix).

Morphological units were mapped as follows:

Water surface (S_w): any area occupied by water at the time of photography;

Active bar surface (B_a): emergent river bed, seasonally water covered and devoid of perennial vegetation;

Inactive bar surface (B_v): emergent river bed, distinctly lower than adjacent floodplain surface, with perennial vegetation. Woody vegetation cover is shrubby and/or immature, but cover may be restricted to herbaceous species, and may be discontinuous;

Floodplain (F_f): the wooded (or cleared) valley flat, deposited by flood sedimentation but only occasionally water covered, adjacent to the river (distinguished from terraces by elevation difference; terrace surfaces were not classified for this study);

Island surface (F_i): floodplain surface isolated from the main floodplain by river channels on all sides;

Alluvial fan (F_a): a sedimentary surface deposited by a tributary stream at its mouth. Only on large fans were active channel zones separately mapped.

The definition of floodplain requires some clarification inasmuch as the Peace River floodplain formed in the predam, unregulated regime has, in effect, become a low terrace, while new floodplain is forming at a lower elevation, most of it former bar surfaces. Most of the "new" floodplain is still mapped as B_v, so that F_f generally comprises old floodplain. However, any floodplain area created after regulation will be "new," lower floodplain. The outer limits of the floodplain unit (at the base of the valley wall) often were not mapped—in Reach AB4, in particular, the floodplain merges imperceptibly into extensive wetland and would be difficult to define—so that meaningful statistics related to this unit pertain to areal change only.

Mapped units were stored as polygons in the GIS in separate coverages so that statistics of their dimensions could be extracted. Derivative polygons indicating change from one mapping to another were obtained by overlaying appropriate coverages. To study morphological changes along the river we have summarized areal changes between different mappings for all possible transitions from one identified morphological unit to another (see Appendix for direction to the online supplement that gives the tables of areas and changes for all morphological units, by sub-reach and period). Altogether, the methods are similar to those employed by Van Steeter and Pitlick (1998a) and by Miller and Friedman (2009) but were developed independently.

Air photo dates for which maps were constructed were 1950, 1966 to 1969, 1974, 1988, 1993, and 1999 to 2006 (see Appendix for direction to the online supplementary table that records air photo details). The period 1966 to 1969 indicates that there was not complete photo coverage for the river in any one of those years, but the composite coverage is considered to represent adequately the river morphology immediately before regulation. We will refer to this coverage as the 1967 mapping (regulation commenced in December 1967). Similarly 1999 to 2006 represents available coverage for mapping after the major flood of 1996. It will be referred to as 2006. Coverage in AB4B is limited by the unavailability of photography for the epoch 1967, and both parts of Reach AB4 lack coverage for 2006. Actual image dates vary for some parts of other reaches as well.

Figure 7.3 shows the history of flood flows at the main gauges on the river and identifies the photo dates. The 1950 photos constitute the earliest comprehensive coverage along the river and were selected so that the period 1950 to 1967 could be examined to reveal rates of geomorphic change in the absence of regulation. Mean annual flood at Hudson's Hope during this time was 5840 m^3s^{-1} and at TPR was 9700 m^3s^{-1} (the magnitude changes little farther downstream). During the period 1968 to 1972, the reservoir was filled and flows remained very low, though there was a brief high flood in 1972 when the Bennett Dam spillway was tested. Flows exceeded 2000 m^3s^{-1} at Hudson's Hope on 29 of 46 days during June and early July, peaking at just over 5000 m^3s^{-1}, while flow reached 14 000 m^3s^{-1} at TPR. The 1974 coverage was selected to isolate changes occurring during this period of reservoir commissioning. The 1988 coverage is to isolate the initial period of "normal" regulated flows when major changes are expected to have occurred, while the 1993 coverage then brackets a short interval within which a notable natural flood occurred in the river. After normal operations commenced at the dams, mean annual flood at Hudson's Hope was 1930 m^3s^{-1} and at TPR 5564 m^3s^{-1}. The post-regulation mean annual flood at Hudson's Hope is 33% of that before regulation, while 57% at TPR. In the proximal part of the river, normal high flows no longer reach the competent level to dislodge river-bed materials (Chapter 2). The 1990 flood is the all-time flood of record on Peace River from TPR downstream, and the post-regulation flood of record in the upper river. Flow at Taylor reached 5190 m^3s^{-1} (in comparison with a

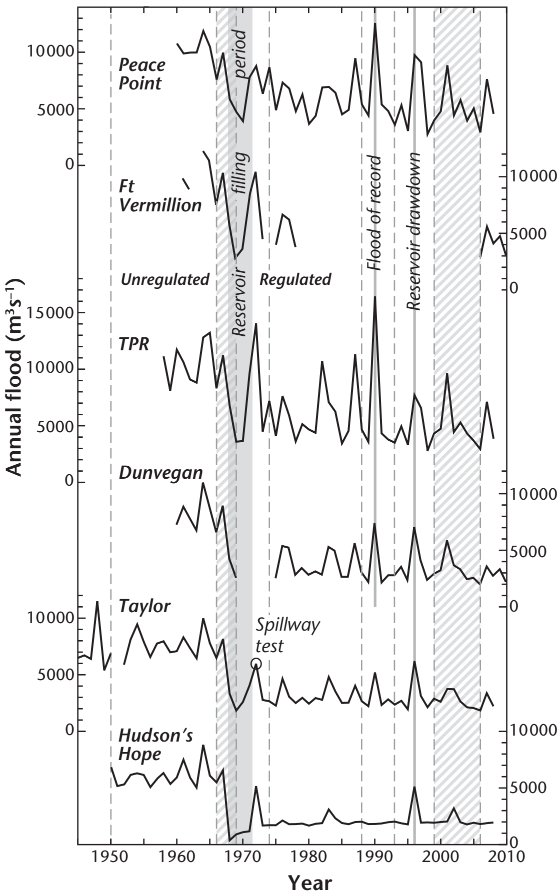

Figure 7.3 Annual maximum daily discharge at six principal gauging stations along Peace River. The dates of photography used in this study are also shown. The cross-hatched periods represent times when portions of the photography were flown in different years.

post-regulation mean annual flood of 2945 m^3s^{-1}), while at Peace River it reached 16 500 m^3s^{-1}, with a contribution of 8620 m^3s^{-1} from Smoky River.

The 2006 coverage postdates the extended reservoir drawdown flood of 1996; hence it documents the response of the channel, subject to regulated flows for 30 years, to the first seasonal hydrograph in those 30 years to approximate an unregulated annual flood (albeit a modest one).

Water level varies from one mapping to another because of different flows at the time of photography. Actual image epochs and imaged flows are reported in the online supplement of air photo details. Stage differences between two mappings bias mapped areas and reported changes in area for water surface and active bar, and may affect the delineation of other units where they abut water. Adjustment for this effect requires knowledge of channel topography that is not available. Attempts were made to minimize this factor by selecting photography taken at uniformly low flows. Over all selected coverages, flows varied within a relatively narrow range, 915 to 1760 m^3s^{-1} at Taylor and 1360 to 3140 m^3s^{-1} at Peace River. These figures translate into stage ranges of 1.09 and 1.10 m, respectively. Table 7.3 gives the variance in observed waterline position that is associated with these stage ranges for various offshore streambed lateral gradients. Errors due to stage variation dominate mapping errors for bottom gradients less than 10° (slope of 0.18). For an average 500 m river width, the proportional error at one bank is less than 5% for lateral gradients greater than 2°. In considering the implication of these numbers it must be recognized, on one hand, that there will be stage-mediated variation in width on both banks, but that it is uncommon for both banks to have very shallow gradients, and that period-to-period comparisons will always be less extreme than the tabulated figures, which are based on the total stage variation observed over all dates. It is supposed that bias introduced by flow variations is, in general, less than 10% of channel width.

Changes in river channel position and channel width have customarily been made by comparing superposed positions of a channel extracted from sequential mappings. The errors are those associated with point positioning and combine errors of image rectification with errors of apparent bankline position mapping (Mount and Louis, 2005; Swanson *et al.*, 2011). In this study, changes in river channel width are studied over the length of sub-reaches (typically the order of 20 km) by dividing mapped channel area by channel length. This procedure produces much more precise estimates of mean changes but it yields no information on changes at specific places.

Mapped units are typically the order of 200 m in diameter, or greater. Considering a mapping error of ±4 m (appropriate for terrestrial boundaries), the worst error in the area calculation for such a unit would be ±8% and the pooled error of change in area from mapping to mapping would be ±11%. These numbers would change for larger or smaller units and, for relatively narrow morphological units along the river edge, typically bars, errors might be relatively large. The important channel

Table 7.3 Apparent width variation induced by stage change on Peace River

Streambed lateral gradient	Absolute change (m)		Percent change at one bank[c]	
	Taylor[a]	TPR[b]	Taylor	TPR
1°	48	62	9.5	12
2°	24	31	4.8	6.2
3°	16	21	3.2	4.1
5°	9.5	12	1.9	2.5
10°	4.7	6.2	0.94	1.2
20°	2.3	3.0	0.46	0.60
30°	1.4	1.9	0.29	0.38

[a]Based on stage range of 0.83 m, determined over all photo dates.
[b]Based on stage range of 1.09 m, determined over all photo dates.
[c]Based on river width of 500 m.

zone edge (based on mapping the vegetation trim line) is not, however, affected by this consideration.

Mapping Reach AB4 presented some difficulties because there is far less photography from which to choose. The “1967” photography for Reach AB4A was flown in June 1964, when river flow was near 8000 m^3s^{-1}. However, Reach 4, unlike upstream reaches, exhibits cohesive, near-vertical banks along much of the reach so that errors, which remain unassessed, are apt not to be excessive. However, results for Reach AB4 are altogether the least reliable. No photography is available at all for the 1960s in Reach AB4B and only partial coverage is available for 2006 so that the records of change remain incomplete.

7.4 Characteristic patterns of morphological change

In the following, we explore characteristic examples of morphological change before and after regulation in each of the study reaches. We quote values or proportions (of reach total area) for “deposition,” “erosion,” and “exposure.” “Deposition” is indexed by areas of former water surface and active bar surface that have converted to vegetated bar surface, or to island or floodplain surface in a subsequent period. Deposition amounts mainly to lateral accretion, changes on the wetted river bottom remaining inaccessible. “Erosion” is represented as the reverse transitions. “Exposure” is the area of water surface in an earlier period that subsequently appears as active bar surface: this measure is not unbiased since the measure depends, in part, on water level at the time of photography. Over the long period after regulation, however, it does index a characteristic change in the exposed morphology of the river. We also consider gain and loss of “riparian forest.” “Gain” is the area of former water surface and of both active and vegetated bar surface that has converted to island or floodplain status—that is, become fully terrestrial in character. “Loss”’ is the reverse set of transitions. The exchange is asymmetric in the sense that “gain” represents area upon which young, fully terrestrial forest may establish whereas “loss” usually represents the loss of mature forest. The changes are summed for successive periods: inasmuch as the same area may sequentially be involved in deposition/gain and erosion/loss, the data give a gross summary of river activity since regulation rather than a measure of net change. In the following, the “active channel” is that area below the limit of perennial terrestrial vegetation, including both open water and bare bar surface (see Equation 7.1 below), while the “channel zone” includes also vegetated bar and island surfaces (see Equation 7.2 below).

In the BC reach, the river generally flows without confinement and the channel frequently is divided about channel islands. With the reduction of flows in the regulated regime and general absence of flows capable of entraining the river bed, it is in these places, with many inter-island channels, that the most dramatic morphological changes have occurred. Figure 7.4 illustrates successive periods of change at Strawberry Islands, an island group of about seven kilometers length immediately upstream of the Kiskatinaw River confluence, about 135 km from the dams (see Figure 7.1 for the locations of the reaches illustrated in Figures 7.4 to 7.8). In the period before regulation, the balance of changes

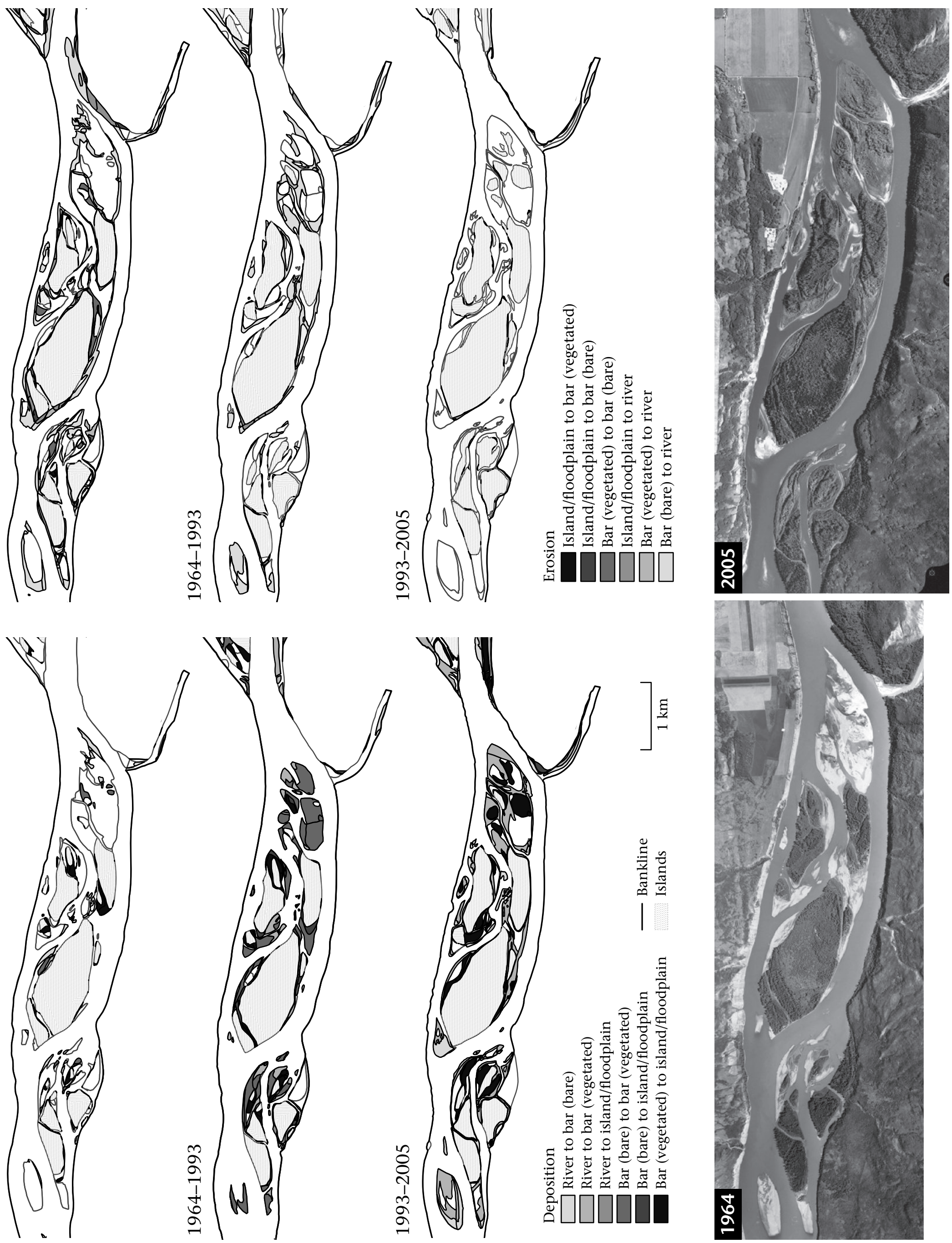

Figure 7.4 Morphological changes between 1950 and 1993 at Strawberry Islands (Reach BC6, "Beatton River"). Left-hand panels illustrate deposition (mainly lateral accretion) for 1950 to 1966 (pre-regulation); 1966 to 1993 (normal reservoir operation); 1993 to 2005 (including the 1996 reservoir drawdown flood). Right-hand panels illustrate erosion for the same periods. Vertical air photos illustrate the site in 1964 (BC5113-142; September 6, $Q \sim 1630$ m^3s^{-1}: left) and 2005 (15BCC05129-78; April 25, $Q \sim 1900$ m^3s^{-1}: right) at approximately the same scale (Copyright © Province of British Columbia. All rights reserved. Reproduced with permission of the Province of British Columbia).

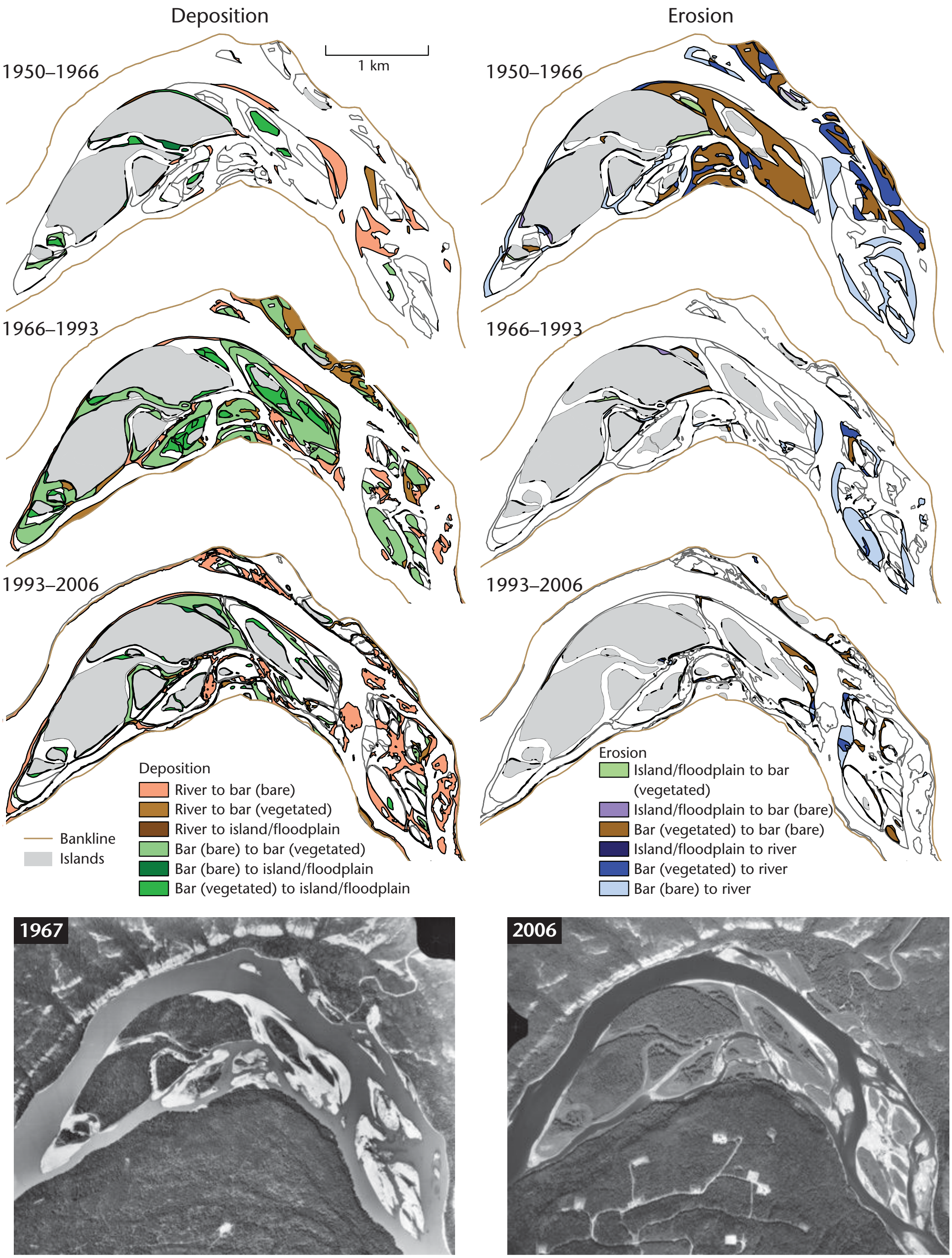

Figure 7.5 Morphological changes between 1953 and 2006 at Many Islands (Reach AB1.4, "Many Islands"). Map panels are arranged as in Figure 7.4. Vertical air photos illustrate the site in 1964 (AS928-21; September 15, $Q \sim 1480\ m^3s^{-1}$: left) and 2005 (AS53788-143; August 25, $Q \sim 710\ m^3s^{-1}$: right) at approximately the same scale (Alberta Crown copyright).

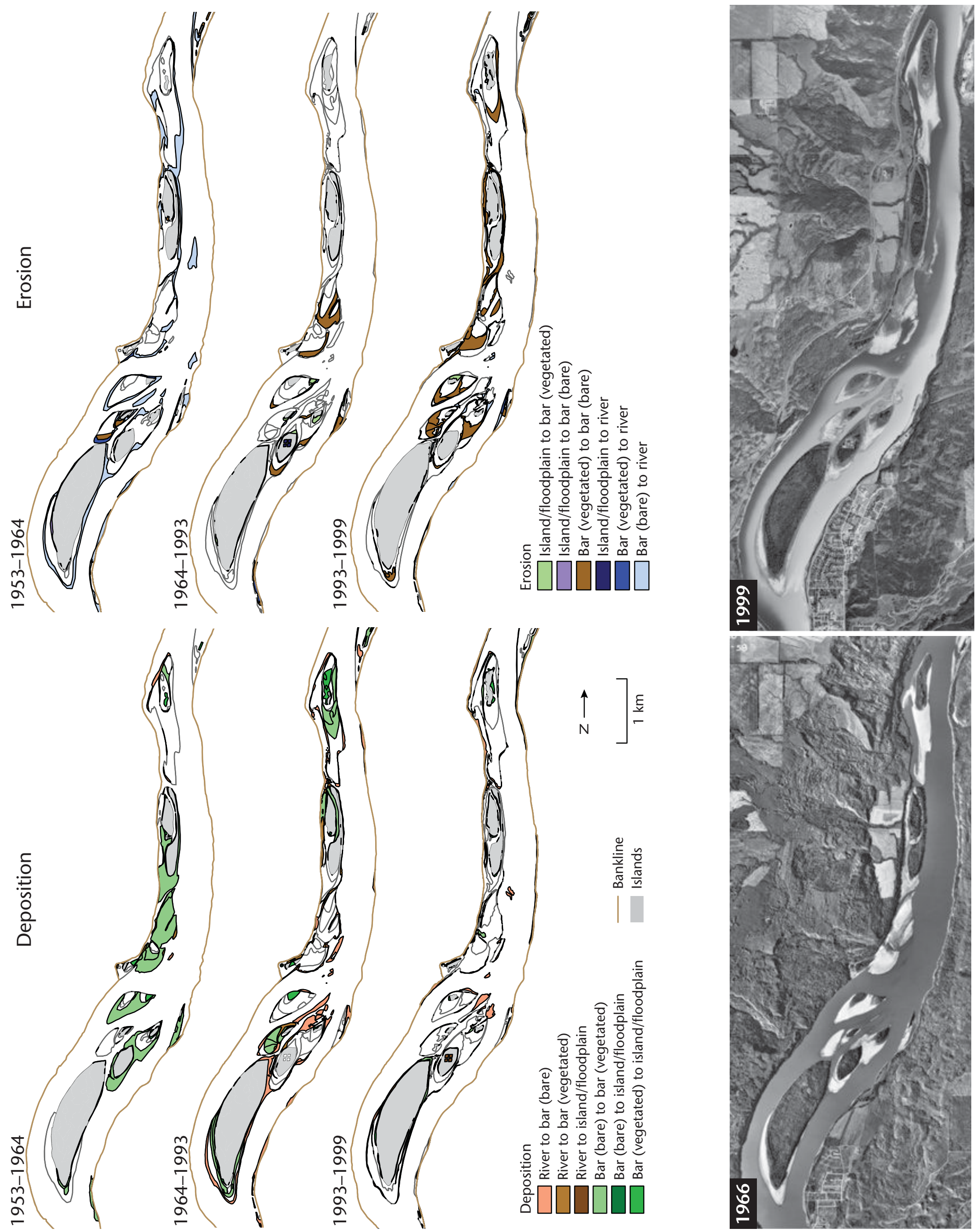

Figure 7.6 Morphological changes between 1953 and 1999 immediately downstream from the Town of Peace River (Reach AB2.3, "Peace River") and downstream from the Smoky River confluence. Map panels are arranged as in Figure 7.4. The prominent sediment plume in 1999 is Smoky River inflow. Vertical air photos illustrate the site in 1966 (AS928-60 and AS929-217; September 15, $Q \sim 1900\ m^3s^{-1}$: left) 1999 (AS5070-216 and 250; August 3, $Q \sim 1230\ m^3s^{-1}$: right) (Alberta Crown copyright).

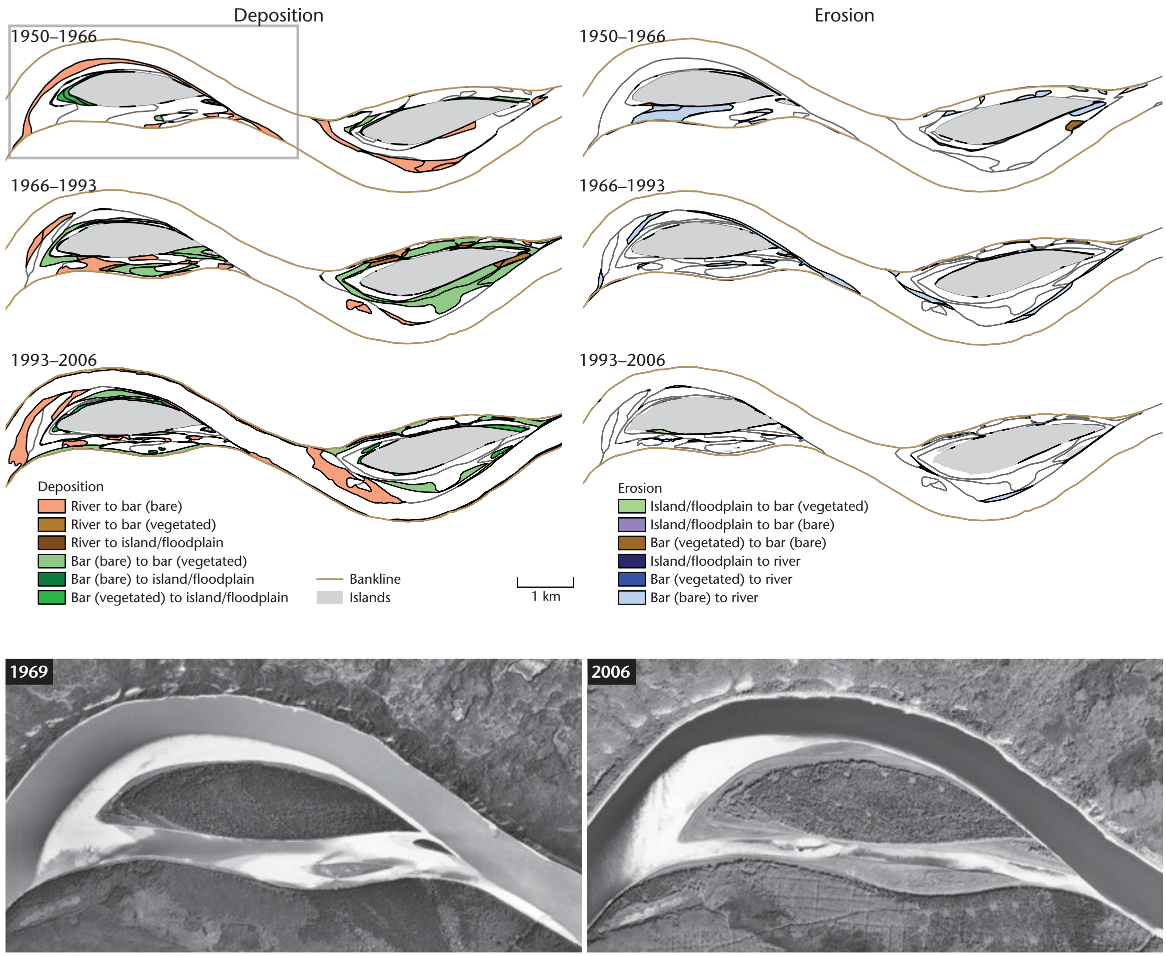

Figure 7.7 Morphological changes between 1950 and 2006 near Moose Island (Reach AB3.2, "Moose Island") downstream from Tompkins Landing. Map panels are arranged as in Figure 7.4. Vertical air photos illustrate the site in 1969 (AS1022-5802; June 24, Q ~ 1330 m^3s^{-1}: left) and 2006 (AS53908-248; August 31, Q ~ 740 m^3s^{-1}: right) (Alberta Crown copyright). The square outline in the first map panel indicates the area portrayed in the photos, which are displayed at a larger scale.

favored erosion around the island edges. After regulation, major changes have overwhelmingly favored aggradation in the form of accretion of sediment around bar edges and the reduction or cutoff of small inter-island channels. The dominance of accretion is most pronounced in the period 1993–2006. After 38 years of regulated flows, however, the main inter-island channels remain active. In the 28-km-long sub-reach (Beatton River) in which Strawberry Islands occurs, net deposition affected 21% of the total area, while erosion affected 9.2%. There was, in addition, a net gain of 767 000 m^2 of exposed bar surface (1.9% of total area) within the channel zone. The riparian forest zone gained 353 ha on new island and floodplain surfaces, while losing 76 ha to the river. This is, of course, an exchange of mainly mature forest for early successional forest. The net result of these changes is a narrowing of the active channel by 184 m (638 to 452 m: 29% of the 1967 width), and a 5% shrinkage in total channel zone width. These changes are well distributed along the reach, but the illustrated Strawberry Islands reach accounts for more than one-quarter of the totals.

Along most of Reach AB1 systematic change is again limited by the fact of the river being no longer

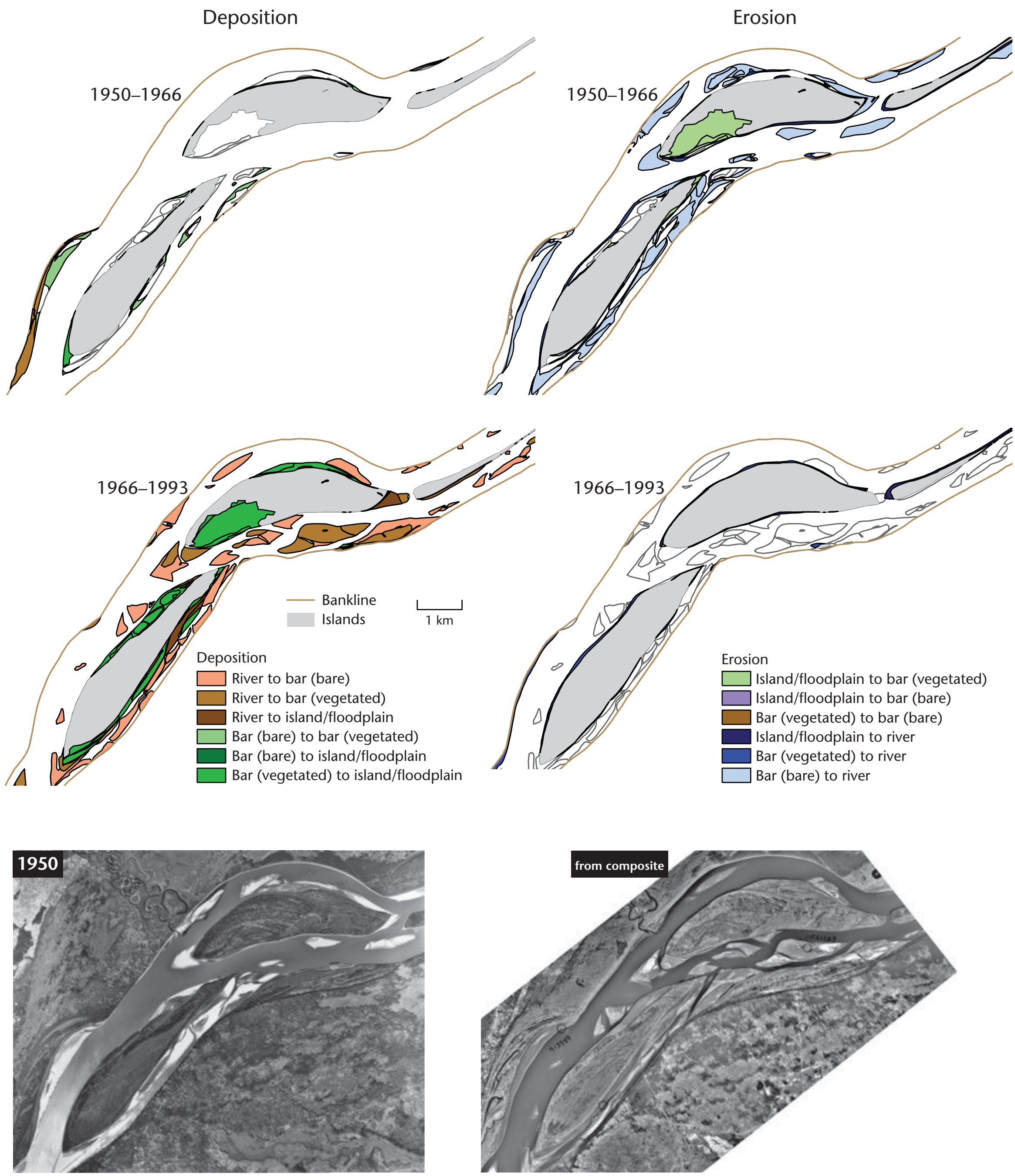

Figure 7.8 Morphological changes between 1967 and 1993 near Fifth Meridian (Reach AB4). Map panels are arranged as in Figure 7.4. Vertical air photos illustrate the site in 1964 (AS885-131/132; June 29, $Q \sim 7160\ m^3 s^{-1}$: left) and 1983 (AS2783-210/211; August 28, $Q \sim 1620\ m^3 s^{-1}$ (right) (Alberta Crown copyright).

normally competent to move the gravel bed, but also by river confinement. Active changes are concentrated at sites of historic instability. A notable example occurs at Many Islands (km 205: Reach AB1.4). Many Islands represents a substantial accumulation of sediments (Figure 7.5) deposited where river currents are slowed down by the resistance to flow presented at a 90° bend in the valley. The morphology has not changed fundamentally since regulation but, between 1967 and 1993, net deposition affected about 26% of the total area of the "Many Islands" sub-reach (length 13 km) while erosion affected 8.4%. There was a net gain of 986 000 m^2 of exposed bar surfaces within the channel zone. There were also 74 ha of riparian forest gained on islands and floodplain, some of which was open water in 1967, while 42 ha were lost to erosion. The result was a narrowing of channel width from average 570 to 439 m, including the closing of some side channels. The reach-length changes are proportionally fairly similar to those in the upstream Beatton reach but, in the mainly confined channel in Reach AB1 nearly all of the measured change actually occurred at the Many Islands bar complex. Bar accretion was concentrated immediately downstream of the bend in the main (left bank) channel and along the right bank channel. It is likely that the right bank channel above the bend will eventually be abandoned. In the downstream group of islands, which were mainly active bars in 1967, there has been both accretion and erosion. Primary succession of sedges and grass meadows has occurred on bar tops there, and they will eventually become new floodplain. The left bank channel around these islands has shoaled during the period and it is apparent that the eventual principal channel will cross to the right bank unless an avulsion occurs.

Notable developments at the Smoky River confluence, near the upstream end of Reach AB2, are displayed in Figure 4.11 (chapter 4). The Smoky River fan has prograded into Peace River, creating substantial new bar area and establishing a more significant backwater than formerly existed on Peace River. When spring flood occurs in Smoky River, the tributary stream is now the dominant channel.

In Reach AB2 below the Smoky confluence—that is, most of the reach—the river flows about islands in the river bends. The principal morphological change since regulation has been the abandonment of back channels so that the islands are becoming discontinuous units of ordinary floodplain. Back channels may be maintained or reactivated, however, by ice-jam high stage. Figure 7.6 illustrates the morphological changes in a sequence of medial and lateral bars and fragmentary floodplain in a slight bend of the river in Reach AB2.3 "Peace River," immediately downstream from the town. The remarkable feature of the maps is that there is, contrary to the experience upstream, no obviously dominant trend toward sediment accretion following regulation. Indeed, in the AB2 Reach net deposition between 1967 and 1999 (11.3% of total area) is balanced by net erosion (12.7% of area). Nevertheless, the area exposed within the active channel (2 531 000 m^2) far exceeds the area lost (637 000 m^2), attesting to the characteristically lower open water levels after regulation. Riparian forest surface (the increment of floodplain and island area) constituted 9.3% of the reach area (227 ha), while loss was 5.6% (136 ha); these figures are not unlike those of upstream reaches. The interpretation we place on this outcome is that the effects of ice jamming—most severe in this reach (see Figure 7.2)—act to maintain the active channel at its pre-regulation dimensions, but are not so strongly influencing terrestrialization of the channel periphery.

Immediately downstream from Tompkins Landing in the proximal sand-bed reach (AB3.1), the river has shoaled dramatically as sand is deposited on the reduced gradient there (see Figure 7.2). Shoaling continues into Reach AB3.2 (Moose Island), where the river flows through a series of relatively gentle bends with a major island-bar area in each bend (Figure 7.7). Net accretion covers 13.0% of total riverine area (39.9×10^6 m^2), while erosion has consumed just 2.7%. There has, then, been much more deposition than erosion, reflecting the substantial sand deposition. The back channels behind the two islands in Figure 7.7, which displays 40% of the 26.2 km sub-reach, have both been largely filled in, so that the islands are becoming attached and the river is assuming a single-thread habit. However, ice-jam high water still passes through the back channels. Forest establishment has covered 117 ha, but loss has been 94 ha. Erosion has mostly been bankline erosion of modest magnitude but extending over considerable distances as the channel adjusts its conveyance to adapt to the loss of back channels and to shoaling. The average width of the channel had fallen from 727 to 572 m by 2006, with losses in the back channels and widening of the main channel. Channel zone width declined by 6% from 1720 to 1609 m.

In Reach AB4A.3 (Fifth Meridian), the period 1950 to 1966, before regulation, was dominantly one of erosion, with a net expansion of 4.2% of the active channel. While 2.8 ha of forest were established, 134 ha were lost, mainly by bank erosion. In contrast, the post-regulation period (to 1993) saw a net establishment of 289 ha of forest in 11.2% of the (former) channel zone, incorporating both floodplain accretion and island expansion. In addition, there was a large increase in exposed bar area, amounting to 6.8% of the channel zone. Meanwhile, the water area shrank by 15.6% (percentage changes do not balance because there was a net addition to the riverine zone in the period, an accounting artifact of the unappraised total floodplain area). Figure 7.8, showing two major island groups in the reach, graphically demonstrates the change from erosion dominance in the early period to the dominance of sedimentation effects after regulation.

(a) Reach: 2b. Location: km 662.5, left bank. Date: Jul 23, 1995

(b) Reach: 2b. Location: km 781.3, left bank. Date: Jun 27, 1996

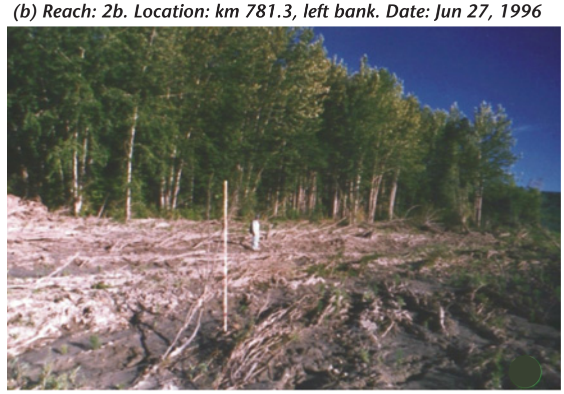

Figure 7.9 Photographs to illustrate the lower limit of persistent terrestrial vegetation. (a) Vegetation galleries on laterally accreting sands immediately upstream from Tompkins Landing (river km 670); (b) Ice scour trim line with extensive damage and removal of shrubs at the mouth of Notikewin River (river km 543) (Photos by L. Uunila).

7.5 Reach-wide trends of morphological change

In this section we consider the pattern of changes in channel width and bar and island development over time, and we estimate trends of lateral erosion and deposition along the river.

7.5.1 Channel width

Channel width is developed from our database by considering "channel area" (C_a), as defined above, the area within the lower limit of perennial vegetation at each edge of the channel;

$$C_a = S_w + B_a \tag{7.1}$$

Channel area excludes vegetated bar surfaces and islands. This definition specifies the *active channel* as the area that is inundated or ice scoured sufficiently frequently to prevent the establishment of persistent terrestrial vegetation (Figure 7.9). The boundary is identical with the limit of normal high water established in Chapter 6 as a longitudinal datum. It avoids the bias that would be introduced by stage change if only the observed water surface was considered. Channel width is, then, $\langle W \rangle = C_a/L$, wherein L is the length of channel, measured along the channel centerline, over which the determination is made (typically a sub-reach) and the brackets indicate a spatially averaged quantity.

Figure 7.10 shows the temporal trends in channel width. In general, width has declined since regulation, in the first instance because of the reduction in flows, though there is little net change in Reach AB2, which is strongly affected by ice jams. Nor is the change demonstrably significant in Reach AB4a. In comparison, the period 1950 to 1967, before regulation, experienced a modest increase in width in the proximal two reaches. The largest increase was about 5% on average in AB1. Most reaches have shown a steady decrease in width since 1967. The change is proportionally the greatest in Reaches BC and AB3 where the width in 2006 was only 78% of the pre-regulation width. Reach AB3 is the proximal sand-bed reach. Both reaches are relatively wide and shallow, with abundant bar area that was more or less permanently dewatered after regulation. Between these two Reaches, AB1 and AB2 are both

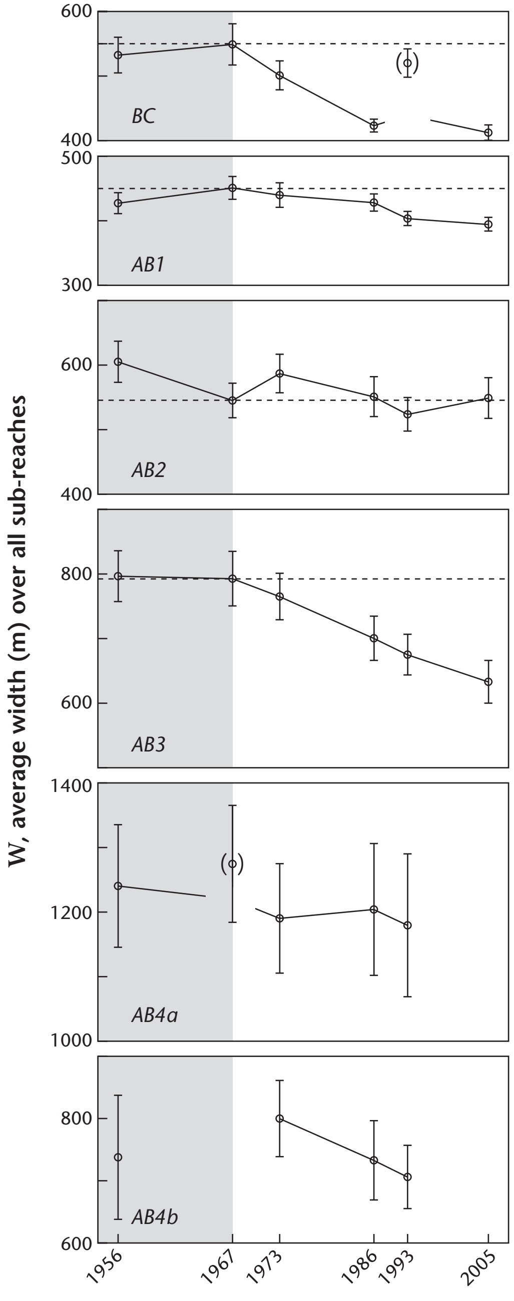

Figure 7.10 Temporal trend in channel width along Peace River, by major channel reach: the dashed line indicates the channel width at the beginning of flow regulation. The 1993 datum in the BC reach should be disregarded because of high flows at the time of air photography. Error bars represent 2s ranges of variance based on sub-reach data. The grey background indicates the period before regulation. The connecting lines are to aid comprehension of the pattern of change and are not meant to imply linear trajectories of change between data.

partially confined within a much narrower valley and have more nearly single-thread channels with more limited channel-edge shallows and ice-jam effects.

Absolute rates of change average about five meters per annum in Reaches BC and AB3 and four meters per annum in AB4A, the reaches with wide, multi-thread channels. In the remaining reaches, rates are one to two meters per annum. The trends of width contraction are essentially linear, which probably reflects the rate of progradation of perennial terrestrial vegetation into the former channel zone. This suggests a mainly passive adjustment by vegetation succession on the channel fringes that were abruptly dewatered in late 1967 and have remained normally dewatered ever since. Nonetheless, it is clear (see Figures 7.4 to 7.8) that active erosion and sediment deposition continue to occur. A feature of the data is that the variance of change (calculated as the variance of sub-reach averages) increases downstream, being least in the proximal two reaches, intermediate in Reaches AB2 and AB3, and greatest in the distal Reach AB4.

7.5.2 Bar and island development

In order to study bar and island development we define the *channel zone* (C_{cz}), as above, to include the active channel (as defined above) plus the areas of vegetated bar surface and islands. It comprises all defined units except floodplain and fans.

$$C_{cz} = C_a + B_v + F_i \qquad (7.2)$$

Then the adjustment of active bar area and of vegetated surface area within the channel zone are studied as the ratios

$$I_a = B_a / C_{cz} \qquad (7.3)$$

and

$$I_v = A_v / C_{cz} \qquad (7.4)$$

wherein $A_v = B_v + F_i$, the vegetated area within the channel zone. Combining both channel zone vegetated surfaces within a single ratio avoids the question whether vegetated bar surfaces and island surfaces have been separated entirely successfully. I_a facilitates examination of whether recent bar sedimentation is becoming more prominent within the channel zone (though it will not include sedimentation that may occur below normal water levels), while I_v allows us to examine whether

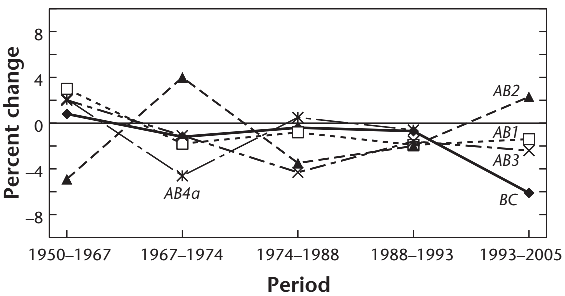

Figure 7.11 Percent change in channel zone width in the major reaches along Peace River in the period 1950 to 2005. Reach AB4b is not shown for lack of complete data. Note that the abscissa demarcates periods, not absolute dates.

vegetation is becoming more extensive within the channel zone. It is, in effect, a "channel vegetation index." Inasmuch as the ratios are established in relation to concurrent channel zone area, they are not based on a constant reference area.

Changes in the channel zone area over time are displayed in Figure 7.11. Changes in Reach BC and in AB1 and AB3 follow the same pattern, with positive change in the 1950 to 1967 pre-regulation period and steady negative change (reduction in width) since. Changes are generally within ±5% in each period, and mostly near or less than 1%. However, the BC reach contracted in width by 6.1% in the 1993 to 2006 period, no doubt the consequence of the prolonged summer soaking of elevated areas during the 1996 flood leading to vigorous seed germination thereafter and the emergence of floodplain character on many former bar tops. Changes mainly involve the development or erosion of floodplain area (there is a very minor effect of tributary mouth fans). Reach AB2 varies from the general pattern inasmuch as it exhibits an irregular pattern of change and generally larger changes. This is not surprising given the prominence of ice jams and ice-jam flood damage to channel margins in this reach.

Figure 7.12 shows trends in the ratios I_s and I_v. It should first be noted that I_s before 1967 exhibited a steep spatial decline from values near 0.20 (i.e., 20% of the channel zone occupied by seasonally exposed bars) in the BC reach to values generally less than 0.1 in the rest of the river. Conversely, I_v exhibited an increase from values near 0.25 in the BC reach to near 0.55 in the rest of the river. The fraction of the channel zone occupied by "active" and vegetated surfaces was

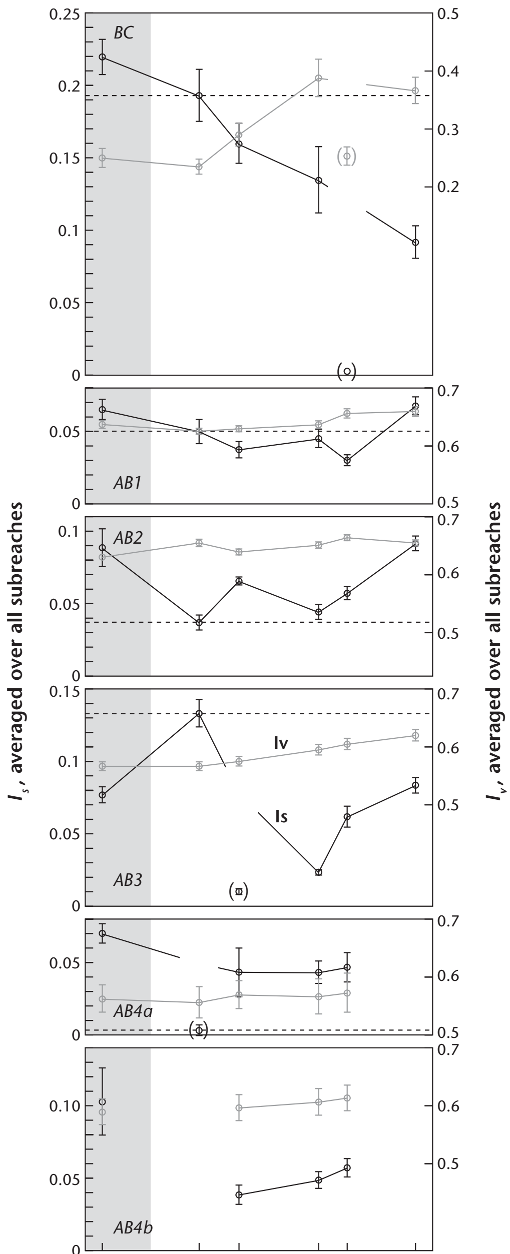

Figure 7.12 Temporal trend in bar ratios along Peace River; ratio I_s is the proportion of active bar surface exposed in the channel zone; ratio I_v is the proportion of vegetated surfaces within the channel zone, including both bar and island surfaces. Error bars represent 2s ranges of variance based on sub-reach data. The connecting lines are to aid comprehension of the pattern of change and are not meant to imply linear trajectories of change between data. The 1967 datum (actually 1964 photography) for I_s in Reach AB4a should be disregarded because of very high flows.

roughly similar in the BC reach, but vegetated surfaces were proportionally more extensive, by as much as an order of magnitude, in the rest of the river. The distinction is interpreted to represent the relative prominence of cobble-gravel additions to the river and subsequent transport in the BC reach, leading to an actively wandering and low-order braided channel before regulation, versus the generally confined nature of much of the rest of the river with island development in channel bends. The relatively refractory nature of cobble gravel delivered to the BC reach by mountain-sourced tributaries in comparison with the friable lithologies delivered from the Alberta Plateau by downstream tributaries is also an undoubted factor in this contrast: the initial establishment of vegetation on recently deposited surfaces is more easily accomplished with the greater downstream supply of finer sediments. Reach AB4 is distinctive in that it is a meandered and locally anabranched lowland river with islands but relatively few exposed bars.

Following regulation the fraction of active bar area declined along much of the river, but most dramatically in the proximal BC reach, the most highly regulated reach. Conversely, the fraction of vegetated area within the channel zone increased all along the river, again most dramatically in the BC reach, where the rate of increase has averaged 0.33% a^{-1} since 1967, but reached 0.73% a^{-1} in the early period of regulation (1967 to 1988). These relative figures hide a more detailed story, however, since total channel area also declined (as indexed by the changes in channel zone width) while the relative rates of change obscure absolute changes (Table 7.4). In the BC reach, there has been persistent loss of active bar area since regulation (13.25 km^2 to 2005) and gain of vegetated surface (11.83 km^2, including increment to islands) in a total channel zone area of 107 km^2; that is, an exchange of about 12% of channel zone area. The changes chiefly signify vegetation encroachment onto formerly "active" bars no longer regularly inundated and, inasmuch, reflect the largely passive adjustment of the channel in this dam-proximal reach (Figure 7.13). This effect accounts for 43% of the total contraction of active channel width in the post-regulation period: the balance is accounted for by former bar areas that are deemed converted to floodplain status or island status.

In Reach AB1 there is a post-regulation increase of both active and vegetated bar areas. The former is not a reliable indication since the appearance could arise simply from stage change between photo sets. The latter (7.1 km^2), however, accounting for 41% of active channel contraction in the reach, is consistent with the changes immediately upstream. In both reaches, the post-regulation changes reverse an observed loss of vegetated bar surface in the pre-regulation period of observation.

Reach AB2 is quite different. The increase in active bar exposure between 1967 and 2006 is 9.77 km^2, much of which is surely real. In comparison, vegetated bar area has increased by only 0.53 km^2. This nevertheless accounts for more than half of the contraction in active channel width (7 m). These outcomes are the result of ice activity maintaining a substantial channel zone with widespread exposure of active bars—many of them ice gouged—during open water. The reach is also singular in that it accreted vegetated bar surface in the pre-regulation period.

Table 7.4 Changes in bar areas in Peace River, by major reach

	Pre-regulation		Post-regulation (to 2006)			
Reach	Active	Vegetated	Active (10^6 m^2 = km^2)	Vegetated	ΔW_b (m)	ΔW_a (m)
BC	−2.571	−1.442	−13.246	+11.831	−78.7	−184
AB1	−1.788	−2.181	+1.569	+7.099	−53.4	−131
AB2	−9.008	+7.342	+9.773	+0.529	−3.7	−7
AB3	+17.674	−0.734	−16.942	+25.363	−164.9	−155
AB4a*	−12.001	−0.427	+7.784	+2.349	−38.1	−92

"Post-regulation" is the period 1967 to 2006 (nominal). ΔW_b, vegetated bar area/reach length is the reduction in active channel width in the period 1967 to 2006 due to the stabilization of bars by vegetation development; ΔW_a is the total contraction of channel zone width in the period 1967 to 2006.

*To 1993 only. There is insufficient information in Reach AB4b.

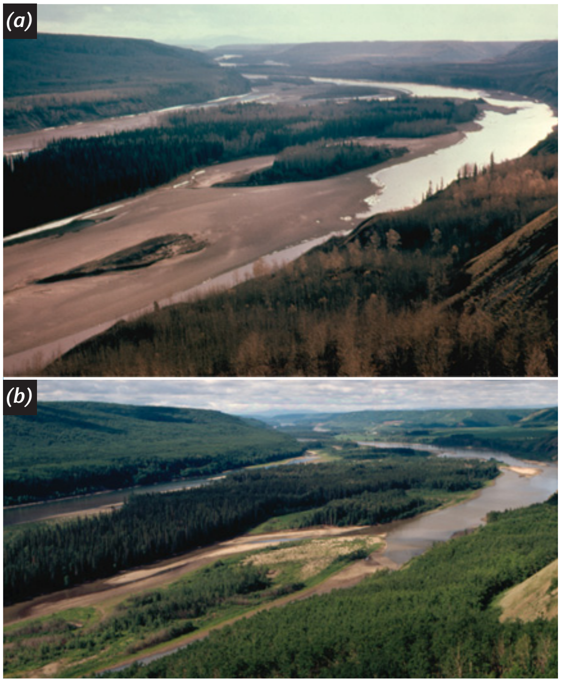

Figure 7.13 Change in the vegetated channel zone in the British Columbia reach, views upstream near Bear Flat: (a) May 1968, extremely low flow during reservoir filling, $Q \sim 200\ \mathrm{m^3 s^{-1}}$ (Photo courtesy of R. Kellerhals); (b) July 1998, $Q \sim 550\ \mathrm{m^3 s^{-1}}$. The principal channel is near the far (right) bank.

In AB3, there has been a large increase in vegetated bar surface (25.36 $\mathrm{km^2}$), partly balanced by apparent loss of active surface (−16.94 $\mathrm{km^2}$), reflecting, as in BC, the progradation of riparian vegetation over surfaces normally exposed in the regulated regime. In this reach, however, those surfaces are in significant degree located in major seasonal back channels where much of the net siltation in the reach is occurring.

The gain in vegetated bar surface in Reach AB4a (to 1993) was restricted to less than three square kilometers, not a surprising result in a relatively narrow and deep channel with characteristically high banks. There has been, however, a substantial increase in active bar exposure; an increase that probably is largely real, reflecting the characteristically lower flows through most of the open water season.

7.5.3 Erosion and deposition

To examine erosion and deposition along the river it is necessary to consider areas that change from one unit to another between two mappings (e.g., area classified F_f in an earlier mapping that has become S_w in a later mapping is an area of floodplain that has been eroded by the river). This is, in effect, an examination of lateral erosion and accretion. Volumetric erosion and deposition within a unit are not generally accessible to us, but morphological transitions are accessible from our GIS database. We use the notation $\Delta A(F_f/S_w)$ to indicate the transition floodplain to river, and similarly for other changes. Then area eroded between two mappings, is

$$A_e = \Delta A(F_i/S_w) + \Delta A(F_f/S_w) + \Delta A(F_a/S_w) + \Delta A(B_v/S_w) + \Delta A(F_i/B_a) + \Delta A(F_f/B_a) + \Delta A(F_a/B_a) + \Delta A(B_v/B_a) \quad (7.5)$$

This equation includes all transitions from the channel zone and floodplain into the active channel, as defined above. It excludes certain transitions within the channel zone, $\Delta A(F_i/B_v)$, $\Delta A(F_f/B_v)$ and $\Delta A(F_a/B_v)$ that appear unequivocally to indicate a history of erosion (which would lead to S_w or B_a) but, at the end of the mapping period, also to indicate further, offsetting transitions $\Delta A(S_w/B_v)$ or $\Delta A(B_a/B_v)$. The included transition $\Delta A(B_v/B_a)$ is ambiguous, since it could be achieved simply by vegetation stripping (for example, by an ice run). On the other hand, we do not include the transition $\Delta A(B_a/S_w)$; we examine this transition separately as an indicator of erosion within the channel. It is, however, subject to stage change bias.

The opposite transition, indicating lateral deposition, is

$$A_d = \Delta A(S_w/F_i) + \Delta A(S_w/F_f) + \Delta A(S_w/B_v) + \Delta A(B_a/F_i) + \Delta A(B_a/F_f) + \Delta A(B_a/B_v) \quad (7.6)$$

This equation includes all transitions from the active channel to other channel zone and extra-channel area except the transitions to F_a which we suppose to indicate alluvial fan progradation, not Peace River sedimentation. We include the potentially passive transition $\Delta A(B_a/B_v)$ since we suppose that it usually indicates sedimentation on the bar to the point that it can sustain terrestrial vegetation. We separately consider the transition $\Delta A(S_w/B_a)$, indicating deposition within the channel since it probably indicates significant new deposition in order to be positively identified, even though the actual area estimate is subject to stage bias. We also consider separately

$$\Delta A(F) = \Delta A(B_v/F_i) + \Delta A(B_v/F_f) \quad (7.7)$$

These transitions, occurring entirely within the initial channel zone, indicate vertical accretion. There may, however, be some ambiguity in identifying some of these transitions from air photographs since they rely chiefly on identifying vegetation changes which might also occur by simple growth or succession.

Erosion and deposition rates involving transitions between the channel and the channel zone + extra-channel area are expressed as

$$r_{\mathrm{cze}} = A_{\mathrm{e}}/L^{*}T \qquad (7.8)$$

and

$$r_{\mathrm{czd}} = A_{\mathrm{d}}/L^{*}T \qquad (7.9)$$

wherein T is the period (in years) between mappings. These rates are expressed in m a^{-1} and may be interpreted roughly as meters of retreat or advance of the active channel boundary. The difference, which may be called the "net accretion rate"

$$r_{\mathrm{czn}} = r_{\mathrm{czd}} - r_{\mathrm{cze}} \qquad (7.10)$$

indicates the rate of net lateral change of the active channel boundary, a positive result indicating lateral accretion and channel narrowing. We also consider

$$r_{\mathrm{cn}} = [\Delta A(S_{\mathrm{w}}/B_{\mathrm{a}}) - \Delta A(B_{\mathrm{a}}/S_{\mathrm{w}})]/L^{*}T \qquad (7.11)$$

which approximately indicates the net accretion rate within the active channel but remains subject to a doubled stage bias. Finally

$$r_{\mathrm{gf}} = \Delta A(F)/L^{*}T \qquad (7.12)$$

provides an index of vertical accretion rate, though it cannot be interpreted as sediment thickness because it is based on lateral map unit transitions.

Figure 7.14 shows the trend of r_{czn}. There is evidently an overall positive change, indicating net accretion along the channel, consistent with the observed reduction in channel width. Rates are in the order of one to five meters per annum, similar to the direct measures of active channel width and rate of change of channel width. Most of the change is due to simple progradation of perennial vegetation onto dewatered surfaces.

r_{cn} (Figure 7.14) is generally positive after regulation, as one would expect, in some reaches reversing a trend of channel expansion in the immediate pre-regulation period. A notable anomaly occurs in Reach AB3 for the period 1967 to 1974, which is due to the 1976 flow (the

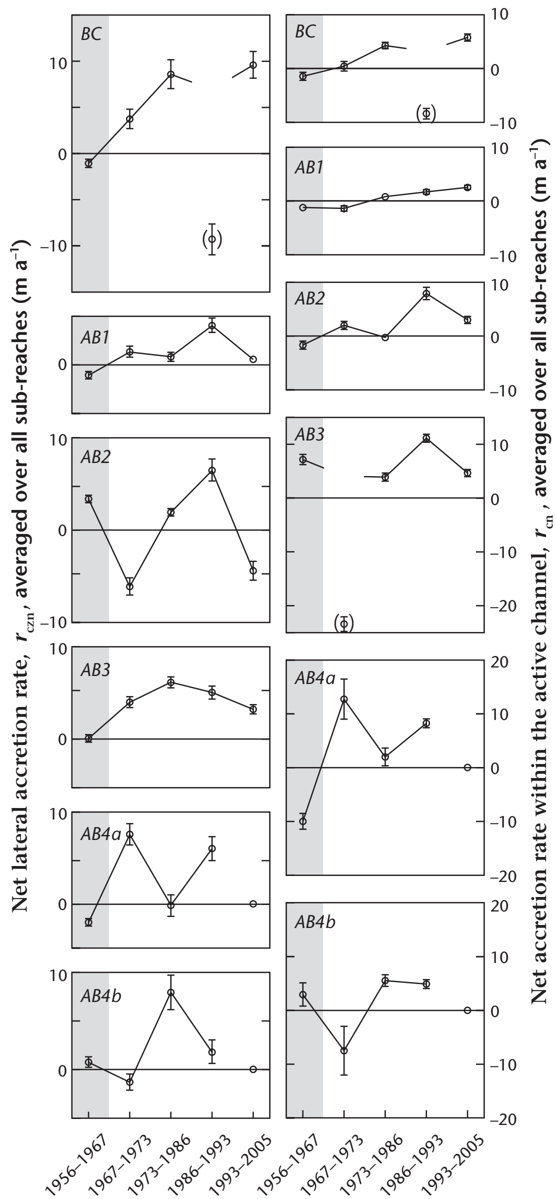

Figure 7.14 Trends in channel accretion ratios by major study reach along Peace River. r_{czn} is the rate of lateral channel gradation; r_{cn} indexes the rate of within-channel sedimentation. The period four to five datum for the BC reach should be disregarded because of high flows at the time of the 1993 photography. Error bars represent 2s ranges of variance based on sub-reach data. The light grey shading indicates the period of pre-regulation change. Note that the abscissa demarcates periods, not absolute dates. The connecting lines are to aid comprehension of the pattern of change and are not meant to imply linear trajectories of change between data.

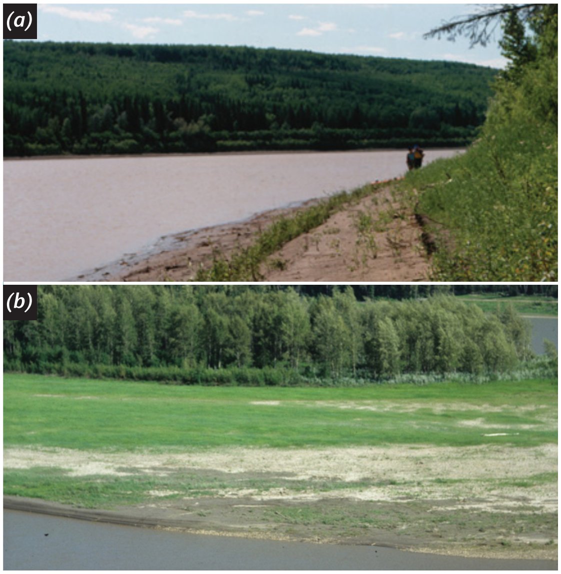

Figure 7.15 Sediment accretion in Peace River: (a) sand accumulation at the shoreline on a river bend in Reach AB1; (b) sand accumulation on a bar surface in Reach AB2. Both views July 1991.

actual date of the photography) being three times that of 1969. In the middle and lower river (Reaches AB2 and beyond), a high rate (5 to 10 m a^{-1}) is observed in the period 1988 to 1993, which probably reflects the effect of the 1990 flood of record along this part of the river. The implication for sedimentation (i.e., vertical accretion of the bar surfaces) implied by the values of r_{cn} can be estimated by realizing that for one meter per annum lateral change, sediment accretion on a bar side gradient of 0.01 would be one centimeter, and on a gradient of 0.05, five centimeters. For 10 m a^{-1} lateral change, implied accretion rates are also 10 times larger. Such conversions cannot be closely interpreted, however. Figure 7.15 gives some views of the actual physical processes associated with sediment accretion.

r_{gf}, an index of vertical accretion by virtue of its measure of floodplain production (Figure 7.16), is consistently positive with a tendency for an increasing trend in time, most clearly in the BC reach. Rates are the order of 0.1 to 1.0 m a^{-1}. This likely is the consequence of the time required for floodplain vegetation communities to become established to the point that the substrate is mapped as floodplain. The increasing trend is, similarly, likely the consequence of a lag period following regulation for new floodplain communities

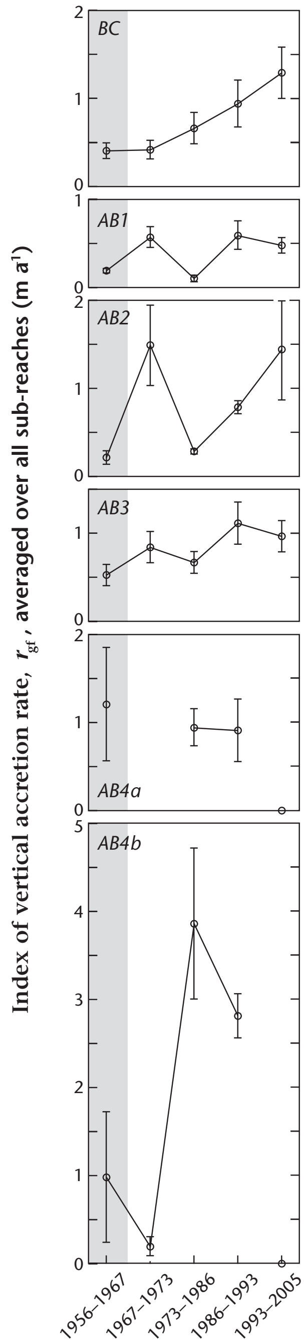

Figure 7.16 Trends in the rate of within-channel sedimentation, r_{gf}, along Peace River. The period four to five datum for the BC reach is credible because the floodplain was not inundated at the time of the 1993 photography. Error bars represent 2s ranges of variance based on sub-reach data. Note that the abscissa demarcates periods, not absolute dates. The connecting lines are to aid comprehension of the pattern of change and are not meant to imply linear trajectories of change between data.

to become established, hence to be mapped as such. This appearance is consistent with the finding that forest age on recent floodplain surfaces around tributary junctions shows a trend toward more recent dates in the BC reach (Figure 4.12; chapter 4). In Reaches AB1 to AB3, the rate of floodplain production declined in the 1974 to 1988 inter-survey period, that is, the period of persistently normal regulated flows.

7.6 The spatial pattern of morphological change

Figure 7.17 shows the changes in active channel width along the river between successive epochs of measurement. Relatively minor and spatially variable changes occurred before 1967 (Figure 7.17a), with a notable reduction in widths in Reach AB2. In the upper river widths increased in some sub-reaches, while the lower river was generally stable. During the period of generally very low flows, 1967 to 1974 (Figure 7.17b), width declined substantially in the BC reach but did not change much in most of Reach AB1, reflecting the partly confined, single-thread nature of the channel. In Reach AB2, channel width increased, possibly the consequence of enhanced ice scour during these low-freshet years. Farther downstream widths contracted or remained little changed.

The "normal flow" period, 1974-1988 (Figure 7.17c), shows width contraction everywhere along the river, the expected consequence of flow reduction and a time scale dominated by vegetation succession onto dewatered surfaces. In Reach AB1, width reduction was concentrated around Many Islands and the Montagneuse River confluence, where secondary channels amongst the islands were abandoned. The largest changes occurred in Reaches BC and AB3, respectively the proximal reach and proximal sand-bed reach. The period encompassing the flood of record (Figure 7.17d), perhaps surprisingly, reveals continued width contraction along the entire river except for the BC reach, where the observation is spurious due to the high flow at which the 1993 photography was taken. The post-1993 period again shows width contraction, except in Reach AB2, where a small increment to width occurred, bringing the channel nearly back to its 1967 dimensions. Figure 7.17f shows the cumulative effect of 38 years of regulated flow, with width contraction everywhere along the river except in

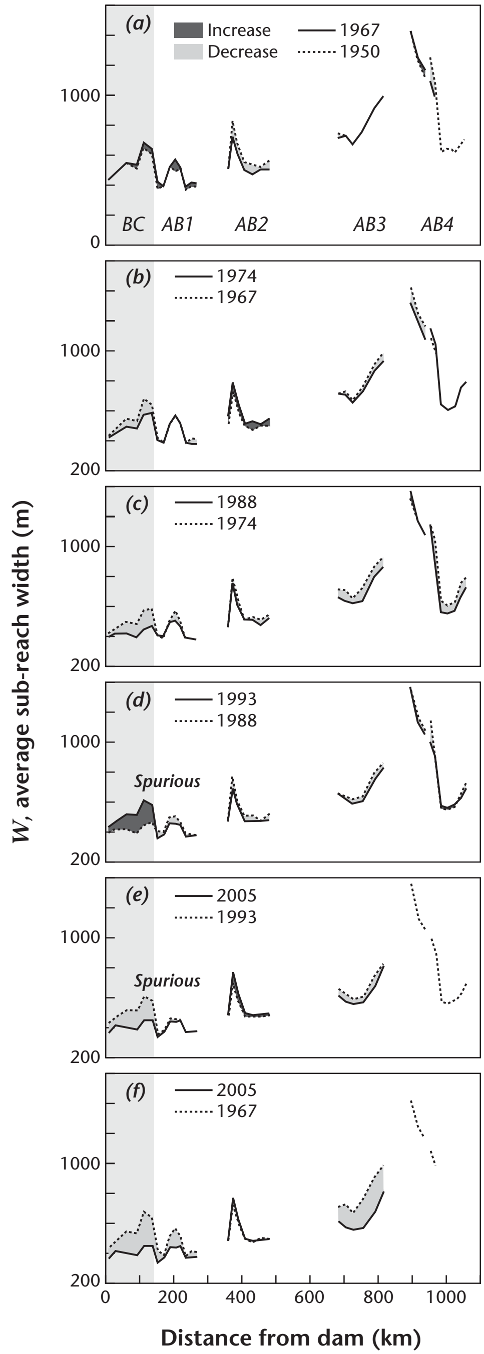

Figure 7.17 Spatial trends in channel width along Peace River displayed as cumulative change at the end of each survey period. Panel f indicates net change since regulation. The indicated changes in panels d and e for the BC reach should be disregarded because of high flows at the time of the 1993 photography. Reach AB4 data are incomplete due to limited air photo coverage.

the distal part of Reach AB4, while the net change is very small in Reach AB2. We have observed a similar trend in channel zone width (Figure 7.11) but while those changes are the order of −5% since regulation, summary post-regulation change in active channel width varies from −21% in Reaches BC and AB3 to near-zero in Reach AB2.

The proportion of the channel zone occupied by active bars (Figure 7.18a) declined in most of the river in the nonregulated period, except in Reach AB3. The large apparent decrease in Reach AB3 in the low-flow period 1967 to 1974 is an artifact of high flows in the 1976 (date flown) photography, while the large compensating changes in BC for 1988-1993 and 1993-2005 are the artifact of the high flows in the 1993 photography. While a reduction in active bar area was generally observed in the immediate post-regulation period (Figure 7.18b), the proximal sub-reaches in BC (i.e., those immediately below the dams) accumulated active bar area, as did Reaches AB2 and AB4A. By 1993 most of the river was accumulating active bar area and by 2005 the appearance is that all of the river was doing so. A pattern appears in this history, with the switchover from loss to gain proceeding upstream from the distal reaches—that is, those least severely influenced by flow regulation—toward the proximal, highly regulated reaches. In reading this statistic, one must bear in mind that the actual fraction of active bar area is on the order of 0.1 along most of the river, so that the statistics of change are apt to be sensitive. Nevertheless, the pattern suggests that sediment accretion is occurring as the consequence of reduced flows. The overall result since regulation, however, (Figure 7.18f) is for net loss of active bar area in all but Reaches AB2 and AB4.

I_v, the ratio of vegetated area within the channel zone, on the other hand, averages about 0.6 everywhere except in the BC reach and appears to be much more stable (Figure 7.18g to 7.18l). In the nonregulated period (panel g) there are losses in the upper river and in the reservoir-filling period of low flows there are losses in Reach AB2, consistent with the observed increase in width in that reach during that period. Otherwise, there are consistent small increments along the river in all periods (again excepting the ice-affected Reach AB2), conforming with expectations. Again, results in the BC reach in the last two periods must be discounted. The net gain in vegetated bar area is the main reason for the net loss in active bar area here.

Figure 7.19 displays trends in time and along the river of the main indices of erosion/accretion of sediment. In these graphs, the tendency in one inter-survey period is being compared with that in the next period. Hence, Figure 7.19a shows that in the low-flow period 1967 to 1974, lateral boundary change (accretion) became more positive (i.e., channel zone area was reduced more rapidly than in the preceding period of unregulated flow), except in AB2. Similarly, floodplain production occurred at an increased rate nearly everywhere along the river (Figure 7.19e), mainly the consequence of reclassification of abandoned high bar tops to floodplain following rapid vegetation succession. The succeeding period of "normal regulated flows" (1974 to 1988), experienced continued reduction in channel zone width along most of the river (Figure 7.19b) but a general reduction in rate of floodplain production (Figure 7.19f). The period encompassing the flood of record showed mainly increased rates compared with the "normal regime" in both indices, the large contrary trend in the BC reach again being an unfortunate artifact. In comparison, the final period, which includes the long reservoir drawdown flood of 1996, showed reduced rates of lateral boundary change but a mixed pattern in floodplain production. These results conform reasonably with expectations based on the history of flows.

7.7 Factors controlling channel change

In this section we seek to identify some factors that influence the observed trends of morphological change and channel adjustment downstream. Channel change is created by the entrainment and deposition of bed material along the channel, which depend upon the balance between imposed sediment load and the capacity of the river to transport that load. The capacity to transport sediment depends upon the strength of the flow and upon the magnitude of resistance to flow along the channel. Channel change also depends on the degree to which wash load is trapped and remobilized along the channel margins. The information available permits us to construct the following indices of these conditions.

To index flow strength, we use unit area, or specific, stream power at competent flow,

$$\omega = \gamma Q_{\max} S/\langle W\rangle \quad (7.13)$$

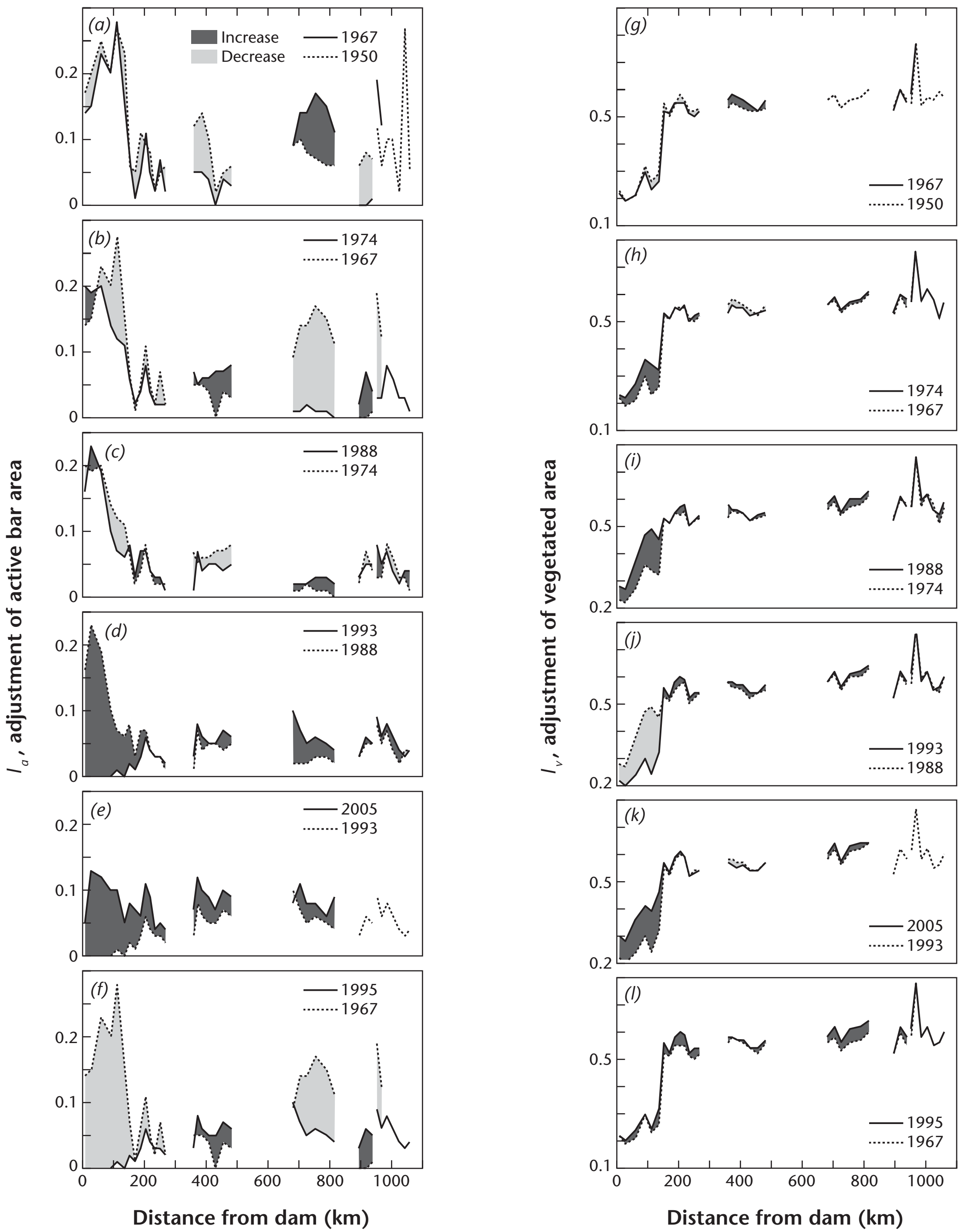

Figure 7.18 Spatial trends in bar ratios along Peace River: (a to f) ratio I_a, the proportion of active bar surface exposed in the channel; (g to l) ratio I_v, the proportion of vegetated surfaces within the channel zone, including both bar and island surfaces. The large changes in the BC reach in panels d and e should be disregarded because of the very high flows in the 1993 photography; similarly, large changes apparent in panels (a) and (b) for AB3 are due to relatively low flows in 1967 (actually photographed in 1969).

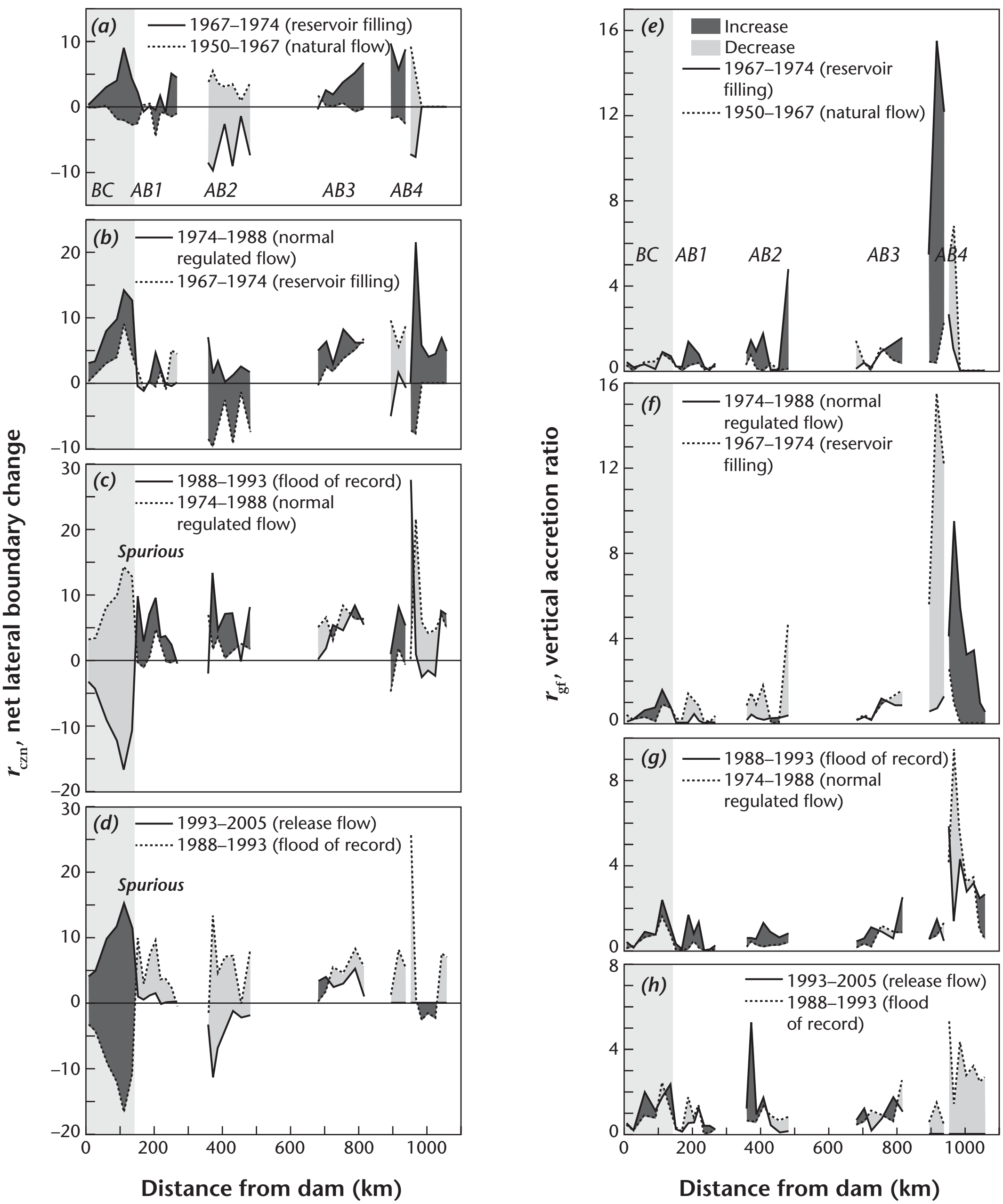

Figure 7.19 Period-to-period comparison of indices of channel change: r_{czn}, the index of lateral channel erosion/accretion; r_{gf}, the index of vertical accretion. Positive values indicate net accretion (channel narrowing) and net floodplain production. These charts show the change in the indices from one inter-survey period to the next. Therefore the graphs indicate changes within periods, not conditions at absolute dates.

(units watts m^{-2}) in which Q_{max} is mean annual flood determined for the appropriate period from the nearest gauge or, in the case of the 1988 to 1993 period and the 1993 to 2006 period, the magnitude of the major flood that occurred. S is river gradient (Table 7.1), and γ is the unit weight of water. Mean width is width of the active channel at the beginning of the period in each sub-reach (the assumption being that vegetated areas in the channel zone that are inundated during high flows convey only a small portion of the flow).

To index flow resistance we use two measures that represent independent contributions to flow resistance. Channel shape is an important factor in channel form resistance. Channel shape is expressed by the aspect ratio, but information of water depth is not available to us. We introduce an index of channel shape by considering the scaling relation of hydraulic geometry, $W = aQ^{0.5}$. For a given discharge, the coefficient, a, becomes larger in proportion as the channel becomes *relatively* wider and more shallow. Thus we adopt the index

$$a = \langle W \rangle / Q_{max}^{0.5} \tag{7.14}$$

to express channel shape. The higher the value of a, the relatively wider and more shallow will be the channel, in general. We suppose that this factor will be highly correlated with bar resistance.

Another factor that indexes resistance to flow is the vegetation on bar surfaces in the channel zone. Accordingly, we adopt the index

$$n_v = B_v / L \tag{7.15}$$

to represent this source of flow resistance. This value differs from I_v inasmuch as it excludes island area and it is divided only by reach length, so that it represents the width of channel occupied by vegetative growth. At flood level, this would be an addition to the active channel width discussed above which reflects normal flows in the river, not high flows.

We ignore grain resistance. We do have information of grain size downstream in the gravel reach. We are aware that the channel bed in the sand reach deforms into dunes (*McLean and Anderson*, 1980), but we have insufficient information on the spatial variation of sediments and bedforms, nor do we have information on bed surface state (imbrication; grain structures) in the gravel reach. We suppose that the variation in grain resistance is relatively conservative.

The channel shape factor and the vegetation index have varied systematically in time as the channel morphology has changed in response to flow regulation. Temporal trends are displayed in Figure 7.20. The shape factor, a, behaves consistently all along the river. During the low-flow period it increased, by as much as 1.75 times in the BC reach, but by only 1.35 times in the three sandy reaches. Following the low-flow period, a has consistently declined in all reaches in an approximately linear fashion, but values remain above those calculated for the unregulated river. The two major floods appear not to have disturbed the rate of adjustment. The adjustment is concordant with the adjustment in channel width itself. The actual values of a index the hydraulic geometry of the river. In the gravel-bed reaches of the river, initial values were in the range five to six, corresponding with the value of about five determined for Alberta gravel-bed rivers (Church, 1995). Following regulation, they increased to about 7.5, and to 11.5 in the proximal BC reach. These numbers imply a river that has contracted into the essentially flat bed of its central channel and is too wide and shallow to transport its bed material. The bed has indeed become immobile in the upper river. Values have since retrogressed toward normal values, indicating the adjustment of channel form to the regulated regime, but after 40 years and some major floods have still some distance to go. In the sand reaches, values increased from near 8 (12 in Reach AB4A) to 10 to 11 (16.5), and have since similarly retrogressed. All of these figures are larger than expected for Alberta sand-bed rivers (Church, 1995). The results are consistent with results from hydraulic geometry (Chapter 5) indicating the initial passive contraction of the regulated river into the lower, flatter central channel but, in addition, suggest that a narrower and somewhat redeepened channel has slowly been developing since.

The vegetation index, n_v, increases consistently throughout the observed history, except for an initial decline in the upper river in the pre-regulation period, irregular behavior including a decline in the low-flow period in AB2, and a longer decline in AB4A. In some reaches the pattern reflects the behavior of I_v and in some it does not.

Spatial trends in these two flow resistance indices are displayed in Figure 7.21. Only the initial change following regulation and net change since regulation are displayed. Following regulation, both values increased,

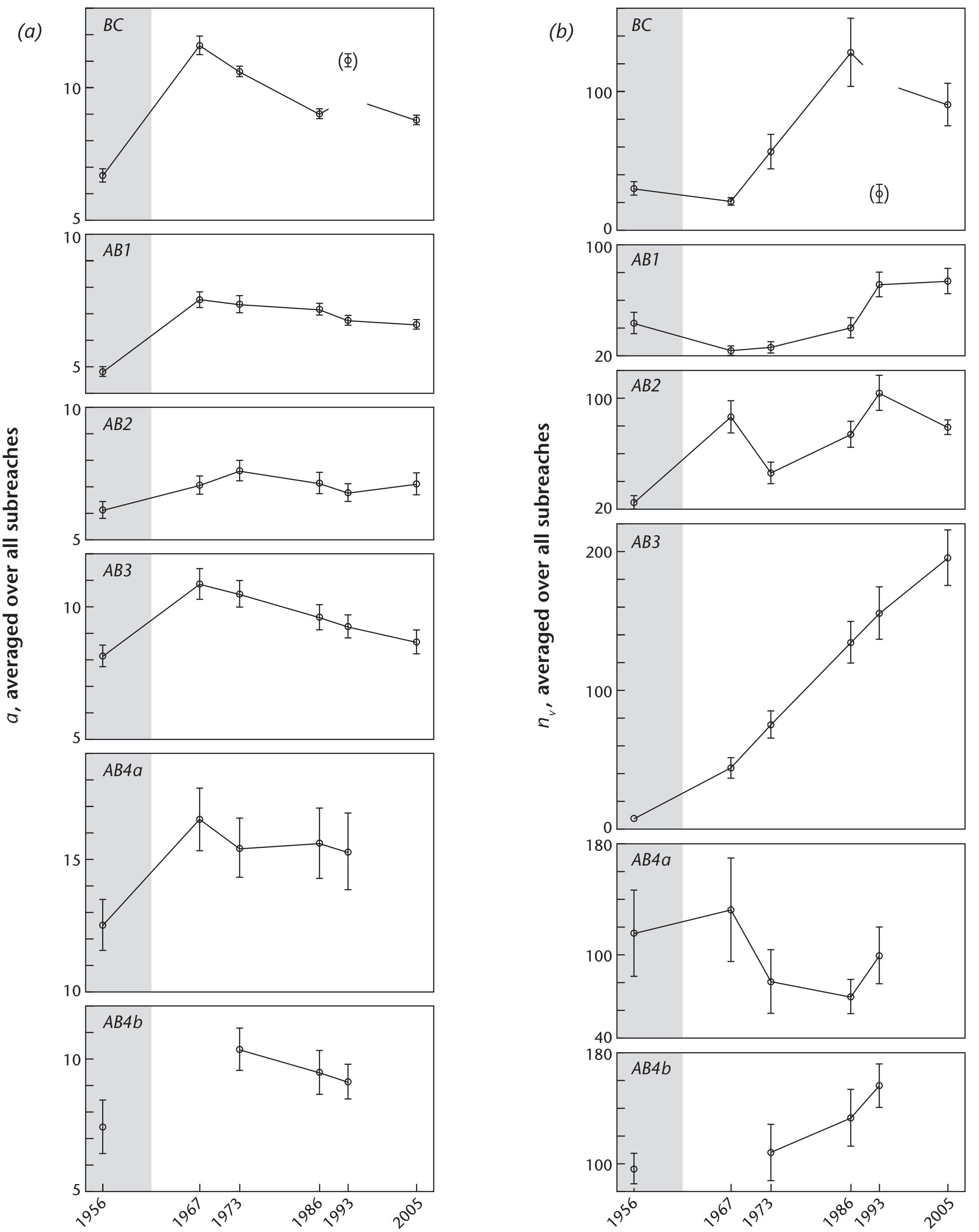

Figure 7.20 Reach-level temporal trends in the controlling factor indices along Peace River: (a) channel shape index; (b) vegetation index. The error bars represent 2s ranges of variance based on sub-reach data. The grey background indicates the period before regulation. The connecting lines are to aid comprehension of the pattern of change and are not meant to imply linear trajectories of change between data.

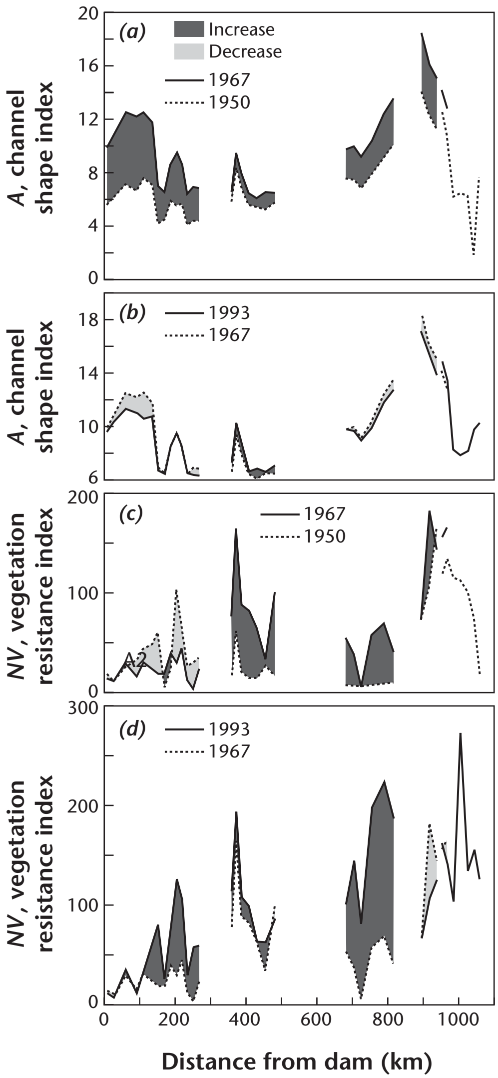

Figure 7.21 Spatial trends in flow resistance factors along Peace River: (a) and (b) channel shape index; (c) and (d) vegetation index.

except n_v in the BC and AB1 Reaches. Since that initial change, a shows the universal decline revealed by the temporal plots while n_v exhibits the expected near-universal increase (the exception being AB4).

Thinking of the two factors additively, then, the effect in the period of dramatically reduced flows immediately following regulation was a significant increase in factors governing the index of flow resistance. The further effect after another 30 years is, in the main, a further increase in the vegetation resistance factor, but little

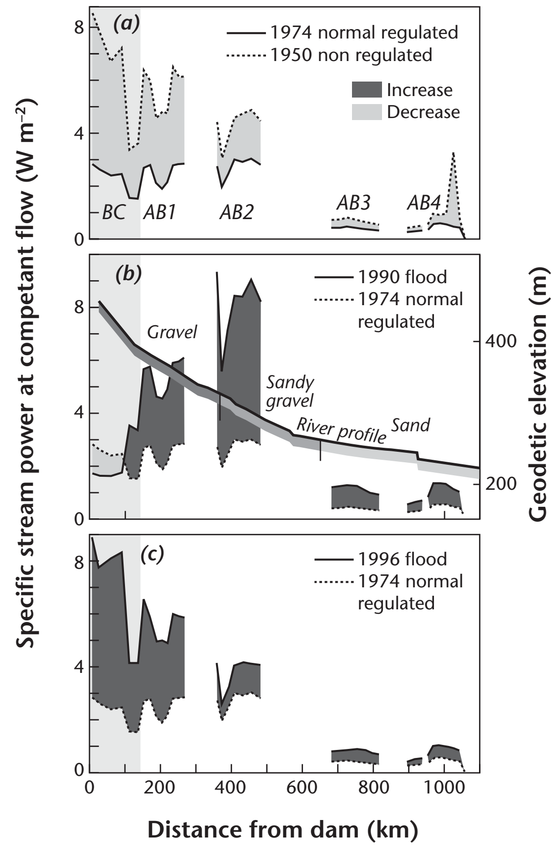

Figure 7.22 Spatial trends in specific stream power along Peace River.

further change in channel shape factor. Reach AB4, however, shows little overall change.

Stream power is displayed in Figure 7.22. There is a big decline from the pre-regulation period to that of normal post-regulation flows (Figure 7.22a): stream power declines downstream, indicating that the decline in gradient is more important than increasing discharge in mediating power. The trend is, however, considerably attenuated under the regulated regime and, indeed, power becomes essentially constant at values near 2.5 W m^{-2} through the entire upper and middle reaches and at <1 W m^{-2} in the distal sand-bed reaches. There are, however, some significant variations. In BC, the two sub-reaches below the Pine River confluence have substantially diminished power: these are wide reaches with a significant number of island groups developed under the influence of abundant gravel delivery from Pine River, which was formerly distributed farther downstream. Similarly, in AB1, the sub-reaches in the vicinity of Many Islands and Montagneuse River have reduced stream power, again dominated by the reduction in gradient upstream from and through the significant sediment accumulations at these places. In AB2, the Smoky confluence also has reduced stream power.

The two floods returned stream power to values that approach pre-regulation values, but the downstream pattern of variation in stream power was different for the 1990 flood of record (Figure 7.22b). Power increased from Pine River all the way to the end of Reach AB2. This is the consequence of the significant increments to flow from all the tributaries in these reaches, over which the storm passed.

The variation downstream in stream power in the 1990 and 1996 floods can be explained by the origin of the water: from the southern part of the basin in 1990, entering Peace River in midcourse, while entirely from the proximal dams in 1996. Hence, flow frequency downstream was by no means similar during these events. In comparison, the 1974 "normal flow" can be assumed to reflect a common flow frequency. The approximate sectoral equality of specific stream power along the river in this case supports a hypothesis put forward by several investigators (see Molnar and Ramirez, 1998, 2002) concerning optimal rate of energy expenditure, but our data show that the absolute rate of expenditure differs substantially between the gravel and sand reaches.

There is no close correlation between the trends in stream power and those of our resistance indices, reflecting the importance of factors not encompassed by those indices in mediating stream power. Gradient is the principal factor controlling stream power and sediment texture is the most sensitive direct response factor (see Figure 7.22b), but overall morphological style of the channel is also important, revealing itself particularly in the sub-reach variations.

7.8 Discussion

River width has persistently declined along Peace River since regulation, except in Reach AB2. The adjustment has mainly been passive and vegetation encroachment over formerly active bars is proceeding. The river is locally aggrading in the upper river by deposition of tributary-contributed gravels in-channel—the consequence of loss of competence. Sand deposition in the upper river is occurring by accretion along the channel edges while in Reach AB3 general aggradation has occurred, most notably in the reach immediately below the gravel-sand transition. Vegetation has become established within the channel zone on bar surfaces and this has contributed to an increase in the index of resistance to flow all along the channel. All three of the hypotheses articulated in the introduction to this chapter are sustained. In addition, we observe loss of side channels by dewatering in the upper river (Figure 7.23) and by sedimentation in the lower river, though some side channels are being maintained as the result of seasonal ice-jam high stage, especially in Reach AB2 that, in many respects, has responded unlike the other reaches as the result of severe ice effects.

The picture that emerges from our observations is of a river adjusting to a regulated flow regime that has significantly reduced the competence of the river to transport its sediment load. Unlike many regulated rivers, however, that load has not been significantly modulated. Hence the channel is adjusting by occupying a smaller, somewhat simpler channel within its channel zone, and by sedimentation at places along the river where bed

Figure 7.23 Dewatered side channel in the British Columbia reach downstream from Halfway River. Seasonal flow may still occur in winter. Residual pools are fed by hyporheic water and valleyside seepage.

Table 7.5 Estimated Shields numbers for Peace River principal gauges

			Pre-regulation			Post-regulation		
Gauge	S $\times 10^4$	D_{50} m	Q m^3s^{-1}	d^* m	τ^*	Q m^3s^{-1}	d^* m	τ^*
Taylor	6.9	0.064	7180	6.9	0.045	2850	3.8	0.025
Alces River	3.4	0.032	–	–	–	3020	6.1	0.039
Dunvegan Bridge	2.2	0.053	8100	7.9	0.020	3280	4.7	0.011
Carcajou	0.74	0.0070	9330	9.3	0.060	–	–	–
Fort Vermilion	0.41	0.00022	9300	10.1	1.14	4710	8.3	0.937
Peace Point	0.74	0.00022	9700	9.9	2.0	5510	6.7	1.37

d^* is hydraulic mean depth; it underestimates thalweg depth, hence maximum value of τ^* in the section by some 10% to 20%.
D_{50} is surface grain size. Surveyed slopes from Kellerhals *et al.* (1972).
There will be minor inconsistencies in the flow data due to different lengths of record.

material is contributed by tributaries and, episodically, by landslides. These effects are reflected in a substantially reduced active channel and a slowly shrinking channel zone. The major evident mechanism signaling reduction of the active channel is the progradation of riparian vegetation onto formerly active bar surfaces, but this process is largely inhibited in Reach AB2, where significant ice scour is maintaining the channel, and it is of limited importance in the confines of Reach AB1. The aberrant character of Reach AB2, in comparison with the balance of the river, provides the most direct evidence available that the ice regime in boreal rivers may indeed influence channel dimensions (compare discussion in Chapter 6).

The upper river is no longer competent to transport the major part of the cobbles and gravel introduced by tributaries to the river with the consequence that they accumulate in fan-like sediment bodies near the point of introduction. The river profile is consequently becoming stepped, with significant upstream backwater (Chapter 3). The sand load, including the abundant load delivered by Smoky River, is transported through the relatively steep AB2 Reach, but is partly deposited below the gravel/sand transition in the reach downstream from Carcajou, where significant channel shoaling has occurred, signaling that the channel in Reach AB3 is now transport-capacity limited. Sedimentation onto lateral bars and in side-channels makes an additional contribution to channel narrowing and floodplain construction all along the river. The new floodplain is being built, however, at a level comparable with the major bar tops, lower than the formerly active flood surface.

Because we lack information of river depth, we cannot directly estimate shear forces for mobilization of bed material in the river. However, we may speculate by using data derived from the gauging sections. From hydraulic geometry presented in Chapter 5 (Tables 5.2 and 5.3) we estimate flow depth for the two-year partial duration flood at the principal gauging stations along the river and the corresponding values of the Shields number (τ^*: Table 7.5). It appears that, in the natural, pre-regulation regime, the upper river was barely capable of moving bed material—as we have inferred from other lines of evidence. In the upper river, this would especially be the case if one considers structural strengthening of the bed gravels (Church *et al.*, 1998). Values are especially low at Dunvegan Bridge, probably because slope is low as the river is backwatered by the prograding fan of Hines Creek, immediately downstream. At Carcajou, just upstream of the gravel–sand transition, $\tau^* = 0.06$ and probably moved the 10-mm bed material at low rates while easily moving the large, overpassing sand load. In the sand-bed reach, the river was, and remains, competent. Post-regulation, the upper river appears to be incapable of moving the bed in normal regime flows, consistent with field observations. Unfortunately, we do not have post-regulation data for the critical site at Carcajou. In comparison with natural flows, however, it appears that the 1996 flood in the upper river was just competent; that is, it may have replicated the pre-regulation annual flood condition.

Amongst the substantial range of prior studies of the downstream effects of dams and other river flow management manipulations, few bear similarities to the present case. Sear's (1995) study of the cobble-gravel River North Tyne downstream from Kielder Reservoir (Northumberland, United Kingdom) revealed a response very similar to that of the proximal reach of Peace River: modest scour and fill of riffles and pools, respectively (not noted on Peace River), formation of confluence bars at tributary entrances signaling aggradation there, and the formation of sandy berms along the margins of the reduced channel (observed in Peace River below the Pine River confluence).

Van Steeter and Pitlick (1998a, 1998b) studied the effect of flow regulation by a substantial number of small reservoirs constructed since 1950 on the upper Colorado River. Some of those reservoirs are for flow diversion, so both flood flows and mean flow have been reduced on the river. Peak flows have been reduced by 30% to 40% (the value changes along the river) but regulation is not so severe that flows exceeding the unregulated mean annual flood are entirely eliminated. Hence, the river remains capable of transporting the bed material (D_{50} of surface material ~50 mm). Van Steeter and Pitlick have observed general narrowing of the channel with advance of riparian vegetation and abandonment of side channels, as on Peace River. Lateral accretion is observed along the main channel and vertical accretion of fine sediment in side channels. While 0.5 to 1.0 m of scour or fill were observed at individual sections, there was no consistent trend of aggradation or degradation in the main channel. Occasional high flows may persist for periods of days to a month. For example, in 1995 peak flow at Cameo, Colorado was 838 m^3s^{-1} (current return period nine years), compared with a pre-regulation MAF of 725 m^3s^{-1}, and the current magnitude of MAF (517 m^3s^{-1}) was exceeded for 28 days. Such floods do mobilize the bed and are capable of reactivating side channels by scouring side-channel entrances, but they have not reversed the general trends of narrowing and simplification of the river channel.

The likely trajectory of further morphological change along Peace River is an important topic. One normally would expect a negative exponential response to flow adjustment, driven by the magnitude of change remaining to reach the new equilibrium of channel form dictated by the changed flows. In fact, most of the adjustments depicted in Figures 7.12, 7.14, 7.16, and 7.20 are either approximately linear, often with a delayed initial response, or irregular. The periods defined in those figures are designed to isolate significant events in the post-regulation history of the river. The observed changes suggest that two factors dominate the response:

i. the progradation of vegetation within the channel zone, which appears to be approximately linear, probably in consequence of the progression of successful seed set in front of established vegetation;

ii. the occurrence of singular events, such as the floods of 1990 and 1996, in delaying or augmenting that progression.

The initial delay may be a consequence of the 1972 spillway test flood or of the time required for colonizing species to initiate progradation onto formerly inundated areas. In any event, the process appears not to be gradient driven in any classical sense.

7.9 Conclusions

The morphological response to flow regulation in the upper, cobble-gravel reach of Peace River has been largely passive. Normal flows are not competent to move the bed material of the river so that progradation of vegetation onto former bar tops, along with marginal deposition of sand below Pine River confluence, are the principal general means of channel shrinkage. Below principal tributary confluences, local aggradation is occurring. In the confined Reach AB1, overall response is muted except at the multichannel sub-reaches at Many Islands and Montagneuse River, where backchannel abandonment is occurring.

In Reach AB2, below Smoky River confluence, ice jams are maintaining the dimensions of the pre-regulation channel, attesting to the importance of ice effects in setting the morphology of northern rivers. Beyond Carcajou (Reach AB3), reduced gradient, reduced confinement, and the transition to a sand-bed channel have promoted channel narrowing, largely by siltation of back channels. General aggradation has occurred immediately below the gravel–sand transition. Changes in the Peace–Athabasca Lowland (Reach AB4) largely consist of increased emergence of river channel bars, which may presage future increase in anastomosis.

Overall, the channel zone and the active channel have narrowed, the latter more than the former. Establishment of vegetation on emergent bar tops and, in the lower channel, siltation of back channels are the principal processes by which narrowing has been achieved. This has been accompanied by an increase in overall resistance to flow along the channel.

The pace of channel adjustment is largely controlled, then, by the rate of progradation of channel margin vegetation, hence will require many decades to be completed. This response is in marked contrast to the response that one observes upon increase of river flows, when hydraulic effects rapidly adjust the channel to the dimensions required to handle the changed regime flows.

Acknowledgments

Data that form the basis of this paper rely heavily on mappings of Peace River at successive dates, carried out by Arnold Moy, Jason Barraclough, and Karen Kranabetter under the direction of Lars Uunila. The 2006 mapping was produced by Rowan Arundel. Vegetation data were obtained under the direction of Margaret North. Chris Adderley constructed many of the diagrams.

References

Andrews, E. D. (1986) Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah. *Geological Society of America Bulletin*, 97, 1012–1023.

Brandt, S. A. (2000) Classification of geomorphological effects downstream of dams. *Catena*, 40, 375–401.

Church, M. (1995) Geomorphic response to river flow regulation: case studies and time scales. *Regulated Rivers: Research and Management*, 11, 3–22.

Church, M., Xu, J., Moy, A., and Uunila, L. (1997) *Changes in Morphology and Riparian Vegetation Following Flow Regulation: Peace River, 1968 and 1993. NRBS Study, Project Report,* 102, 91 p. Edmonton, Canada.

Church, M., Hassan, M., and Wolcott, J. F. (1998) Stabilizing self-organized structures in gravel-bed stream channels: field and experimental observations. *Water Resources Research*, 34, 3169–3179.

Cruden, D. M., Ruel, M., and Thomson, S. (1990) Landslides along the Peace River, Alberta. *Proceedings of the 43rd Canadian Geotechnical Conference*, 1, 61–68. Geotechnical Society of Canada.

Desloges, J. R. and Church, M. (1989) Wandering, gravel-bed rivers: Canadian landform examples—13. *The Canadian Geographer*, 33, 360–364.

Evans, S. G., Hu, X.-Q., and Enegren, E. G. (1996) The 1973 Attachie Slide, Peace River Valley, near Fort St. John, British Columbia, Canada: a landslide with a high velocity flowslide component in Pleistocene sediments, in *Landslides*, vol. 2, edited by K. Senneset. Proceedings of the 7th International Symposium on Landslides, Jun 17–21, Trondheim, Norway. A. A.Balkema, Rotterdam, The Netherlands. pp. 715–720.

Gaeuman, D., Schmidt, J. C., and Wilcock, P. R. (2005) Complex channel responses to changes in stream flow and sediment supply on the lower Duchesne River, Utah. *Geomorphology*, 64, 185–206.

Galay, V. J. (1983) Causes of river bed degradation. *Water Resources Research*, 19, 1057–1090.

Gerard, R. and Karpuk, E. W. (1979) Probability analysis of historical flood data. *Journal of the Hydraulics Division* [Proceedings of the American Society of Civil Engineers], 105, 1153–1165.

Grant, G. E., Schmidt, J. C., and Lewis, S. L. (2003) A geological framework for interpreting downstream effects of dams on rivers, in *A Peculiar River*, edited by J. E. O'Connor and G. E. Grant. Vol. 7: Water Science and Application. American Geophysical Union. pp. 203–219. doi:10.1029/007WS13

Hughes, M. L., McDowell, P. F., and Marcus, W. A. (2006) Accuracy assessment of georectified aerial photographs: implications for measuring lateral channel movement in a GIS. *Geomorphology*, 74, 1–16.

Kellerhals, R., Neill, C. R., and Bray, D. I. (1972) Hydraulic and geomorphic characteristics of rivers in Alberta. *River Engineering and Surface Hydrology Report* 72-1, 48 p. Research Council of Alberta, Edmonton, Canada.

McLean, D. G. and Anderson, M. D. (1980) Hydraulic and Morphological Processes on the Peace River near Fort Vermilion, *Report,* SWE 80-2, 118 p. Alberta Research Council, Transportation and Surface Water Engineering Department, Edmonton, Canada.

Miller, J. R. and Friedman, J. M. (2009) Influence of flow variability on floodplain formation and destruction, Little Missouri River, North Dakota. *Geological Society of America Bulletin*, 121, 752–759. doi:10.1130/B26355.1

Molnar, P. and Ramirez, J. A. (1998) An analysis of energy expenditure in Goodwin Creek. *Water Resources Research*, 34, 1819–1829.

Molnar, P. and Ramirez, J. A. (2002) On downstream hydraulic geometry and optimal energy expenditure: case studies of the Ashley and Taieri Rivers. *Journal of Hydrology*, 259, 105–115.

Mount, N. and Louis, J. (2005) Estimation and propagation of error in measurements of river channel movement from aerial imagery. *Earth Surface Processes and Landforms*, 30, 635–643.

Petts, G. E. (1984) *Impounded Rivers: Perspectives for Ecological Management*. John Wiley & Sons, Ltd, Chichester, UK. 326 p.

Sear, D. A. (1995) Morphological and sedimentological changes in a gravel-bed river following 12 years of flow regulation for hydropower. *Regulated Rivers: Research and Management*, 10, 247–264.

Severin, J. M. (2004) Landslides in the Charlie Lake Map Sheet, Fort St. John. M.Sc. thesis. The University of British Columbia.

Shaw, J. and Kellerhals, R. (1982) The composition of recent alluvial gravels in Alberta river beds. *Alberta Geological Survey*, Bulletin, 41, 151 p. Alberta Research Council, Edmonton, Canada.

Swanson, B. J., Meyer, G. A., and Coonrod, J. E. (2011) Historical channel narrowing along the Rio Grande near Albuquerque, New Mexico in response to peak discharge reduction and engineering: magnitude and uncertainty of change from air photo measurements. *Earth Surface Processes and Landforms*, 36, 885–900.

Van Steeter, M. M. and Pitlick, J. (1998a) Geomorphology and endangered fish habitats of the upper Colorado River. 1. Historic changes in streamflow, sediment load, and channel morphology. *Water Resources Research*, 34, 287–302.

Van Steeter, M. M. and Pitlick, J. (1998b) Geomorphology and endangered fish habitats of the upper Colorado River. 2. Linking sediment transport to habitat maintenance. *Water Resources Research*, 34, 303–316.

Walstra, J., Chandler, J. H., Dixon, N., and Wackrow, R. (2011) Evaluation of controls affecting the quality of spatial data derived from historical aerial photogaphs. *Earth Surface Processes and Landforms*, 36, 853–863.

Williams, G. P. and Wolman, M. G. (1984) *Downstream Effects of Dams on Alluvial Rivers. United States Geological Survey*, *Professional Paper*, 1286, 83 p. U.S. Government Printing Office, Washington.

Winterbottom, S. J. (2000) Medium and short-term channel planform changes on the Rivers Tay and Tummel, Scotland. *Geomorphology*, 34, 195–208.

CHAPTER 8

Studies of riparian vegetation along Peace River, British Columbia

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8.1 Introduction

As human populations increase and demands for energy grow, rivers throughout the world are being harnessed for generation of hydroelectric power. This addition to a river's natural functions has impacts on the entire system (Petts and Gurnell, 2005). The obvious loss of valley floor beneath reservoirs has been a focus of attention, along with microclimatic and seismic effects of large reservoirs and the problems of maintaining habitat and spawning routes for fish (e.g., Ward and Stanford, 1989). Much attention has also been directed to the downstream effects of altered river flow (e.g., Ligon *et al.*, 1995). Initially these studies examined changes in floodplain and channel morphology, and in aquatic ecology (Petts, 1984). More recently, downstream effects on riparian vegetation have been studied (Williams and Wolman, 1984; Braatne *et al.*, 1996; Rood *et al.*, 1999; Polzin and Rood, 2000; Samuelson and Rood, 2004; Marston *et al.*, 2005).

Riparian ecosystems are strongly influenced by the fluvial regime of their river, particularly if the river is laterally active, so that channel, bar, and floodplain areas are continually destroyed and renewed. But riparian vegetation strongly influences fluvial processes as well in what amounts to a system of reciprocal process and response (Murray *et al.*, 2008). Flow regulation for hydroelectric power production almost always results in a change in the hydrological regime of the river so that peak flows are diminished and minimum flows are augmented. It often leads to a change in the seasonal occurrence of high and low flows as well. These primary hydrological changes have significant effects on floodplain development and riparian ecosystems. In particular, plant succession in floodplains, while subject to the normal autogenous processes, is also subject to periodic resetting by the erosional and depositional processes of the river (e.g., Johnson, 2000). Flow regulation may change these processes by largely stabilizing the channel (Shields *et al.*, 2000) so that riparian succession is much less frequently and less commonly restarted. The result is an increasingly "terrestrial" valley flat (no longer an active floodplain) with reduced plant community diversity as early successional units become more rare (e.g., Bravard *et al.*, 1986; Marston *et al.*, 2005). However, late succession may be influenced as well since the reduced or eliminated incidence of flooding and generally lower groundwater levels may lead to premature death of some floodplain plants that no longer successfully reestablish (e.g., Bradley and Smith, 1986).

The construction of two dams on Peace River near Hudson's Hope, the first having been closed in December 1967, established a regulated flow regime on this formerly free-flowing, major boreal river (Chapter 2). The purposes of this study are to elaborate a model that can be applied to explain and predict altered riparian vegetation along Peace River in British Columbia and to analyze observations from the first 38 years of the regulated regime in light of that model. Specific objectives of the paper are, therefore,

i. to describe "normal" patterns of riparian succession along a large boreal river;
ii. to construct and test a model of normal riparian succession for the river;
iii. to apply the model to identify ways in which regulation of the river has modified the normal succession.

The Regulation of Peace River: A Case Study for River Management, First Edition. Michael Church.

Companion website: www.wiley.com/go/church/peaceriver

8.2 Study area

Peace River flows from its headwaters, now above Williston Lake (the major reservoir), in north-central British Columbia, eastwards across the province, entering Alberta just north of the 56th parallel, whence it flows east and then north to the Peace–Athabasca delta and eventually to the Arctic Ocean via Mackenzie River. The significance of the northward flowing course is that, though much of the river freezes over in winter, ice usually melts in the upper reaches before lower reaches are freed, so ice jams are a feature of fluvial processes along the river (Uunila, 1997; Chapter 6).

In British Columbia (Figure 8.1) the river flows in a valley incised about 250 m below the adjacent prairie level. The valley provides winter habitat sheltered from extreme wind chill and a summer habitat of higher temperatures and greater moisture for wildlife than on the prairie. This crucial habitat comprises steep valley sides, floodplain, and islands. The floodplain is narrow and discontinuous, the river frequently impinging on the valley walls. The river's mean width is about 500 m, but width

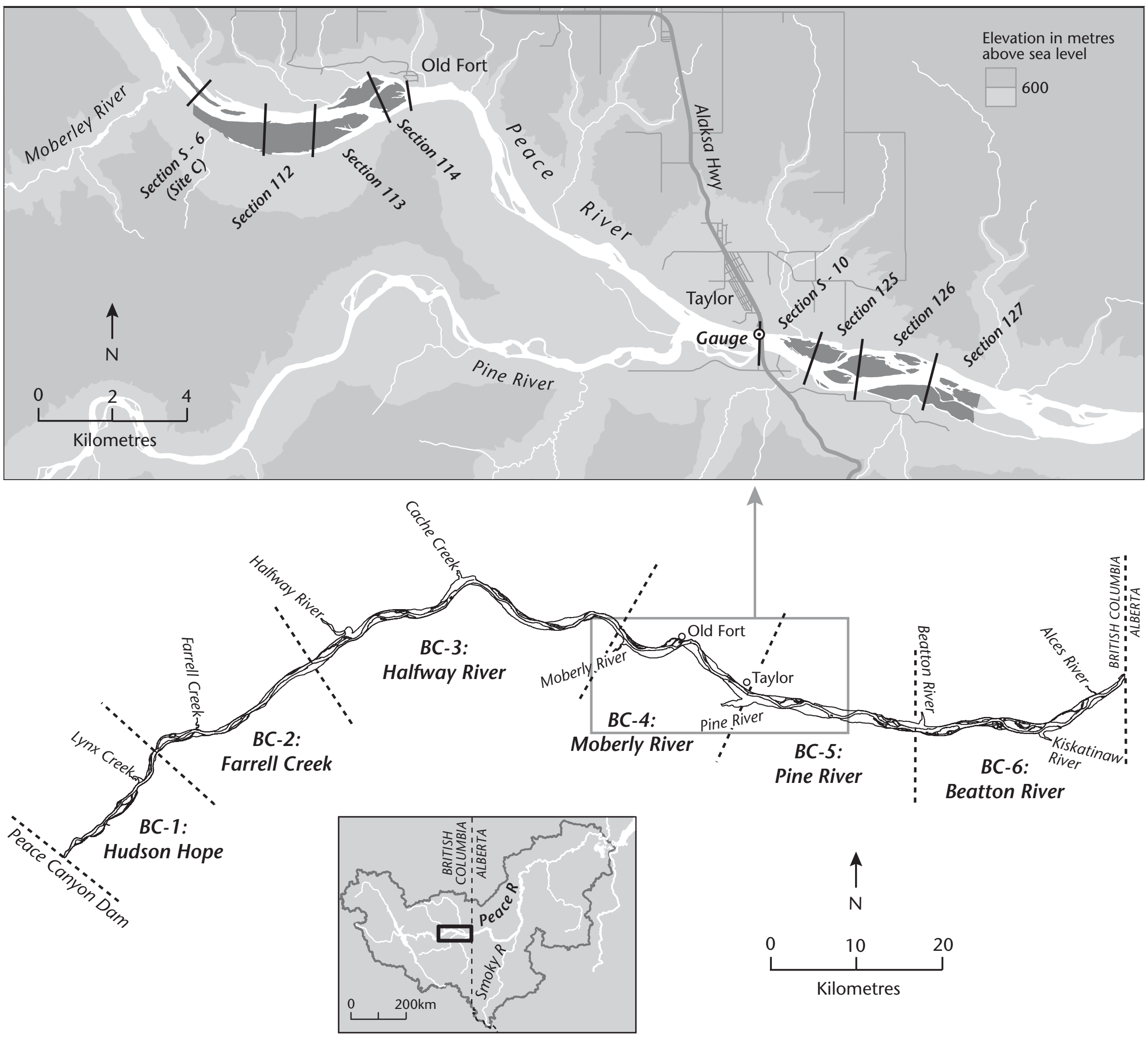

Figure 8.1 Location map of the Peace River field study area and the British Columbia reach, showing the sub-reach division; inset, Peace River basin.

Figure 8.2 Peace River floodplain stratigraphy: nearly three meters of silty sand overlying channel gravel. This stratigraphy is typical of gravel-bed rivers in the Canadian Cordillera and in its foreland. The former floodplain forest here includes *Betula papyrifera*, *Alnus incana*, and *Populus balsamifera*. As the result of flow regulation, the floodplain level is now a terrace. The holes are bank swallow nests. View near the Beatton River confluence, British Columbia, July 2005.

varies from 300 to 1800 m with islands taking up to 600 m or more. This variable, discontinuous, and often poorly accessible habitat provides significant remnants of natural riparian vegetation.

The river exhibits cobble-gravel "wandering" channel morphology (Desloges and Church, 1989). Sedimentary style is lateral construction of gravel bars as bed material is moved and redeposited. Once bars build sufficiently high, floods deposit sand on top and terrestrial vegetation can be established. The plant cover slows succeeding floodwaters and thereby accelerates sand deposition. As riparian succession occurs denser vegetation traps more sand so that the sandy top layer builds and the floodplain aggrades (Figure 8.2). The floodplain deposits vary from one to three meters in depth and the surface consists of fine sand and silt upon which soils develop.

The riparian vegetation is typical of active floodplains in the Subboreal Spruce zone, the ecosystem that covers much of central interior British Columbia (Meidinger and Pojar, 1991, p. 210). Figure 8.3 shows typical parts of this riparian landscape. Vegetation varies in species composition and height from open herbaceous communities to dense shrubs to closed stands of trees. The plant communities show a definite imprint of the fluvial geomorphology of the river. Outer edges of islands, where coarser sediments are continuously or seasonally accreting, have a sparse plant cover. The margins of older back channels, where finer sediments have settled, support a low but dense herbaceous or shrub cover. More stable island surfaces support a variety of cover types ranging from shrubs to stands of deciduous trees. Centers of islands support patches of mixed deciduous and coniferous species and, in some places, stands of purely coniferous trees. Coniferous forest also occurs on the floodplain adjacent to valley walls where these surfaces have not been cultivated. Some islands and floodplain edges have sharp cut banks indicating active lateral erosion (Figure 8.2); here mature mixed or coniferous forests precariously border the river channel. Adjacent prairies north of the valley are now mainly cultivated farmland. Where accessible floodplain is contiguous with farmland, it is often altered by cultivation or by grazing. South of the valley the uplands are covered by continuous forest, mixed deciduous and coniferous where the vegetation has been disturbed by fire or forest harvesting, and coniferous where undisturbed. This forest cover extends down the north-facing valley slopes to the floodplain. South-facing slopes adjacent to farmland are often open grassland, with shrubs or trees along drainage lines only. In many places, the valley slopes are disturbed by landslides.

The unregulated flow regime of Peace River was dominated by a nival freshet and low winter flows (Figure 8.4), but regulation has reversed this pattern immediately below the dams (Chapter 2) so that high flows (1500 m^3s^{-1}) occur in winter when electric power demand peaks, and low flows (1000 m^3s^{-1}) occur in midsummer. Below the confluence with Pine River—the principal British Columbia tributary—an early summer freshet is reintroduced, but it is scarcely larger than the high winter flows. Below the Pine confluence, higher water levels may still occur in winter due to ice dams

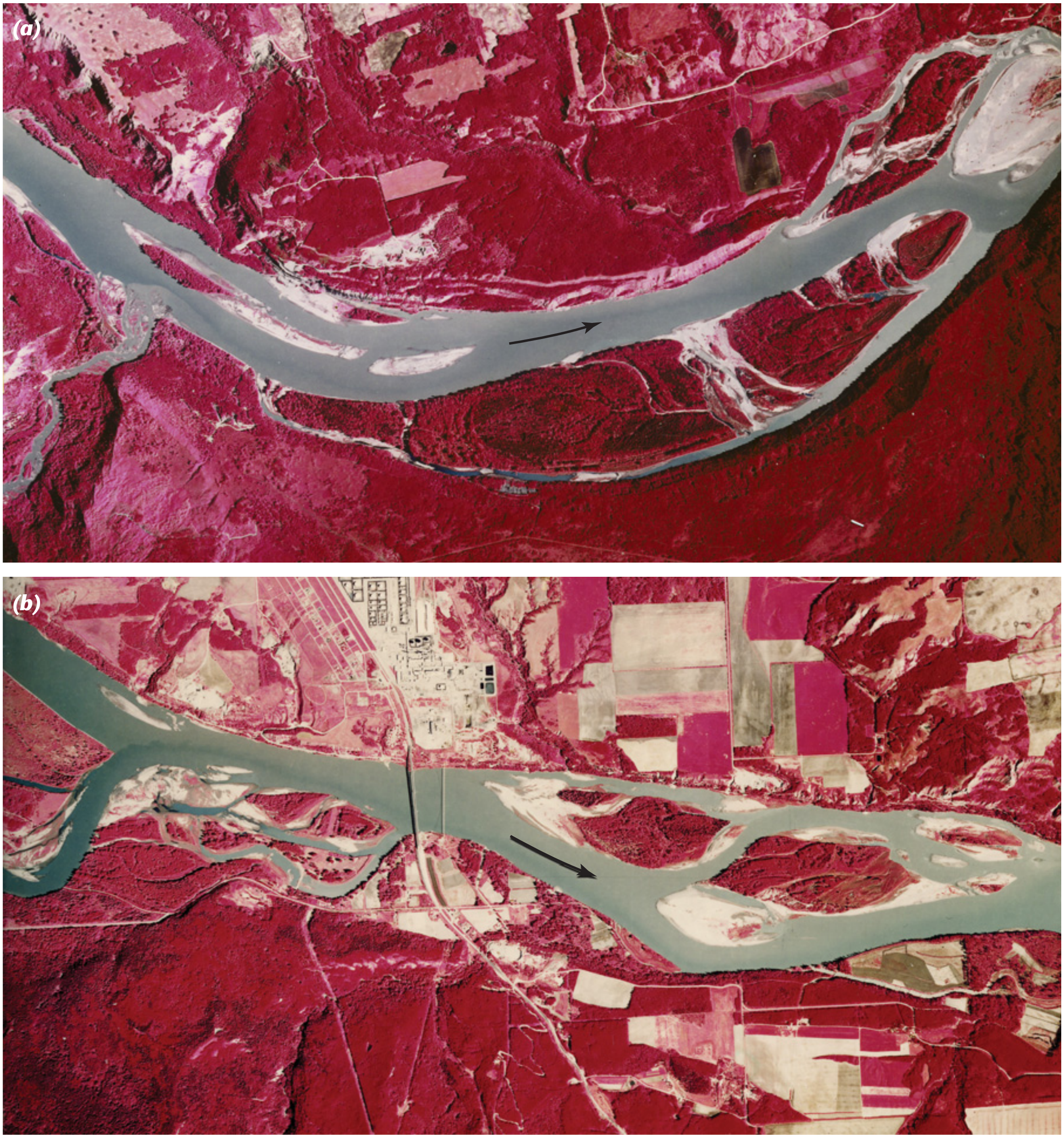

Figure 8.3 Field study areas on Peace River; (a) upstream, and (b) downstream islands shown in false-color infrared images, June 5, 1977; (a) The upstream study area comprises the large island on the south side (right bank) of the river channel and the smaller islands downstream and on the north side (left bank) of the channel (photo A37448IR-106); (b) The downstream study reach lies east of Taylor Bridge and comprises the westernmost downstream island and that immediately east of it (photo A37448IR-119). North of the river is agricultural land, fields showing pale gray to speckled pink at the start of the growing season. The bright red colors on the islands, both upstream and downstream of Taylor Bridge, indicate riparian cottonwood forest. The similar red area south of the river is aspen forest. Large patches of dark red to black on the southwest side of the aspen forest, in a patch opposite the south end of the bridge and on the westernmost small island downstream of the bridge are spruce-dominated forest, or mixed forest with conifers overtopping deciduous trees. The predominantly pale gray areas surrounding the forests on the islands show faint pink and/or greenish colors; these mark the herb and shrub communities, dominated by cottonwood or willows. (Crown copyright for photos reserved in right of Canada.)

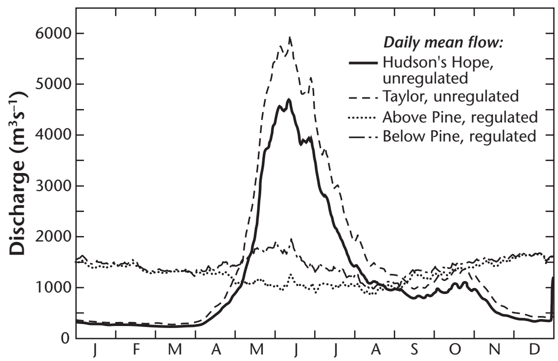

Figure 8.4 Comparison of Peace River flows before and after regulation: daily mean flows at Hudson's Hope, five kilometers below Peace Canyon Dam (WSC Stn. 07EF001), and at Taylor (07FD002), immediately below the Pine River confluence, before and after regulation.

resulting from the consolidation of pan ice and frazil ice (above the Pine, ice cover is now limited due to the slightly elevated temperature of the reservoir water). In 1996, an unusual summer flood occurred between late June and mid-August when it was necessary to draw down the reservoir for repair work. Water was at flood level for about seven weeks, reaching about 5200 m^{3}s^{-1} upstream of the Pine River confluence and 6200 m^{3}s^{-1} below it. These flows approximated a moderate pre-regulation freshet but occurred later in the season.

8.3 Methods

A field study was conducted on four islands that lie upstream and downstream from the Pine River confluence; two islands near Old Fort, referred to as the "upstream islands," and two immediately downstream of Taylor Bridge, the "downstream islands" (Figure 8.3). These islands were selected to represent the variety of plant communities identified on air photos of Peace River in the British Columbia reach between the dams and the Alberta border. Data derived from a series of vegetation maps of the entire British Columbia reach extend the field data analysis. These data are based on interpretation of air photos from six dates between 1953 and 2005.

8.3.1 Initial air photo mapping, ground checking, and site selection

Initial air photo interpretation and mapping of the field study area were based on infrared (IR) photography flown on June 5, 1977, at 1:46 000 scale. False-color IR imagery (e.g., Figure 8.3) provides sharper definition of dominant deciduous trees and shrubs than conventional photography. Fourteen cover types were delimited on the 1977 photos (Figure 8.5; Table 8.1); further divisions were based on stand height and age. Ground checking in 1981 of the photo-based map involved rapid reconnaissance from the river and transects on foot. Location of permanent plots for detailed study was arbitrary, constrained by the need to represent each cover type, by accessibility and by the need to ensure long-term security of the sites. In 1998 the GPS location of each plot was established and this information is attached to the data files (see Appendix).

Nine vegetation types were studied in plots located on the "upstream islands"—a large island group just downstream of the Moberly River confluence (Figures 8.1, 8.3a, 8.5a)—while a tenth plot was located on an island opposite the downstream end of this group. A further eight plots were established on the two islands immediately downstream of the Taylor Bridge (the "downstream islands"—Figures 8.1, 8.3b, 8.5b). These eight were chosen to replicate the first set of sites. However, we were unable to find a replicate of Plot 2, a dense stand of dogwood shrubs; Plot 6, located in a stand of white spruce; or Plot 10, located in decadent cottonwood. While the 1977 photography was used to guide the selection of field sites, by 1981 there had already been alteration in the cover types at the lowest elevations. Hence Plots 1 and 14, though located in an unvegetated (1977) map unit, were in fact supporting a discontinuous herbaceous cover that included tree seedlings and saplings. In addition to the plots, a transect was run from the upstream island southeast into a back channel in order to monitor vegetation change related to the elimination of normal flow through this channel (Figure 8.5a). The channel remains open at its downstream end.

8.3.2 Photo identification of plant communities

Communities were mapped from the color IR air photos (Figure 8.3) on the basis of dominant cover type (Figure 8.5). Photo signatures of the communities are given in Table 8.1. All recently deposited surfaces that are exposed during the growing season are likely to have a discontinuous to continuous cover of herbaceous species (types H: Figure 8.6a). The photo signature for these

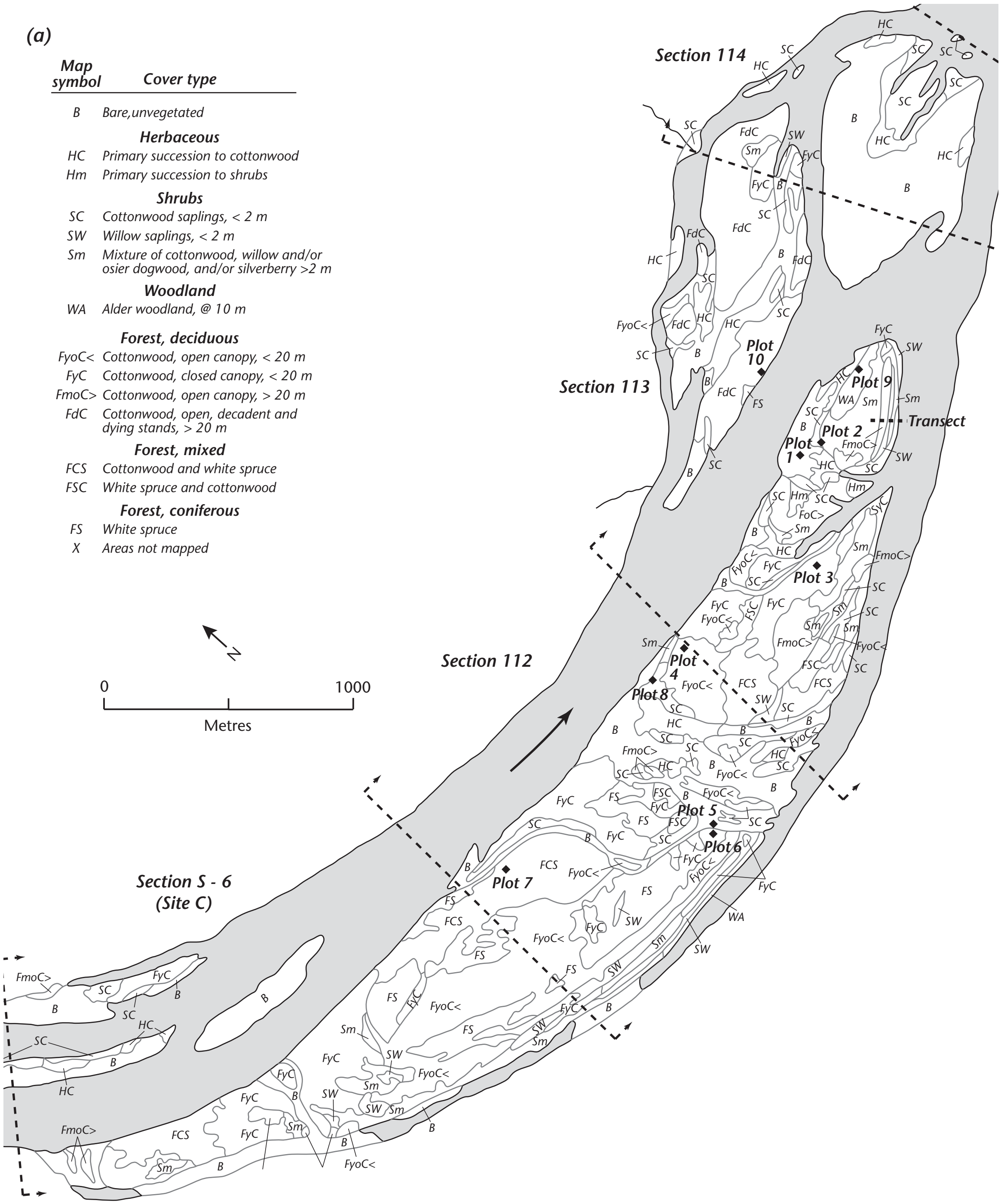

Figure 8.5 Vegetation maps showing plant communities mapped from 1977 color infrared photography (Figure 8.3) and field checked. (a) Upstream islands showing location of Plots 1 to 10 and transect; (b) islands downstream of Taylor Bridge showing location of Plots 11 to 18.

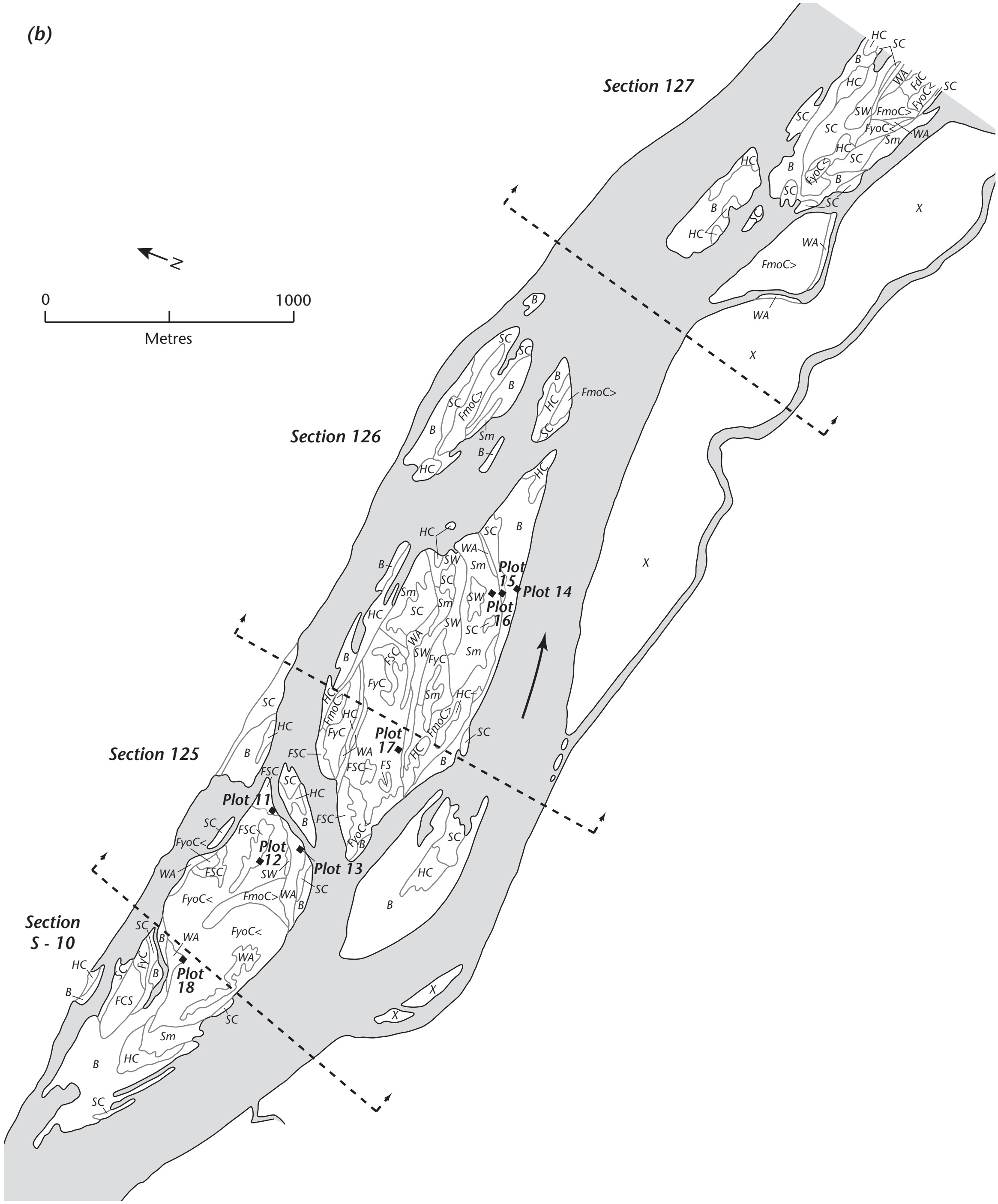

Figure 8.5 (*Continued*)

Table 8.1 Riparian vegetation of Peace River, British Columbia—map legends

Map symbol					
Figure 8.5	**Figure 8.9**	**Interpretation**	**Plots[a]**	**Infrared photo signature**	**Black and white photo signature**
B	B	Unvegetated surfaces: recently deposited sediments		White; grey where wet	White; grey where wet
HC	H	Herbaceous communities: varying from discontinuous cover to almost 100% cover and may include scattered trees and shrubs < 1 m	1, 14, 14A	Pink speckle on white ground; variable density	Grey speckle on white ground; variable density
Hm	Primary *Populus balsamifera* seedlings or sprouts, <1 m, cover varies from sparse to 100%	8			
S	S	Shrub communities, including			
	SC } Sy	Medium (young) *P. balsamifera*, <2 m	15	SC: uneven pale pink	Uneven pale grey
	SW } Sy		T	more even as density	
		Medium (young) *Salix* spp., <2 m		increases	
				SW: uneven pink tinged with green	Uneven grey
Sm	Sm	Mixture of *P. balsamifera* shrub, *Salix* and/or *Cornus stolonifera* and or *Eleagnus commutate*, >2 m	5,16	Uneven pale to medium	Uneven pale grey
			2	Pink, willow tinged Tinged with green, more even as density increases	
WA	Sm	Woodland, *Alnus incana* ssp. *tenuifolia*, 2 to 10 m	9, 13	Even red, velvety texture	Not discriminated
F	F	Forest			
FyoC	FyoC	*P. balsamifera*, < 20 m, open canopy	4	FC: bright red, uneven darker for older stands	Uneven grey, darker for older stands
FyC	FyC	*P. balsamifera*, <20 m, closed canopy	3, 8, 17, 18		
FmC	FmC	*P. balsamifera*, >20 m, closed canopy			
FmoC	FoC	*P. balsamifera*, >20 m, open canopy, shrubs beneath	T	Patchy	Includes decadent stands
FdC	FoC	*P. balsamifera*, decadent, > 20 m, shrubs beneath	10	Decadent stands patchy	Decadent stands patchy
FmCS	FmCS	Mixed *Picea glauca* and *P. balsamifera*	7, 11	FCS: patchy bright and dark red	Patchy grey and black
FmS	FmS	*P. glauca*	6	FS: dark red	Black
	A	cultivated			By field pattern

[a]Relocated plots are indicated by the plot number followed by letter A, without a separating comma, as in 14A below. T refers to the transect.

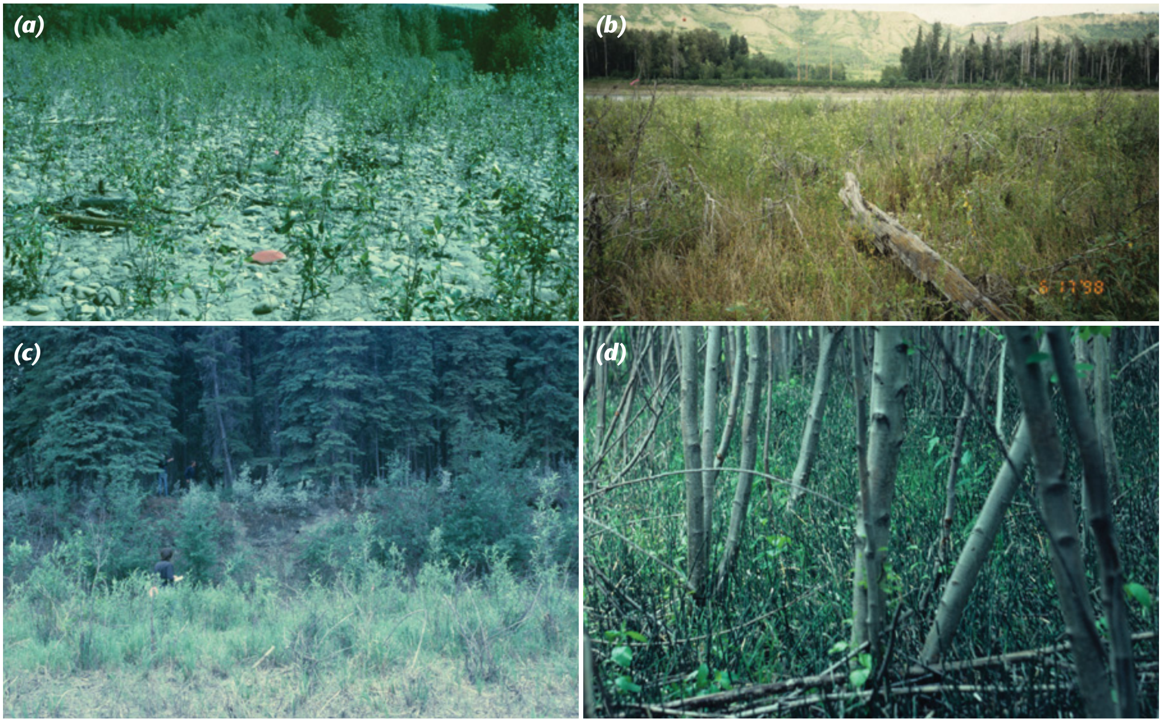

Figure 8.6 Photographs of selected vegetation plots and transect. (a) Herbs and shrubs, primary succession (HC). Plot 1 on June 5, 1986. Cottonwood saplings dominate the sparse cover, growing from a surface of 50% cobbles and 50% sand. (b) Plot 1 on June 17, 1998. This plot is now in low shrub, mainly cottonwood but with some willow. The broken, dead-looking shrubs in the foreground had grown to two meters before being scythed down by ice. This area was also completely immersed by the summer floods of 1996. Looking north, across the main arm of Peace River, along the power-line cut. To the right, east, of the cut is the high bank of the old floodplain with a small patch of spruce and the decadent cottonwood forest, sampled in Plot 10. This area is mapped as open canopy cottonwood >20 m on the GIS maps but as decadent cottonwood forest >20 m on the more detailed map Figure 8.5a. (c) Looking down on Plot 5, high shrubs (Sm >2 m), dominated by willows, towards Plot 6, mature spruce forest (FS). Between the two plots is a deep, abandoned channel, the deciduous tree crowns are mainly cottonwoods and alder growing on the steep banks (June 5, 1986). (d) Alder woods at Plot 13, June 21, 1981. The trees were then seven to eight meters tall and grew to 10 m in the following 17 years. Canopy cover remained constant at around 70%, dominance of horsetail in the herb layer continued throughout the survey period. Next page: (e) Young cottonwood stand at the seral stage between high shrub (2 to 10 m) and low tree (<20 m). Plot 8, June 1981, average tree height was below 10 m, on the 1977 map it was classified as SC >2 m. In the following 17 years the cottonwoods increased in height to 12 m and the mapping unit changes to FyC < 20 m. (f) Mature cottonwood forest, Plot 17, June 1981, osier dogwood dominates the shrub layer under a closed canopy of trees around 22 to 23 m high. This area was mapped as FyC in 1977 (cottonwood <20 m) and over the next 17 years the canopy height increased to 25 to 26 m. (g) Mixed cottonwood–spruce forest, Plot 7, June 1981. Close-up view of the trunks contrasts the deeply fissured bark of the mature cottonwood with the gray scales of the spruce; note also the lack of lateral branches on the cottonwood and the presence of numerous dead and dependant branches on the spruce. Under this dense canopy there is little light and hence few shrubs or herbs. Over the 43-year span of the photo record of this site it remains classed as FCS, however during 17 years of field study the number of spruce reaching the canopy steadily increased. (h) A view westwards along the back channel of the upstream island, looking towards the transect line. Photo taken in June 1998. The dense cover of different grass species in the foreground indicates the high habitat value of this herbaceous zone. The zone's width is constrained by the amount of water occupying the back channel during the growing season. Nearer and into the water the vegetation changes to a community dominated by reeds and rushes. Towards the island, on the right, the grass community is limited by a belt of high willow shrubs (appearing as spindly light green plants in the photo), and on the bank a discontinuous line of alder with cottonwood and willows over 10 m high (darker and brighter green massed crowns).

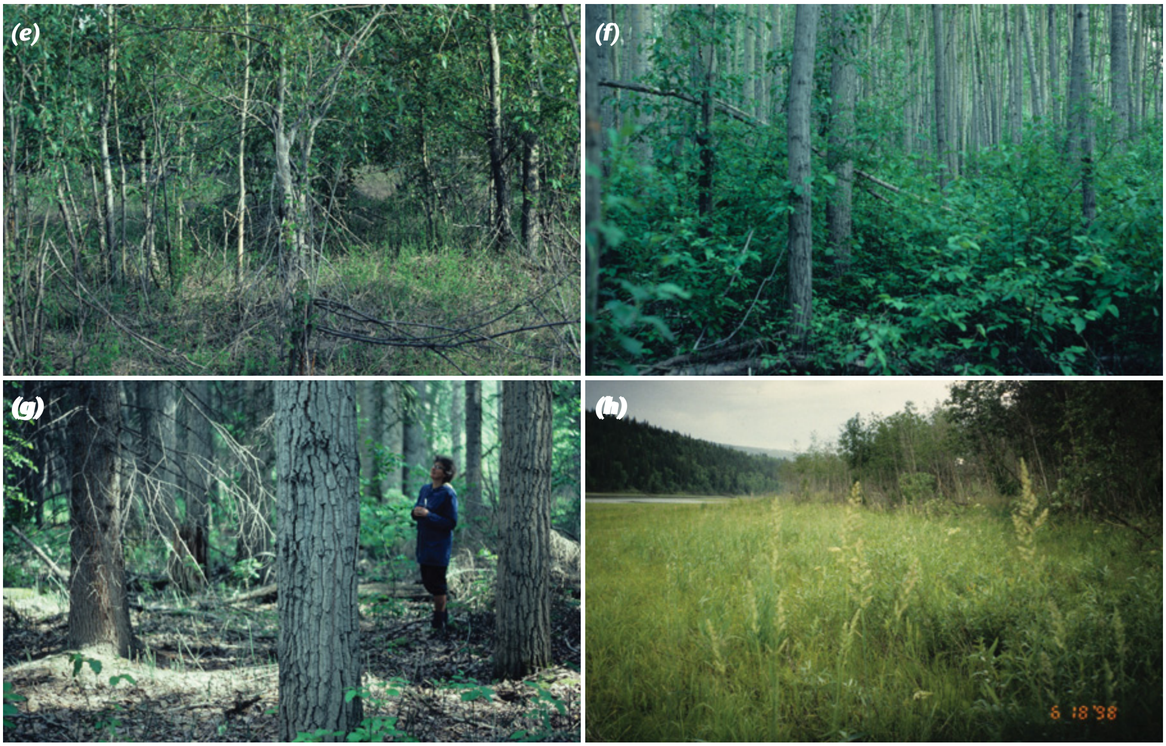

Figure 8.6 (*Continued*)

communities is not strong and the underlying surface materials of river sediments have the strongest signature (see Figure 8.3). In 1977 many of these surfaces were mapped as bare (B). Field examination of these herbaceous areas (H) in 1981 (Plots 1, 14) showed that the species present may include tree seedlings and/or shrubs and/or annual herbs. Figure 8.6a shows a herbaceous plot dominated by cottonwood seedlings.

Shrub communities (S) range in height from under 2 m to under 10 m and vary in species composition. Three different types are distinguishable from air photos. Young cottonwood (*Populus balsamifera*) under two meters; young willow (*Salix* spp.) under two meters (Figure 8.6b); mixed shrubs, willow, cottonwood, and/or osier dogwood (*Cornus stolonifera*) and/or silverberry (*Elaeagnus commutata*) from under 2 to 10 m (Figure 8.6c).

Woodland communities (W) have closed canopies under 10 m in height and are restricted to stands of mountain alder (*Alnus incana* ssp. *tenuifolia*) (Figure 8.6d). The signature of this type is less distinctive in black and white photography and these woodlands were not separately mapped in the time sequence.

Forest communities (F) are of three types: deciduous, mixed and coniferous. The deciduous forests are made up entirely of cottonwood. Four cottonwood forest types are recognizable; young stands with open canopy below 20 m (Figure 8.6e); young stands with closed canopy below 20 m (Figure 8.6f)—different units may be different ages; mature cottonwood in open stands of varying heights with shrubs beneath; old and decadent/dying cottonwood above 20 m with open crowns. Mixed forests of cottonwood and white spruce (*Picea glauca*)(Figure 8.6g) and of white spruce and cottonwood are differentiated by the amount of spruce overtopping the cottonwood. It is easy to pick out these emerging crowns in the cottonwood forest. Mature spruce occurs in the study area on the upstream islands, and is widespread on the north-facing valley slopes and on the plateau south of the river (Figure 8.3).

8.3.3 Vegetation mapping from sequences of black and white images

Following the initial IR mapping, a sequence of maps was constructed based on air photos flown for the entire BC reach from Peace Canyon dam to the Alberta border. The photos used were flown on September 8, 1953; August 15, 1967; June 5, 1977 (IR); July 21, 1986; July 14, 1996; and on September 5, 2005 (below Halfway River) and July 1, 2006 (proximal reach). The cover classes initially identified in the IR photos were also identified on contemporaneous black and white photos. The mapping was entered into a Geographical Information System (GIS). For analysis, the reach was divided into six sub-reaches, each of homogeneous morphological character and hence divided principally at the major tributary junctions (see Figure 8.1). Our field sites located in sub-reaches BC-4 upstream and BC-5 downstream of Pine River—by far the most significant tributary—hence straddle the most important hydrological change in the British Columbia reach of the river.

Because all but the 1977 photos were black and white, vegetation identification relied on gray tones (see Table 8.1) and stereoscopically detected height. The finer classes of the shrub vegetation by species dominance and the presence of alder woodland, visible in the false-color IR, were lost and are subsumed under two shrub categories based on height; below two meters are medium shrubs, greater than two meters are referred to as tall shrubs. The tall shrub height category extends up to 10 m, hence alder woodland, with a height around 8 to 10 m, is classified as a tall shrub. The cottonwood forests were mapped as either open or closed canopy and as below or above 20 m. This grouping by height does not distinguish the tallest, oldest cottonwood forests. The simplification and generalization of the IR-based classification reduced the number of vegetation cover classes to 10 on the GIS-based maps, but a category was added for cultivated areas (Table 8.1).

8.3.4 Field sampling

A set procedure was followed for data collection at each site (Table 8.2). The type and variety of dominant life form determined the size of the plot. The herbaceous cover of recently vegetated bars was surveyed in 4 × 4- or 5 × 5-m plots. The shrub communities required a 10 × 10-m plot size for adequate representation of the species diversity. The forests were surveyed in 20 × 20-m plots, the relatively small plot size reflecting the lack of diversity in the dominant tree species. See the Appendix for reference to the primary data.

Fieldwork was completed within a span of 8 to 10 days, either in early June (1986) or mid-June (1981), or early July (1991, 1998). This short field time and the seasonal variation from one visit to the next are likely to have affected collection and identification of annuals, both grasses and forbs, many of which were not at the flowering stage when sampled. Early or late season sprouting and/or short lasting herbaceous species would not have been recorded. Collection of nonvascular plants, mosses, lichens, and fungi was not made in a systematic manner.

Particular problems were experienced in disturbed communities. Shrub communities that had been scythed down by ice and were regrowing from the base were recorded at the height attained before being mowed down. (However, the GIS mapping records these scythed communities as shrubs below two meters in height.) Despite continued attempts to mark and establish the correct locations of the plots, several were not relocated and new plots had to be set up (annotated in primary data). Replacement plots were set up using the surveyed locations but there is no certainty that the replacements were on exactly the same sites as before. Photographic records of the plots were made but, as the photos were not taken from a consistent point or direction, their use for plot relocation or for detailed analysis is limited (Hall, 2003).

8.3.5 Species identification

The majority of plants were identified in the field or within 12 hours of collection using the regional flora (MacKinnon *et al.*, 1992) or Family specific flora (e.g., Brayshaw, 1976). The dominant deciduous tree is balsam cottonwood, *P. balsamifera* spp. *balsamifera*, however it is possible that black cottonwood, *P. balsamifera* spp. *trichocarpa* intergrades with this species in the study area (Brayshaw, 1965). The decadent cottonwood stands in Plot 10 (Figure 8.7) certainly are taller than any other cottonwoods in the area and approach the 40-m height that Brayshaw (1996, p. 78) and MacKinnon *et al.* (1992, p. 25) state is indicative of black cottonwood at maturity. Where the two species overlap they are known to interbreed, producing progeny of intermediate character (Brayshaw, 1965).

Table 8.2 Data recorded in the field

***Species**: list arranged by height/strata:
Trees, main canopy and understorey
High shrubs (2 to 10 m)
Medium shrubs (1 to 2 m)
Low shrubs (30 cm to 1 m)
Herb layer, including shrubs >30 cm
Mosses and lichens
Cover: for each species in each stratum, recorded on a 6-point scale
0 = absent (or area left blank)   + =<1%   1 = 1% to 5%   2 = 5% to 25%   3 = 26% to 49%   4 = 50% to 74%   5 = >75%
Total number of trees per plot, living and standing dead
Height of selected trees in each plot
Height, cover, and total number of shrub species per plot
Height, cover, and total number of herbaceous species per plot
Ground conditions: bare, moss, lichen, litter, dead trees, driftwood cover.
Surface texture: cobbles (c), gravel (g), sand (s), silt ($).
Soil: depth and nature of: litter, FH layer, A horizon, depth to and nature of substrate.
Soil sample taken from top 10 cm for analysis
Type of disturbance
Two photographs taken into the plot
A GPS location for each plot was established in 1998 and is attached to the data files

Location of each plot is shown in Figure 8.5.

*Species identification in the field was made using MacKinnon *et al.*, 1992. *Plants of Northern British Columbia*, Brayshaw, 1996 *Trees and Shrubs of British Columbia*, and Brayshaw, T. C. 1976. *Catkin Bearing Plants of British Columbia.* A herbarium sample of each species collected was authenticated at the UBC Herbarium.

Pressed plant specimens were taken to the University of British Columbia herbarium for confirmation or establishment of identifications. Considerable effort has been expended on the identification of the many willow species that occur in the plots. MacKinnon (1992, p. 54) acknowledges the difficulty of identifying willows. Hybrids do occur and this area may have interbreeding populations with overlapping characteristics.

Figure 8.7 Decadent cottonwood forest, view toward Plot 10, June 2005.

Table 8.3 Cover types in the principal field areas[a]

	1953	1967	1977	1986	1996	Avge	Std. dev.	CV
	Area in m²							
B	4 638 876	4 695 195	4 192 729	3 083 208	4 613 889	4 244 780	679 409	0.160
H	187 729	187 631	535 358	1 189 622	17 837	423 636	467 771	1.104
Sy	61 213	53 788	180 627	570 866	286 995	230 698	212 963	0.923
Sm	202 139	273 116	301 863	299 071	216 277	258 493	46 635	0.180
FyoC	565 724	334 440	217 811	201 911	183 541	300 685	159 477	0.53
FyC	66 076	77 164	187 761	144 018	119 380	118 80	49 762	0.419
FmC	617 309	911 544	884 008	967 073	1 016 418	879 270	155 086	0.176
FoC	366 678	368 857	335 631	370 883	379 913	364 393	16 847	0.046
FCS	409 319	224 473	227 461	192 559	148 792	240 521	99 543	0.414
FS	211 644	227 938	278 421	255 700	293 259	253 392	33 955	0.134
A	59 201	50 564	50 370	46 870	95 632	60 528	20 143	0.333
Total	**7 385 908**	**7 404 708**	**7 392 040**	**7 321 782**	**7 371 933**	**7 375 274**	**32 144**	**0.004**
B	5 004 763	5 034 678	4 344 163	3 193 307	4 420 670	4 399 516	746 359	0.169
H	131 852	21 809	184 742	623 829	33 065	199 059	247 044	1.241
Sy	125 142	210 899	626 879	1 196 866	65 861	445 129	474 142	1.065
Sm	145 129	8 058	79 216	97 882	38 226	73 702	53 114	0.721
FyoC	236 334	327 648	167 357	176 924	257 143	233 081	65 203	0.280
FyC	362 782	202 528	289 730	273 315	240 625	273 796	59 900	0.219
FmC	1 142 705	979 638	580 982	598 877	651 490	790 738	254 835	0.322
FoC	958 924	1 120 794	1 247 715	1 182 308	1 097 351	1 121 418	107 984	0.096
FCS	27 001	30 347	53 398	40 400	47 835	39 796	11 214	0.282
FS	0	0	0	0	0	0.0	0	0
A	512 839	745 152	1 093 898	1 280 939	1 564 925	1 039 551	418 729	0.403
Total	**8 647 471**	**8 681 550**	**8 668 078**	**8 664 646**	**8 417 192**	8 615 787	111 681	0.013

[a] See Figure 8.5 for area included.

8.3.6 Map data

The production of a time series of maps in GIS format provides both a view of the changing spatial arrangement of the vegetation and a comprehensive set of numerical data on the areas of each cover type for the principal field areas (Table 8.3) and for the entire BC reach (Table 8.4). Mapping was conducted photogrammetrically from provincial and federal survey

Table 8.4 Cover types in the British Columbia reach

Veg Code	1953	1966	1975	1988	1993	2006	Mean	Std. dev.	CV
Area in m²									
B	81 848 792	84 547 547	76 867 354	64 577 350	79 289 532	not meas.	77 426 115	7 732 240	0.100
H	3 384 681	2 245 027	4 850 159	8 350 626	1 798 435	10 620 987	5 208 319	3 550 589	0.682
Sy	1 129 473	1 056 364	3 679 478	11 282 710	3 025 224	3 641 061	3 969 052	3 771 440	0.950
Sm	1 033 454	775 738.5	1 366 669	1 182 489	682 267	7 104 149	2 024 128	2 501 509	1.236
FyoC	11 626 982	9 059 777	8 376 738	9 509 443	8 271 485	5 900 405	8 790 805	1 866 989	0.212
FyC	7 023 243	5 720 452	6 303 895	5 138 070	5 409 523	7 940 211	6 255 899	1 065 891	0.170
FmC	8 333 885	8 912 465	8 235 165	7 987 547	8 399 988	10 745 947	8 769 166	1 014 894	0.116
FoC	7 081 782	6 845 098	6 932 001	7 334 596	6 530 503	4 232 340	6 492 720	1 138 739	0.175
FCS	7 301 116	6 722 488	6 574 973	6 354 988	5 629 135	4 323 395	6 151 016	1 047 207	0.170
FS	2 146 851	1 646 551	1 764 981	1 766 169	1 768 305	3 218 260	2 051 853	596 340.4	0.291
A	3 850 974	7 439 875	9 243 259	10 345 001	12 352 861	10 957 473	9 031 574	3 029 259	0.335

photography using a Carto® AP190 analytical stereoplotter in planimetric mapping mode. Reference points were control points in the Geodetic Survey of Canada national network located on 1:80 000 diapositives. Data were orthorectified in Carto software and imported into Arc/INFO®, adjusted to reconcile mapped unit boundaries, and displayed.The plotter is designed to measure the position of objects to within ±60 cm from 1:30 000 scale photos obtained with metric cameras but control point transfer and photo print resolution degrade horizontal precision by a factor of 5 to 10 (Walstra *et al.*, 2011). Hence, community boundary errors the order of three to five meters are to be expected at this scale, and the error may to some degree be systematic (i.e., biased) as the precise boundary of the tree communities is difficult to place. Many units are linear and relatively narrow so that systematic boundary errors might lead to significant errors in the estimation of ground area. For purposes of analysis, however, units are aggregated by subreach so that errors compensate each other. Given that many hundreds of units were mapped, aggregate errors are expected to be small, but no summary error analysis could be undertaken.

There are problems interpreting these data. The areas of different vegetation types may vary from survey to survey for a variety of reasons. Succession will increase or decrease the area of a particular cover type from epoch to epoch. Any cover type may be diminished by the erosive action of the river in flood. Sufficiently high water levels affect the revealed area of low-cover types (especially herbaceous cover) at any particular epoch. Hence, statistical manipulations of these data, such as calculation of one cover type as a percentage of all vegetation, is apt to be skewed by the variable amount of area in herbaceous and shrub cover. As these occupy the lowest elevations they are prone to dramatic area fluctuations caused by variable water level, as shown in the 1996 data (Tables 8.3 and 8.4).

Human activity may alter cover types by removing or reducing areas of commercial timber or by land clearance for cultivation or partial clearance to allow grazing. Selective logging may change the incidence of cover types. The decrease in area of mixed cottonwood-spruce forest from 1953 to 1967 and increase of mature cottonwood at the same time on the upstream island (Figure 8.9a) are most likely due to selective logging. Evidence of this activity in the form of logging roads was first seen in 1981 in the vicinity of Plot 7. Cutting along power lines has led, at least temporarily, to a reduction in the area of all cover types along the route. Animals may have similar effects, though usually in smaller areas. Beavers have felled large cottonwoods along the banks of several islands, thus altering the species composition of forest along the banks as well as destabilizing the banks themselves. Finally, errors occur in photo interpretation. Causes of variation in the numerical data can often be determined by examination of their spatial pattern, but at other times field data are needed to clarify the numbers.

8.4 A model of riparian succession and variations

There are two different causes of vegetation change. One is internally generated (autogenic) succession. The other is externally generated (allogenic) change that alters the plants' physical or biotic environment and thereby leads to change within the community. In the riparian zone, river dynamics—including flow variations, erosion, and sedimentation—dominates the plants' environment, producing fresh surfaces for colonization as well as impacting established vegetation. Like succession, this is a natural process along active alluvial rivers, particularly important on rivers with a lateral style of instability, such as Peace River. Vegetation normally displays a palimpsestic pattern of plant communities resulting from the interplay of internal and external causes that bring about the visible spatial variation. The purpose of the present analysis is to distinguish those variations that have resulted from damming Peace River from those—both internal and external—that preceded or are independent of this event. In particular, it is necessary to separate the particular effects of flow regulation from the normal effects of flow variation and of normal succession.

8.4.1 Internal change: temporal succession

Change occurs over time in response to plants modifying their own environment by enriching soil and by changing the microclimate, creating shade, increasing humidity, and decreasing wind speed. In areas of primary succession, where new surfaces are exposed for plant colonization, species with prolific wind-blown seeds arrive first and, if they are herbaceous plants, they may grow to maturity and set seed in one season. Along river margins, seed that floats on the river may colonize newly exposed sediments first. When the site remains undisturbed for some length of time, initially seeded shrubs or trees overtop the herbaceous species, eventually shading them out. In undisturbed riparian habitats of northern British Columbia shrub communities are eventually over-shaded by trees, deciduous first and then coniferous. The order of succession is partly determined by availability of seed that can germinate and grow in the floodplain environment and partly by relative speed of growth and ultimate height of competing species.

The environment of a floodplain is not homogeneous. There are four distinctly different substrates deposited by Peace River and available for plant colonization and initiation of primary succession—cobbles and gravel, sand and silt, silt and clay, and organic rich logjams. Variation in sediment type favors the survival of one group of species over another so the details of succession vary, at least in the earlier stages.

After the initial field season we developed a normative model of riparian succession (Figure 8.8), based on three sources of evidence. Mapping of plant cover from interpretation of the 1977 IR photos (e.g., Figure 8.3) showed the spatial distribution of plant communities at that time (Figures 8.5a and 8.5b). Field observation and sampling of the surface materials underlying the different plant communities allowed us to establish the relation that exists between substrate texture and plant community composition. The assumption of spatial contiguity as a surrogate for time sequence was made for plant communities that occupied the same textural substrates on undisturbed floodplain surfaces and such communities were thus assumed to represent the seral stages in autogenic succession.

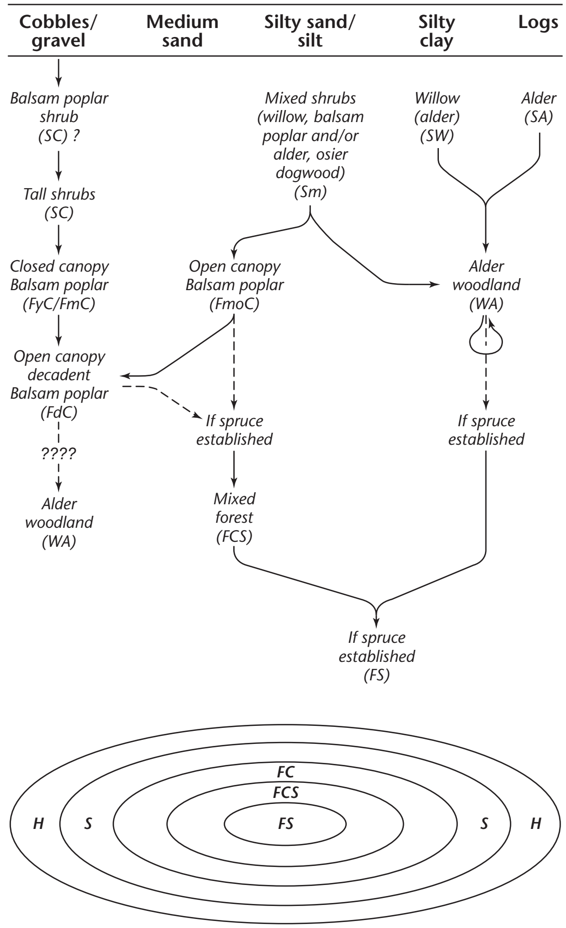

Figure 8.8 Model of riparian vegetation succession: temporal sequences above and hypothetical spatial model of vegetation on an undisturbed island below.

8.4.2 Verification of the successional model by air photo analysis

Plant succession is slow; it takes a long time to observe and hence to validate a model, but the observation period on Peace River is extended by the use of air photos. Changes in each cover type can be examined at each site over more than two decades preceding the start of this study (Figures 8.9a and 8.9b: 1953, 1967, 1977), including 14 years before regulation of the river.

We expect to see changes from one seral stage to the next in those areas where no river flooding or other disturbance has occurred; thus areas of primary cottonwood colonization become areas of young cottonwood stands and then evolve into closed cottonwood stands. Figure 8.9a shows an area of herbaceous vegetation becoming shrubs after 10 years, and shrubs developing into open cottonwood forest below 20 m that grows into closed cottonwood forest higher than 20 m. Figure 8.9b shows two areas on the westernmost island where cottonwood forest begins to show emergent conifers that succeed over time to mixed forest of cottonwood and spruce. From these and similar observations of changes in the height, density, and species dominance, the proposed successional model was judged to be valid.

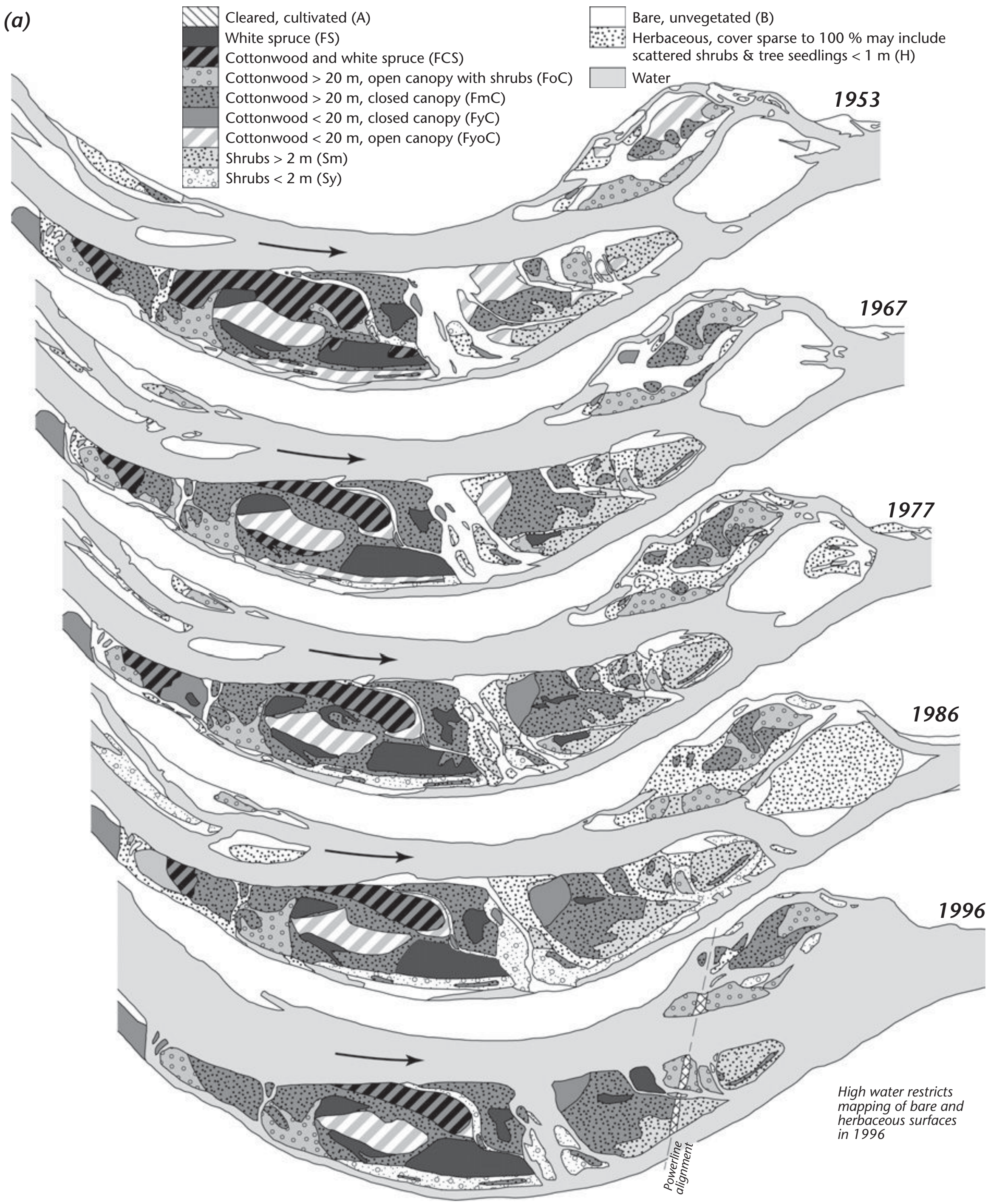

Figure 8.9 Vegetation mapped on sampled islands from panchromatic photography 1953, 1967, 1977, 1986, and 1996. The classification is simplified from that shown in Figure 8.5 (see Table 8.1). (a) Upstream islands; (b) downstream islands.

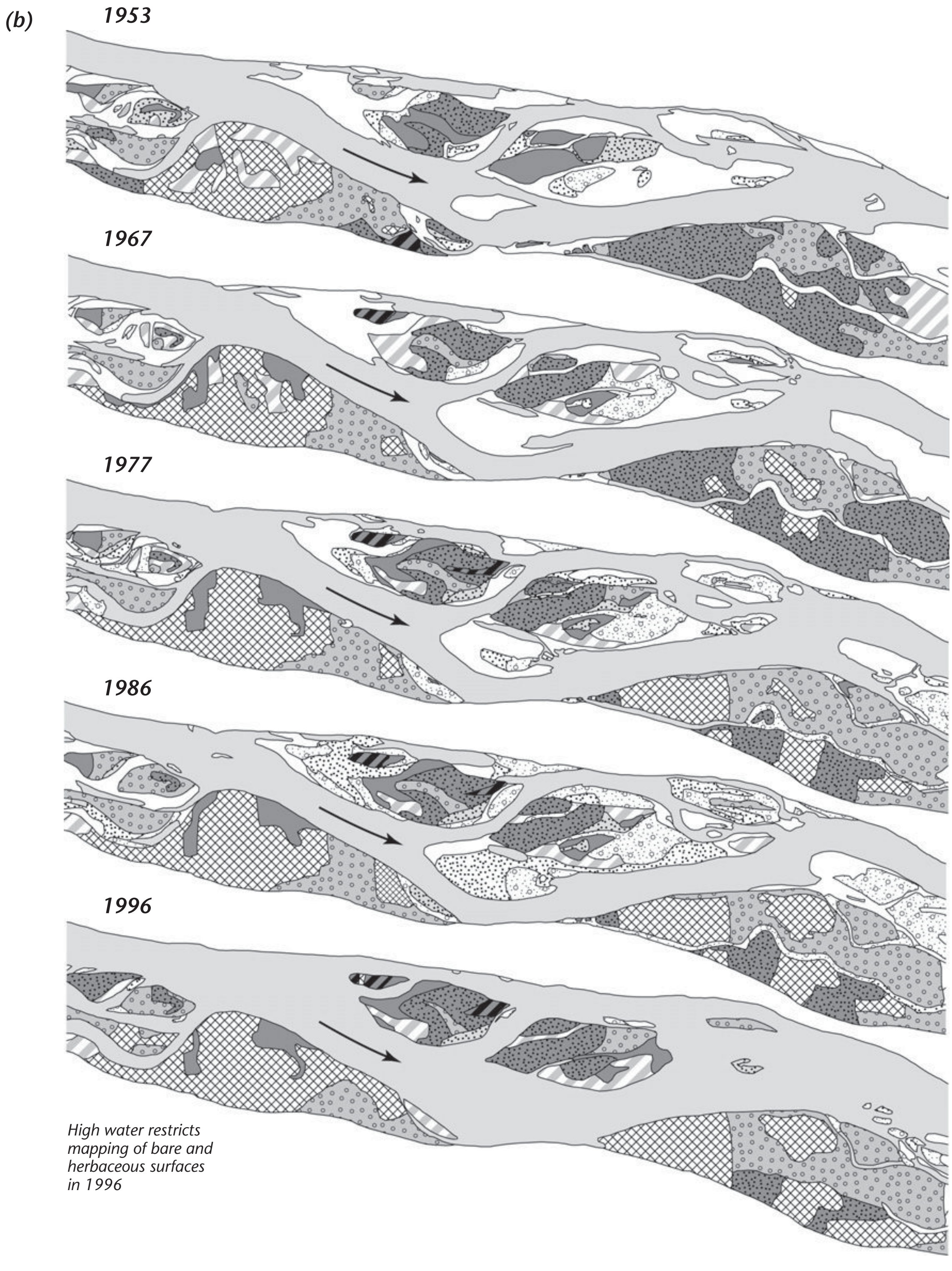

Figure 8.9 (*Continued*)

8.4.3 A spatial model of riparian succession

If we locate our model of riparian succession on a hypothetical island, we may visualize the spatial arrangement of the vegetation cover. We postulate an island created by a steady and symmetric rate of accretion around a medial river bar; then we would expect the mature island to support concentric belts of vegetation of decreasing age from the center to the outer edge (Figure 8.8). The primary herbaceous community occupies the most recently deposited material on the edge of the island and the oldest, conifer-dominated forest occurs on the oldest deposits in the center of the island. Comparison of such an idealized model to actual islands (Figures 8.5a and 8.5b) shows that only part of the model exists in reality. In fact, we observe that disturbance of the substrate is the norm, so that steady accretion is an unlikely condition. Younger plant communities cut across older communities as the result of river activity, creating the ecological equivalent of a geological unconformity that allows us, as in geology, to infer events in the past.

8.4.4 Externally generated change: effects of normal fluvial processes

Vegetation cover, both in total area occupied and in species composition, varies spatially in response to the type of substrate and frequency of disturbance caused by the river.

In Peace River, cobble and gravel along the main channel margins is first colonized by ephemeral herbaceous species. Both native and introduced species are blown in, the latter from the adjacent farmlands on the plateau to the north. Viable seeds arrive in floodwater. These fast draining and nutrient poor sites are often colonized early by cottonwood (Figure 8.6a). The cottonwood may sprout from uprooted trees, carried down river and partly or wholly buried, or may sprout from a single setting of seed. Sprouting from buried trees produces a scattered distribution of uneven-aged saplings, whereas establishment from seed is likely to produce a closely spaced, even-aged, often linear stand. Examples of both types are found in the study area. Cottonwood establishment by vegetative reproduction is mainly influenced by the biotic content of the sediment load deposited by the river. Establishment by seed depends upon the coincident existence of viable seeds, suitable bare surfaces, and moisture conditions (Mahoney and Rood, 1998; Johnson, 2000). Suitable moisture conditions are related to the river flow, discussed below. Uneven survival, due to physical conditions and/or external biotic conditions such as grazing pressure, leads to an open cottonwood stand even if the original establishment was from seed (Rood, personal communication, 2004).

Along the river margin where sand and silt deposits overlie coarser materials, a different community may establish. Seeds of colonizing species arrive by air or water, but the finer substrate is less droughty than the cobble and gravel surfaces and can support a greater range of species. Monospecific stands of herbs, or mixed herbs, shrubs, and cottonwood tree seedlings establish. If there is no major disturbance by floods, stands initially dominated by herbs succeed to mixed shrubs and young trees composed of osier dogwood, willows, cottonwood, and alder (Figure 8.6b). The early shrub community progresses to higher shrubs and then to open cottonwood stands as the cottonwood overtops and shades out the lower shrubs. If cottonwood is seeded onto this finer substrate in suitable conditions, it establishes a dense stand of seedlings that may grow into a stand of single age trees. Continued growth of both cottonwood and willow seedlings depends on root elongation keeping pace with a falling water table in summer. This requirement sets an upper elevation limit for seedling growth (Amlin and Rood, 2002). A lower elevation limit is related to ice scouring and/or floods that destroy the young plants (Scott *et al.*, 1997). The fact that single age cottonwood stands make up the major part of the forest cover in the riparian zone indicates that conditions in the past were favorable for their establishment.

Silt and clay, deposited in abandoned channels, is dominated by willows from the early stages of succession on (Figure 8.6c, foreground). Alder may enter the succession and a mixture of willow and alder may make up linear bands of vegetation following old channels (Figure 8.6h). We have no clear idea of the end pathway of this succession on the Peace. On other large river systems, such as the Lower Fraser, further south, dense thickets of willow have been very persistent through time (North and Teversham, 1984, p. 54). A combination of lack of space and light plus occasional reoccupation of the channel by water may be sufficient to prevent other tree species invading this community.

Log jams commonly formerly occurred on the ends of islands and along side channels. Here the river's load of large organic debris floated in during flood and has not been subsequently buried by inorganic sediment. Large amounts of organic debris, resulting from the rotting of these piles, produce a eutrophic substrate. Dense thickets of alders occupy these sites. Whether the alder saplings sprout from driftwood is difficult to ascertain. Alders are known to require a high nutrient content in the soil to establish from seed (Krajina *et al.*, 1982). No other tree species established on the two alder sites investigated (in Plots 9 and 13; Figure 8.6d) during the 17 years of field study. Because of the relatively short life span and low height of the alder, we tentatively suggest that an open canopy of cottonwood and, eventually, a spruce forest would succeed on these sites. If, however, spruce seeds into these areas first, there may be no cottonwood stage.

Prior to dam closure, Peace River flooded most frequently in the early summer (Figure 8.4). In sites regularly disturbed by flooding, seeds of slower growing shrub and tree species, despite reaching the site and growing for a season, may be unable to survive until or through the next flood. Such surfaces are fixed in the primary stage of succession until such time as aggrading sediments raise the surface above the normal flood height. The 1996 photos provide useful information about areas flooded as they record an unusual summer high water stage caused by lowering the reservoir water level in order to repair the dam (Chapter 2). Water covered large areas of herb and shrub communities as seen in Figures 8.9a and 8.9b. The GIS data (Table 8.4) indicate a 75% loss in the total area of these three cover types between 1986 and 1996 for the entire British Columbia reach. The fact that these areas were underwater during this unusual event does not mean that the entire plant cover was destroyed, but succession may have been slowed or altered by the elimination of flood intolerant species. Plots 1 and 14, revisited in 1998, two years after the 1996 summer flood, both recorded the same shrub species mix as in 1991, but the average shrub height, that had been increasing up to 1991, decreased to below one meter (Figure 8.6b).

Once flooding becomes less frequent plants grow to a size that withstands damage by all but the most severe floods. The larger the plants, the more likely that the floodwater will slow down and drop the finer sediment load, building up the surface with successive layers of fine sediments. This is recorded in cumulic soil horizons beneath the cottonwood stands in Plots 4, 10, 12, and 18. A reciprocal relation exists between the internally changing plant communities and the effects of the external changes produced by flooding.

The persistence of shrub communities in certain locations was noted (Figures 8.9a, downstream end of large island; 8.9b downstream end of downstream island). Here, the type of disturbance, though related to flooding, is in fact caused by the "scything" effect of floating ice. Ice jams occur during break-up at specific places along the river (Uunila, 1997; Chapter 6). In the regulated regime this now occurs mainly downstream from Taylor, and not in every winter, as open water persists through most winters nearer the dams. Water impounded behind the ice jam lifts any remaining river ice and floats it onto adjacent flood surfaces. Sheets of river ice, moving laterally across the land, mow down shrub-height vegetation. Shrubs are characteristically broken about one meter above the bole (Figure 8.6b). The damage does not kill the shrubs; they sprout from the broken, horizontally fallen stems. Field data indicate that this type of damage has occurred regularly since the survey began in 1981. Uunila (1997; Chapter 6), working at downstream sites, documented its occurrence at least since 1967. The maps from 1953 and 1967 (Figure 8.9) show the persistence of these shrub communities in the study area before the dams were built. Winter and spring flooding behind ice jams is a natural disturbance on Peace River that cannot be ascribed to river regulation, though regulation certainly has altered the incidence of ice-jam events in the British Columbia reach.

Large floods in the pre-dam period had the power to disturb surfaces that had been stable for long periods of time. River banks were eroded and parts of islands removed, stripping away established communities. This often resulted in the juxtaposition of communities in very different seral stages. Primary herbaceous communities (Hm) are seen in contact with closed canopy cottonwood (FC) or mixed (FCS) or even spruce dominated (FS) forest (see Figure 8.5), marking the position of former channels that postdate the mature forest communities that they now cut through.

The oldest and least disturbed surfaces are occupied by closed spruce forest. These forests make up only 4% of the present riparian vegetation in the entire British Columbia reach. The absence of any substantial ground cover of fallen logs may indicate that the present trees are the first generation to occupy these surfaces. Hence the surfaces underlying these forests may be only moderately older than the spruce trees on them.

Alternatively, the forest may have been subject to disturbances such as flood, fire, or human use that have regularly or occasionally removed all large fallen trees. If this has been the case then the underlying surfaces may be considerably older than the trees now growing there. Evidence to support such disturbances should exist in the soil profiles as buried horizons, as ash layers, and as stumps, and in the traditional knowledge of the indigenous people. We have found no such evidence. This leads us to suggest that the islands underlying the mature coniferous forest are not significantly older than the trees of these forests, which leads further to the hypothesis that the cores of the present islands are perhaps no older than 200 to 300 years and bespeaks a formerly laterally active river.

8.5 Analysis: field study data

River control has altered the "normal" (unregulated) disturbance regime by regulating the flow to maintain optimal hydropower generation (Figure 8.4). This has had two effects with significant consequence for the riparian vegetation. Large areas of formerly seasonally inundated gravel bar surface have become more or less continually exposed, establishing what is, in effect, a new, lower floodplain level. Occasional high flows, such as spillway releases, and ice-jam floods may still inundate these surfaces. Second, bank erosion has been reduced to local and limited occurrence, so that "normal regime" reinitialization of the successional sequence by river erosion and sedimentation has been reduced to a low incidence. Analysis of the field data and GIS-compiled historical data allows us to examine both the present and past riparian vegetation in order to isolate those changes that are predictable from "normal" events and those that must be ascribed to other causes.

8.5.1 Plot data

The analyses of data collected at 18 plots and 1 transect over a period of 17 years indicate that the communities represented by most plots are following "normal" succession; that is to say observed changes are predictable (Figure 8.8). Data collected from some plots indicate an altered succession that varies from what might be predicted.

Plots that appear to be following "normal" succession include Plots 3, 4, 6, 7, and 11 to 18. Trees grew taller and increased in canopy cover, then became decadent and thinned out. Plot 17 (Figure 8.6f) experienced a reduction in total number of cottonwood trees from 60 to 42 to 35 to14 through the 20-year time span. Through this time tree cover increased from Class 4 (50% to 74%: see Table 8.2) to Class 5 (>75%) as each tree developed a greater canopy spread, followed by a decrease to Class 4 and 3 (49% to 26%) as some individuals lost out in competition, leaving 15 dead snags standing amongst 14 living trees. Tree heights were recorded as 22 and 23 m in 1981, and 25 and 26 m in 1998. Shrub cover decreases as canopies close, and then increases again as canopies open when densely set cottonwoods start to die off. Plot 17 illustrates this well with a shrub cover of three decreasing to two (25% to 5%) as the tree cover closed over, then increasing to three and four by 1998. Herbaceous species cover shows the same inverse relation to the combined tree and shrub cover.

The lowest elevation herbaceous communities (represented by Plots 1, 5, 14, and 15; see Figures 8.6b, 8.6c, and 8.6h) and some shrub communities (Plots 2 and 16) remained unchanged through the 17 years of fieldwork. The lowest elevations remain subject to seasonal floods, though the time of flooding has changed. High water flow during the winter, the normal management regime throughout the period of this study, leads to high mortality of seedlings established on the summer strand level.

Some of the shrub communities (represented by Plot 16) are remarkably persistent. Comparison of air photos from 1953 and 1997 of the island downstream from Taylor Bridge shows the same areas in shrubs over the 44-year photo history (Figure 8.6b). Field examination of Plot 16 on this island shows that shrubs have been freshly ice scythed at least once in each of the five- to seven-year periods between data collection years. Both the failure of some herbaceous and shrub communities to follow the theorized succession, and the lack of plant colonization in many back channels, are seen to be due to the continuing occurrence of high water. The 1996 photos provide satisfactory evidence that the areas covered by floods coincide with the perpetual shrub communities, and that floodwater reoccupies both side channels and inter-island channels.

Some of the plots show changes that might not be predicted from natural succession. We predicted that infilled back channels would be colonized by willows. We had hoped to record this development on the transect, but it has not yet occurred. Infilling seemed to be underway when the transect site was selected but the river apparently has reoccupied this back channel at intervals sufficiently frequent to prevent the shrub stage developing. The transect passes across a series of bands of vegetation paralleling the back channel (Figure 8.6h). A discontinuous line of alder and willow marks a previous channel bank. From here a zone of high willow and alder shrubs merges into a zone of low shrubs and dense herbs which merges into a zone with decreasing dryland species and increasing water plants such as sedges and rushes. In each survey willows in the alder and the high-shrub zones show ice damage and have fallen in an upstream direction, indicating that the back channel has refilled from the downstream end during flooding caused by high winter flows and/or ice jams. The low-shrub zone contains driftwood and indications of heavy browsing (by deer and moose) and, in 1998, dead shrubs lay buried under layers of silt. This back channel was flooded during the management-created summer flood of 1996 (Figure 8.9a).

There has been a rapid collapse of the oldest, mature cottonwood in Plot 10, our only representative of this community (Figure 8.7). The ground is now crisscrossed by dead tree trunks of greater than one meter in diameter. Rood and Mahoney (1990) have documented early mortality of mature cottonwoods in similar riparian communities downstream from dams on the American western prairies. They concluded that early mortality is due to a combination of decreasing fertility, as the soils are no longer supplemented annually with fresh sediment, and a falling water table that further decreases the trees' ability to take in nutrients. Plot 10 is located on the former floodplain, now a terrace about two meters above the level of the contemporary floodplain. The dominance of prickly rose (*Rosa acicularis*) in the shrub layer indicates the dryness of the site (MacKinnon *et al.*, 1992, p. 27). The narrow ridge of cottonwood at the eastern end of the upstream island, where the transect starts, also shows signs of early mortality. In 1953 this area was in high shrub; by 1967 the ridge of trees was apparent; by 1998 trees of only 24 m height, no more than 50 years old, that appeared healthy in the previous three visits, had fallen haphazardly along the ridge. Similar decadent cottonwood stands have been observed on high terraces in other reaches of Peace River.

The absence of any spruce seedling source in some of the over-mature cottonwood stands leads to a break in the normal successional path. As there are no spruce it is not yet obvious what species will come to dominate these cottonwood stands when the existing trees die. There is no replacement cottonwood generation, as this species does not regenerate in shade. At Plot 10 the only lower canopy trees were two alders. If spruce seedlings are established at any stage of the development sequence then the stand becomes mixed and eventually the conifers dominate. This occurs at the westernmost end of the downstream islands (Figure 8.9b). The stand of open, mature cottonwood present in 1953, by 1967 succeeded to a mixed cottonwood and white spruce forest. This site is in close proximity to a possible seed source on the north bank of the Peace where a small, forested tributary valley enters the main river. When there is no closely adjacent mature spruce to provide seeds the commonest invasion route for spruce is along the banks of the river on trails created by animals. These paths are often lined with young spruce, though no seed source is anywhere near. Many larger animals shelter under mature spruce trees and the cones become caught on their fur or hair. The seeds are thus transported long distances from their source, falling to the ground when the animal brushes against plants on a narrow path.

8.5.2 Historical data

The photogrammetrically generated maps allow a close study of individual areas over time, confirming the successional paths initially theorized. We pursue this appearance further by quantitative comparisons of proportional distributions of riparian communities derived from the maps. The first question is the reliability of mapped communities for quantitative comparison. Mappings were not replicated, hence we have no direct measure of interpretive variation. Table 8.5 gives measures of mean area and variance for individual vegetation types and for total mapped area over the five mappings. For individual communities, the variance mainly reflects real variation and is high, as expected, for shrub communities, young to mature cottonwood and mixed spruce–cottonwood forest. Total mapped areas, which include bare bar and herbaceous areas, should vary only insofar as water stage varied between mappings. The coefficient of variation for the islands is on the order of 1% or smaller and there is no temporal trend in the total mapped area, implying relatively high fidelity. This does not, however, guarantee truthful mapping of individual units within the map areas.

Table 8.5 Measures of mapping variance: field study islands

	Upstream island			Downstream island		
Vegetation Type	**Mean (m^2)**	**Std. dev. (m^2)**	**CV**	**Mean (m^2)**	**Std. dev. (m^2)**	**CV**
B	4 244 780	679 409	0.160	4 399 516	746 359	0.169
Hy	423 636	467 771	1.10	199 053	247 044	1.24
Sy	230 698	212 963	0.923	445 129	474 142	1.0651
Sm	258 493	46 635	0.180	73 702	53 114	0.720
FyoC	300 685	159 477	0.53	233 081	65 203	0.279
FyC	118 880	49 763	0.418	273 797	59 900	0.219
FmC	879 270	155 086	0.176	790 738	254 835	0.322
FoC	364 393	16 848	0.0462	1 121 418	107 984	0.0963
FCS	240 521	99 543	0.413	39 796	11 214	0.2824
FS	253 392	33 955	0.134	0	0	0
A	60 528	20 143	0.333	1 039 551	418 729	0.403
Total	7 375 274	32 145	0.00435	8 615 787	111 681	0.0130

The pre-regulation data (Figure 8.10) indicate that the 10 cover types were relatively stable over a 14-year period. The most notable post-closure changes are in the areas of shrubs, the lowest lying woody perennial types.

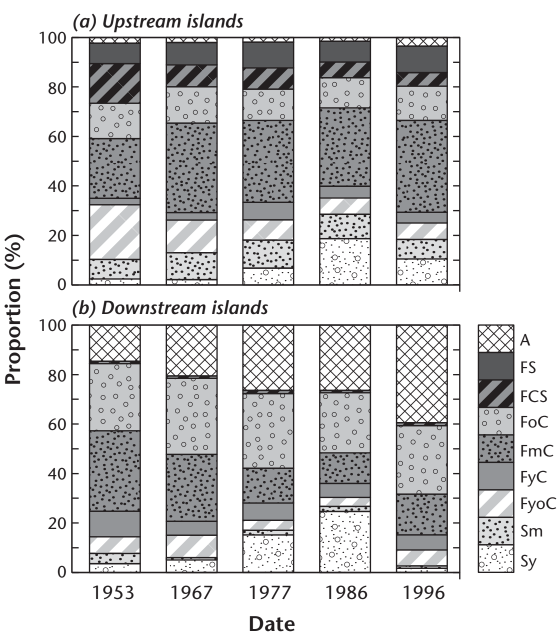

Figure 8.10 Proportional distribution of the vegetation communities in the field study areas (as depicted in Figure 8.9): all communities except (B) bare bar and (H) herbaceous surfaces. These latter are considered still to be part of the active channel and have high apparent variance due to changing water level between mappings. Key as in Figure 8.9.

The increase in these cover types had been predicted; the narrowing of the river channel, abandoning and infilling of back channels were expected consequences of regulated flow (Chapter 7). Exposed fine sediments would be open for colonization by wind- or water-borne seeds. However, the 1996 summer high water maps show the continuing vulnerability of these sites to flooding, and help to explain the failure of these increased areas of early successional stages to reach the young forest stage.

A comparison of the areas of the medium (<2 m) and high (>2 m) shrub classes does not suggest any successional linkage. If they were successionally related then the three-fold increase in medium-shrub area of 1977 should affect the high-shrub area nine years later, in 1986. But the 1977 medium-shrub area of 3.7 million m^2 did not lead to an increase in the high-shrub area, which in fact decreased slightly from the 1977 total. One reason for this apparent failure of medium shrubs to grow into high shrubs is that many shrub communities have been regularly scythed down by ice and thus register as medium shrub in the photogrammetric interpretation.

There is no apparent connection between the herb and shrub communities and the later successional stages of cottonwood, then mixed, and finally spruce forest that occur on the old floodplain surface. These forest types maintain approximately the same proportional areas as before dam closure (Figure 8.10).

Quantitative expression of the proportional distribution of floodplain communities (i.e., all mapped units except bare bar and herbaceous vegetation that are

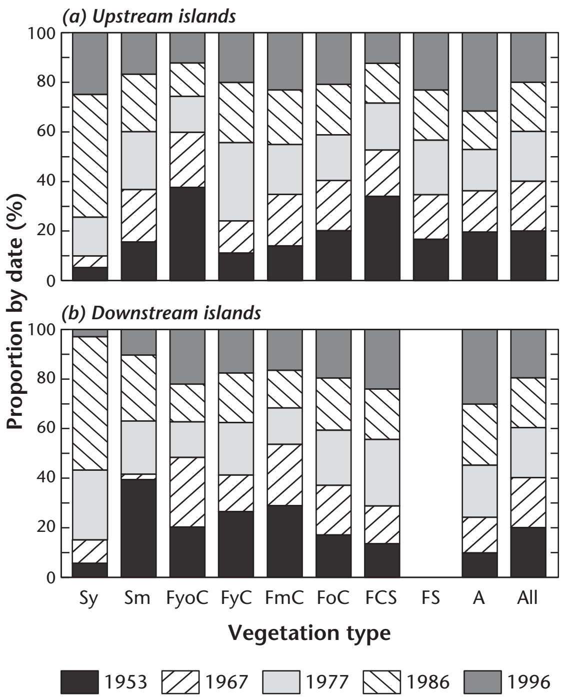

Figure 8.11 Proportional representation of individual communities in the study regions by period. Note that, at the downstream study island, there was no pure spruce stand (FS). (a) upstream islands; (b) downstream islands.

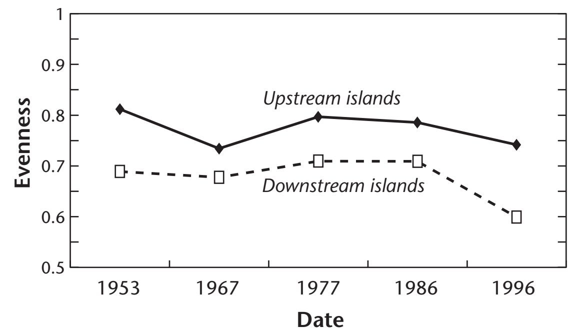

Figure 8.12 Evolution of community evenness in the field study reaches.

considered still to be part of the active channel) shows that the shrub communities (Sy, Sm) have made the most aggressive expansion, as would be expected. The apparent contraction of these communities in the 1996 mapping is an artifact of high water in that year. Young, open cottonwood is seen to have given way to expansion of mature cottonwood on the upstream islands, while mixed cottonwood–spruce has given way to expanding spruce forest, as the model predicts. On the downstream islands the within-forest trends are less clear because of the proportionally dominant expansion of agricultural land. Mature cottonwood forest here has declined in favor of decadent cottonwood and mixed spruce–cottonwood, once more following the model.

An interesting perspective is provided by classifying the proportional representation of individual communities *by period* (Figure 8.11). These plots clearly demonstrate the increasing importance of young shrub (Sy) from periods one through four in both study areas, the relative prominence of open young cottonwood (FyoC) in the earlier periods, and the increasing significance of agricultural clearing in the later periods. In comparison, the forest communities appear to be relatively stable in proportional representation.

Evolution of the community mosaic is indexed by the modified Simpson's Index of relative evenness in the distribution of individual communities (Pielou, 1977):

$$E = \ln \sum p_i^2 / \ln \sum (1/n)^2$$

wherein p_i is the fraction of the total area occupied by the ith community, both sums running over n communities. The denominator is the sum when the area is evenly distributed amongst all n communities. The range of E is $0 < E \leq 1.0$. As $E \to 0$, a single community becomes increasingly dominant while for $E = 1.0$, all communities are evenly represented. The index is shown in Figure 8.12. Evenness is relatively high in both study areas, the upstream islands exhibiting the greatest evenness and greater variation. The downturn in 1996 is undoubtedly the transient consequence of the drowning of the shrub communities. The overall variation does not exceed what might be expected from mapping variance; that is, the distribution of communities (though not necessarily their positions) has remained relatively stable over the first 30 years of regulation.

8.6 Analysis: reach-wide data

In this section we extend our analysis to the entire British Columbia reach of the river, using as our data the reach-wide mappings. The information represented on the maps is similar to that displayed in Figure 8.9.

Data are analyzed by sub-reach (Figure 8.1). Sub-reach 1, extending from the dams to Lynx Creek is singularly characterized by bedrock banks for most of its course. Alluvial substrates occur on river bars, but the reach is, on the whole stable with little opportunity for riparian change. Sub-reach 2, extending to Halfway River is alluvial in character but flows remain nearly entirely regulated, the few tributaries in the reach contributing very small flows in comparison with the outflow from the dams. The river is semi-confined with limited floodplain area. The rest of the reaches are delimited by the major tributary junctions (see Figure 8.1), each of which has some effect on the character of the river downstream by virtue of the sediment load and flow increase that it affords. While the river still impinges on the valley walls, floodplain area is more extensive. Sub-reaches 5 and 6, below Pine River, are the most active. These reaches still enjoy a modest late spring freshet as the result of the Pine River inflow.

Figure 8.13 portrays the absolute amounts and proportional distributions of floodplain vegetation communities by sub-reach and for the entire British Columbia reach through all mappings. The first notable feature is the steady increase in absolute vegetated area through the 1986 mapping and the abrupt decline in 1996 (when the shrub communities were largely submerged by high flow), not entirely recovered by 2005/2006, except in Sub-reach 1, immediately below the dams. Young shrub communities account for much of the increment to area occupied except that, after 1996, mature shrub area has replaced much of the young shrub area. This is an expected development along the regulated river and was visually obvious on field visits. The fraction of agricultural land has also expanded in most sub-reaches. Sub-reach 1, with a limited amount of truly riparian ground is an exception to both of these trends.

The forest communities have been surprisingly stable through time, although the effects of succession can be discerned. In most reaches, the area of young, open stands of cottonwood has declined while the area of young, closed cottonwood has expanded. Mature cottonwood shows relatively little change except for an apparent spectacular expansion in Sub-reach 2 after 1996. The area of decadent stands has declined, again excepting Sub-reach 2, where expansion occurred. It is possible that an exceptional water and nutrient flush in 1996 in Sub-reach 2 (an entirely regulated reach) stimulated forest growth to produce the exceptional outcomes there. Areas of mixed forest and spruce have not varied greatly, but pure spruce stands have become relatively more prominent in most sub-reaches, with a major expansion in Sub-reach 1.

We pursue the succession question further by examining *transition ratios* within communities from one period to the next. We array the areas of the communities for a specific mapping in each sub-reach as a vector. Then the inner product of the initial area times a transition ratio yields the area of that community in the next mapping (or, practically calculated, the quotient of division of the vectors of successive mappings yields a transition ratio):

$$\begin{pmatrix} X_{11} \\ X_{21} \\ \cdots \\ X_{91} \end{pmatrix} \circ \begin{pmatrix} t_{11} \\ t_{21} \\ \cdots \\ t_{91} \end{pmatrix} = \begin{pmatrix} X_{12} \\ X_{22} \\ \cdots \\ X_{92} \end{pmatrix}$$

wherein X_{ij} is the area of the ith community in the jth period and t_{ij} are the transition ratios. $t_{ij} > 1$ indicates an increase in the type from one period to the next, while $t_{ij} < 1$ indicates a decrease. The results are most easily examined graphically (Figure 8.14). The pioneer units H (herbaceous), Sy (young shrubs) and Sm (mature shrubs) show positive and generally large increases except for the 1986 to 1996 transition, an artifact of high water in 1996, and the subsequent transition is inflated for the same reason. All other transitions fluctuate about 1, indicating that gains and losses in most communities are nearly balanced. Notable variations include the values dominantly <1 (indicating reduction in area) for decadent cottonwood (FoC) and >1 for spruce (FS). The final transition (1996 to 2005/2006) exhibits larger changes than in preceding periods. The distribution of forest communities will not have been significantly affected by the 1996 flood. A reason for the appearance of significant change after 1996 may be inconsistent mapping, the 2005/2006 maps having been made seven years after the earlier ones.

We examine transitions directly by enumerating the area in each identified vegetation type that is reclassified as a different type (or remains unchanged) from mapping to mapping. This process generates a 12 × 12 matrix of *transition fractions* (11 vegetation types, including bare surface, plus water) for each sub-reach for each period; that is the fraction of type 1 at the earlier date that becomes type 2 at the later date. Here we present only the transition matrices for the entire British Columbia

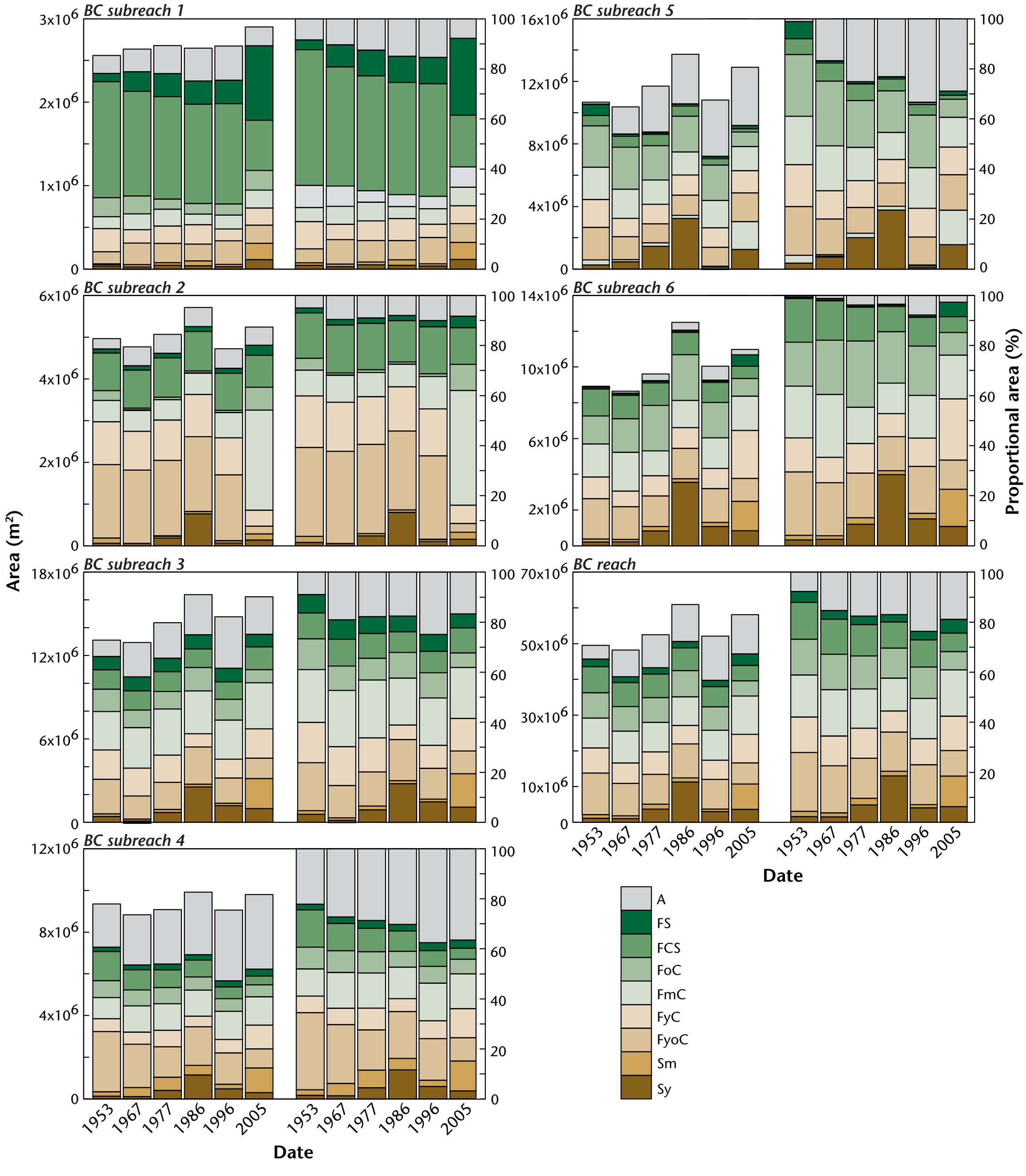

Figure 8.13 Statistics of vegetation communities in the British Columbia reach: all communities except (B) bare bar and (H) herbaceous surfaces. These latter are considered still to be part of the active channel. Absolute amounts and proportional distributions are shown.

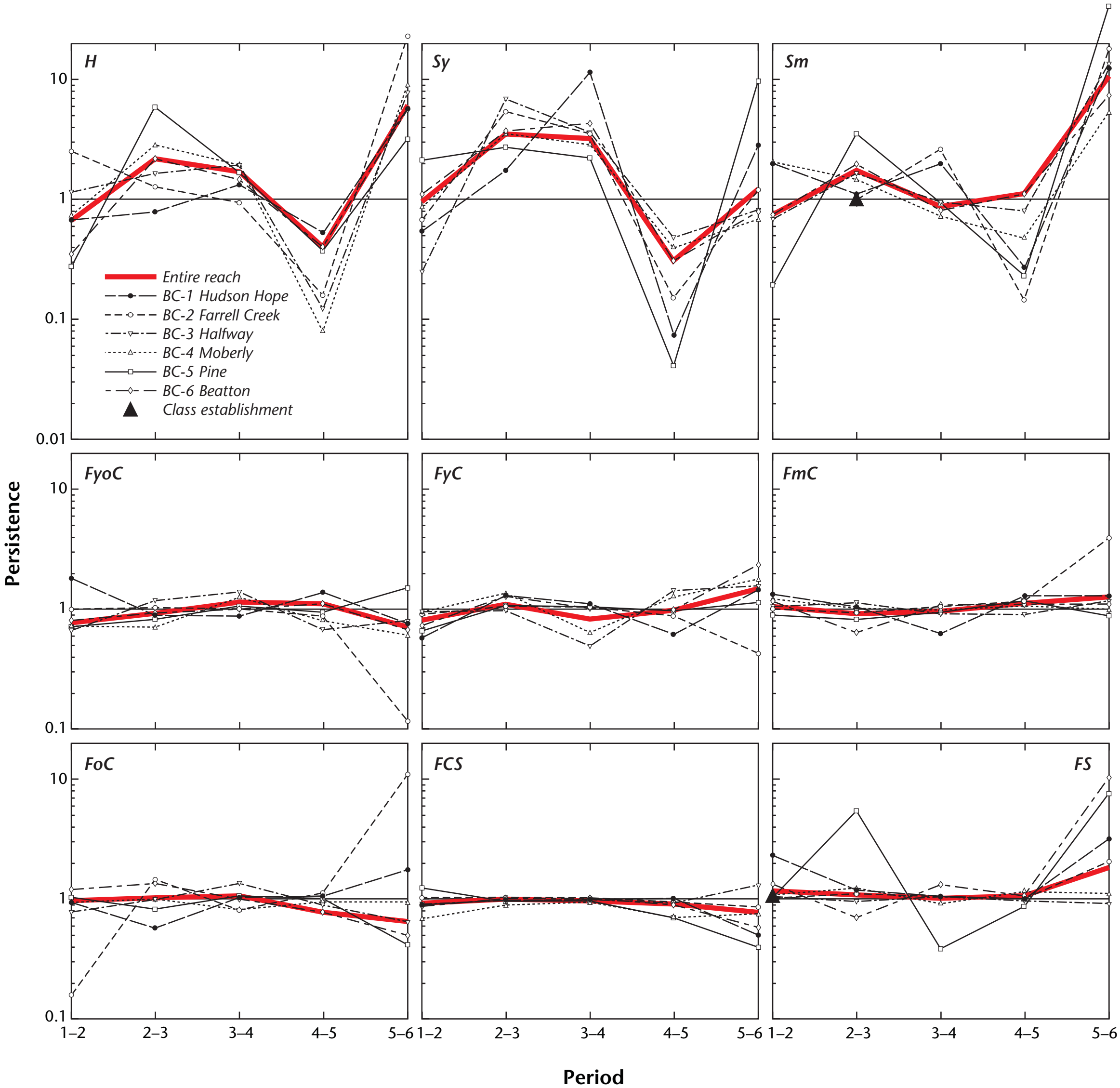

Figure 8.14 Transition ratios for communities in the BC reach. Note that the abscissa represents time periods within which the plotted ratios were observed, not absolute dates. Community key as in Figure 8.9.

reach in the period before regulation (1953 to 1966), and as an average over four mappings (to 1996); that is, the mean of four post-regulation transitions. The latter permits a measure of inter-period variance to be recovered. The results are presented in Table 8.6. The strong diagonal (null transition, or persistence of the type), with values varying from 0.20 for early successional communities to as high as 0.90 for late ones and the preponderance of transition fractions >0.03 in the direction of increasing successional "maturity" (values below the diagonal: see Figure 8.8 for supposed succession sequences) provide significant support for the successional model. The string of values along the top of the matrix (rows "water" and B) indicates the effect of erosion (transitions from terrestrial community to water); this effect is particularly prominent in the early period of natural flow (Table 8.6a). A set of apparent transitions from spruce to early successional communities would

Table 8.6 Transition fractions between vegetation types for the British Columbia reach

(a) Period of natural flows (1953 to 1966)

	1966	1953 River	B	H	Sy	Sm	FyoC	FyC	FmC	FoC	FCS	FS	A
>0.3	River	0.7522	0.1246	0.0551	0.0379	0.0410	0.0285	0.0188	0.0247	0.0167	0.0114	0.0352	0.0943
>0.1	B	0.1183	0.6505	0.3948	0.1498	0.1484	0.0184	0.0151	0.0387	0.0196	0.0167	0.0384	0.0922
>0.03	H	0.0074	0.0397	0.2549	0.0989	0.0142	0.0024	0.0022	0.0042	0.0026	0.0008	0.0001	0.0013
>0.01	Sy	0.0012	0.0133	0.0788	0.1299	0.0348	0.0047	0.0156	0.0064	0.0023	0.0003	0.0001	0.0006
	Sm	0.0005	0.0033	0.0139	0.0824	0.2752	0.0024	0.0055	0.0013	0.0235	0.0016	0.0000	0.0000
	FyoC	0.0018	0.0079	0.1016	0.2332	0.1534	0.5409	0.1246	0.0185	0.0500	0.0431	0.0004	0.0091
	FyC	0.0034	0.0040	0.0287	0.1339	0.1738	0.0759	0.5671	0.0062	0.0097	0.0094	0.0003	0.0102
	FmC	0.0086	0.0093	0.0115	0.0483	0.0477	0.0515	0.1512	0.7046	0.0649	0.0358	0.0027	0.0034
	FoC	0.0012	0.0053	0.0058	0.0482	0.0351	0.0416	0.0352	0.0700	0.6877	0.0433	0.0006	0.0083
	FCS	0.0013	0.0037	0.0029	0.0020	0.0013	0.0082	0.0153	0.0567	0.0335	0.7726	0.0008	0.0006
	FS	0.0942	0.1184	0.0422	0.0270	0.0719	0.0118	0.0338	0.0458	0.0176	0.0641	0.9212	0.0078
	A	0.0099	0.0199	0.0097	0.0085	0.0032	0.2136	0.0155	0.0227	0.0719	0.0008	0.0002	0.7722

(b) Period of regulated flows (1966 to 2006); mean of all periods

	Initial Final	River	B	Hy	Sy	Sm	FyoC	FyC	FmC	FoC	FSC	FS	A
>0.3	River	0.6779	0.1685	0.1782	0.1692	0.0664	0.0090	0.0159	0.0174	0.0099	0.0182	0.0404	0.0647
>0.1	B	0.1008	0.3142	0.0909	0.0284	0.0119	0.0053	0.0248	0.0055	0.0036	0.0058	0.0333	0.0131
>0.03	Hy	0.0195	0.1453	0.2184	0.0562	0.0224	0.0053	0.0052	0.0039	0.0027	0.0013	0.0039	0.0087
>0.01	Sy	0.0270	0.1184	0.2447	0.4278	0.0888	0.0127	0.0071	0.0106	0.0064	0.0020	0.0019	0.0089
	Sm	0.0014	0.0045	0.0255	0.0760	0.4655	0.0116	0.0046	0.0053	0.0036	0.0012	0.0002	0.0005
	FyoC	0.0013	0.0079	0.0631	0.0472	0.1263	0.7373	0.0994	0.0198	0.0605	0.0148	0.0011	0.0062
	FyC	0.0022	0.0058	0.0175	0.0558	0.0664	0.0793	0.7222	0.0136	0.0104	0.0078	0.0004	0.0068
	FmC	0.0060	0.0097	0.0122	0.0214	0.0482	0.0248	0.0469	0.7649	0.0451	0.0371	0.0048	0.0070
	FoC	0.0015	0.0049	0.0132	0.0268	0.0572	0.0244	0.0104	0.0798	0.7449	0.0401	0.0008	0.0067
	FSC	0.0009	0.0048	0.0032	0.0031	0.0109	0.0108	0.0091	0.0222	0.0168	0.8390	0.0016	0.0012
	FS	0.1436	0.2072	0.1294	0.0778	0.0174	0.0088	0.0204	0.0255	0.0111	0.0134	0.9113	0.0206
	A	0.0179	0.0088	0.0036	0.0103	0.0185	0.0707	0.0339	0.0314	0.0850	0.0194	0.0003	0.8556

(c) Coefficient of variation of averaged transition frequencies in the regulated period

		River	B	H	Sy	Sm	FyoC	FyC	FmC	FoC	FCS	FS	A
	River	0.1254	1.0198	1.1286	1.1500	1.0487	0.7847	0.5066	0.4243	0.5568	0.2291	0.4532	0.7280
>1.0	B	0.7667	0.7734	0.9313	0.4739	0.7535	0.6052	1.0338	0.7514	0.7948	0.7965	0.8869	0.7164
>0.3	H	0.9389	0.7845	0.5759	0.5139	1.1553	0.5218	0.4577	0.6953	0.6144	0.5726	1.1555	1.2682
>0.1	Sy	1.0787	0.9610	0.7797	0.5350	0.1793	0.3695	0.1313	0.4821	0.7746	0.5639	0.9677	0.7843
<0.1	Sm	0.7670	0.7543	1.0251	0.8660	0.1782	1.2116	0.1007	0.3346	0.5226	0.9639	0.7491	0.9931
	FyoC	0.3449	0.5140	1.0391	0.7417	0.8171	0.0820	0.8660	0.3447	0.5741	0.3994	0.4536	0.3874
	FyC	1.0142	0.4421	0.5840	0.9219	0.4572	0.6633	0.1116	0.2615	0.5527	0.1834	0.2585	0.5320
	FmC	0.6990	0.6213	0.2903	0.5187	0.1241	0.2473	0.7483	0.0646	0.3164	0.2083	0.6640	0.2889
	FoC	0.5848	0.4737	0.3893	0.4094	0.4147	0.2057	0.3425	0.3558	0.0914	0.1461	0.5771	0.3138
	FCS	0.4882	0.0252	0.4036	0.2218	0.1681	0.4291	0.4692	0.2719	0.5142	0.0291	0.3798	0.8528
	FS	1.1565	1.3200	1.4318	1.2936	1.0935	0.6128	0.6420	0.1124	0.4962	0.4810	0.0601	1.3730
	A	1.2132	0.5641	0.0403	0.6649	0.6181	0.1386	0.4091	0.3221	0.5181	1.0290	0.7010	0.0468

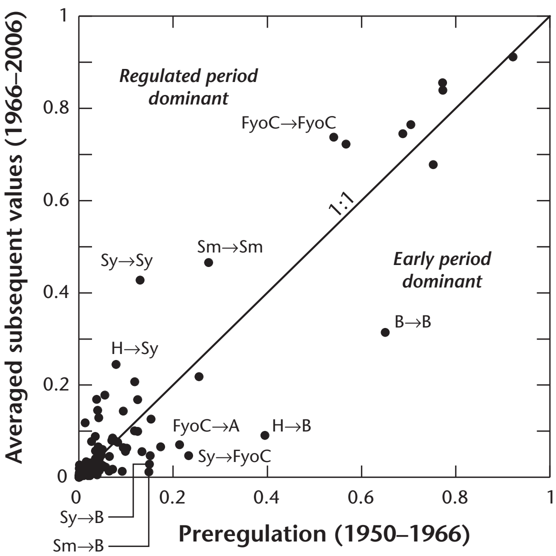

Figure 8.15 Comparison of vegetation transition frequencies before and after flow regulation. Pre-regulation frequencies are on the abscissa.

indicate erosion followed by reoccupation, at river level, of the eroded area, but it probably also reflects, in part, the difficulty to properly identify the water edge and narrow (the order of meters) shore zone communities on heavily shaded shores. This problem would particularly affect the spruce unit because it appears black, as does shadow, on the air photos.

The variance of the data, indexed by the coefficient of variation (Table 8.6c) and available only for the post-regulation period, is generally high. In part, this reflects real variance in conditions in the successive periods: it is notably higher for the early successional transitions than for the later ones (to the lower right of the table). However, it also incorporates the measure of interpretive error that exists in the data. Hence, while the pattern of changes may be accepted as qualitatively reasonable, the indicated rates of transition should be considered only comparatively, at best.

An interesting insight is gained by plotting the transition frequencies before and after regulation against each other (Figure 8.15). There is generally a high correspondence for equivalent transitions, suggesting that the post-regulation pattern of succession has proceeded much as it did before. However, notable departures include those transitions that signify river erosion and resetting of the succession sequence—much more prominent before regulation—and "null" transitions in the post-regulation period. The latter effect probably indicates, in the main, the relatively short period of observation (30 years) in comparison with the time scale for succession of plant communities.

A significant indicator of community structure is the measure of which communities are adjacent to which ones. We have enumerated the "constrained adjacencies" for communities in the reach; "constrained" meaning that when one particular community is adjacent to two or more units of another community the adjacency is counted only once. Results for 1966 (the last analysis before the inception of regulation) are shown in Figure 8.16a and results for 2005 to 2006 are displayed in Figure 8.16b. To conform with the model of riparian succession adjacencies should peak close to the diagonal position. The observed results is less organized in this manner than one would expect, indicating a more palimpsestic distribution of vegetation types than a pure succession model would exhibit. We infer that fluvial disturbance, still evident after nearly 40 years of regulation, has led to some disorganization of the terrestrial succession and reduced interpretive efficacy for the model of riparian succession.

To examine the overall evolution of the community mosaic along the river we again present the modified Simpson's Index of relative evenness in the distribution of individual communities. Results for the sub-reaches and for the entire BC reach are shown in Figure 8.17. The expectation is that community evenness will decline over time in the regulated regime since fluvial disturbance has declined dramatically and the floodplain communities should be progressing toward a successional endpoint. In fact, the evenness in most sub-reaches changed little before the 1996 flood, when a significant dip occurred in some sub-reaches due to the apparent loss (to floodwater) of the shrub communities. The 2005 data show a recovery in most sub-reaches, implying that the dip is mainly an interpretive artifact. However, Sub-reach 2 shows a continuing decline in evenness. In contrast, Sub-reaches 1 and 6 exhibit an increase in evenness, initiated, in the latter case, before the 1996 event. The effect in Sub-reach 2 can be assigned to the dramatic expansion of mature cottonwood forest (Figure 8.13). The rise in evenness in Sub-reach 1 reflects the relatively reduced dominance of mixed forest whereas in Sub-reach 6 a general evening up of all communities is evident.

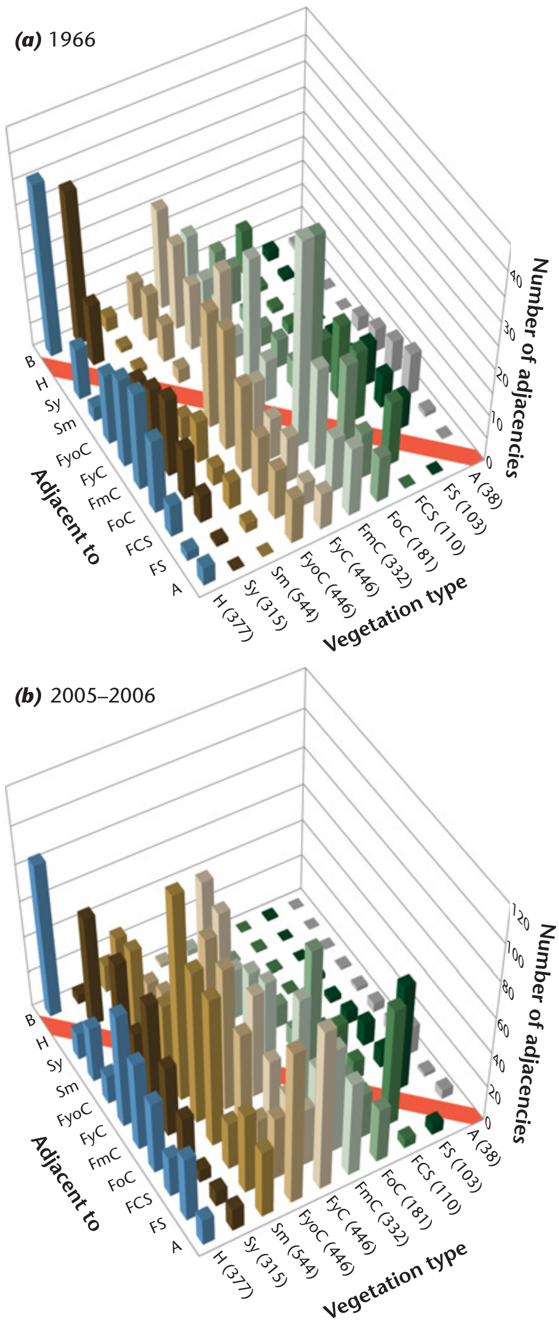

Figure 8.16 Measures of community adjacency in the British Columbia reach: (a) adjacency in 1966, before the commencement of flow regulation; (b) adjacency in 2005 to 2006, after 38/39 years of regulation.

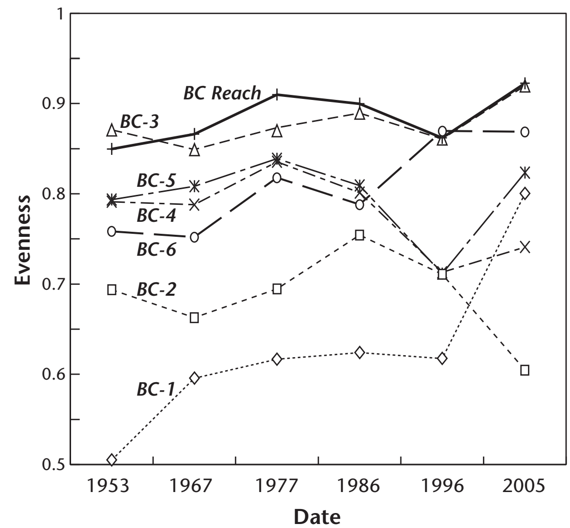

Figure 8.17 Evolution of community evenness in the mapped study reaches.

Finally, a note of caution should be voiced: all of the foregoing analyses depend upon delineation of the principal communities from mainly black and white air photography. There is bound to be some errors in community identification (see notes above on photogrammetric error and shadow effects); hence individual statistics cannot be read as precise numbers.

8.7 Discussion

Riparian vegetation in northern Canada is of critical importance as over-wintering habitat for large ungulates. In these latitudes, where both winter and summer climate are severe on uplands and plateaus, valley floor and slope vegetation offer a relatively protected environment. Many of the animal species that over-winter in the valleys are a source of food and revenue for indigenous people who follow traditional life styles of hunting and trapping. Alterations in either total area or composition of these winter habitats is of concern as it affects the survival of animal species and the wellbeing of the hunters. Thus, change to riparian vegetation has been recognized as an environmental impact that must be assessed when rivers are dammed.

The riparian vegetation along Peace River is composed of a mosaic of plant communities whose existence and spatial arrangement can be explained in terms of the normal succession on variably textured surfaces subject to varying frequencies and intensities of disturbance. The model of succession, initially developed from 1977 air photo mapping and field study in 1981, has been validated by post-diction using 1953 and 1961 air photos, and by 17 years of field observation. The replicate sampling of plots four times over 17 years provides field data that indicate successional trends are continuing at some locations. The data also indicate changes that would not have been expected using the succession model. Such changes are examined in relation to the altered river flow.

Reduction in water flow variation and seasonal flooding appear to be the causes, directly or indirectly, of observed changes in the rate or path of succession. However, the effects of regulated river flow are not easily predicted. The dramatic reduction of flood frequency and severity in the study reach has virtually eliminated floodplain construction but has established an extensive area of former bar top as a "proto-floodplain" at a lower elevation. Furthermore, the seasonal distribution of flow has changed (Figure 8.4). The questions now become, "how has disturbance changed?" and "can the altered disturbance explain observed vegetation changes that cannot be accounted for by 'normal' processes?"

In the regulated regime, the highest flows occur in winter in the first 100 km from the dams to the confluence with Pine River, and the seasonal regime is substantially modified all the way to the Alberta border. These flow regime changes lead to an increase or decrease in the area of different substrates and hence potentially alter the total areas occupied by different plant communities. Observations that support this conclusion include the following:

i. The expected result of the back channels filling and becoming dry enough for the establishment of shrub communities, though very slow in the sediment-starved reach near the dams, is becoming apparent from photo-mapping and field observation of the transect. But the rate at which such primary succession occurs in the side channels seems to vary depending on the regularity with which the channel is filled by water ponded behind ice jams or by winter high flows due to hydropower management. Though such flooding may not be an annual event it still impedes the development of primary succession by retarding the establishment of shrub communities.

ii. Shrub communities, once established, are remarkably persistent. Field examination at several sites, particularly downstream from the Pine confluence, shows that shrubs have been "scythed off" about a meter above the surface. Both willows and cottonwoods sprout from broken stems, producing a dense thicket of shrubs. The frequency of the "mowing" appears to prevent succession to a cottonwood forest. The existence of these shrub communities throughout the time of the photo record indicates that their persistence is not simply due to river regulation but, without regulation, winter flows would be much lower so ice probably would not invade these communities so frequently, while summer floods might be less damaging. The phenomenon may be site specific, linked to configurations of the channel that encourage the collection of ice. The effect may also be reduced with time as flows are managed to minimize ice-jam formation and ice damage.

iii. Changes in flood conditions have reduced the amount of woody debris moved downstream, a result in part of the reduced range of flow variation and in part the result of the much reduced rate of bank erosion. This affects the establishment of cottonwood sprouting from buried trees. If cottonwood colonization becomes dependent on seed sources then research by Mahoney and Rood (1998) would suggest that it may take longer for cottonwood to establish in the future. The large accumulations of wood that have provided the essential eutrophic conditions for alder to establish in the past are not a current feature of the river's deposits in the reach studied.

iv. The persistence of cottonwood domination of forests appears to be related to the absence of a spruce seed source. Clearance for agriculture removed much of the riparian spruce 60 to 90 years ago, not long before the river was dammed. Changes in riparian habitats may affect the use of the trails by animals carrying seeds and/or cones that provide essential seed sources for establishing spruce trees in places remote from mature spruce.

v. The rapidity with which mature cottonwood stands become decadent and start to fall is a commonly recognized downstream effect of regulated flow (Rood and Mahoney, 1990). The cause of the premature mortality is ascribed to site impoverishment due to reduced flooding and critical lowering of the summer water table. The combination of early cottonwood mortality, failure of spruce to establish, and the decline in recruitment of new cottonwood stands should become evident in the general opening of the riparian forest cover over the next 30 years. This leaves a question about the next stage in succession on these sites.

vi. The apparent lack of recruitment from cottonwood shrub stage to young forest is also a trend that is likely to continue if aggradation of the floodplain fails to occur—as will happen under strictly regulated peak flows—or occurs only at a slower rate. The combination of low recruitment rates with early mortality of existing cottonwood forest could lead to a substantially altered riparian forest in the future.

vii. Species changes in the shrub layers of some communities have occurred because plant diseases have weakened the competitive advantage of one species, thus favoring species that were previously less able to compete. The change in shrub dominance does not appear to have any effect on the dominant tree species. It may, however, affect habitat use by wildlife.

The BC reach overall maintains a continuing high level of community evenness, slightly increasing over the period of study, probably due to the increasing prominence of the shrub communities. There is no indication in this index of any move toward successional endpoints in this 55-year history. Reasons for that are probably the transient rise to prominence of shrub communities along the river fringe and the extended succession interval for the forest communities. While we identify succession in progress both in the field study and in some individual reach-wide trends, it has not yet strongly influenced the structure of the riparian forest as a whole.

Along the entire British Columbia reach, Sub-reach 1, the most "terrestrial" of the sub-reaches, and that in which the effect of flow regulation is absolutely greatest, exhibits the nearest approximation to our model of riparian succession, expected to be dominant where the river is stable and leading, in the long term, to reduced community diversity. Elsewhere succession is evident in the seeming advance of the cottonwood forest stage and slow transition toward coniferous forest, but most changes are not dramatic, nor perhaps should we expect them to be in 40 years. Our evidence points toward an adjustment of the riparian ecosystem that will proceed at the rate dictated by the cycle time for the dominant *Populus-Picea* boreal forest community (Timoney and Robinson, 1996), that is, a time scale of centuries. The contemporary changes inferred from our mapping studies are not unlike those observed in the field study areas (Figure 8.10), whence we may conclude that lessons learned from the more detailed field study are of general value for interpretation of changes along the river.

8.8 Conclusions

This study was initiated to examine downstream effects on riparian vegetation of regulating Peace River flow. The severity, duration and timing of floods have been altered. These alterations have not eliminated disturbance by flooding in the new, lower floodplain (the former bar-top level), though this now occurs primarily during winter high flows as well as at spring breakup downstream from the Pine confluence. Spring ice runs, a major cause of interruptions in normal succession in the past, continue to be a cause of perpetuation of shrub communities but, now, winter high flow also damages the pioneer communities established on exposed surfaces during summer. On the other hand, lack of higher floods has reduced the fertility of old floodplain soils and, along with a lowered floodplain water table, leads to early mortality of cottonwood stands that occupy old floodplain surfaces, now two meters above present floodplain level. Reduced flow also affects the downstream transport of large woody debris and thus alters the scale and location of debris accumulation on the banks, prime sites for alder growth. This also reduces the source of vegetative reproduction for cottonwood, willow, and alder. The changed flow regime appears to be having a significant effect on riparian communities, and we expect this effect to become more apparent as time passes.

We have modeled the normal plant succession in the riparian zone on different substrates. We find evidence for the efficacy of the model, but also evidence for fluvial disturbance that has created a more palimpsestic distribution of vegetation types than undisturbed succession would suggest. If we link the model to the ability to predict effects of flow regulation on the hydromorphology of Peace River, we should be able to predict changes in present and future plant communities. A word of caution is however necessary. Predictions that can be made about riparian systems' responses to river regulation are based upon a normative model of system response. Forecast success in such circumstances becomes poorer and poorer as the time scale lengthens because the effects of imperfect forecasts accumulate. Deterioration in forecast success is especially notable for biological systems since significant contingent events, events determined by developments outside the immediate system, or ones with specific antecedents not foreseeable, will eventually affect the course of development of the system. For example, river morphology may be influenced by major landslides or by new engineering developments. The riparian ecosystem may be impacted by fire, by disease, or by unforeseen changes in land and water management. In the case of the biological system, there are normal, internal factors that are impossible to predict with certainty. The path of succession may depend upon the vagaries of seed dispersal, or upon the way in which seasonal weather or longer term climatic change, or fluctuations in the summer water table influence seedling viability or the spread of plant disease.

Moreover, the time scale for effective succession in the more mature floodplain communities is long—evidently longer than our 40-year observing window, so that we may not yet see the ultimate consequence of changes that our data indicate are indeed underway. Most simply put, the time scales and the history of the system determines its further development and though we can predict, we cannot do so with certainty.

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References

Amlin, N. M. and Rood, S. B. (2002) Comparative tolerances of riparian willows and cottonwoods to watertable decline. *Wetlands*, 22, 338–346.

Braatne, J. H., Rood, S. B., and Heilman, P. E. (1996) Life history, ecology, and conservation of riparian cottonwoods in North America [Chapter 3], in *Biology of Populus and its Implications for Management and Conservation. Part I*, edited by R. F. Stettler et al. N.R.C. Research Press, National Research Council of Canada, Ottawa, Canada. pp. 57–85.

Bradley, C. E. and Smith, D. G. (1986) Plains cottonwood recruitment and survival on a prairie meandering river floodplain, Milk River, southern Alberta and northern Montana. *Canadian Journal of Botany*, 64, 1433–1442.

Bravard, J.-P., Amoros, C., and Pautou, G. (1986) Impact of civil engineering works on the successions of communities in a fluvial system. *Oikos*, 47, 92–111.

Brayshaw, T. C. (1965) The status of the black cottonwood (*Populus trichocarpa* Torrey and Gray). *Canadian Field-Naturalist,* 79, 91–95.

Brayshaw, T. C. (1976) *Catkin Bearing Plants of British Columbia.* Occasional Paper No. 188, Royal British Columbia Museum, Victoria, B.C.

Brayshaw, T. C. (1996) *Trees and Shrubs of British Columbia*. Royal British Columbia Museum Handbook, UBC Press, Vancouver, BC.

Desloges, J. R. and Church, M. (1989) Wandering, gravel-bed rivers: Canadian landform examples—13. *The Canadian Geographer*, 33, 360–364.

Hall, F. C. (2003) *Photo Point Monitoring Handbook: Part A—Field Procedures, Part B—Concepts and Analysis.* General Technical Report PNW-GTR-526. United States Department of Agriculture, Forest Service, Pacific Northwest Research Station. 134 p.

Johnson, W. C. (2000) Tree recruitment and survival in rivers: influence of hydrological processes. *Hydrological Processes*, 14, 3051–3074.

Krajina, V. J, Klinka, K., and Worrall, J. (1982) *Distribution and Ecological Characteristics of Trees and Shrubs of British Columbia.* University of British Columbia, Faculty of Forestry. 131 p.

Ligon, F. K., Dietrich, W. E., and Trush, W. J. (1995) Downstream ecological effects of dams: a geomorphic perspective. *BioScience*, 45, 183–203.

MacKinnon, A, Pojar, J., and Coupe, R., editors. (1992) *Plants of Northern British Columbia*. British Columbia Ministry of Forests. Lone Pine Publishing, Edmonton, Canada. 352 p.

Mahoney, J. M. and Rood, S. B. (1998) Streamflow requirements for cottonwood seed recruitment—an integrative model. *Wetlands*, 18, 634–645.

Marston, R. A., Mills, J. D., Wrazien, D. R., Bassett, B., and Splinter, D. K. (2005) Effects of Jackson Lake Dam on the Snake River and its floodplain, Grand Teton National Park, Wyoming, U.S.A. *Geomorphology*, 71, 79–98.

Meidinger, D. and Pojar, J. (1991) *Ecosystems of British Columbia*. Research Branch, British Columbia Ministry of Forests. 330 p.

Murray, A. B., Knaapen, M. A. F., Tal, M., and Kirwan, M. L. (2008) Biomorphodynamics: physical–biological feedbacks that shape landscapes. *Water Resources Research*, 44, W11301. 18 p. doi:10.1029/2007WR006410

North, M. E. A. and Teversham, J. M. (1984) The vegetation of the floodplains of the Lower Fraser, Serpentine and Nicomekl Rivers, 1859 to 1890. *Syesis*, 17, 47–66.

Petts, G. E. (1984) *Impounded Rivers: Perspectives For Ecological Management*. John Wiley & Sons, Ltd, Chichester, UK. 326 p.

Petts, G. E. and Gurnell, A. M. (2005) Dams and geomorphology: research progress and future directions. *Geomorphology*, 71, 27–47.

Pielou, E. C. (1977) *Mathematical Ecology*. John Wiley & Sons, Inc., New York.

Polzin, M. L. and Rood, S. B. (2000) Effects of damming and flow stabilization on riparian processes and black cottonwoods along the Kootenay River. *Rivers*, 7, 221–232.

Rood, S. B. and Mahoney, J. M. (1990) Collapse of riparian forests downstream from dams in Western Prairies: probable causes and prospects for mitigation. *Environmental Management*, 14, 451–464.

Rood, S. B., Taboulchanas, K., Bradley, C. E., and Kalischuk, A. R. (1999) Influence of flow regulation on channel dynamics and riparian cottonwood recruitment along the Bow River, Alberta, Canada. *Rivers*, 7, 33–48.

Samuelson, G. M. and Rood, S. B. (2004) Differing influences of natural and artificial disturbances on riparian cottonwoods from prairie to mountain ecoregions in Alberta, Canada. *Journal of Biogeography*, 31, 435–450.

Scott, M. L., Auble, G. T., and Friedman, J. M. (1997) Flood dependency of cottonwood establishment along the Missouri River, Montana, USA. *Ecological Applications*, 7, 677–690.

Shields, F. D., Jr., Simon, A., and Steffen, L. J. (2000) Reservoir effects on downstream river channel migration. *Environmental Conservation*, 27, 54–66.

Timoney, K. P. and Robinson, A. L. (1996) Old-growth white spruce and balsam poplar forests of the Peace River lowlands, Wood Buffalo National Park, Canada: development, structure and diversity. *Forest Ecology and Management*, 81, 179–196.

Uunila, L. S. (1997) Effects of river ice on bank morphology and riparian vegetation along Peace River, Clayhurst to Fort Vermilion. *Proceedings of the 9th Workshop on River Ice*. Fredericton, Canada. pp. 315–334.

Walstra, J., Chandler, J. H., and Dixon, N. (2011) Evaluation of the controls affecting the quality of spatial data derived from historical aerial photographs. *Earth Surface Processes and Landforms*, 36, 853–863.

Ward, J. V. and Stanford, J. A. (1989) Riverine ecosystems: the influence of man on catchment dynamics and fish ecology. *Canadian Special Publication of Fisheries and Aquatic Sciences*, 106, 56–64.

Williams, G. P. and Wolman, M. G. (1984) Downstream effects of dams on alluvial rivers. *United States Geological Survey, Professional Paper*, 1286, 83 p. U.S. Government Printing Office, Washington, DC.

CHAPTER 9

The response of riparian vegetation to flow regulation along Peace River, Alberta

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9.1 Introduction

Along alluvial rivers, sedimentation and riparian vegetation interact in reciprocal process and response to determine the form of the river channel and the vegetation community structure in the riparian zone. River currents spread seed and other reproductive plant parts along the waterway; the timing and persistence of high water influence seed germination, seedling survival, and the longer-term survival of elements of the riparian vegetation. The river also accomplishes erosion that may truncate successional development in the floodplain, and sedimentation that creates fresh surfaces where succession is reinitiated, so that non-succeeding stands may occur in juxtaposition. Floodplain vegetation, on the other hand, slows overbank currents and promotes sedimentation, building the floodplain with cumulic soils; root networks act to moderate erosion along stream banks, while downed vegetation and semiaquatic vegetation may directly reduce impinging currents and inhibit erosion of stream banks.

Along boreal rivers, a second set of river-vegetation interactions comes into play between river edge vegetation and seasonal ice. Seasonal ice runs may pile ice onto river banks, effecting significant damage to vegetation and consequently affecting subsequent direct interaction between the river and the riparian zone. Certain plants are adapted to episodic damage and readily resprout from broken stems or roots. This yields a distinctive tangle of river-edge shrubbery that may be particularly resistant to water damage other than root-drowning. Riparian species, of course, are variably able to withstand periods of inundation (see Amlin and Rood, 2001).

Some species are particularly adapted to the riverine cycle of erosion, sedimentation, and episodic inundation, using these processes to spread to new substrate and to replicate stands. This is true of the riparian cottonwoods (*Populus* spp.) of North America that dominate the floodplains of laterally active rivers throughout much of the continent. Flow regulation, with consequent stabilization of water levels and reduction in river erosion and sedimentation may lead to a failure in reproduction of these trees and a conversion of the floodplain vegetation to more characteristically upland species. Work by Johnson (Johnson *et al.*, 1976; Johnson, 1992, 2000) and by Rood (Rood and Mahoney, 1990; Rood *et al.*, 1999; Polzin and Rood, 2000) and their collaborators, among others, has explored these relations in detail. In general, the floodplains of regulated rivers become more stable and more “terrestrial” in their ecological aspect (Merritt and Cooper, 2000; Marston *et al.*, 2005).

Peace River is a large, northward flowing, boreal river in northwestern Canada (Figure 9.1) that has been regulated for hydropower production since 1967 at W.A.C. Bennett Dam in the Rocky Mountain front ridge in British Columbia (there is now a second dam, a short distance downstream). Nival flood dominance on the upper river has been replaced by a regime that presents a

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The Regulation of Peace River: A Case Study for River Management, First Edition. Michael Church.

Companion website: www.wiley.com/go/church/peaceriver

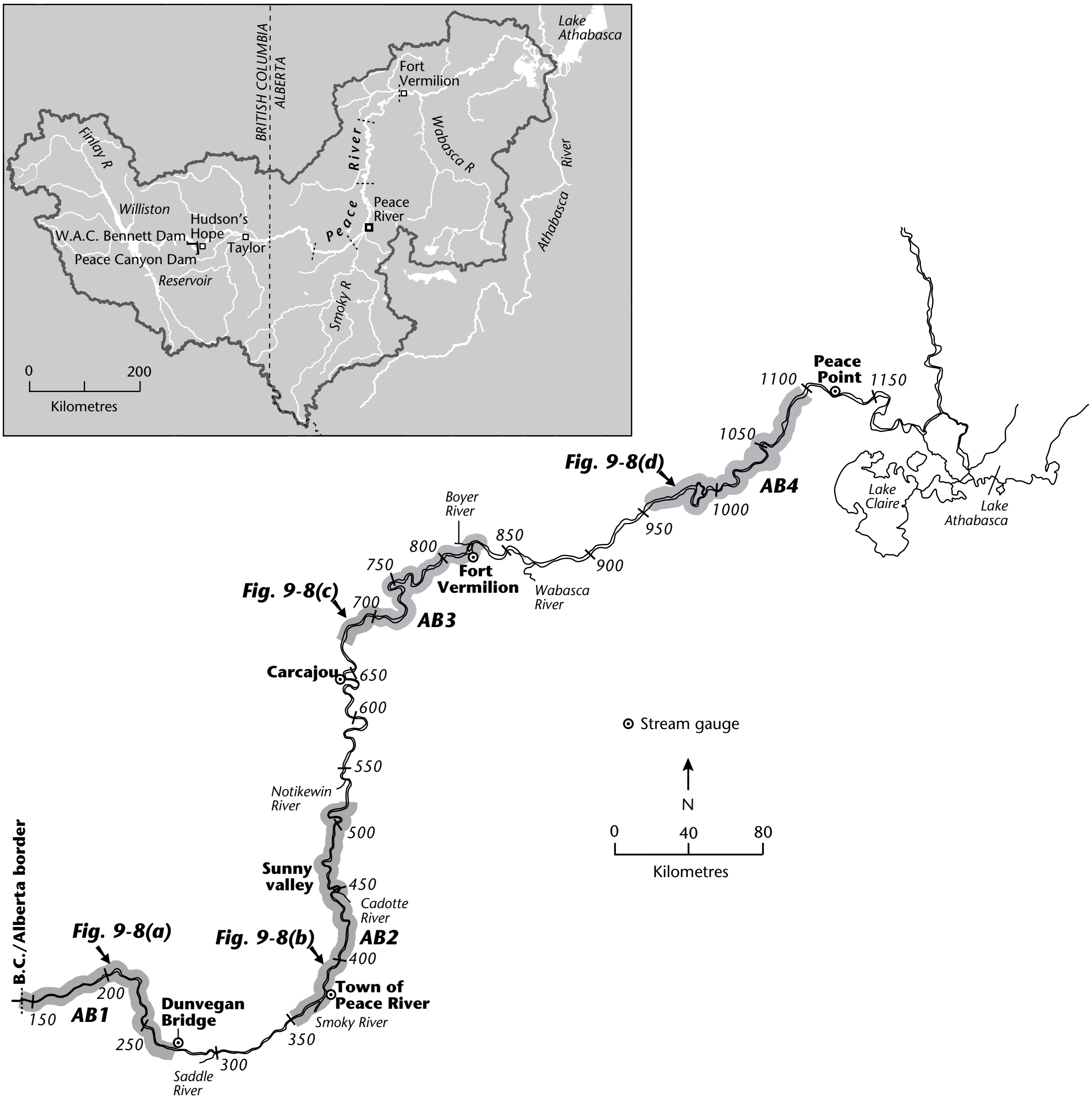

Figure 9.1 Location map, showing study reaches and sub-reaches and the location of the principal gauges along the river. The locations of the maps shown in Figure 9.8 are also indicated.

winter flow maximum or, below the first significant tributary (Pine River, in British Columbia), a weakly dominant nival flood. Below Smoky River, 368 km below the dams, nival dominance is firmly reestablished, yet the seasonal pattern of flows remains significantly affected all the way to Peace Point, nearly 1200 km from the dams (Chapter 2).

In a companion study (Chapter 8), the effect of flow regulation on the subsequent development of riparian vegetation has been closely examined through field study and air photo interpretation of the British Columbia reach of the river. In this chapter, the study is extended to the Alberta reach, between 148 and 1223 km from the dams. Two important distinctions between the British Columbia and Alberta reaches influence these two studies. In the British Columbia reach, the river flows in a valley wide enough to permit some floodplain development on one or both sides of the river; the river formerly was a wandering, occasionally anabranched channel with frequent channel islands, whereas in much of the Alberta reach, the river is largely confined with discontinuous floodplain development, limited room to move laterally, and infrequent channel islands. Second, since regulation ice action has been less common—though still noted—in the first 100 km below the dams and limited all the way to the Alberta border (km 148); in comparison, significant ice activity has persisted in the Alberta reaches of the river. These differences might predispose different riparian responses to flow regulation.

A methodological difference between the two studies arises from the field work in the British Columbia reach. No equivalent work was undertaken in Alberta, although a reach-length reconnaissance was conducted in 1993. However, in Alberta an extensive field survey of ice damage to riparian vegetation was accomplished (Chapter 6) while no comparable work was undertaken in British Columbia.

A final factor that influences observations and interpretations in this chapter is that Peace River is a large river that formerly built its floodplain to a considerable elevation —3 m or more—above normal summer water level. Most trees in the boreal floodplain are species with laterally spreading root systems rather than vertical tap roots. The consequence is that the effectiveness of root systems as discouragement to erosion is limited to low, accreting banks; high banks of mature floodplain are attacked by the river below the level of root penetration and the potential mitigation of erosive attack represented by root systems is not effective.

The purposes of this chapter are (i) to describe riparian vegetation community trends in the Alberta reach of Peace River before and after regulation, and to compare them; (ii) to understand the role of river ice in effecting those trends; (iii) to compare trends in the largely confined and more distal Alberta reach with those in the proximal, unconfined British Columbia reach: and (iv) to compare observed trends with the model of riparian succession elaborated for the British Columbia reach (Chapter 8). To assure comparability, the methods used in this study are similar to those developed for the study of the British Columbia reach; they will be reviewed briefly in order that the chapter may remain an independent report.

9.2 Study area

Peace River enters Alberta from British Columbia at Clayhurst, just north of the 56th parallel (Figure 9.1), from where it flows east and north to the Peace–Athabasca delta at the western end of Lake Athabasca, where it largely bypasses the lake and becomes Slave River. The northward flowing course means that winter ice melts in the upper reaches before lower reaches thaw, so ice jams are a feature of fluvial processes along the river (Chapter 6). The total length of the river in Alberta is 1075 km, which is more length than we have been able to survey. Accordingly, the study has been conducted in four reaches selected to represent the major morphological styles of the entire river. Total surveyed length is 620 km, about 60% of the entire river.

Whereas in British Columbia the river flows in a pre-Quaternary valley wide enough to permit floodplain development, at the Alberta border it enters a narrow, gorge-like valley, 200 to 250 m deep that is the product of Quaternary drainage derangement and the excavation of a fresh river course. Hence, floodplain extent is limited and the river is entirely confined along most of the 134-km reach to Dunvegan (Alberta Reach 1: AB1). Channel islands in this reach are rare except at two abrupt major bends of the river, Many Islands and the Montagneuse River confluence, where substantial sedimentation has occurred. The lower portion of the valley sides adjacent to the river consists of terraces or colluvial deposits from the frequent landslides that occur all along the river. The river for the most part occupies a cobble-gravel single-thread channel. Below Dunvegan, there is, once again, limited floodplain development down to the Smoky River confluence near the Town of Peace River (TPR).

Smoky River is the principal tributary of the river, delivering some 20 million tonnes a^{-1} of sand and silt to Peace River. Beyond TPR, then, the bed becomes sandy gravel. The river enters a 145-km reach in which it is partly confined within a bedrock valley. Here the river has formed a sequence of sinuous meanders, partly rock controlled. There has been lateral activity, however, and the river has developed discontinuous floodplain segments in a valley flat that varies between one and two kilometers in width. Channel islands also occur in the bends. With the much increased sand load, the style of sedimentation becomes more vertical, in comparison with the distinctly lateral (and therefore largely suppressed) style in the upper river. The northward course of the river and the presence of channel islands and sometimes sharp bends encourage the development of severe ice jams that tend to recur at the same critical locations in this reach. The study reach, Alberta Reach 2 (AB2), commences at Shaftesbury Ferry, 18 km above the Smoky River confluence, at the limit of the backwater induced by the tributary.

Beyond Carcajou (635 km), the valley widens to permit greater floodplain development and near Thompson Landing (674 km below the dams) the river undergoes a gravel-to-sand transition (Shaw and Kellerhals, 1982). The river is meandered and divided about nonoverlapping islands. This reach (AB3) ends below Fort Vermilion, beyond which the river encounters bedrock control at Vermilion Chutes.

Reach AB4 is in the Slave Lowland below Vermilion Chutes. The river here has a sand bed and silty sand banks. The first 75 km (Reach AB4a), between Vermilion Chutes and Fifth Meridian, exhibits low-order anastomosis about frequent islands. The lower 108 km (Reach AB4b) are meandered in loop extension style with islands in the bends. The reach is divided into "a" and "b" segments in recognition of this significant change in morphological style. The surrounding plain is extensive and mostly wet boreal forest.

The riparian vegetation is typical of active floodplains in the Aspen Poplar ecosystem of the drier plains of Alberta (North, 1965) and, farther north, the Boreal Spruce ecosystem. Vegetation varies in species composition and height from open herbaceous communities to dense shrubs to closed forest (Figure 9.2). The plant communities are distinctly influenced by the river. River bottoms are generally dominated by *Populus balsamifera*. Island and floodplain edges where sediments are continuously or seasonally accreting have a sparse herbaceous plant cover. The margins of back channels, where finer sediments have settled, support a low herbaceous or shrub cover. Farther back from the shore one finds a variety of cover types ranging from shrubs to stands of deciduous trees. Gallery stands of willow are a distinctive feature of the front ranks of shrubby vegetation. Centers of islands support patches of mixed deciduous and spruce forest and in some places stands of pure

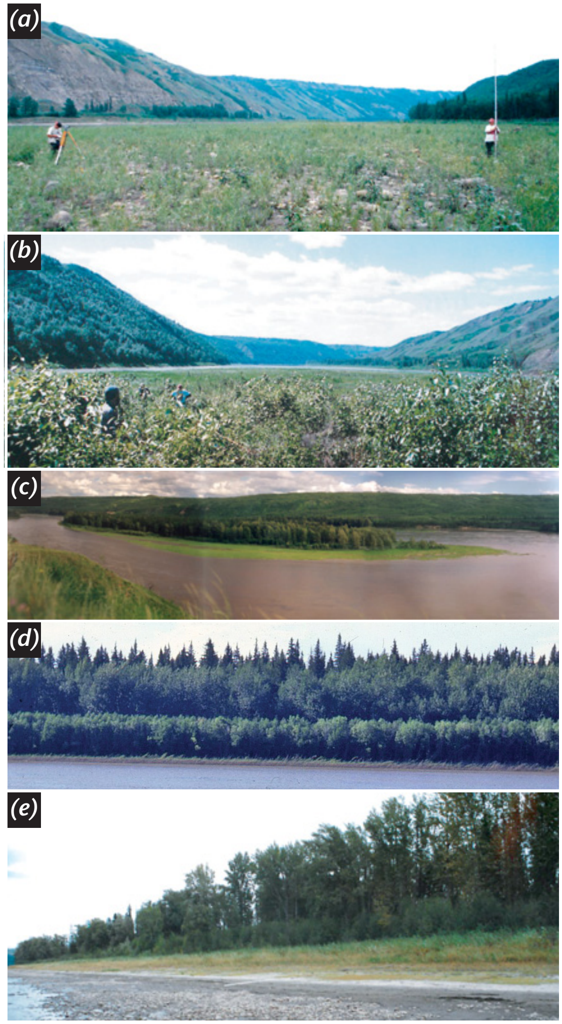

Figure 9.2 Riparian vegetation communities along Peace River in Alberta: (a) Herbaceous cover (H) and young shrubs on a lateral bar at km 256, July 1995; (b) mature shrubs (Sm), including young cottonwood and willow on a barhead at km 271.4 near Dunvegan Bridge, June 1995; (c) Herbaceous cover (H) on abandoned bar surface flanking an island with mature cottonwood (FmC), near km 357, upstream of Shaftesbury Ferry: view downstream, June 1996, Q ~8000 m^3s^{-1}; (d) Gallery forests near Fort Vermilion, mature shrubs (Sm) in front, including willow and alder, young cottonwood (FyC) behind and mature spruce (FS) farther back, near km 812, June 1991; (e) Characteristic riparian sequence: young shrubs (Sy) with an abrupt transition to mature shrubs (Sm) on recently stabilized surface, then decadent cottonwood forest (FoC) on the old floodplain behind, km 318 (Photos (a), (b), and (e) by L. Uunila; (c) and (d) by M. Church).

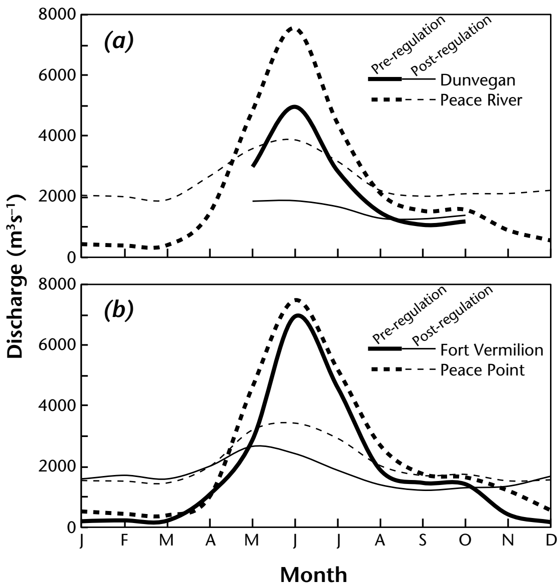

Figure 9.3 Pre-regulation and post-regulation flow regime based on monthly mean flows in the upper (Dunvegan Bridge), middle (TPR), and lower (Fort Vermilion; Peace Point) reaches of Peace River in Alberta. Dunvegan data are seasonal.

spruce. In the absence of disturbance *Picea glauca* is the climax species along the river and undisturbed floodplain forest along much of the river consists of spruce forest. As far north as Fort Vermilion, the floodplain is commonly cleared and cultivated, and forestry occurs in some places along the river. The forest cover extends down the steep valley slopes to the floodplain, except that slopes with a southerly aspect in the reach to TPR often are open grassland with shrubs or trees along seepage lines only. In many places, the valley slopes are disturbed by landslides.

The unregulated flow regime of Peace River was dominated by a nival freshet and low winter flows (Figure 9.3), but regulation has altered this pattern in the Alberta Peace River so that, along the length of the river much higher flows (1500 m^3s^{-1}) than formerly occur in winter when electric power demand peaks. In comparison, the spring freshet above Smoky River, is scarcely larger (Figure 9.3a). Below Smoky River, a significant spring freshet is reestablished, but flows still reach only about 60% of pre-regulation values (Figure 9.3b). High water levels unrelated to flow magnitude may occur in winter due to ice dams resulting from the consolidation of pan ice and frazil ice (Chapter 6). In 1996, an unusual summer flood occurred when it was necessary to draw down the main reservoir for repair work. Water was at flood level for about six weeks, reaching 7750 m^3s^{-1} at TPR and 9760 m^3s^{-1} at Peace Point. These flows are equivalent to a moderate pre-regulation freshet. Moreover, the flood of record on the river occurred in June 1990, when a large and intense frontal storm passed over the southern part of the drainage basin. Flows reached 16 500 m^3s^{-1} at TPR as the result of an 8620 m^3s^{-1} contribution from Smoky River, and still was 12 600 m^3s^{-1} at Peace Point, far beyond the storm's limits. On the highly regulated upper river, this event was merely the maximum post-regulation flood.

9.3 Mapping methods

Mapping was conducted on vertical air photographs at scales varying between 1:30 000 and 1:60 000; mostly the former, but varying to 1:80 000, with a short segment in one year at this smallest scale. The photos are standard federal and Alberta government photographs and are all black and white except for the final, 1999 to 2006 set (photo flight lines and data are given in the online supplement: see the Appendix for reference). Initial training for air photo interpretation was conducted on color infrared (IR) photos (because contrasts between different stands are more clear on IR photos) of a portion of the British Columbia Peace River, followed by remapping on equivalent black and white photographs of the same cover classes initially identified in the IR photos.

Because all but the 1999 to 2006 photos were black and white, vegetation identification relied on gray tones (see Table 9.1) and stereoscopically detected height. Shrub vegetation is not distinguished by species but is subsumed under two shrub categories based on height; below two meters are immature (young) shrubs, greater than two meters are referred to as mature shrubs. Dominant shrub species are *Salix* spp. and young *P. balsamifera*, with subordinate *Cornus stolonifera* and *Eleagnus commutata*. The mature shrub height category extends up to 10 m, hence alder woodland, with a height around 8 to 10 m, is classified as a tall shrub. Cottonwood forests were mapped as either open or closed canopy and as below (young) or above (mature) 20 m. The tallest, oldest cottonwood forests commonly occur in open canopy

Table 9.1 Riparian vegetation of Peace River, Alberta—map legends

Map symbol	Interpretation	Black and white photo signature
U	Unvegetated surfaces: recently deposited sediments	White; gray where wet
H	Herbaceous communities: varying from discontinuous cover to almost 100% cover and may include scattered ground; variable density trees and shrubs <1 m	Gray speckle; variable density
S	Shrub communities	
Sy	Primary *Populus balsamifera* including seedlings or sprouts, <1 m, cover varies from sparse to 100% young *P. balsamifera*, <2 m young *Salix* spp., <2 m	Uneven pale gray; more even as density increases
Sm	Tall *P. balsamifera* shrub, >2 m tall *Salix*, >2 m tall mixed *Salix* and *P. balsamifera*, >2 m *Cornus stolonifera, Eleagnus commutata*	Uneven gray
F	Forest	
FyoC	*P. balsamifera*, <20 m, open canopy	Uneven gray, darker for older stands
FyC	*P. balsamifera*, <20 m, closed canopy	
FmC	*P. balsamifera*, >20 m, closed canopy	
FoC	*P. balsamifera*, >20 m, open canopy, shrubs beneath, includes decadent stands	
FdC	*P. balsamifera*, decadent, >20 m, shrubs beneath	Decadent stands patchy
FCS	mixed *P. balsamifera* and *Picea glauca*	Patchy gray and black
FS	*P. glauca*	Black
A	Cultivated	By field pattern

stands with significant deadfall and are recognized as decadent cottonwood. There are 10 mapped vegetation cover classes, but a category was added for cultivated areas (Table 9.1). The classes adopted for mapping are identical with those used for similar mapping of the British Columbia reach (Chapter 8).

Following training, a sequence of maps was constructed based on air photos flown over the Alberta reaches on September 8, 1953; August 15, 1967; June 5, 1977 (IR); July 21, 1986; July 14, 1993 and various dates between June and September 2006, except August 3 to 8, 1999, in Reach AB2. Mapping was conducted photogrammetrically using a Carto® AP190 analytical stereoplotter in planimetric mapping mode. Control points in the Geodetic Survey of Canada national network were obtained from 1:80 000 diapositives and additional points were identified for bridging between photos (see Chapter 7 for more detail on mapping procedures). Data were orthorectified in Carto software and imported into ARC/INFO®, adjusted to co-register mapped unit boundaries and displayed. Examples of the maps are displayed in Figure 9.8. The nominal horizontal resolution of the plotter is ±60 cm from 1:30 000 scale photos obtained with metric cameras but control point transfer and photo print resolution degrade horizontal precision by a factor of 5 to 10 (Walstra *et al*., 2011). Hence, community boundary errors the order of three to six meters are to be expected. The error may to some degree be systematic (i.e., may represent bias) as the precise boundary of tree communities is difficult to place because of shadow effect. Many units are linear and relatively narrow so that systematic boundary errors might lead to significant errors in the estimation of ground area. For purposes of analysis, however, units are aggregated by sub-reach so that errors compensate each other. Given that many hundreds of units were mapped, aggregate errors are expected to be small, but no summary error analysis was undertaken.

For analysis, the reaches were divided into sub-reaches, each of homogeneous morphological character and hence divided principally at the major tributary junctions. These sub-reaches are the same ones used to delineate morphological changes along the river (Chapter 7), but not all of the dates of analysis are the same. An important feature of the mapping is that the final mapping, conducted on color photographs (by a different operator), was carried to finer resolution than the earlier mappings.

9.4 Riparian succession on Peace River

Some examples of the riparian forest along Peace River in Alberta are illustrated in Figure 9.2. North and Church (Chapter 8) have elaborated a model of riparian succession for the river (Figure 9.4) that might serve to explain the development of these forests. The model supposes that succession begins on newly emergent sediment surfaces, the product of sedimentation by the river. Different substrates, after the initial herbaceous stage, are preferentially colonized by different early succession species. Cottonwood, with the ability to withstand a level of summer drought, occupies the more readily drained gravel and sandy substrates, while mixed shrubs or dominant willow colonize finer soils that tend to remain saturated, or nearly so, for longer periods. In either case, however, the most common successional path is for cottonwood (*P. balsamifera*), which eventually overshadows other shrub species, to grow to dominance. White spruce (*P. glauca*) establishes under cottonwood cover—provided a seed source is available—so that, after about a century, a mixed forest develops in which cottonwood slowly becomes less dominant, eventually giving away to a spruce forest. Black spruce (*P. mariana*) occupies swampy floodplain sites, especially along the lower river.

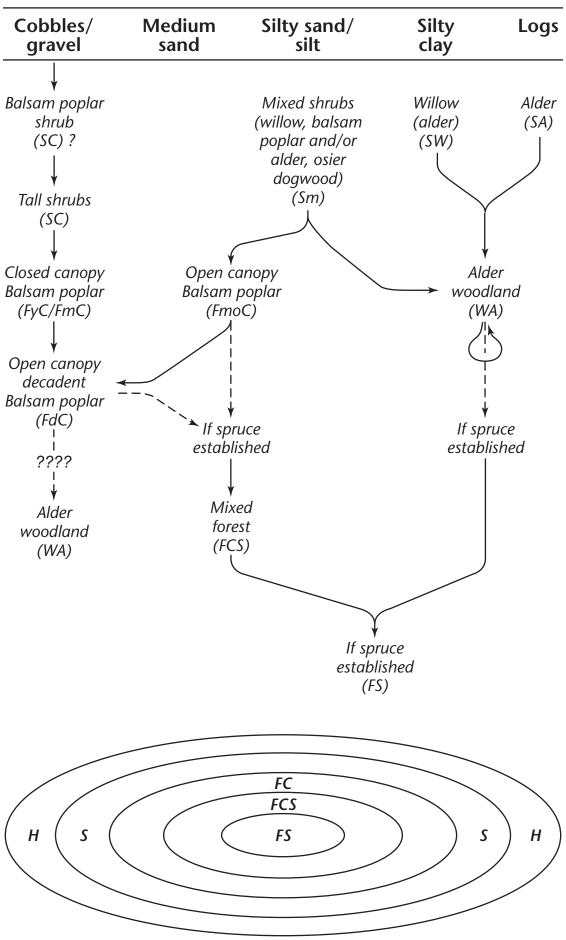

Figure 9.4 Riparian succession model of North and Church (Figure 8.6): temporal sequences on various substrates and ideal spatial configuration.

Initial establishment may be by wind-blown seed (usual for initial herbaceous communities), by river-borne seed, or by the deposition of plant fragments carried to the site by the river that are then capable of sprouting. In the case of water-borne seed, dense, even-aged stands develop along the shore in linear galleries reflecting the waterline at which the seed was abandoned. Such galleries of willow are common along the middle river. Whether the gallery resulting from a particular seed set long survives depends on whether it survives the high waters that immediately succeed that which delivered the seed. Marooned plant fragments tend to produce more patchy and uneven growth.

This temporal sequence, successively initiated on adjacent patches of emergent sediments as the river shifts persistently in one direction, gives rise to the spatial pattern of adjacent successional communities presented in Figure 9.4 as an "ideal island." Examples derived from bank transects along the river are given in Figure 9.5.

Some persistent variations on this sequence occur on finer substrates. Silty substrates initially host willow or willow/alder communities that may develop into persistent alder woodland. Former backchannels that have silted up may be subject to this development. Alder woodland or mixed shrubs may develop under decadent cottonwood if there is no seed source for spruce.

The activity of the river also disturbs the sequence. Most obviously, the river not only deposits sediment that becomes new substrate available for plant colonization, but also erodes its bank, undercutting communities at various stages of succession. If the river later reverts to depositing sediment on a formerly eroded site, the result is the seemingly anomalous juxtaposition of

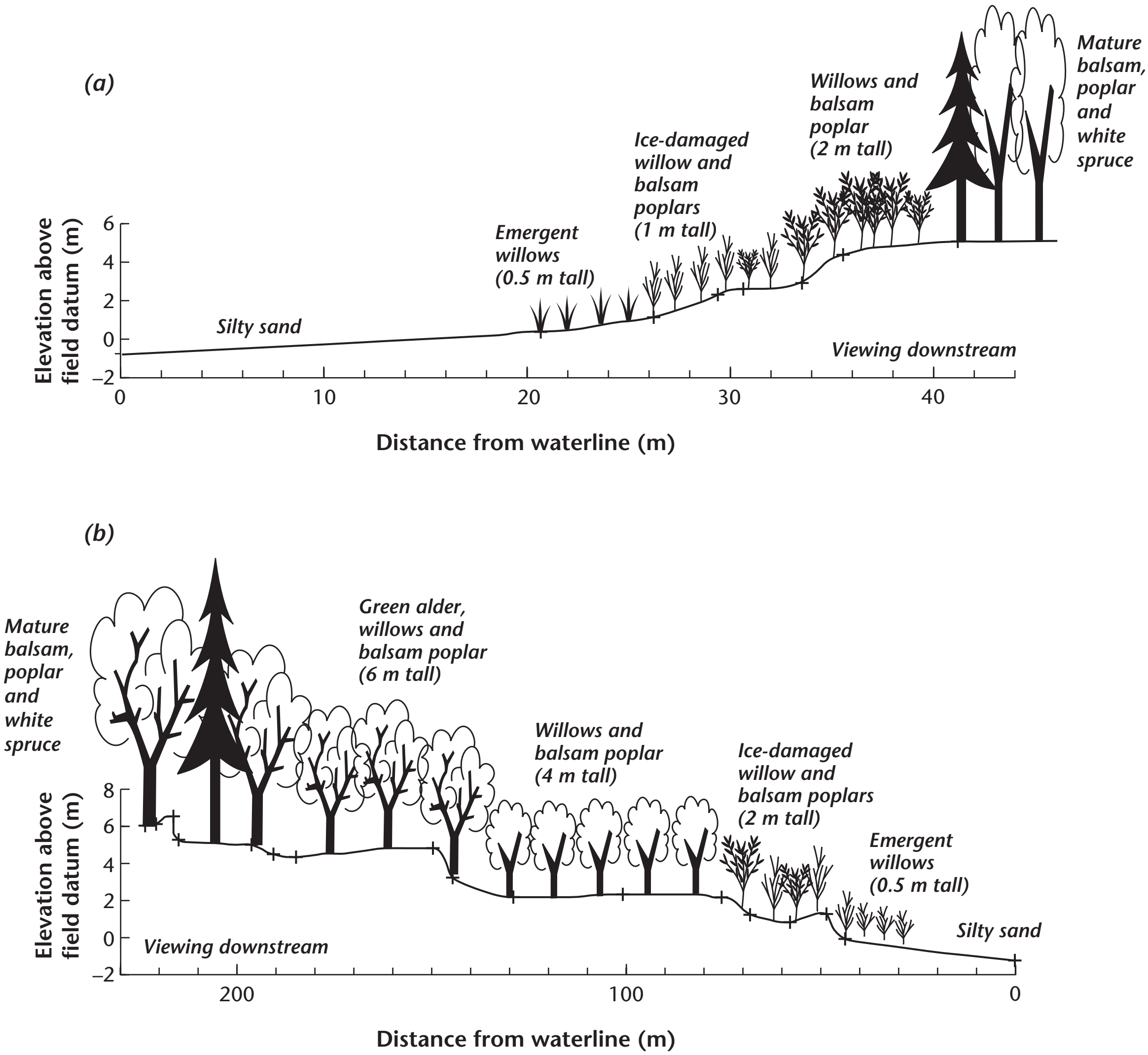

Figure 9.5 Riparian forest spatial sequence at two sites along Peace River: (a) right bank immediately upstream from the Smoky River confluence (km 368); (b) left bank at km 671, downstream from Carcajou. The sequence reflects substrate age, elevation, and frequency of inundation and ice disturbance.

early and late succession communities. In this way, the riparian zone becomes a palimpsest of communities, not all reflecting any normal successional sequence.

More distinctively along this northern river, ice may significantly affect the condition of riparian vegetation (Chapter 6). Most notably, ice may persistently break stems in early successional shrub communities, which occur at relatively low elevations (Figure 9.6). Plants are usually broken some tens of centimeters above the bole and they are capable of resprouting. This leads to an exceedingly dense and tangled shrub zone along the river margin. Because ice jams tend to occur repeatedly at some sites, repeated damage and resprouting may lead to a persistent tangle of willow, alder or osier dogwood shrub communities.

This model of vegetation succession provides a reference against which the actual history of Peace River riparian vegetation over a period of 50 years may be compared. We seek to understand to what extent the processes of "normal" succession dominate riparian

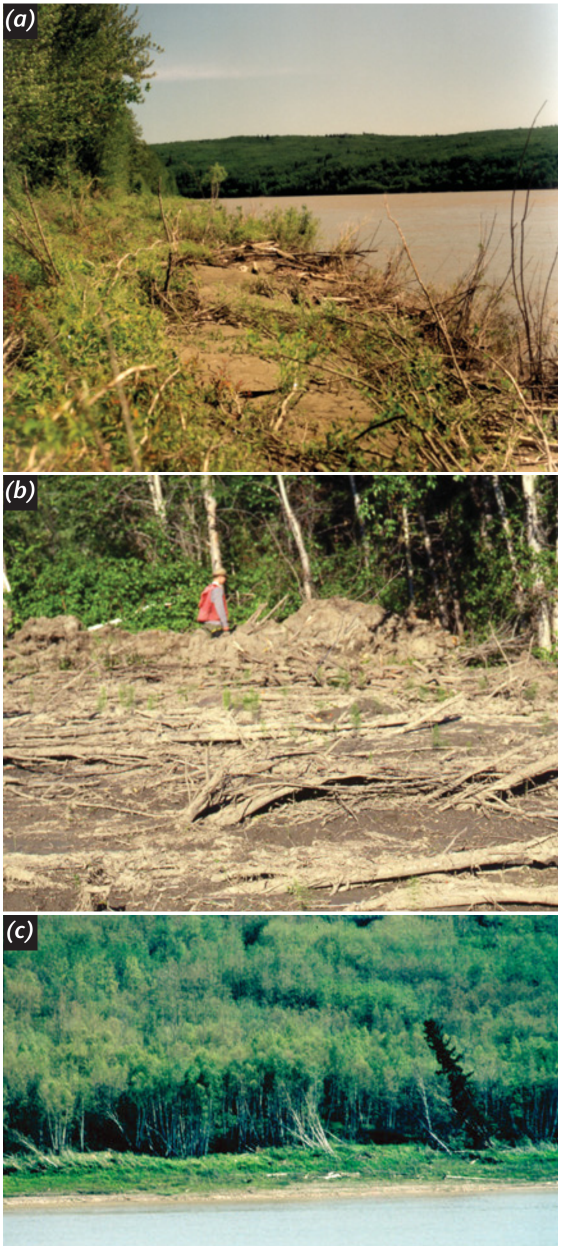

Figure 9.6 Ice damage along Peace River: (a) Ice-damaged willow showing stripped stems: located on the left bank on the upstream side of a bend where ice moves onshore, Carcajou, July 1993; (b) Severe ice damage and ice-pushed river sediments behind: mouth of Notikewin River, June 1996; (c) ice-shove damage in mature cottonwood-spruce forest with ice-mown shrubs in front: Alberta Reach 2, July 1993.

communities, and to what extent erosion and sedimentation processes of the river disturb the succession. We are also interested in whether there is evidence for a change in the balance between "normal" succession and riverine disturbance that may have occurred after regulation of the river.

We will principally use two tools to investigate these questions. Using our sequence of vegetation maps, we can determine the frequency with which one community or successional stage replaces another (testing the temporal aspect of the model), and we can determine the frequency with which communities or stages are spatially adjacent to each other (testing the spatial aspect). The methods are introduced by North and Church (Chapter 8) and are reviewed briefly below in concert with the results. The model predicts expected patterns with which the observations may be compared.

We will also be interested in the extent to which replacement and adjacency vary along the river, either systematically with distance downstream, or more specifically in response to the changing overall morphological character of the river. For this purpose, we will introduce comparisons with the British Columbia reach analyzed by North and Church (Chapter 8), the reach most strongly impacted by the flow regulation.

9.5 Analysis

For purposes of analysis, each reach is divided into a number of sub-reaches, varying from 9 to 43 km in individual length, but most between 15 and 25 km. Reach boundaries are significant tributaries or places where the valley and/or river morphology notably change. Hence, hydrology and morphological character of the river are reasonably consistent within each reach. The sub-reaches are the same as those defined in Chapter 7. Analyses in this chapter are presented at the level of the major reaches with the sub-reaches serving to derive measures of local variance.

9.5.1 Total and proportional area

We first consider the absolute and proportional distribution of vegetation communities in each of the major reaches (Figure 9.7). We restrict our attention to the terrestrial shrub and forest communities since herbaceous cover may still be subject to frequent inundation (marking the area as part of the still-active channel) and is,

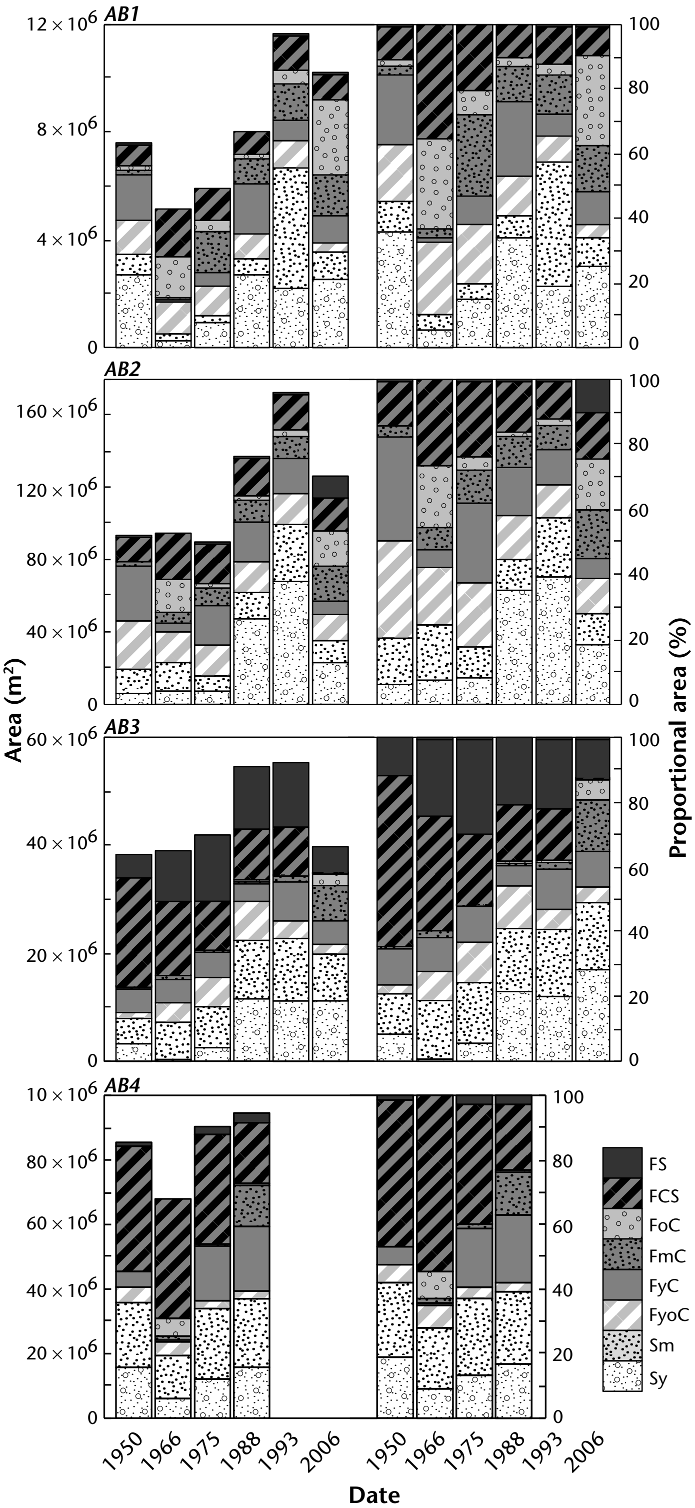

Figure 9.7 Absolute and proportional area occupied by terrestrial riparian vegetation communities at each date of mapping, by major reaches. Key as in Figure 8.9 (chapter 8).

in any case, possibly only partly identified in the case of somewhat elevated flows. Vegetated island areas are included in the assessments. Agricultural land is not considered except in Reach 3 since its extent is very limited in the riparian zone in Alberta, comprising 0.3% in Reach 2 and 0.9% in Reach 3 at the date of its maximum proportion. Reaches 1 and 4 have no agricultural development in the riparian zone. There is some forestry activity in the riparian zone of Reach 3 which has had some influence on the vegetation.

The area of riparian vegetation has expanded in all four reaches following regulation, consistent with the decrease in active channel area. The expansion was proportionally most dramatic in Reach 1, being 2.25 times between 1966 and 1993. However, there was an exceptional decline in this reach between 1953 and 1966 to 0.65 times the initial area. In the succeeding reaches, the expansion was 1.86 times, 1.44 times, and 1.38 times. These results were achieved between 1966 and 1993 (except in Reach 4 where the figure refers to 1988, the last available complete mapping). The major step change occurred after 1983 in Reach 1, after 1975 in Reaches 2 and 3, and after 1966 in Reach 4, with expansions of 1.3 times to 1.5 times. In all cases the major step is associated with a substantial increase in shrub communities—signifying the colonization of former bar surfaces. These results are roughly consistent, as to both the size of the change and the timing of it, with diminishing total change downstream and a progressively earlier main adjustment. This outcome is most likely related to the decreasing severity of the hydrological adjustment from Reach 1 to Reach 4, though ice activity may also be implicated. All changes in the Alberta Peace River are proportionally larger than in the British Columbia reach (1.26 times expansion, 1966 to 1986). This contrast is influenced by the wandering-braided morphological character of the British Columbia reach and relatively extensive riparian zone there, in contrast with the dominantly single-thread, or single-thread with non-overlapping islands, morphology and partial to strong confinement of the Alberta reaches. In contrast to this trend of vegetation expansion, Reaches 1 to 3 all lost riparian area after 1993, probably in consequence of the 1996 drawdown flood, but severe ice conditions in 1997 may also have been important.

The total area of the riparian zone increases from reach to reach downstream. Alberta Reach 1 (e.g., Figure 9.8a) has the smallest riparian zone, less than 12 km^2 at its maximum extent (1993). This follows from the strongly confined nature of the reach and is the reason why modest actual change in area (6.4 km^2) seems so relatively large. The change that occurred is strongly associated with the post-regulation diminution of ice-jam activity in this reach. Reach 2, below the Smoky confluence (e.g., Figure 9.8b), is partially confined and strongly impacted by ice-jam activity (Chapter 6). Here, the absolute increase in vegetated area following regulation nevertheless was 7.8 km^2 to 1993, in an area of 17.2 km^2, much of it associated with the siltation of secondary channels behind islands. Reach 3 (e.g., Figure 9.8c), where the river loses confinement except in limited sub-reaches, has a much larger riparian area, 55 km^2 at its maximum extension (1993) and the absolute extension was 16.3 km^2 to 1993. Finally, Reach 4 (e.g., Figure 9.8d), with 94 km^2 of riparian area, added 26.2 km^2 to 1986, but that followed a significant apparent reduction in area between 1953 and 1966; over the entire record the riparian area has remained relatively unchanged. The downstream trend of absolute changes in riparian area following regulation, then, reverses the trend of relative changes, emphasizing the significance of overall morphological style—hence absolute available area in the riparian zone—in coloring the comparison.

After 1993, Reach 1 lost 12% of its 1993 riparian area, while Reaches 2 and 3 lost 26% and 28%, respectively. The obvious difference between these reaches is the incidence of ice jamming. In comparison, one would expect the effects of the 1996 flood to have diminished downstream. However, there is no compelling evidence for a recent intensification of ice-jam activity in the lower river, though a notable event was recorded in 1997 (Chapter 6).

Proportional areas of the various vegetation communities are less securely known than total vegetated area, discussed above, because they depend upon the fidelity of air photo interpretation (see Chapter 8 for discussion of this point). In Reach AB1, the steadily expanding proportion of shrub stages (Sy, Sm: see Table 9.1 for definitions) after regulation, to 1993, and the apparent setback afterward, are consistent with the hydrological history. Proportionally, the shrub effect influences the appearance that some other classes have declined: absolute areas suggest that this was much less significant than appears in the proportional numbers. The major changes that did occur include the steady decline of young, open cottonwood stands (FyoC) and the dramatic expansion

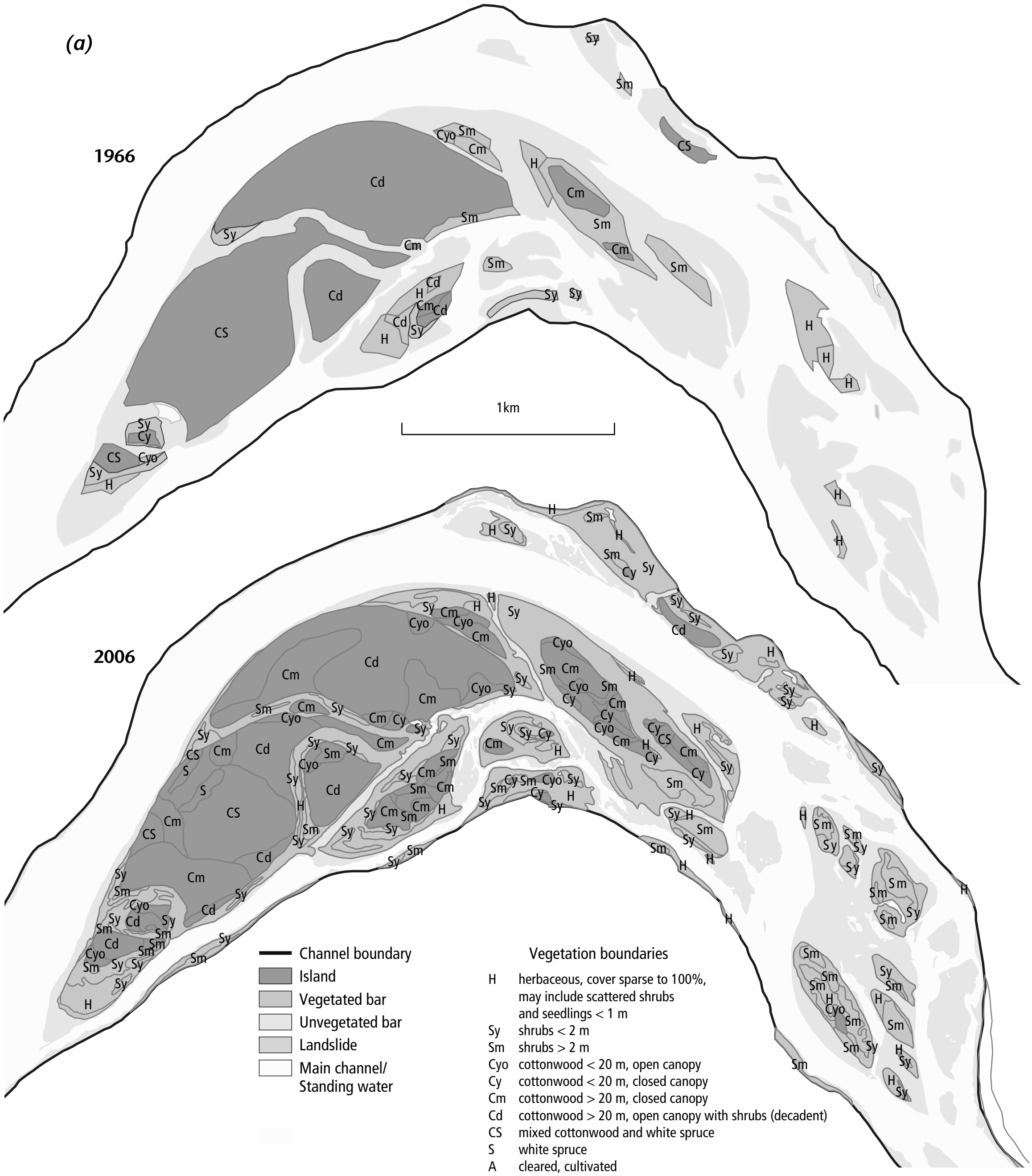

Figure 9.8 Representative mappings of riparian vegetation in the Alberta reaches immediately before regulation compared with the most recent mapping. Some apparent variations in areas already vegetated before regulation are due to the greater detail of the 2006 mapping. Sites are located in Figure 9.1. (a) Many Islands in Reach AB1; (b) immediately downstream from TPR, Reach AB2; (c) near Moose Island, Reach AB3; (d) near Fifth Meridian, Reach AB4A. These are the same reaches as are illustrated for morphological changes in Figures 7.5 to 7.8. (*Continued*)

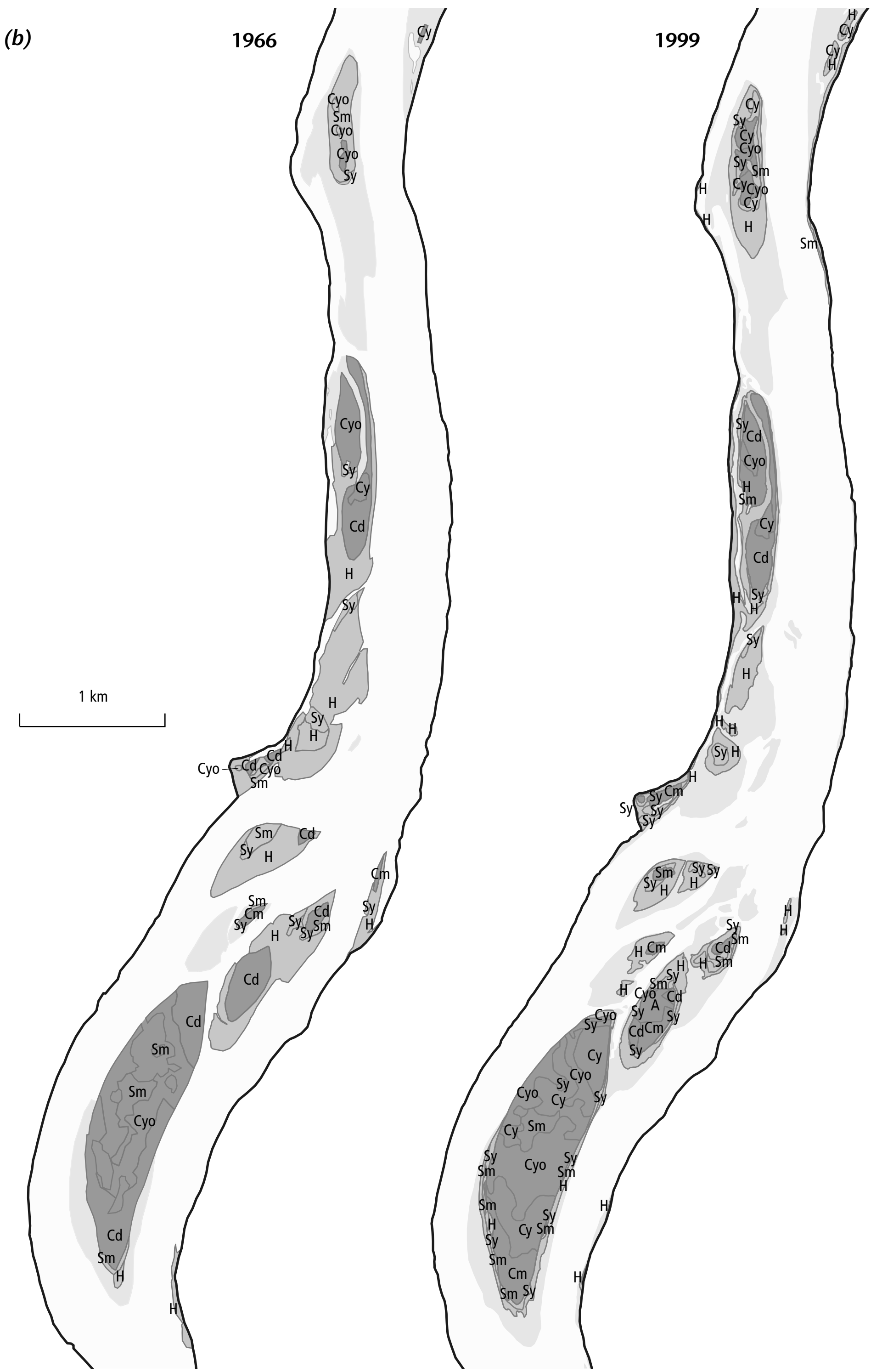

Figure 9.8 (*Continued*)

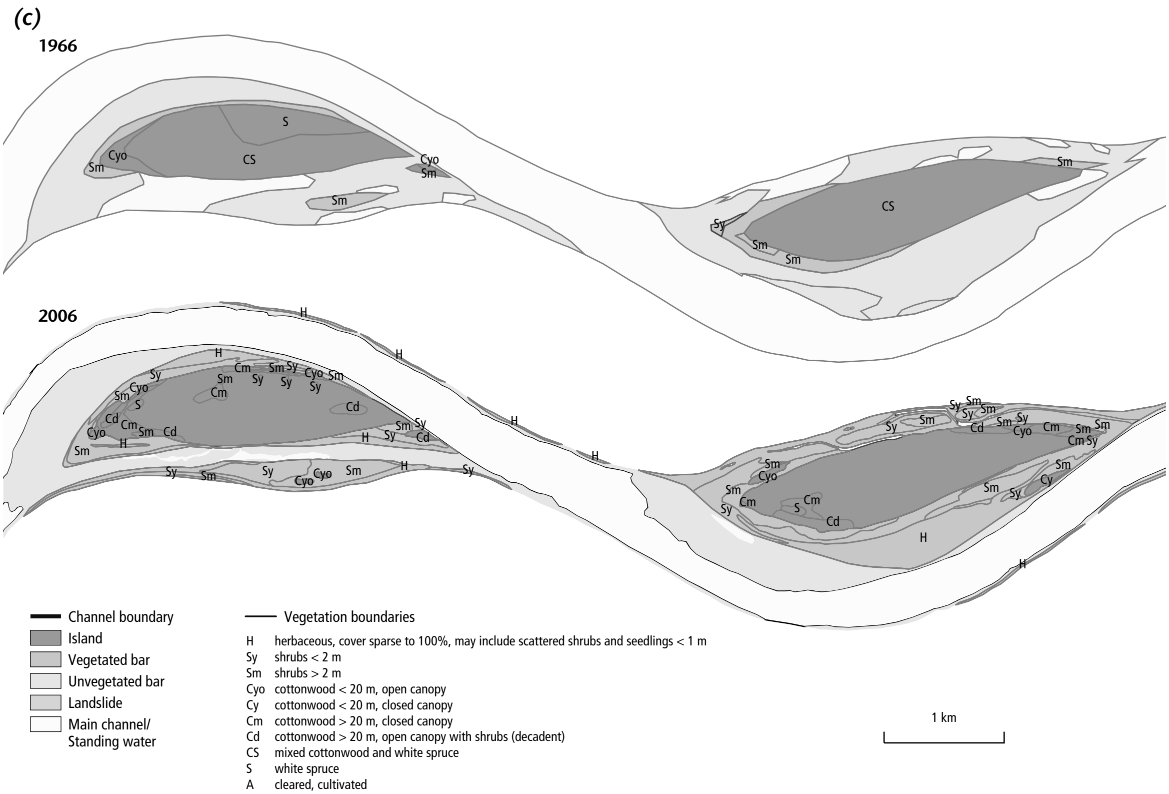

Figure 9.8 (*Continued*)

of decadent cottonwood (FoC) after 1993. The former is matched by staged expansions in FyC and FmC. In contrast, it is probable that the apparently high incidence of FoC in 1966 is an artifact of photo interpretation. The pattern of proportions in Reach AB2 is similar to that in Reach 1, with increasing prominence of FmC and FoC later in the record and the appearance of FS, all indicating the development of a mature terrestrial forest on riparian areas that formerly were frequently disturbed by flooding.

Reach AB3 records a consistently increasing proportion of shrub stages to 2006, though a modest absolute setback after 1993, and a shift in the proportions of FyoC and FyC (young cottonwood) toward FmC and FoC (mature and decadent cottonwood) as in the upstream reaches. The second outstanding feature of the record, however, is the decline in relative and absolute prominence of FCS and FS, most especially after 1993—this is the legacy of forest harvesting and is in part responsible for the continuing prominence of shrub stages. Reach AB4 shows the smallest proportional changes of any reach, as one would expect from its extreme distal position and isolated northern location. The prominence of shrub communities and the slow succession from extensive FCS toward FS forest are the major features.

9.5.2 Transitions

We may examine community transitions in two ways. One way examines the relative change in area in each community from survey to survey; a complementary analysis is to examine the relative proportion of each community that is transformed into a different community at the next survey. We may, in a more strict sense, label the first perspective "persistence analysis" and the second perspective "transition analysis."

To study persistence, we obtained transition fractions as the quotients

$$t_{ij} = X_{i,j+1}/X_{i,j}$$

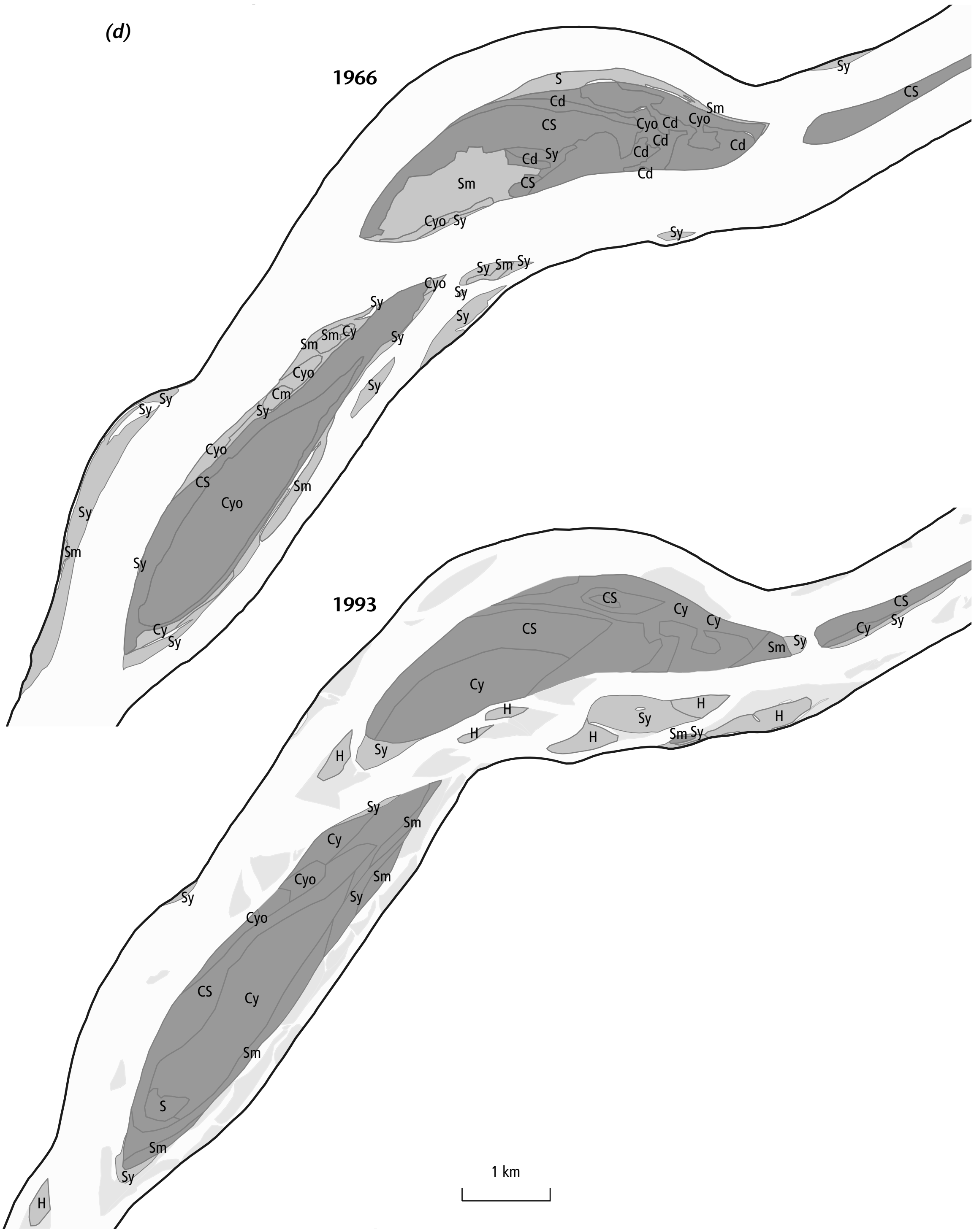

Figure 9.8 (*Continued*)

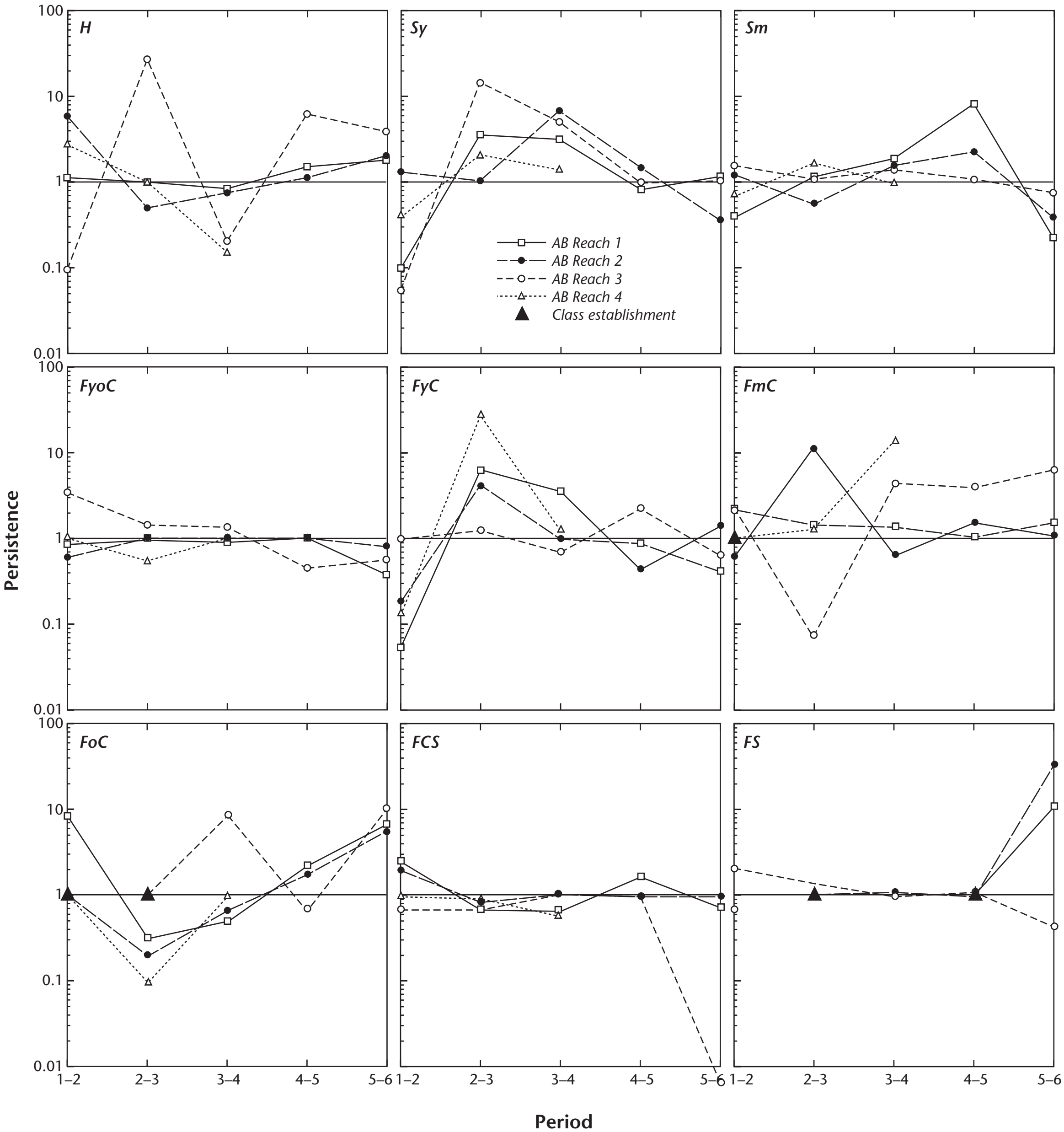

Figure 9.9 Persistence ratios for riparian communities in the Alberta reach of Peace River. The abscissa indicates periods between successive surveys, not absolute dates (for which, see figure 9.7).

wherein X_{ij} is the area of the *i*th community in the *j*th period and t_{ij} are the transition ratios, which might alternately be interpreted as indices of community persistence. $t_{ij} > 1$ indicates an increase in the type from one period to the next, while $t_{ij} < 1$ indicates a decrease. Results are plotted for each community for each of the Alberta study reaches in Figure 9.9.

The pioneer communities H (herbaceous communities) and Sy (young shrubs <2 m tall) exhibit substantial instability from one period to the next. The pattern of temporal variation in Reach AB1 is similar to that in the British Columbia reach upstream except that the dramatic apparent decline associated with the 1996 flood mapping in the British Columbia reach is not recorded (because the dates of mapping are different). Farther downstream, there is a significant decline in H in Reach AB2 during the period of unregulated flow but a more stable pattern otherwise. Young shrub communities increased dramatically after regulation, in the early period in Reaches AB1 and AB3, but after some delay in Reach AB2, in keeping with the trend of total vegetated riparian area in that reach. Mature shrubs (Sm) have been, in comparison, much more stable, apart from a significant transient increase in Reaches AB1 and AB2 after some 20 years of flow regulation.

Cottonwood forest communities are generally more stable, particularly the incidence of pioneer cottonwood (FyoC), though the ground area occupied by this type has changed significantly over time and there is a persistent slow decline, most notably in Reach AB3. FyC showed a notable increase in occurrence immediately after flow regulation in all reaches except Reach AB3, where mature forest (FmC) also declined dramatically after regulation. This change may be the consequence of forest harvest and agricultural clearance, which occurred in that period. Overmature or decadent stands are more restricted in area and first appeared in three of the four reaches within the period of study. Their identification from air photos is a somewhat difficult matter of judgment, hence the irregular temporal pattern of this category cannot be too confidently interpreted. Spruce forests are the endpoint of riparian succession along most of Peace River, provided seed is available. However, the area of spruce forest along the river is very restricted except in Reach AB3. The occurrence of mixed cottonwood and spruce has been stable except in the most recent period in Reach 3—again a consequence of forest harvest—while pure spruce stands are very limited in extent.

The transition analysis is displayed reach by reach in Figure 9.10 and the data for the combined reaches are given in Table 9.2, which show the fraction of each community that formed from a different community in each period of analysis. The figure emphasizes the clustering of significant values about the diagonal of the matrix (fraction not changed), which arises from persistence or from orderly succession. There are, however, some notable outliers, largely entailing regression to pioneer communities as the consequence of river erosion or ice activity. In Table 9.2, cells above the diagonal (fraction not changed) represent this regression to an earlier successional stage, possibly with subsequent restarting of succession, but conceivably also due to fire (about which we have no information). Values below the diagonal indicate succession. Significant values should cluster about the diagonal, except that regression may occur right back to bare ground (or river area). Values down to 0.01 (1% of area in the transition) are highlighted. Agriculture is omitted from the table as it occupies much less than 1% of the total area. Small values may arise from the error in mapping communities from one survey to another: the small number of unlikely values (i.e., elevated values well below the diagonal, implying passage of several stages in succession) are probably the consequence of interpretive errors.

Further insight into these data is gained by comparing one period with another by conducting a cell-by-cell correlation of transition ratios, as displayed in Figure 9.11. As one expects of almost any ecological correlation, there is a discernable positive trend in the data, implying consistency in patterns of vegetation development from period to period, but substantial variation. Points falling above the line of concordance indicate accelerating rates of change in the successor period, while points falling below indicate declining rates. There is roughly a 10-fold range in the data, but the most extreme changes occur in the direction of acceleration, implying that the later period is experiencing an increased rate of community transitions. It appears that, in the preponderance of vegetation communities along the river, flow regulation has set in train a still-accelerating rate of change in riparian vegetation.

9.5.3 Adjacency

While transition relations represent one sort of test of the succession model proposed for boreal riparian ecosystems, a stronger test is represented by adjacency—that is, which communities are immediate neighbors of which—since those spatial relations constitute the essence of the model. Constrained adjacencies are shown in Figure 9.12 for each of the Alberta study reaches at the inception of regulation (1966), and again for the most recent available photography (mainly 2006). ("Constrained" means that when a unit of one vegetation type abuts two or more units of another type,

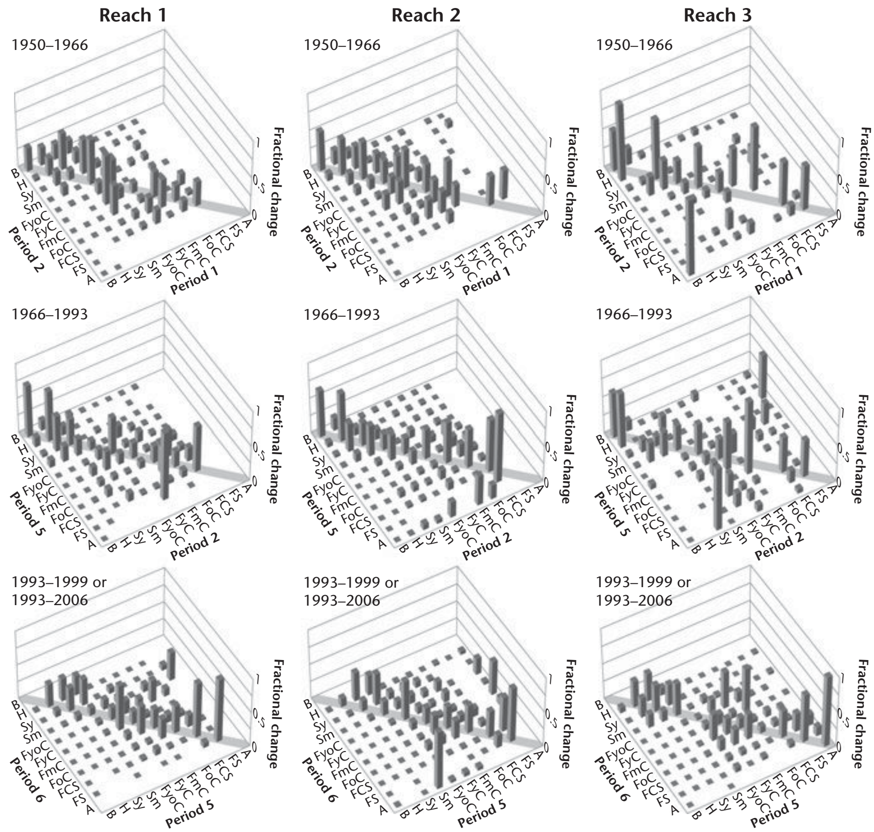

Figure 9.10 Comparison of vegetation transition fractions for the Alberta Peace River. In each column the first graph compares the period before flow regulation with the first 26 years of normal regulated flows; the second graph compares the period of normal flow regulation with the recent period encompassing major flooding: period five is "normal"; the third graph compares the flood period with subsequent development, to the latest mapping.

the adjacency is counted only once.) Two features stand out in all periods: there is a strong propensity for units to lie adjacent to the pioneer communities H, Sy, and Sm (herbaceous and shrub communities), and there is a notable concentration of adjacencies amongst these pioneer communities. In many places these appearances are the consequence of the restricted nature of the riparian zone, such that one later successional community lies behind shore-zone pioneer communities. The intimate intermingling of the pioneer communities themselves is also a consequence of recent colonization of bar surfaces characteristically exposed only since regulation.

There is otherwise little evidence of a systematic pattern of succession: adjacencies do not in general reveal a pattern of adjacency in successional sequence. One outstanding feature in Reach AB3 is the high frequency of mature forests (FCS and FS) adjacent to shrub communities prior to regulation (Figure 9.12). This reach exhibits the strongest meandering tendency, hence the lateral instability might bring the shore zone frequently into contact with old forest along recently eroded banks. But after regulation, this feature largely disappears. There is evidence (Figure 9.12) that this may in part be a consequence of stabilization of the river such that some of the former Sy and Sm units have advanced into early cottonwood stages. However, harvesting of the spruce forests, which occurred in the intervening years, no doubt eliminated some adjacencies.

Table 9.2 Transition fractions between vegetation types for the combined Alberta reaches

	(a) Period of natural flows (1953 to 1966)										
	1966	1950 B	H	Sy	Sm	FyoC	FyC	FmC	FoC	FCS	FS
	B	0.9678	0.8418	0.3908	0.2095	0.0352	0.0251	0.0509	0.0358	0.0087	0.0107
>0.3	H	0.0094	0.0693	0.0533	0.0442	0.0132	0.0092	0.0028	0.0062	0.0000	0.0000
>0.1	Sy	0.0078	0.0624	0.0884	0.1937	0.0410	0.0235	0.0085	0.0049	0.0127	0.0090
>0.03	Sm	0.0070	0.0117	0.4114	0.4139	0.1358	0.1984	0.1516	0.1829	0.0273	0.0141
>0.01	FyoC	0.0008	0.0036	0.0099	0.0378	0.3054	0.0525	0.0395	0.2424	0.0117	0.0091
	FyC	0.0017	0.0049	0.0168	0.0142	0.0543	0.4807	0.6533	0.4088	0.0509	0.0970
	FmC	0.0002	0.0006	0.0003	0.0013	0.0000	0.0640	0.0435	0.0539	0.0003	0.0000
	FoC	0.0000	0.0000	0.0006	0.0003	0.0021	0.0001	0.0217	0.0173	0.0013	0.0003
	FCS	0.0049	0.0054	0.0287	0.0849	0.4099	0.1168	0.0282	0.0478	0.8795	0.4377
	FS	0.0005	0.0003	0.0000	0.0002	0.0029	0.0297	0.0000	0.0000	0.0076	0.4223
	(b) Early period of regulated flows										
	1993	1966 B	H	Sy	Sm	FyoC	FyC	FmC	FoC	FCS	FS
	B	0.9830	0.7282	0.7274	0.6712	0.0154	0.6115	0.0214	0.0201	0.0142	0.0119
	H	0.0112	0.2554	0.2006	0.0735	0.0065	0.0029	0.0150	0.0378	0.0018	0.0001
	Sy	0.0001	0.0035	0.0160	0.0202	0.0106	0.0035	0.0115	0.0275	0.0021	0.0000
	Sm	0.0020	0.0066	0.0245	0.2075	0.1439	0.0459	0.0635	0.0370	0.0156	0.0113
	FyoC	0.0004	0.0003	0.0036	0.0049	0.3090	0.0642	0.0858	0.0378	0.1000	0.0849
	FyC	0.0008	0.0010	0.0005	0.0077	0.0177	0.0934	0.1655	0.0225	0.0287	0.0534
	FmC	0.0006	0.0006	0.0010	0.0013	0.0149	0.0173	0.1317	0.2435	0.0058	0.0009
	FoC	0.0003	0.0025	0.0036	0.0054	0.0699	0.0190	0.3543	0.3692	0.0146	0.0001
	FCS	0.0010	0.0002	0.0056	0.0058	0.2021	0.1126	0.1472	0.2038	0.7832	0.2758
	FS	0.0005	0.0016	0.0011	0.0025	0.2096	0.0296	0.0042	0.0008	0.0339	0.5616
	(c) Period encompassing major flooding (1996)										
	2006	1993 B[a]	H	Sy	Sm	FyoC	FyC	FmC	FoC	FCS	FS
	B		0.3608	0.1155	0.0619	0.0118	0.0114	0.0063	0.0129	0.0071	0.0066
	H		0.1258	0.0795	0.0615	0.0042	0.0018	0.0029	0.0036	0.0012	0.0013
	Sy		0.3316	0.3750	0.1777	0.0246	0.0204	0.0088	0.0105	0.0056	0.0022
	Sm		0.1656	0.3908	0.5672	0.1134	0.1000	0.0472	0.0581	0.0156	0.0074
	FyoC		0.0032	0.0115	0.0280	0.2914	0.2638	0.2068	0.1171	0.0311	0.0234
	FyC		0.0056	0.0190	0.0722	0.2916	0.4220	0.3384	0.2447	0.0585	0.0048
	FmC		0.0016	0.0041	0.0108	0.1236	0.0565	0.1200	0.2317	0.0102	0.0054
	FoC		0.0003	0.0006	0.0058	0.0315	0.0471	0.0129	0.0845	0.0014	0.0003
	FCS		0.0040	0.0012	0.0057	0.0679	0.0588	0.1537	0.1806	0.5096	0.0969
	FS		0.0014	0.0028	0.0082	0.0396	0.0098	0.1022	0.0562	0.3581	0.8507

[a]No data for 2006 mapping.

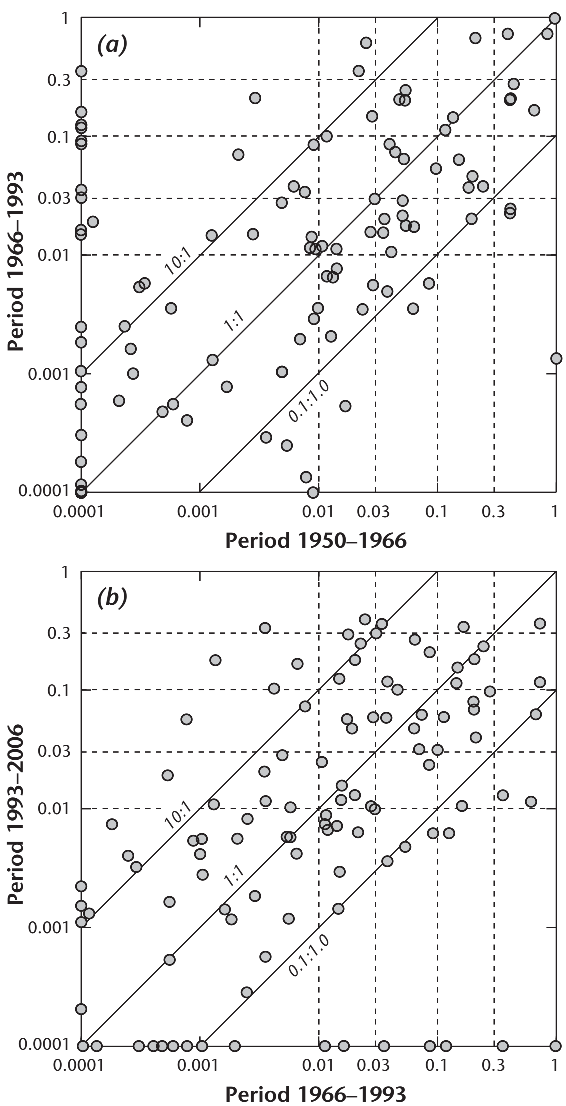

Figure 9.11 Correlation of transition ratios from period to period. Null transitions (those indicating no change in the community) have been suppressed. Points above the 1:1 line indicate accelerating rates of transition; points below indicate decelerating change.

In summary, the data reveal a more palimpsestic (or random) pattern everywhere along the river than do the persistence or transition analyses, both in pre-regulation and post-regulation periods. Most communities show dominant adjacency to later stages in the riparian succession, but not necessarily to the immediately succeeding stage, to the immediately preceding stage, or to the pioneer herbaceous and shrub stages. In the adjacency of non-successive stages, the imprint of river disturbance remains prominent.

9.5.4 Evenness

The modified Simpson's Index of relative evenness in the distribution of individual communities (Pielou 1977) is a measure of relative dominance by one vegetation community or another. It is given by:

$$E = \ln \sum p_i^2 / \ln \sum (1/n)^2 : 0 < E \leq 1.0$$

wherein p_i is the fraction of the total area occupied by the ith community, both sums running over n communities. The denominator is the sum when the area is evenly distributed amongst all n communities. As $E \rightarrow 0$, a single community becomes increasingly dominant while for $E = 1.0$, all communities are evenly represented. Figure 9.13 shows evenness for the four Alberta reaches. The range of values is similar to that observed within the British Columbia sub-reaches. The reach (AB4) in which we expect the greatest stability of terrestrial riparian vegetation was, before regulation, least even, as was the most stable British Columbia sub-reach (BC1). However, the entire group of Alberta reaches exhibits a post-regulation drift toward greater evenness, converging toward values around 0.8, an evolution that is not observed in British Columbia. This signifies development toward similar representation of all the mapped communities, presumably the consequence of the increased prominence of the pioneer communities and early cottonwood stages after regulation (Figure 9.7). This development, in turn, is the result of vegetation prograding onto abandoned bar tops and channel margins.

9.6 Discussion

The Alberta Peace River is morphologically quite unlike the British Columbia reach. More or less strongly confined through most of Reaches AB1 to AB3, it is dominantly a single-thread river with mainly non-overlapping islands in channel bends. Only the short reaches at Many Islands and Montagneuse River in Reach AB1 duplicate multi-island morphology seen in parts of the British Columbia reach. Nonetheless, riparian forest dynamics in the two regions are quite similar, with a significant pattern of normal forest succession occurring on individual sites, to judge by transition

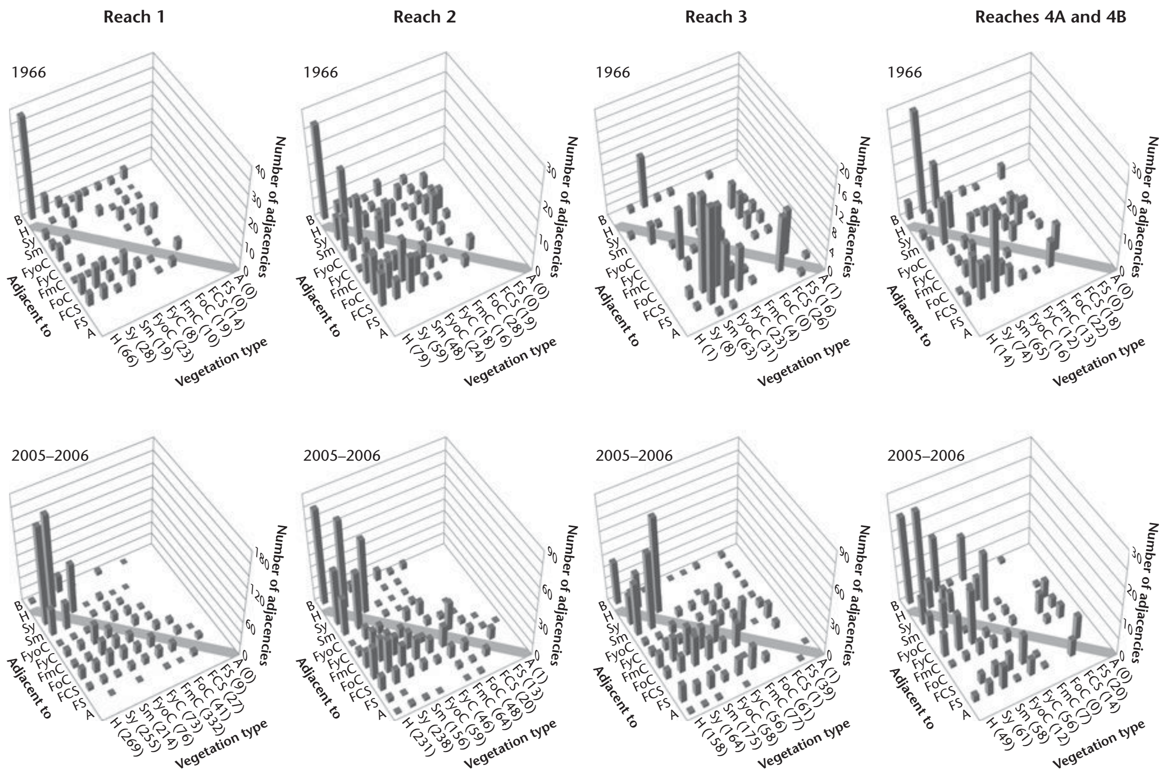

Figure 9.12 Constrained adjacencies in the Alberta study reaches: first histogram for each reach shows adjacencies in 1966, immediately prior to regulation while the second histogram shows adjacencies observed in 2006 (1999 for Alberta Reach 2, for which more recent photography is not available): numbers are higher because of the more detailed mapping.

and persistence statistics. The pattern is confirmed by transects conducted from the river bank into the forest (e.g., Figure 9.5 and views in Figure 9.2) but we lack the additional confirmation that could be provided by longitudinal field study, as in British Columbia. On the other hand, the spatial pattern of communities in both field areas is substantially palimpsestic (Figure 9.12) and evenness is high (Figure 9.13), both evidences of succession interrupted by river erosion, the subsequent effects of which are juxtaposition of early and late successional stages and substantial presence of all, or nearly all stages. The succession model of North and Church (Chapter 8) has temporal validity, then, but its spatial expression is quite strongly disturbed. In British Columbia, this result can be ascribed to lateral erosion and sedimentation by the river, a process strongly curtailed since regulation, the effect of which has not yet disappeared because of the long time scale for riparian succession. There are, as well, minor continuing ice effects in the British Columbia reach and dominant winter high water. In Alberta, lateral activity by the river has always been more limited, though long-term meander loop extension is evident in Reaches AB3 and AB4. However, ice effects were and remain more severe. Such effects constrain succession on newly exposed ground on bar tops

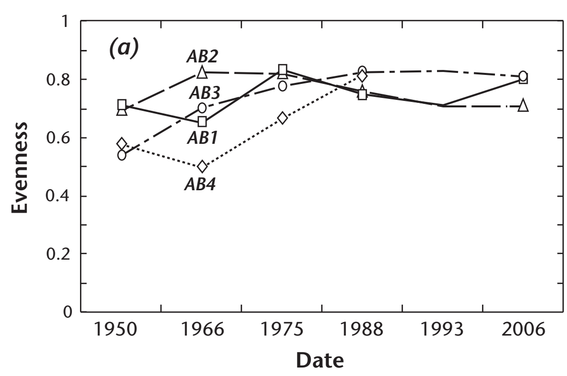

Figure 9.13 Evolution of the index of evenness in the Alberta reaches.

and along the river edge and perpetuate the juxtaposition of early and late successional stages. Altogether, the data of the Alberta reach confirm that riparian vegetation along Peace River is composed of a mosaic of plant communities whose existence and spatial arrangement can be explained in terms of the normal succession on variably textured surfaces subject to varying frequencies and intensities of fluvial disturbance.

Effects of river ice, known to be most severe in Reach AB2 (Chapter 6) are evident in the high proportion of shrub communities in this reach (Figure 9.7) and in the strong reduction of these communities between 1993 and 2006, when a notable ice run was experienced as well as a major flood. The vegetation signature is similar in Reach AB3, where ice effects may still be relatively severe, but neither reach shows a qualitatively different pattern of response than the remaining two.

In all four reaches there has been a strong progression of vegetation into the former river channel, proportionally (but not absolutely, because of limited area) greatest in Reach AB1 and least in Reach AB4. In comparison, changes immediately before regulation saw a reduction in riparian cover in Reaches AB1 and AB4, and approximate stasis in the intermediate two reaches. These two reaches fall consistently into the spatial order of post-regulation change, with riparian expansion intermediate within the range established by the end reaches. Similarly, the strength of the summer freshet increases downstream, though the major change occurs at the Smoky River, near the beginning of Reach AB2. The pattern of riparian vegetation expansion is, then, consistent with the degree of flow regulation that has occurred: greatest in AB1 and least in AB4, and is perhaps the strongest evidence for the dominating effect of the flow regulation in the development of the riparian forest along the full downstream length of Peace River over the first 40 years.

9.7 Conclusions

The evolution of riparian vegetation in the Alberta Peace River has been studied on the basis of vegetation mappings repeated at six intervals over a 56-year period between 1950 and 2006. Air photo scales varied between 1:20 000 and 1:60 000. Generalized communities considered to be major components of a normative model of riparian succession for northern Alberta were mapped. There undoubtedly are errors remaining in the mapping, but the very large number of vegetation units identified in each mapping holds the prospect that the summary statistics are secure. It is for this reason that the results have been presented by major reach, each the order of 150 km in length, rather than according to the order 20-km sub-reaches that were identified morphologically.

The inferred history throughout the period of study, including the first 40 years of regulated flows, is qualitatively consistent with that found with more detailed study in British Columbia: temporal succession proceeds in accordance with the normative model on stable sites but there is prominent spatial juxtaposition of non-serial communities where river activity erodes the substrate or, through ice action, destroys vegetation. Since regulation, river erosion has become much less pervasive—though by no means absent in the lower river—but ice action has persisted. On much of the surface that has become characteristically exposed since regulation, vegetative succession is held in the early stages represented by herbaceous and young shrub communities by repeated ice events. Nor have higher levels escaped effect since ice may exceptionally become piled meters above the ambient water level.

Total area of riparian vegetation has nonetheless expanded, mainly through the expansion of shrub communities on abandoned bar tops and in the shore zone. Only as a new floodplain is constructed on these surfaces will succession proceed beyond this stage: in the regulated regime of the river, that process will occupy many decades or even centuries.

Acknowledgments

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References

Amlin, N. A. and Rood, S. B. (2001) Inundation tolerances of riparian willows and cottonwoods. *Journal of the American Water Resources Association*, 37, 1709–1720.

Johnson, W. C. (1992) Dams and riparian forests: case study from the upper Missouri River. *Rivers*, 3, 229–242.

Johnson, W. C. (2000) Tree recruitment and survival in rivers: influence of hydrological processes. *Hyrological Processes*, 14, 3051–3074.

Johnson, W. C., Burgess, R. L., and Keammerer, W. R. (1976) Forest overstory vegetation and environment on the Missouri River floodplain of North Dakota. *Ecological Monographs*, 46, 58–84.

Marston, R. A., Mills, J. D., Wrazien, D. R., Bassett, B., and Splinter, D. K. (2005) Effects of Jackson Lake Dam on the Snake River and its floodplain, Grand Teton National Park, Wyoming, USA. *Geomorphology*, 71, 79–98.

Merritt, D. M. and Cooper, D. J. (2000) Riparian vegetation and channel change in response to river regulation: a comparative study of regulated and unregulated streams in the Green River basin, USA. *Regulated Rivers: Research and Management*, 16, 543–564.

North, M. E. A. (1965) Vegetation of Alberta. Map sheet. Government of Alberta and the University of Alberta.

Pielou, E. C. (1977) *Mathematical Ecology*. John Wiley & Sons, Inc., New York.

Polzin, M. L. and Rood, S. B. (2000) Effects of damming and flow stabilization on riparian processes and black cottonwoods along the Kootenay River. *Rivers*, 7, 221–232.

Rood, S. B. and Mahoney, J. M. (1990) Collapse of riparian forests downstream from dams in Western Prairies: probable causes and prospects for mitigation. *Environmental Management*, 14, 451–464.

Rood, S. B., Taboulchanas, K., Bradley, C. E., and Kalischuk, A. R. (1999) Influence of flow regulation on channel dynamics and riparian cottonwood recruitment along the Bow River, Alberta, Canada. *Rivers*, 7, 33–48.

Shaw, J. and Kellerhals, R. (1982) The composition of recent alluvial gravels in Alberta river beds. *Geological Survey, Bulletin*, 41, 151 p. Alberta Research Council, Edmonton, Canada.

Walstra, J., Chandler, J. H., Dixon, N., and Wackrow, R. (2011) Evaluation of controls affecting the quality of spatial data derived from historical aerial photogaphs. *Earth Surface Processes and Landforms*, 36, 853–863.

CHAPTER 10

The floods of 1990 and 1996 on Peace River

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10.1 Introduction

Following the 1967 regulation of Peace River at W.A.C. Bennett dam, the river was subjected to 28 years and 6 months of regulated flows, interrupted only by a brief spillway test in 1972. Before regulation, mean flow in the river below the dam site was 1198 m^3s^{-1} and the mean annual flood (MAF) was 5843 m^3s^{-1} (Table 10.1); since regulation, the MAF has declined to only 1900 m^3s^{-1} (1968 to 1995) and the maximum flows released in the course of normal dam operations is approximately 2000 m^3s^{-1}. Post-regulation MAF is 33% of the unregulated value. Below Pine River, the first major tributary, the flood ration is 39% (Taylor gauge, WSC Stn. 07FD002, 102 km downstream) and below Smoky River, the largest tributary along the entire river, it increases to 57% (Town of Peace River (TPR) gauge, WSC Stn. 07HA001, 378 km downstream).

In June 1990, a major storm occurred over the southern Peace River drainage basin, affecting most southern tributaries as far downstream as Smoky River. This storm produced the flood of record on the lower river, reaching 16 500 m^3s^{-1} at the TPR immediately below the Smoky River confluence (Table 10.2). At Taylor, on the upper river, it achieved the second highest post-regulation flow to that time, 5190 m^3s^{-1} (daily; 5330 m^3s^{-1} instantaneous: the 1972 spillway test reached 6290 m^3s^{-1} instantaneous and 5690 m^3s^{-1} on the day.) Notable rainstorm-generated floods also occurred in the upper river in 1976, 1983, 1987 (Table 10.2), and 2011.

During the summer of 1996, the need arose to draw down the reservoir in order to effect repairs to the dam. The spillway was operated for eight consecutive weeks, during which the mean release flow at Hudson's Hope, immediately below the dams, was 4090 m^3s^{-1}, a flow that would not be expected to occur under normal operating policy (the highest flow previously recorded during normal regulated flows being 3170 m^3s^{-1} (daily) in 2002). The 1996 release flow was designed to approximate a pre-regulation moderate annual flood in the upper river; the maximum rate of release being 5190 m^3s^{-1} (daily—coincidentally, the same value as experienced at Taylor in the 1990 flood): it exceeded the 1972 maximum at Taylor, reaching 6340 m^3s^{-1} instantaneous there, approached the regulated maximum flow at Dunvegan Bridge, but produced a flood with a return period of only five to six years in the lower river (i.e., the reach from the Smoky River confluence, near TPR, downstream). The 1972 spillway test reached flows of similar magnitude, but was sustained for only hours, not weeks and, furthermore, occurred less than five years after the inception of regulation, when the channel might have still retained essentially full pre-regulation conveyance.

Above TPR, the normal regulated flows are not competent to move the bed material of the river (Chapter 2). However, the flood flows of 1990 and 1996 (and of 1972) were competent. What was the response of the river to such unusual flows?

Severe floods have been studied in other contexts, almost always an unusually severe storm runoff event (e.g., Kochel, 1988; Miller, 1990; Costa and O'Connor, 1995), or a disaster such as a dam failure (e.g., Jarrett and Costa, 1986; Clague and Evans, 2000). Both such contexts effectively represent synoptic events, persisting for a relatively short time. The flood of June

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The Regulation of Peace River: A Case Study for River Management, First Edition. Michael Church.

Companion website: www.wiley.com/go/church/peaceriver

Table 10.1 Summary data of Peace River principal hydrometric stations

Stn. Name	WSC[a] No.	Drainage area (km^2)	Distance below dam (km)	Mean annual flow (m^3s^{-1}) Pre-regulation[b]	Post-regulation[c]	%change	Mean annual flood (m^3s^{-1}) Pre-regulation[b]	Post-regulation[c]	%change
Hudson's Hope	07EF001	69 900	5	1198_{1949+}	1135	−5	5843	1927	−67
Taylor	07FD002	97 100	98	1560_{1945+}	1456	−7	7213	2837	−61
Dunvegan	07FD003	130 000	274	–[d]	–[d]	–	8275_{1960+}	3379	−59
Town of Peace River	07HA001	186 000	378	1919_{1957+}	1883	−2	9700	5564	−43
Peace Point	07KC001	293 000	1102	2327_{1959+}	2100	−10	9817	5691	−42

[a]Water Survey of Canada.
[b]From the year indicated by subscript (under mean annual flow) through 1967.
[c]1973 to 1995.
[d]Station operated seasonally: mean annual flow not available.

1990, was a weather-driven event of this kind. If the flood is very extreme, we expect significant changes along the river simply because the forces exerted by the flows are much in excess of the conditioned bed and/or bank strength of the channel. One expects an almost instantaneous adjustment of the channel to the unprecedented hydraulic forces (see Desloges and Church (1992), for a documented extreme instance of such a rapid adjustment).

On the other hand, if the flood is only moderately larger than prior flows and has only a short duration, it is possible that no major changes may occur for lack of sufficient time. A substantial literature has developed on the relative significance of magnitude and duration of competent flows to change river channels (reviews in Kochel (1988) and in Costa and O'Connor (1995)) and the consensus appears to be that extended duration is most significant (see also Huckleberry (1994)). In fact, it is probable that the amount of sediment delivered to the channel during the event is more important than either the magnitude or duration of the flow: a great deal of sediment might be mobilized by hillslope failures and/or bank erosion (Newson, 1980; Kochel, 1988; Miller, 1990), but it must then reach the channel in order to have an effect on the river.

Most of the foregoing insight has been gained by the study of events in rivers draining basins of small to intermediate size (10 to 10 000 km^2). Peace River is an order of magnitude larger.

The Peace River floods of the 1990s are particularly interesting because the normal regulated flows have not significantly modified the channel since the closure of

Table 10.2 Post-regulation extreme flows in Peace River

Year	Hudon's Hope	Taylor	Dunvegan Bridge	Town of Peace River	Peace Point	Remarks
1972a		5610	n.r.	14 100	8810	Spring storm
1972b	5130	5690	n.r.	6680	6170	Spillway test
1976		4620	5580*i*	7700	7330	Summer storm
1983		4770	5390*i*	7140	6930	Upper basin storm
1987		4010	5740	11 400	9500	Summer storm
1990		5190	7600	16 500	12 600	1990 storm
1996	5190	6220	7300	7750	9760	Reservoir drawdown
2001		3720	5960	9630	8850	Summer storm
2011		n.r.	6640	12 800	10 900	Summer storm

Data in m^3s^{-1}, daily mean flow.
n.r., no record; blank space indicates unexceptional flow; *i*, instantaneous figure.

Bennett Dam in late 1967 (Chapter 3). The situation presented by the floods of 1990 and 1996, contrasting magnitude with duration, is as close to being "experimental" as one is likely to achieve in a river of the order of 10^3 m^3s^{-1} flow. In the upper river, neither flood was extremely large in comparison with historical flows of the pre-regulation period. But both were extreme in comparison with the regime of regulated flows. The 1990 flood was of short duration, but the 1996 event was very extended. Indeed, the 1996 release flow simulated the pre-regulation summer regime freshet tolerably well. Two interesting questions arise from these circumstances in the upper river:

1. What is the effect in a regulated channel of a flood substantially larger than normal flows?
2. What is the comparative morphological effect of floods of similarly large magnitude but dramatically different duration?

To a considerable degree, the answers to these questions depend on another circumstance—the degree to which the river has adapted, over more than two decades, to the regulated flow regime. Reduced flow has induced a downward transition in channel size that is proceeding much more slowly than hydraulically driven upward transitions because, absent massive deposition of fine sediment, it is mediated largely by the progression downshore of riparian vegetation (see Church, 1995). This process has been substantially hindered in Peace River by the effects of relatively high flows and ice damage in winter (Chapter 8). It appears that, other than at isolated sediment sources, the upper channel had not dramatically adjusted its potential conveyance before these floods (Chapter 3). The two floods, each representing an exceptionally high flow for the regulated regime, but not for the preceding period of natural flows, provide a direct test of this inference.

In the lower river, we have the opportunity to compare two exceptional floods of quite different character: a synoptic flood of extreme magnitude—the 1990 flood below the Smoky confluence being the flood of record in the lower river—and the more modest but much more extended high flow in 1996.

10.2 The hydrology of the floods

10.2.1 The storm and flood of June 1990

A late spring cyclonic storm developed over central Alberta on June 10, 1990, initially moving slowly eastward toward the Saskatchewan border. On June 11, the low-pressure center moved west again and rapidly deepened from 996 to 984 hPa (compare Figures 10.1a and 10.1b). It then stalled over the Smoky basin for about 30 hours, when it delivered intense rainfall. After 1200 local time (MST) on June 12, the storm began to weaken and move off to the east. By midnight, June 12, the storm center had moved into central Saskatchewan and had weakened to a central pressure of 996 hPa (Figure 10.1c). Total precipitation in the main storm region varied from 25 to 175 mm (Figure 10.2), with the core of the storm centered squarely over the Smoky River basin and right bank tributaries as far west as lower Pine River. The storm followed a prolonged wet spell and streamflows in the major southern tributaries were further enhanced by continuing late snowmelt in the mountains. Lower Peace River received relatively little precipitation, which contributed to the weakening of the flood magnitude from TPR to Peace Point.

Figure 10.3a illustrates the hydrograph that derived from this storm in annual context and in event detail. The flood peak flow of 16 500 m^3s^{-1} (daily, June 14; instantaneous peak 18 500 m^3s^{-1} at 2200 hours, June 13) experienced at the TPR is the highest gauged flow along the river, and more than doubled the incoming flow from the upper river, which was the order of 8000 m^3s^{-1}.

10.2.2 The 1996 emergency release flood

During the emergency release flood of 1996, Peace River flows at Taylor were on the order of 4000 m^3s^{-1} and peaked at over 5000 m^3s^{-1}; this is well above the post-regulation MAF of 2837 m^3s^{-1} and above the estimated threshold for significant bed material movement. The flow approximated a post-regulation bankfull flow as far downstream as TPR. Given its eight-week duration, this was an exceptional episode of potential bed material transport competence in the regulated river. Figure 10.3b illustrates this flood. The event hydrograph is less regular than the synoptically driven hydrograph of 1990, but it emulates a moderate pre-regulation annual flood, one with a return period of about 1.14 years, in substantial detail.

10.2.3 Flood frequency

Figure 10.4 presents flood frequency graphs (assumed log-normally distributed flows) for the period of normal regulated flows, 1973 to 2010, with the 1996

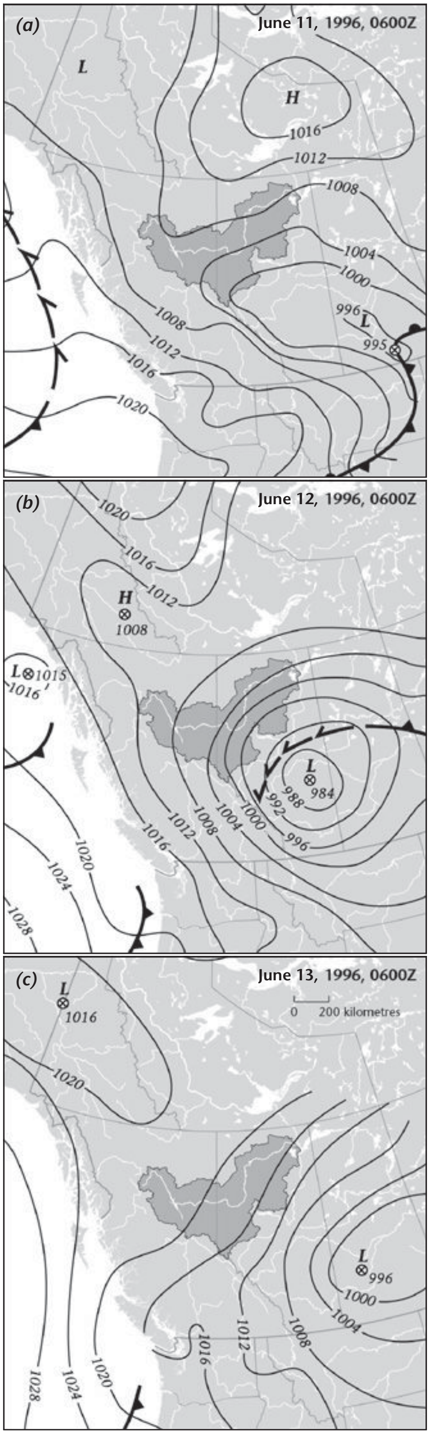

Figure 10.1 The synoptic situation over Peace River basin at 2300 hours (Mountain Standard Time: 0600Z on the following day) on (a) June 10, 1990; (b) June 11, 1990; (c) June 12, 1990 (Surface synoptic charts courtesy of the Meteorological Service of Canada).

flood entirely deleted. The flood of 1990 and a number of lesser, but still outstanding, events are annotated. Two sets of flood frequency relations are estimated. The first assumes that the outstanding events are normal events, the return period of which is reasonably estimated. The second assumes, more realistically, that they are relatively infrequent occurrences for which the return period is underestimated due to the limited record length and omits them as outliers from the estimated frequency relations. The two outstanding years at Hudson's Hope (1983 and 2002), both represent peak days during periods of deliberately increased power generation following heavy snow winters.

The 1990 flood had a return period in the regulated regime (considering both estimates of the flood frequency relation) in the range 40 to 70 years from the Pine confluence downstream, except >100 years at TPR (Table 10.3), where the Smoky River delivered runoff from the storm center. Diminishing contributions downstream and flood wave dissipation reduced the relative severity of the flood at Peace Point. Remarkably, along most of the river, the apparent storm return period is approximately commensurate with the length of the overall gauging history.

The 1996 release flow yielded a peak discharge with nominal return period the order of 1000 years at Hudson's Hope, but that figure must be recognized as a statistical artifact of a comparison with normal release flows—renewed employment of the spillway is very likely to occur within the practical life of the dam, which is much less than 1000 years. More realistically, at Taylor it represented a flow with an expected return period in the range 120 to 200 years, and its relative severity decreased steadily and dramatically downriver from there since there were no unusual downstream inflows. Beyond the Smoky confluence it represented a flow with return period of about five to six years. The key difference between the two events is duration in the upper river.

It is noteworthy that under the natural (pre-regulation) flow regime, all of the discharge values considered here would have had return periods of less than 2.33 years (i.e., less than MAF magnitude), except the 1990 flood on the lower river, where the inflow from Smoky River created what would have been a 90-year flood at TPR and 14-year flow at Peace Point. This underscores the profound damping effect of regulation on the flood regime of Peace River.

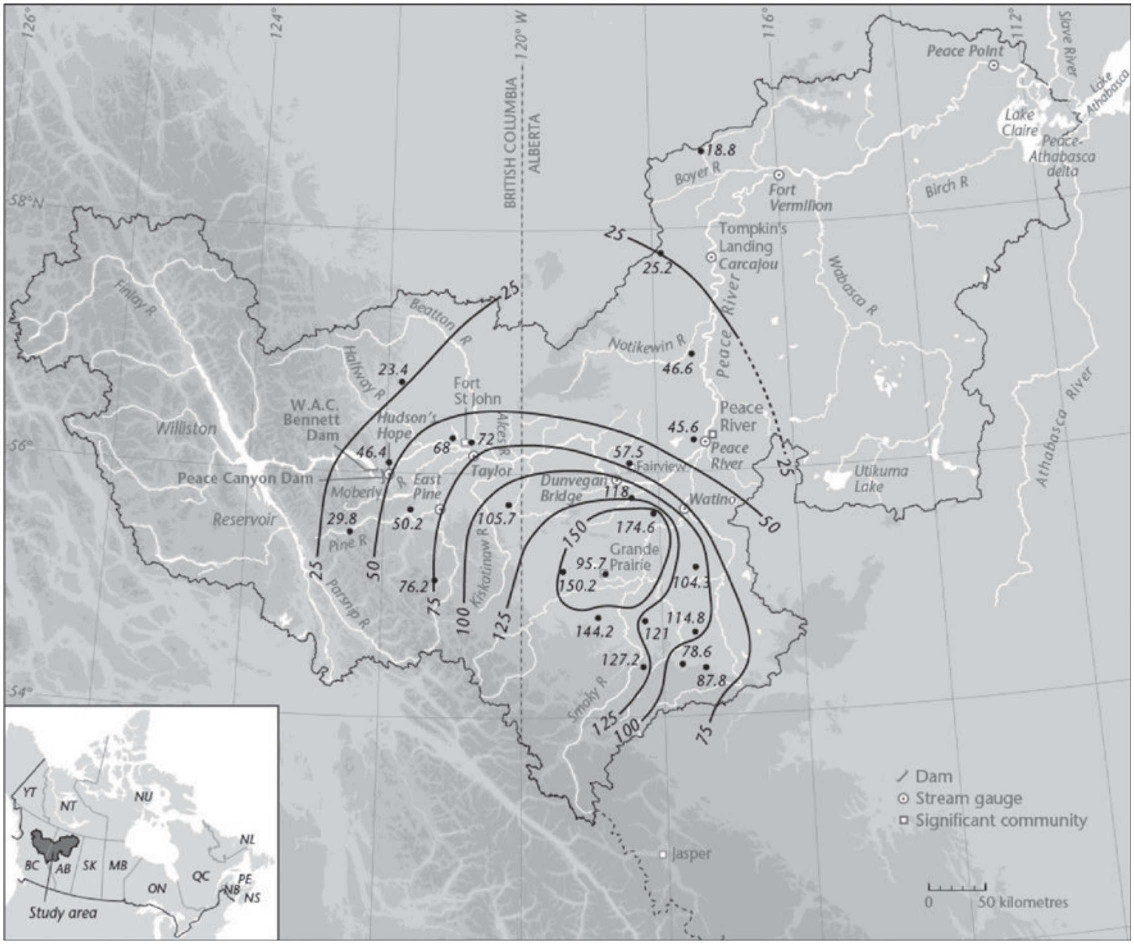

Figure 10.2 Total precipitation for June 10 to 12, 1990 over Peace River basin.

Table 10.3 Data of the 1990 and 1996 flood flows at the principal hydrometric stations on Peace River

Stn. Name	WSC[a] Stn. No.	Drainage area (km^2)	Distance below dam (km)	Maximum daily flow (m^{3}s^{-1}) in 1972	in 1990	in 1996	Return period (a)[b] 1990	1996	Mean flow during the 1996 flood (m^{3}s^{-1})[c]
Hudson's Hope	07EF001	69 900	5	5130	1060	5190	<1.0	>1000	4091
Taylor	07FD002	97 100	103	5690	5190	6220	40 to 60	120 to 200	4862
Dunvegan	07FD003	130 000	275	n.d.	7600	7300	40 to 65	33 to 50	5515
Town of Peace River	07HA001	186 000	376	6680	16 500	7750	110 to 350	~6	6147
Peace Point	07KC001	293 000	1116	6170[d]	12 600	9760	40 to 70	~5	8029

[a]Water Survey of Canada.
[b]Quoted ranges based on the two estimates of flow frequency in the regulated regime.
[c]June 24 to August 17; no adjustment made for downstream flow time.
[d]A flow of 8810 m^{3}s^{-1} was experienced early in the drawdown flood due to heavy runoff in the lower river.

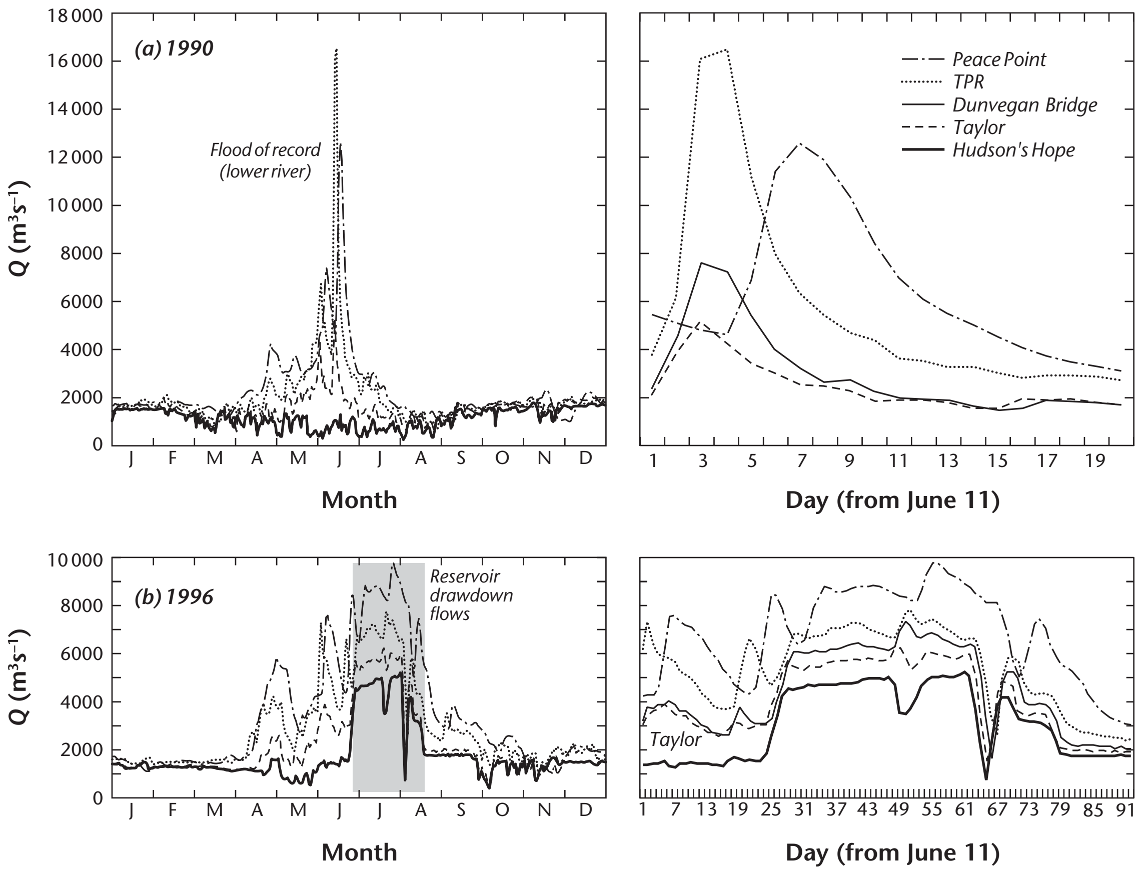

Figure 10.3 Annual and flood event hydrographs for principal stations for (a) 1990 and (b) 1996. See Figure 10.2 for gauge locations.

10.3 Flood gradation

It is apparent that the British Columbia reach below Pine River confluence (Taylor) was relatively heavily affected by both floods. Figure 10.5 illustrates gradation of selected channel cross-sections, both above (not affected in 1990) and below (affected by both floods) that confluence. Gradation is illustrated for the periods between successive surveys, commonly 1986 to 1991 and 1991 to 1998 but it is supposed that the majority of the observed change occurred during the flood episodes. It is apparent that little change was associated with the 1990 flood. To the extent that change occurred, it was aggradational (evident, in the figure, mainly at Section S10). In 1996, in comparison, there were mixed changes, with degradation relatively prominent above Pine River, where the significant flows were initially clear water. Downstream there was mixed gradation or aggradation.

Gradation can be quantified in two ways. Commonly, one considers net change in mean bed elevation. However, the net exchange of bed cross-section (effectively, net exchange of sediment volume for a unit length of channel) is also an indicator of the overall activity in a cross-section. Figure 10.6 shows the relation between net gradation and net sediment exchange for the two floods (considering only sections below the Pine confluence in 1990). The first notable impression is the wider range of change in 1996 compared with 1990: the range of change in mean bed elevation in 1996 was −1.1 m to +0.8 m, compared with −0.01 to +0.35 m in 1990. Mean change was +0.09 ± 0.04 m in 1990 and −0.02 ± 0.08 m (quoted variations are standard errors of the mean) in 1996. The 1990 figure is significantly positive, but does

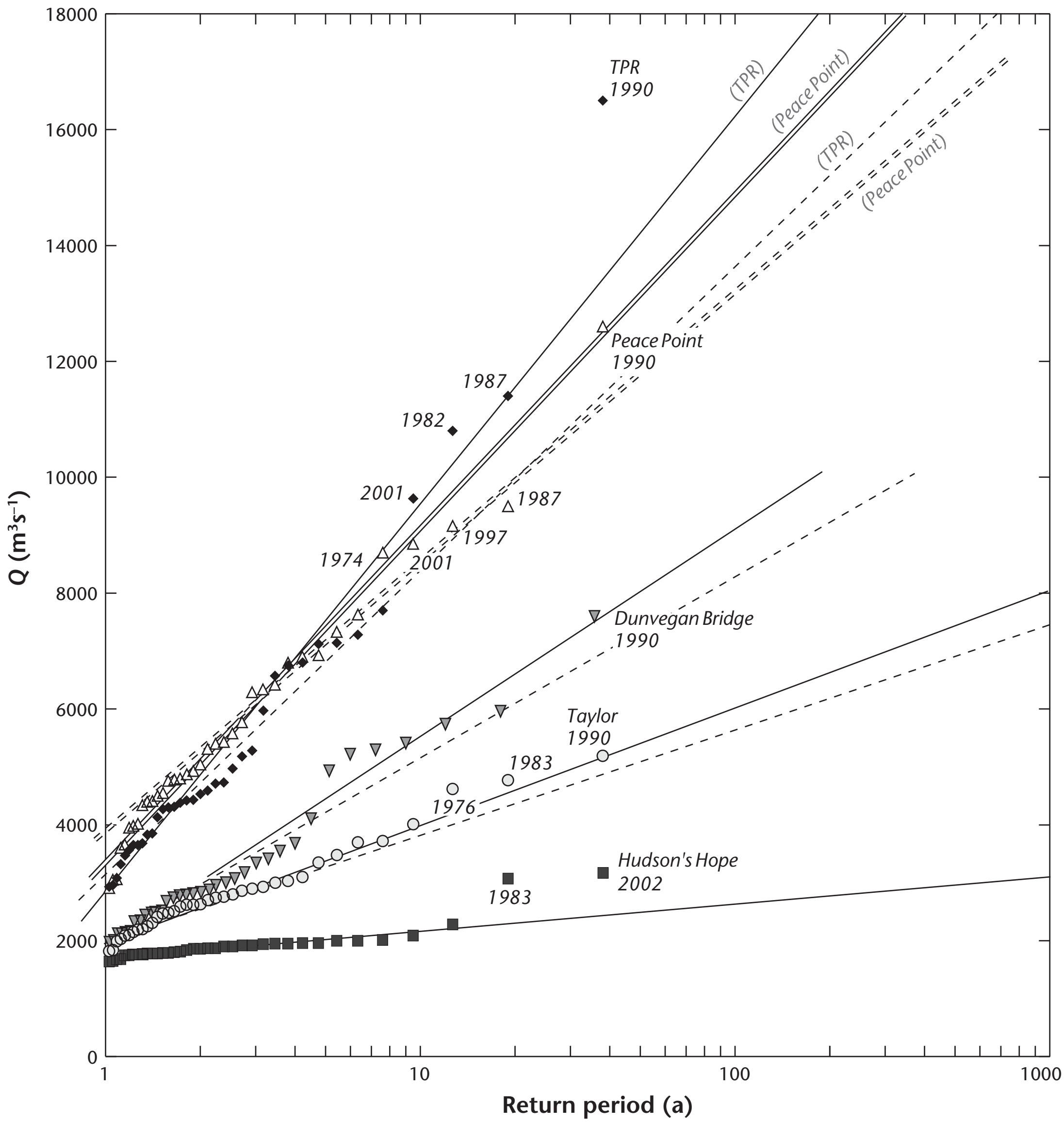

Figure 10.4 Flow frequency diagrams based on the annual extreme value sequence for principal Peace River gauges (see Figure 10.2 for locations) for the period 1973 to 2010 plotted as a log-normal distribution, indicating the anomalous character of the highest experienced flows Mean relations are fitted for the sequence of "normal" regulated flows (dashed lines) and then to include the major weather-generated flood flows (solid lines). Only one relation is shown for Hudson's Hope, with the spillway test of 1972 deleted: the reservoir drawdown event of 1996 is entirely omitted from the analysis.

not exceed the range of expectation of the 1996 data. Net volumetric exchange was 131 ± 28 m^2 in 1990 and 153 ± 15 m^2 in 1996: figures that are not significantly different despite the difference in flood duration and in mean outcome. Of course, gross sediment exchange in 1996 may have been substantially higher but for lack of continuous monitoring no insight is available.

Figure 10.6 shows no correlation between mean change and net exchange in 1996 but in 1990, but for one aberrant point, there is a rough positive correlation

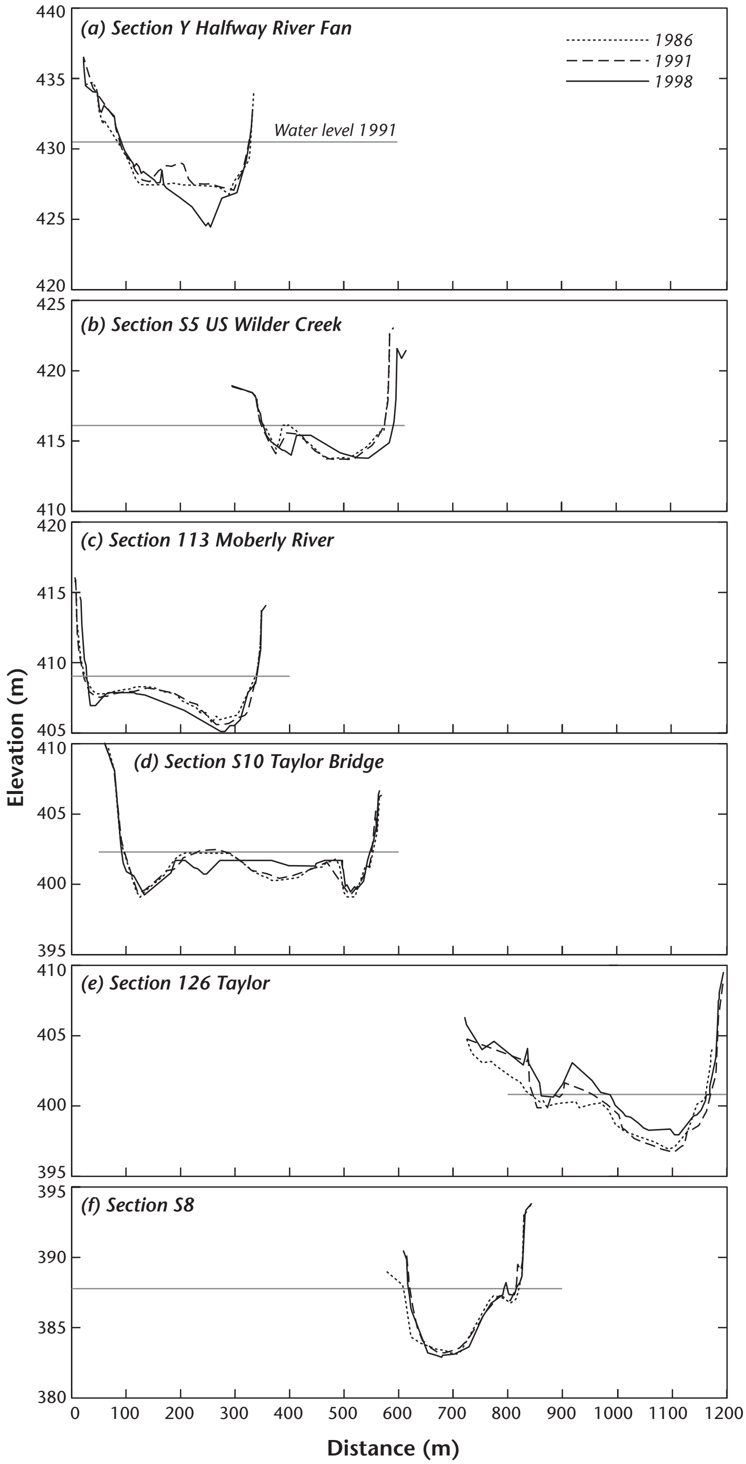

Figure 10.5 Selected surveyed cross-sections in the British Columbia reach of Peace River to illustrate the contrasting effects of the 1990 and 1996 floods. Panels (a) to (c) are from sections above the confluence of Pine River, panel (d) shows the section immediately below the confluence, and panels (e) and (f) are from farther downstream.

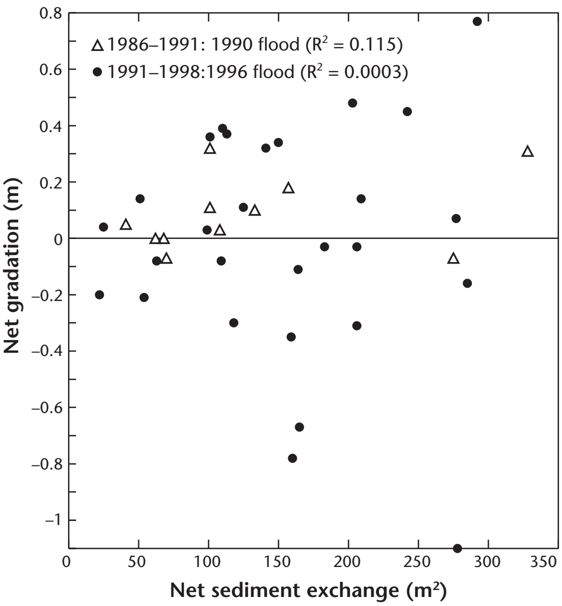

Figure 10.6 Gradation in the British Columbia reach in 1990 and 1996. Net gradation at monumented cross-sections is plotted against net sediment exchange. For 1990, only cross-sections below the Pine confluence are plotted.

between the two measures, probably evident because of the relative lack of instances of degradation. There is no overall correlation between change in bed elevation measured in 1990 and in 1996 ($R^2 = 0.028$). Figure 10.7 shows the distribution of changes in mean bed elevation for 1996 (when sufficient data were available) to be approximately U-shaped, trending either to substantial aggradation or substantial degradation, with a minority of essentially stable sections; that is, sedimentological activity affected most sections in 1996.

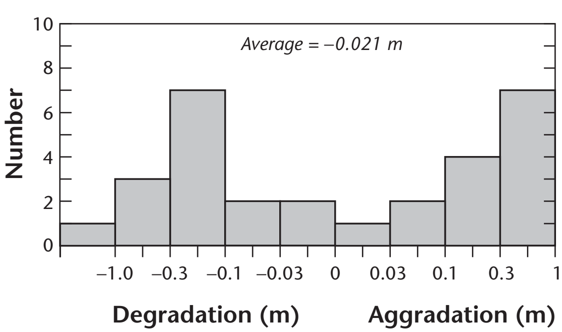

Figure 10.7 Distribution of gradation magnitude in the British Columbia reach, 1996.

Figure 10.8 maps the spatial pattern of aggradation and degradation at monumented cross-sections in the British Columbia reach. One notes in 1996 that the majority of the degrading sections occurred in the proximal part of the reach where there is no reliable fluvial sediment input to the river, while the most persistent run of aggrading sections was that beginning at S10 (Taylor gauge section) downstream of the Pine River confluence. Since Pine River was not running notably high at the time, most of the aggradation presumably derives from downstream redistribution of previously delivered Pine River material and material mobilized from upstream of the confluence. Despite the shift from degradation to aggradation at Taylor, there is no significant serial correlation in section behavior over the reach as a whole ($R_1^{\ 2} = 0.027$). However, downstream from Pine River—a significant sediment source—$R_1^{\ 2} = 0.44$, with aggradation in each successive section declining by about 0.6 times. The data relevant to the 1990 flood show no such correlation ($R_1^{\ 2} = 0.08$). Nor was the gradation pattern similar in 1990 when tributary sediment inputs presumably limited mainstem degradation, leading to the overall average aggradation (Figure 10.8).

Gradation effects of the 1996 flood can also be seen in specific gauge data at Taylor Figure 10.9), which indicates significant aggradation. For this site, immediately downstream of Pine River, there is a consistent post-regulation trend of rising specific gauge but the trend is sharply increased for the 1993 to 1998 period. The gauging site at Old Fort, above the Pine River confluence, has aggraded since 1996; sedimentation there may derive from the recently degrading Section D immediately upstream, or may be associated with a nearby active riffle. In this latest period, however, the Taylor gauging site has remained stable, though a new low-water channel has been excavated, reducing specific gauge at flows below about 2500 m^3s^{-1}—that is, normal regulated flows. There was 0.29 m of degradation at the Alces River gauge, which is consistent with the scour/fill response seen in the 1998 survey at nearby Section E6. The Dunvegan gauge, farther downstream, shows marginal aggradation.

10.4 Morphological changes

Morphological changes that may be ascribed to the flood flows can be inferred only indirectly from channel

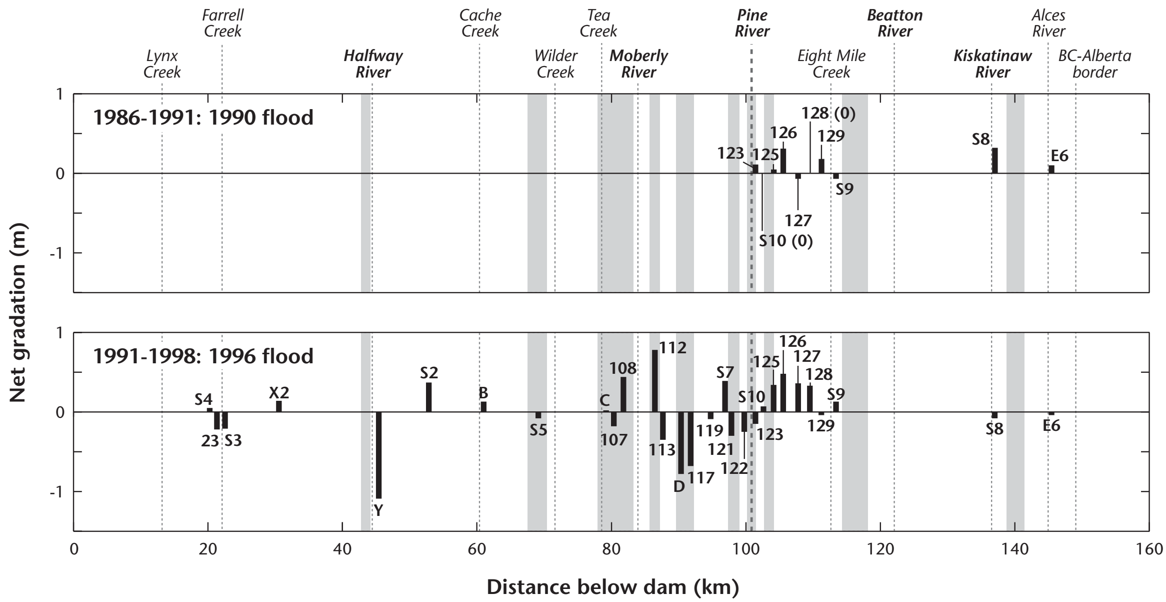

Figure 10.8 Pattern of erosion and sedimentation in the British Columbia reach of the river, plotted as net gradation at monumented cross-sections, resulting from the 1990 flood and 1996 release flow. Gray bars indicate significant sediment sources associated with landsliding.

change maps, dates of which are constrained by the availability of air photography. Results for the British Columbia reach are compromised by the circumstance that the mid-1990s photography was obtained during the actual 1996 flood, so high water levels conceal morphological changes. Data are interpretable from map comparisons for the Alberta reach of the river with the exception that there is no post-1996 photography or mapping available for Reach AB4—the most distal reach. As with the cross-sectional data, we suppose that most

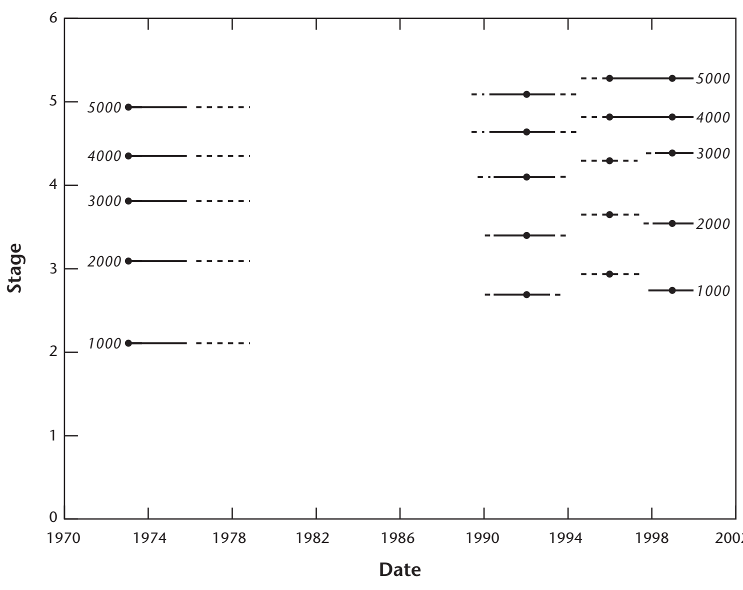

Figure 10.9 Specific gauge, Peace River at Taylor (WSC Stn. 07FD002) for the period of regulated flows.

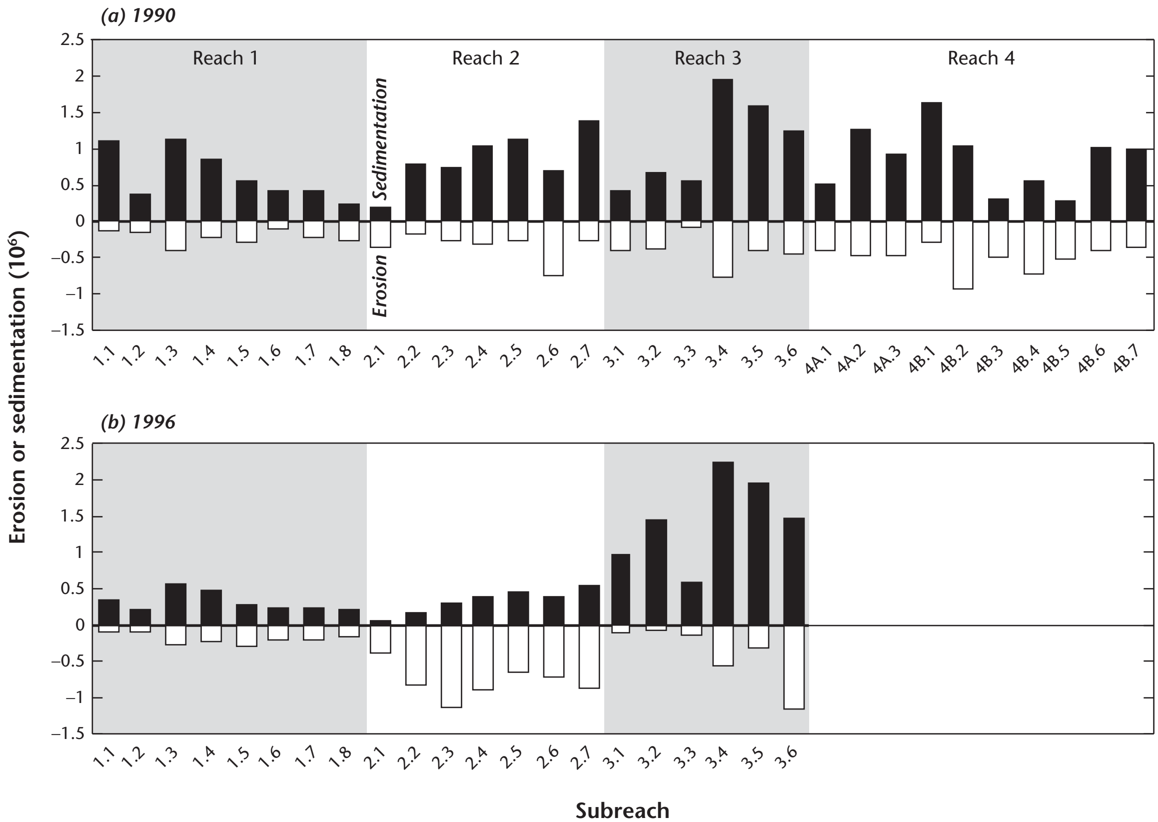

Figure 10.10 Areal change (10^6 m^3) in exposed surface during the periods encompassing the 1990 and 1996 floods in the Alberta Peace River; results aggregated by study sub-reaches.

of the observed period change revealed by the mappings occurred during the exceptional flood flows.

Figure 10.10 shows the summary extent of erosion and sedimentation for each flood period in each of the studied sub-reaches in the Alberta Peace River as millions of cubic meters areal change in exposed surfaces (10^6 m^2 = 1 km^2). (There may be a small bias in the data due to stage differences between the successive sets of air photography upon which the maps are based.) Conventions for erosion and sedimentation are those defined in Chapter 7. The storm-driven flood of 1990 caused a preponderance of sedimentation nearly everywhere along the river. Exceptions occurred at the distal end of Reach AB1 (near Dunvegan Bridge), and in the middle of Reach AB4B in the Peace–Athabasca Lowland. The event was driven by heavy contributions from the southern tributaries, in particular Smoky River, which would have been accompanied by heavy sediment influx to Peace River (there are no actual measurements). The most significant sedimentation occurred in Reach AB2 from Smoky River to the end of the surveyed reach, and in the reach comprising AB3.4 through to AB4B.1 (which includes an unsurveyed reach between AB3 and AB4A). In Reach AB3.4 (Prairie Point) there is a series of tortuous bends with an extensive sedimentation zone where the river is depositing sand derived largely from Smoky River.

In comparison, in 1996 there was a small and steadily declining preponderance of sedimentation in Reach AB1, dominantly erosion throughout Reach AB2, and a return to net sedimentation in the sand-bedded Reach AB3. In Reach AB1, there is a coherent depositional gradient, suggesting that the river was depositing material mobilized from the proximal British Columbia reach by the initially clear water released from the dam. Material was probably entrained from the reach well downstream

Table 10.4 Volume of areal erosion and sedimentation in the floods of 1990 and 1996

Reach	1990			1996		
	Erosion	Sedimentation	Net	Erosion	Sedimentation	Net
Alberta						
Reach AB1	222 387	845 670	623 283	227 564	477 282	249 718
Reach AB2	274 045	742 261	468 216	742 261	305 381	−436 880
Reach AB3	374 561	661 581	287 020	83 238	1 443 544	1 360 306
Reach AB4	463 299	1 275 946	812 647	n.d.	n.d.	
Total 4[a]	1 334 292	3 575 458	2 241 166			
Total 3[a]	870 993	2 299 512	1 428 519	1 437 057	2 226 207	789 150

[a]number of reaches in total. n.d. = no data.

from Pine River, where we have few cross-sections for assessment (Figure 10.8). In Reach AB2 it is likely that fine gravel and, mainly, sand previously deposited from Smoky River floods was re-entrained. Finally, net sedimentation in Reach AB3, again peaking around Prairie Point, would be the sand winnowed from Smoky River deposits in Reach AB2.

The areal magnitude of sediment exchange, overall, was broadly comparable between the two floods (Table 10.4 and Figure 10.10) except that the area eroded in 1996 was substantially greater than in 1990. During the short, weather-driven 1990 event there must have been substantial sediment influx into the river from flooding tributaries, while in the long reservoir release flood of 1996, initially clear water mobilized sediment in the river. A greater area of vegetated (i.e., inactive) bar and island surface was lost in 1996 than 1990—noted by comparing data for the three reaches with coverage in both surveys—while newly deposited area was marginally greater in 1990. Furthermore the spatial distribution of erosion and sedimentation changed. In 1990, there was a large area of net deposition in Reach AB4, constituting more than one-third of the total area gained in that event. As this reach is near the distal end of the river, a similar effect may have occurred in 1996. The ratio of sedimentation area to eroded area (3 reaches considered) was 2.64 (1990) and 1.55 (1996), implying either that high banks were eroded in 1990 or that substantial sediment was added to the system; the latter is very probably the case. The 1996 figure is more consistent with the erosion of high floodplain banks supplying sediment to low-lying new bar surfaces.

Figure 10.11 presents maps of four local reaches, one in each of the study reaches of the Alberta Peace River, where erosion and/or sedimentation were particularly active in 1990 and 1996. They exhibit the dominance of sedimentation in areal change within the channel zone in both events, except in Alberta Reach 2 in 1996, where erosion was clearly dominant.

In sum, the synoptic event of 1990 was as active as the extended 1996 flood in moving sediment in the Alberta reach and gave rise to a more positive net balance. The much greater discharge experienced in the reach below the Smoky confluence is presumably an important factor in this outcome, but sediment influx does indeed appear to be a highly significant factor in determining flood effect, regardless of flood magnitude or duration.

10.5 Geomorphological effectiveness: British Columbia reach

The cross-sections and summary data show that the 1990 event continued the general trend of post-regulation change along the channel in British Columbia with modest aggradation dominating, chiefly at sections a relatively short distance downstream from individual sediment sources. Indeed, above Pine River, the 1990 flows were not exceptional; the main effect occurred below Pine River, which has been the most prominent aggradational reach since regulation.

But there is a distinct change in channel response recorded in the 1998 survey of cross-sections in the British Columbia reach, after the 1996 flood (Table 10.5). While 40% of the sections had been stable (mostly above Pine River) and 50% had exhibited modest aggradation before 1996, leaving only 10% of the sections in a degrading state, afterward degradation was observed at 34% of the stations. The fraction of

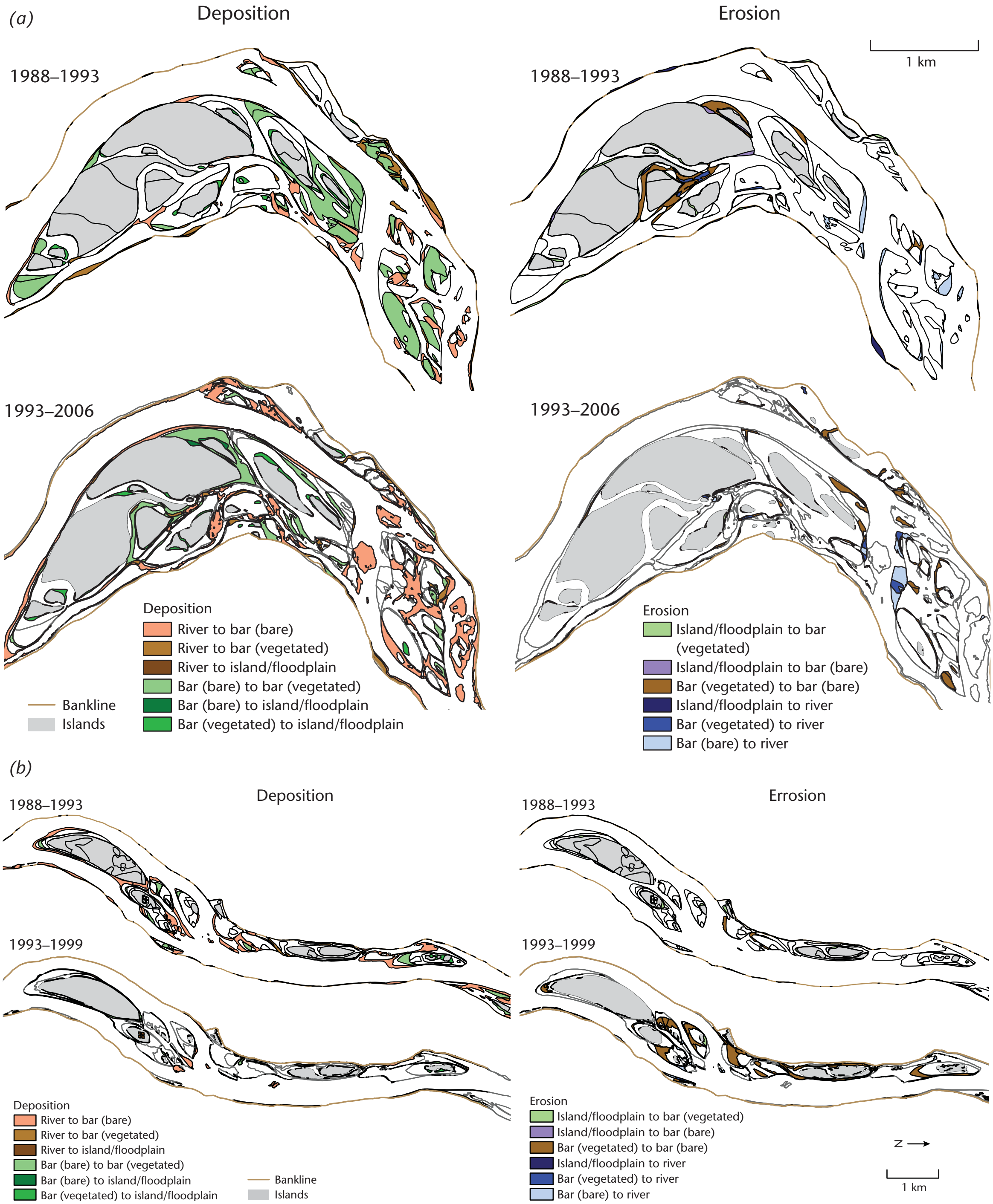

Figure 10.11 Illustrations of significant channel change in the period 1988 to 1993, encompassing the 1990 flood, and 1993 to 2006 (1999 in Reach AB2), encompassing the 1996 flood. (a) Many Islands, Reach AB1; (b) below the TPR, AB Reach 2; (c) near Moose Island, AB Reach 3; (d) near Fox Lake, Reach AB4, record available only for the earlier period.

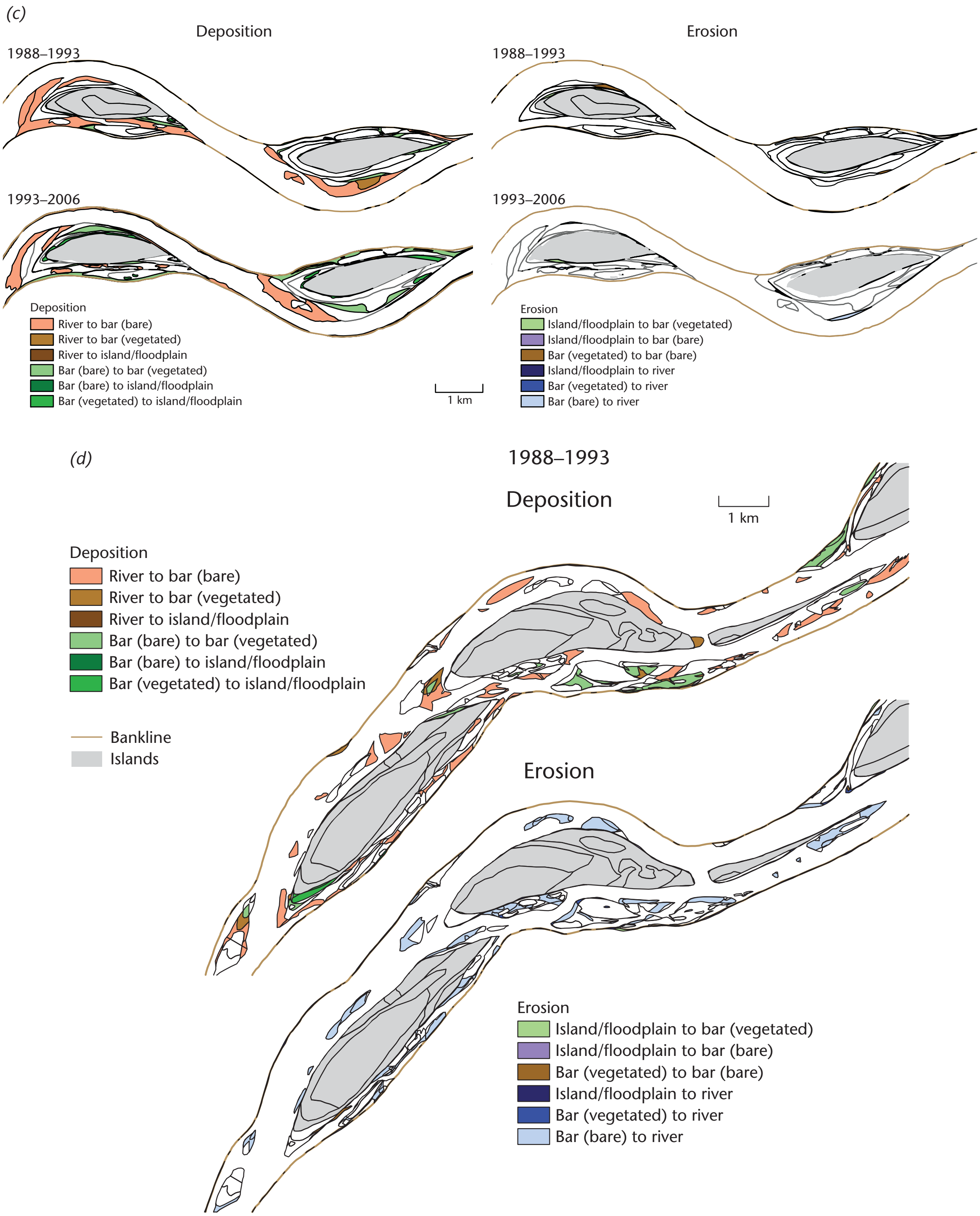

Figure 10.11 (*Continued*)

Table 10.5 Number and frequency of occurrence of cross-sectional gradation response types

Period	1967 to 1991		1991 to 1998		1998 to 2005	
Response type	**No.**	**Freq**	**No.**	**Freq**	**No.**	**Freq**
Stable	14	0.40	11	0.38	9	0.29
Aggrading	18	0.51	8	0.28	8	0.26
Degrading	3	0.09	10	0.34	14	0.45
Total sections	35		29		31	

stable sections did not initially change significantly but the new trend intensified in the post-1998 period so that, to 2005, 45% of the sections experienced degradation and 26% aggradation, leaving only 29% stable. The 6000+ m^3s^{-1} flow of the 1996 flood, unprecedented in the regulated regime, evidently destabilized a previously substantially structurally locked gravel bed, allowing local erosion and sedimentation to occur. Degradation occurred at both formerly aggrading sites and previously stable sites The sites which aggraded in 1996 are all located downstream of significant sediment sources (Figure 10.8), though sometimes at considerable distances.

The flow record suggests that the duration of competent flow is an important factor in destabilizing the structured gravel bed: neither the flood of 1972 nor that of 1990—both of synoptic duration and with flows 500 to 1000 m^3s^{-1} lower than in 1996—effected the requisite loosening of the bed to permit significant degradation at many cross-sections.

In six weeks of near-bankfull flow, the 1996 emergency release flood transformed the observed cross-sections in the British Columbia reach from predominantly aggrading to degrading, with much of the eroded sediment being deposited in previously stable areas. The result was a significant redistribution of sediment that had been stored near tributary confluences and other sources. The redistributed sediment may be expected to have some lasting impact, since it could form the basis of new bars and islands or redirect flow to new points of bank attack. However, sediment sources appear to have driven the pre-1996 gradation response (Chapter 3) and these should mostly remain unchanged.

Due to the dates of the base photos in the British Columbia reach, the planform results offer little insight into the effects of the 1996 flood, though the 1996 maps do show that the flood reoccupied many abandoned backchannels. There has been little opportunity for sedimentation to fill those channels, which have remained mainly dry since the inception of regulation, Most of the post-1996 cross-sectional changes occurred within the active channel, with surprisingly few instances of major bank erosion or channel avulsion. Considering this, and the generally slow rate of planform adjustment, drastic post-1996 planform changes are not anticipated, though it is possible that fine sediment or vegetation in backchannels may have been scoured away.

It seems most likely that the sediment moved by the 1996 flood will stay approximately where it came to rest, with the previous pattern of post-regulation adjustment eventually reasserting itself, although it is clear that the loosening of the bed achieved by the flood has initiated continuing redistribution of in-channel sediment in the ensuing years. In comparison, the effect of the 1990 synoptic flood was consistent with the long-term pattern of river adjustment in the regulated regime—that is, principally, aggradation downstream from significant sediment sources.

The 1996 flood emphasizes that the bed of the regulated Peace River is not truly static. Although most of the regulation-induced changes in the Peace River channel have been passive in nature, erosive processes can still occur. An interesting question is whether exceptional flows—that is, ones significantly in excess of usual regulated flow levels—will occur sufficiently frequently in the British Columbia reach to eventually impose a pattern of grade adjustment significantly different than that outlined earlier in Chapter 3, involving the evolution of a stepped profile downstream from the principal continuing sediment sources.

The 1996 flood may be regarded as a test of the post-regulation channel conveyance and, in this light, its limited effect on the planform geometry of the channel in the upper river was a surprise. Two factors are likely to have conditioned this outcome. (i) While an exceptional flow in the regulated regime, it was not exceptional in comparison with pre-regulation flows.

Reduction of channel capacity has been passive and slow. Thus, when side channels were reoccupied, some of them for the first time in decades, the channel still allowed adequate conveyance for the water. (Indeed, the release was gauged to take advantage of that presumed conveyance.) The result was local bank erosion but no channel avulsion or realignment. (ii) Shrubby vegetation that has occupied many formerly inundated bar surfaces proved resilient in the face of the summertime flood flows and provided a significant measure of protection to the substrate by reducing velocities over flooded bar surfaces on which vegetation succession had occurred. These effects are consequences of the nature of the post-regulation channel adjustment: morphologically largely passive, with limited progradation of riparian vegetation the main adjustment.

10.6 Geomorphological effectiveness: Alberta reach

The character of the 1990 and 1996 floods was different between the British Columbia and Alberta reaches, and the character of our evidence for geomorphological effectiveness is also different. In British Columbia the flow was not unusual above Pine River in 1990, and the 1996 flows exceeded 1990 flows in all of the British Columbia reach. In Reach AB1, the magnitudes were nearly equal, but the 1996 flood lasted much longer. Below TPR, the 1990 flood was much larger (more than twice as large at TPR) though the 1996 flood lasted much longer and delivered, in total, more water. Another important difference is the influx of sediment from tributaries in 1990.

The effect of this latter circumstance is clearly evident. In 1990, there was a significant preponderance of fresh sedimentation throughout the river, two subreaches in Reach AB4 being the only locations where erosion exceeded sedimentation. Furthermore, erosion was modest throughout the system. In 1996, on the other hand, when material for resedimentation was scoured almost entirely from the bed and banks of Peace River itself, sedimentation comparable with that of 1990 occurred only in Reach AB3, below the major slope break and change from gravel to sand bed, where sedimentation has been persistent since regulation of the river. In comparison, net erosion occurred in Reach AB2 while only modest changes were experienced in AB1 (Figure 10.10).

By the time 1996 floodwaters reached Alberta, they carried a modest sediment load. In contrast with British Columbia, both floods appear less unusual, but while the 1990 flood was a record-breaking synoptic event, the 1996 event was more akin to a moderate pre-regulation freshet. Given limited channel adjustment to the regulated regime (very modest in Reach AB2), the channel passed both floods with what can be characterized as "normal incremental change." The sediment charge accompanying the 1990 flow led to significant sedimentation, as would be expected for such a flow, but the likelihood of its being moved on and further redistributed in future is limited by the degree of flow regulation, except possibly in Reach AB2, directly below the Smoky confluence.

10.7 Conclusions

The comparative history of the 1990 and 1996 high flows does not sustain prior observations that flood duration is ultimately more important than absolute magnitude in effecting morphological change along a river. In particular, in gravel-bed rivers in which characteristic transport rates for bed material are never very high, fresh supply to the channel of sediment of bed-material caliber must also be a significant factor in determining the extent of channel change. In the 1990, synoptic flood significant influx of bed material from flooding tributaries was the likely source of observed new sedimentation everywhere below Pine River. Morphological changes were almost entirely restricted to incremental bank erosion and construction of new bars within the channel zone, most of them bank-attached (for additional evidence, see the history of channel zone accretion in Figure 7.14). Changes were greatest in multi-thread sites of chronic sedimentation.

In contrast, the sediment redistributed in the upper river during the 1996 emergency release flood had accumulated in the channel over the preceding years. The result was a change from aggradation to degradation in a substantial number of the monitored cross-sections in the upper river, while other sites markedly aggraded. The extent and nature of the activity achieved by the 1996 flood in the main channel in the British Columbia reach is unusual under the new hydrological conditions of Peace River. The degree of net gradation evident after the emergency clear water release flood was commensurate with the geomorphic work done during the entire previous regulated period. In fact, the recorded changes may be conservative, since they are based on the 1998 channel surveys. Channel processes may have counteracted some of the 1996 flood effects during the intervening time.

Let us return, then, to the questions we posed at the beginning of the chapter. In response to the first, two abnormally large floods in a regulated river channel (the 1990 flood in the lower river, and the 1996 flood in the upper river) produced significant channel gradation, but surprisingly little planform change. This supports the view that Peace River's conveyance remains largely unaltered due to the slow, passive morphological response to its regulated flow regime. As to the second question, neither magnitude nor duration appears to have clearly dominated the response of Peace River to the 1990 and 1996 floods. Sediment influx appears to have been a third critical factor in differentiating the morphological effects of the floods. Hence, the second question remains undecided: neither magnitude nor duration played a decisive role in altering river morphology in the present cases: the relatively slight prior morphological adjustment of Peace River to the regime of regulated flows is a significant reason for that. The channel still retains a significant measure of its pre-regulation conveyance. In this circumstance, sedimentation associated with the synoptic flood of 1990, resulting from the influx of fresh sediment from tributaries, balanced the changes effected along the river during the extended dam release flood of 1996. But the former event was aggradational in character in virtually every sub-reach, whereas significant net scour was experienced in many sub-reaches in the latter.

Acknowledgment

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References

Church, M. (1995) Geomorphic response to river flow regulation: case studies and time scales. *Regulated Rivers: Research and Management*, 11, 3–22.

Clague, J. J. and Evans, S. G. (2000) A review of catastrophic drainage of moraine-dammed lakes in British Columbia. *Quaternary Science Reviews*, 19, 77–87.

Costa, J. E. and O'Connor, J. E. (1995) Geomorphically effective floods, in *Natural and Anthropogenic Influences in Fluvial Geomorphology*, edited by J. E. Costa. Geophysical Monograph Series, vol. 89. American Geophysical Union, Washington, DC pp. 45–56.

Desloges, J. R. and Church, M. (1992) Geomorphic implications of glacier outburst flooding: Noeick River valley, British Columbia. *Canadian Journal of Earth Sciences*, 29, 551–564.

Huckleberry, G. (1994) Contrasting channel response to floods on the middle Gila River, Arizona. *Geology*, 22, 1083–1086.

Jarrett, R. D. and Costa, J. E. (1986) Hydrology, geomorphology and dam-break modeling of the July 15, 1982 Lawn Lake and Cascade Lake dam failures. *United States Geological Survey, Professional Paper*, 1369, 78 p. Larimer County, Colorado.

Kochel, R. C. (1988) Geomorphic impact of large floods: review and new perspectives on magnitude and frequency, in *Flood Geomorphology*, edited by V. R. Baker, R. C. Kochel, and P. C. Patton. John Wiley & Sons, Inc., New York. pp. 169–187.

Miller, A. J. (1990) Flood hydrology and geomorphic effectiveness in the central Appalachians. *Earth Surface Processes and Landforms*, 15, 119–134.

Newson, M. D. (1980) The geomorphological effectiveness of floods—a contribution stimulated by two recent events in mid-Wales. *Earth Surface Processes and Landforms*, 5, 1–16.

CHAPTER 11

The future state of Peace River

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11.1 Introduction

In late 1967, Peace River, a large, northward flowing, boreal river in northwestern Canada, was regulated by the closure of W.A.C. Bennett Dam, completing what was then one of the largest hydroelectric power projects in the world. Mean annual flood (MAF) in the river immediately downstream from the dam was reduced from 5843 to 1927 m^3s^{-1}—a reduction to one-third of its former value. Even at the distal end of the river, more than 1200 km downstream in the Peace–Athabasca delta (Figure 11.1), MAF was reduced to just over half its former value of 9817 m^3s^{-1}. Since regulation, flows have rarely exceeded 3000 m^3s^{-1} immediately below the dam, 5000 m^3s^{-1} at Taylor (immediately below the confluence with Pine River, the first major tributary), and 8000 m^3s^{-1} at the Town of Peace River (TPR), below the Smoky River confluence. What effect might this reduction in high—presumably formative—discharges have on the morphology of the river?

The relations of hydraulic geometry predict that the river should become narrower and less deep. Observations of gravel-bed rivers indicate that this outcome should be achieved by sediment deposition in-channel, leading to bar growth and consequent channel narrowing, while in sand-bed channels it is apt to be accomplished by lateral sand deposition (Brandt, 2000). An exercise based on the empirical hydraulic geometry of Alberta rivers (Chapter 5) indicates that the river has not fully adjusted to the regulated flow regime. Channel width remains 50% greater than predicted in the reach immediately below the dam, and the ratio declines downstream so that it is about 33% wider than predicted at Peace Point. In contrast, depth appears everywhere to have overcompensated—the river is shallower than it should be. The latter circumstance is a straightforward consequence of the former: the river is largely flowing in the bottom of the little modified pre-regulation channel. Sedimentation has been insufficient to effect the expected dynamical adjustment. But empirical projections of the expected geometry may not be entirely reliable, depending, as they do, on an assumption that the river will remain within a specified "regime group."

The development of physically based theories to predict the regime dimensions of alluvial channels has a long history. Early approaches were based on the hypothesis that rivers adjust their form so as to minimize the channel gradient, and thereby stream power (Yang, 1976; Chang, 1979), to maximize sediment transport capacity (Kirkby, 1977; White *et al*., 1982), or to maximize flow resistance (Davies and Sutherland, 1983). These turn out to be generally equivalent propositions (White *et al*., 1982; Davies and Sutherland, 1983; Millar, 2005). Recent work has incorporated bank strength as an important constraint on the system adjustment (Millar and Quick, 1993, 1998; Eaton, 2006) because of its influence on channel width. Accordingly, we can now successfully model the downstream hydraulic geometry of a wide range of streams (Eaton and Church, 2007) and can predict the threshold separating single-thread and multichannel patterns (Millar, 2000; Eaton *et al*., 2010). Here, we use a physically based regime model (UBCRM) to predict the steady state channel dimensions that will be associated with the regulated flow regime of Peace River.

The Regulation of Peace River: A Case Study for River Management, First Edition. Michael Church.

Companion website: www.wiley.com/go/church/peaceriver

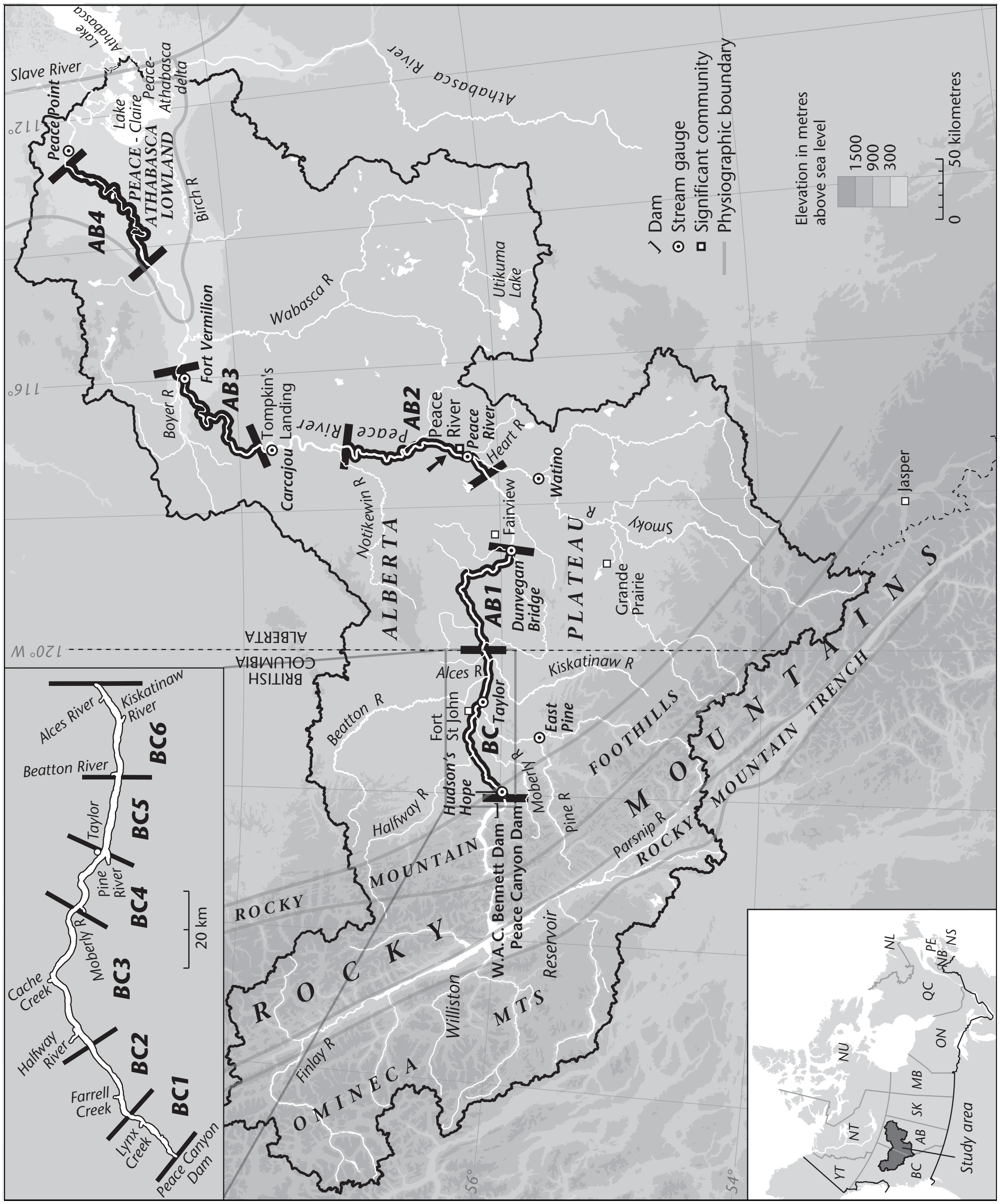

Figure 11.1 Map of the gravel-bed reach of Peace River, showing sub-reaches adopted for modeling hydraulic geometry.

11.2 Modeling approach

UBCRM (University of British Columbia Regime Model) calculates the stable channel dimensions of a self-formed alluvial stream based on estimates of the formative discharge (Q), the reach-average energy gradient (S), the median surface grain size (D_{50}) and the 90th percentile of the surface grain size (D_{90}). The value of D_{50} is used to estimate the sediment transport capacity of a given channel configuration in the model, while the value of D_{90} is used to determine the flow resistance parameter using Ferguson's (2007) function. The D_{90} value is also used to determine the threshold for bank erosion following the approach described by Millar and Quick (1993), assuming that the critical dimensionless Shields number (τ_{*c}) for such large, presumably exposed particles is 0.01 (after Fenton and Abbott (1977)). It is also assumed that the value for D_{90} measured on the channel bed is representative for the lower banks of the river, as it appears to be both from field investigations and from consideration of the lateral style of instability of the river. The version of the UBCRM used in this work adopts the bank strength formulation proposed by Millar and Quick (1993), in which bank strength is represented as a modified friction angle (φ'). The model seeks a stable channel configuration consistent with the imposed channel gradient and incoming streamflow and sediment flux. In the absence of information about the sediment load, a sediment transport formula is used to compute the sediment load at "hydraulic capacity" (i.e., on the assumption that the load is transport-limited); this is equivalent to maximizing the flow resistance for the river system for a constant sediment transport capacity (Eaton *et al.*, 2004). Considering the channel bed condition, we adopted the Parker surface-based bedload transport formula (Parker, 1990) for modeling the British Columbia reach and Reaches AB1 and AB2. For AB3 and AB4, beyond Carcajou, we used the van Rijn formula (van Rijn, 1984) for sand-bed channels. A similar modeling approach was applied to the anabranches of Fraser River (Eaton and Church, 2007), the hydraulic geometry of which is consistent with a bank strength friction angle of $\varphi' = 30^{\circ}$, approximating the lower repose angle for noncohesive clastic sediments.

Peace River is similar to Fraser River in that it exhibits a partly anabranched channel pattern and has a gravel bed at least as far downstream as TPR. Unlike Fraser River, the division of flow between the individual anabranches is not known. Therefore, applying the UBCRM was not a straightforward proposition. We proceeded by first calibrating the UBCRM to the measured widths of single-thread sections of the river as evident on maps of the channel as it existed prior to regulation. The calibration consisted of adjusting the bank strength parameter (φ') to match the width predicted by the model to the median width measured from the maps. Once the UBCRM had been calibrated, the formative discharge was changed to reflect the post-regulation flow regime, and the model was run again to predict the regime geometry of single-thread sections of Peace River. These predictions were then compared against measurements of single-thread widths from the most recent set of maps.

Table 11.1 presents the input data used by the UBCRM. Since the data of energy gradient, S, and the two surface grain sizes (D_{50}, D_{90}) are associated with some degree of uncertainty (due primarily to local variations within the reach), there is some uncertainty about the predictions made by the UBCRM. To represent the effect of this uncertainty, we have used a Monte Carlo modeling approach in which we specified ranges of input parameters and ran the UBCRM model multiple times, each time selecting a new set of input parameters randomly from within the specified ranges. The result is an estimate of both the mean and the plausible range for the modeled channel geometries. These distributions have been compared with the mean and range of the measurements to constitute a strong test of the model (Church, 2003).

In a subsequent set of analyses, we used the UBCRM to estimate how the channel pattern in the BC reach might adjust following regulation. The BC reach has the greatest number of anabranches and experienced the largest relative change in formative discharge, so is the most informative reach for comparison. During a second set of Monte Carlo simulations, we imposed a critical threshold width-to-depth ratio (W/d) of 60. Channels wider than this threshold are assumed to be susceptible to the formation of mid-channel bars which may develop into vegetated islands, and therefore channels with $W/d = 60$ are at the upper end of the stable single-thread domain (Eaton *et al.*, 2010). For single-thread regime predictions that are above this threshold, the discharge is divided in half, and the stability of two equally large anabranched channels is assessed; if these anabranches are wider than the threshold, the

Table 11.1 Input parameters for the UBCRM

Reach	Regime model input variables				
	Q (m^3s^{-1}) pre-regulation	Q (m^3s^{-1}) post-regulation	S range (m/m)	D_{50} range (mm)	D_{90} range (mm)
BC1	5843	1900	0.000624	75	156
			0.000920	103	234
BC2	5843	1900	0.000550	40	116
			0.000624	96	178
BC3	5890	1940	0.000510	39	95
			0.000624	81	177
BC4	5900	1950	0.000470	43	93
			0.000624	67	139
BC5	7213	2945	0.000302	47	95
			0.000480	73	129
BC6	7400	3150	0.000302	33	78
			0.000400	60	118
AB1	7600	3300	0.000302	24	73
			0.000302	40	109
AB2	9760	5940	0.000180	16	94
			0.000340	28	142
AB3	9800	5950	0.000050	0.75	2.3
			0.000065	1.3	3.8
AB4	9820	5950	0.000058	0.24	0.31
			0.000058	0.30	0.37

discharge is divided into three equal anabranches, and so on. This provides a means of assessing the likely number of anabranches to be found in the pre-regulation regime configuration, as well as the change in the frequency of anabranches expected for the regime channel that is to be associated with the current, regulated flow regime. The model remains simplistic insofar as field evidence shows that anabranches do not divide the flow equally.

The British Columbia reach of the river has been divided into six sub-reaches (Figure 11.1), averaging about 25 km in length. Estimates of Q, S, D_{50}, and D_{90}, have been derived accordingly (Table 11.1). In the Alberta Peace River, where our data of bed material grain size, in particular, is much less detailed, we make predictions for entire reaches averaging 150 km in length (Figure 11.1). The estimates of the pre- and post-regulation values of discharge come from an analysis of the available flow records along the river (see Chapter 5). The average energy gradient for each British Columbia sub-reach was calculated in two ways: in the first instance, S was calculated using elevation differences between monumented cross-sections along the river, while in the second, it was calculated by interpolation from Google Earth® imagery. The preferred value and uncertainty in the estimates of D_{50}, and D_{90}, were calculated by determining the mean and variance of multiple samples in each sub-reach (see Figure 3.10). For the Alberta sub-reaches, gradient was estimated by interpolating surface elevations at reach limits from maps, and also using Google Earth®. Grain size was interpolated from a sparse, river-wide set of samples (see Figure 2.3). The uncertainty for D_{50} was assumed to be ±25%, while it was assumed to be ±20% for the D_{90}; these are the typical values calculated for the British Columbia sub-reaches.

In order to estimate the mean and range of channel widths for each sub-reach, we made measurements from a set of 1:20 000 scale maps drawn from orthorectified aerial photographs taken just prior to flow regulation, and a similar set of maps based on the most recent set of photographs. At 500-m intervals along the channel (approximating mean channel width), a cross-sectional profile was drawn perpendicular to the channel centerline, and the widths of bare (i.e., unvegetated) gravel and of water were recorded for all channels on the cross-section. The precision of the measurements is the order of ±10 m which, for a representative channel width of 500 m, represents ±2.0%, compounded for multithread channels to ±3.5% for three branches. From these data, we were able to estimate the total channel width at each cross-section and the number of anabranches at each section. We were also able to estimate the width of those sections where the channel was confined to a single thread, which is a suitable dataset against which to calibrate the UBCRM.

11.3 Results

Peace River is particularly favorable for examining the hydraulic response to regulation. For the first 101 km below Peace Canyon dam, the river flows on cobble gravel with no major tributary. The Pine River confluence at km 101 reintroduces a modest spring freshet to the river, which continues as a cobble-gravel channel to km 368, the Smoky River confluence. Smoky River is the main tributary of the system, delivering a MAF of 2520 m^3s^{-1} (daily basis, 1955 to 2011, measured at Watino, Alberta; Water Survey of Canada Station. 07GJ001), but exceptionally exceeding 8000 m^3s^{-1}, and the order of 15 to 20 million tonnes a^{-1} of sandy sediment. Below this confluence the bed is sandy gravel for 270 km to Carcajou, where a transition occurs to a sand bed. Hence we can examine the response of a channel with varying substrate types, bearing in mind that the relative effect of regulation declines downstream as well, most significantly at the two major tributary confluences.

Our sub-reaches BC1 to BC4 lie in the proximal, most highly regulated reach (Figure 11.1). Sub-reaches BC5 and BC6 and Alberta Reach AB1 lie downstream from Pine River. Reach AB2 lies mainly below the Smoky River confluence, while AB3 is immediately downstream of the gravel–sand transition. Reach AB4 lies in the distal Peace–Athabasca Lowland.

11.3.1 Observed changes in channel width

The analysis of the maps reveals at most modest changes in the distribution of total channel width, the width of single-thread channel sections and the number of anabranches in all reaches. The largest changes are evident for the distribution of total channel width.

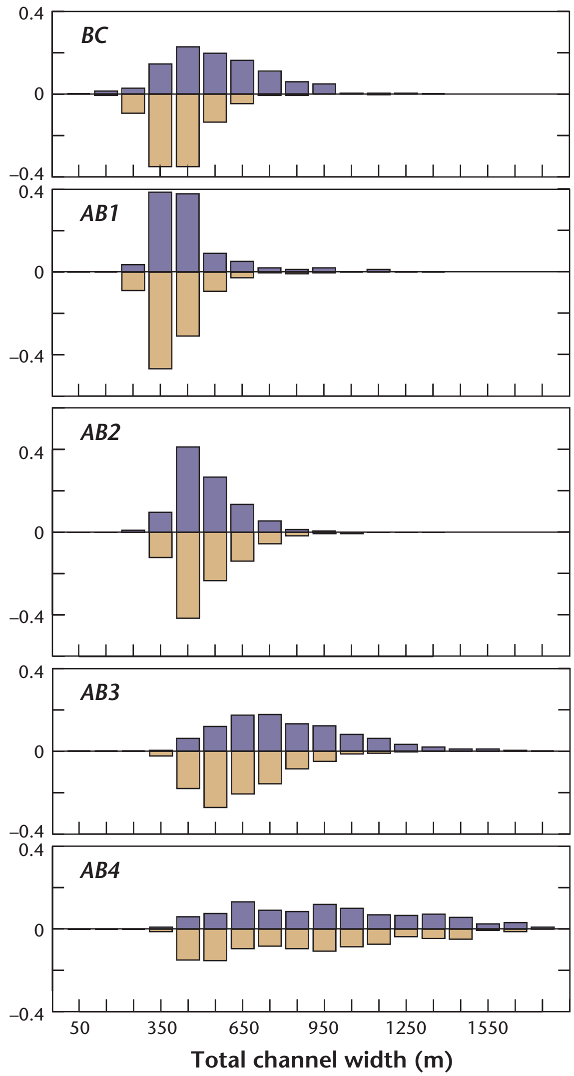

Figure 11.2 Distribution of observed total channel widths along five reaches of Peace River. In each panel, the pre-regulation distribution is shown in the upper histogram, and the post-regulation distribution is shown in the lower one.

Figure 11.2 shows the distribution of total widths pre- and post-regulation for all reaches along Peace River. Clearly, the modal channel width has shifted to a smaller value in the British Columbia reach and Reaches 3 and 4 in Alberta, indicating that the channel is responding to the regulation of flow. In addition, there appears to be a transition from a right-skewed distribution to a more symmetrical one since regulation in the British Columbia reach and Alberta Reach 3. Reaches 1 and 2

Table 11.2 Changes in observed width distributions for total channel width along Peace River

Reach		Total channel width statistics (m)				
		Minimum	1st Quartile	Median	3rd Quartile	Maximum
BC	Pre-reg.	160	424	547	689	1264
	Post-reg.	170	354	411	482	1127
	(Difference)	*(–6%)*	*(–17%)*	*(–25%)*	*(–30%)*	*(–11%)*
AB1	Pre-reg.	263	368	412	482	1140
	Post-reg.	237	351	386	439	939
	(Difference)	*(–10%)*		*(–6%)*	*(–9%)*	*(–18%)*
AB2	Pre-reg.	217	446	500	587	978
	Post-reg.	326	435	495	587	1065
	(Difference)	*(+50%)*				*(9%)*
AB3	Pre-reg.	383	646	781	967	1692
	Post-reg.	375	525	617	758	1233
	(Difference)		*(–19%)*	*(–21%)*	*(–22%)*	*(–27%)*
AB4	pre-reg.	346	683	942	1212	2000
	post-reg.	308	558	812	1077	1942
	(Difference)	*(–11%)*	*(–18%)*	*(–14%)*	*(–11%)*	

Note: only changes larger than 5% of the pre-regulation value are identified in the table.

in Alberta show no discernible change in width distribution: the former is a largely confined reach and the latter is severely disturbed by ice jams (Chapter 5). These results are consistent with findings from the investigation of morphological change (Chapter 7).

The data of observed channel width have been analyzed quantitatively by comparing various statistical metrics associated with the pre- and post-regulation widths (see Tables 11.2 and 11.3). In the British Columbia reach, the minima for the total width and

Table 11.3 Changes in observed width distributions for single-thread sections of Peace River

Reach		Single-thread channel width statistics (m)				
		Minimum	1st Quartile	Median	3rd Quartile	Maximum
BC	Pre-reg.	160	372	434	583	1264
	Post-reg.	170	327	374	419	827
	(Difference)	*(+6%)*	*(–12%)*	*(–14%)*	*(–28%)*	*(–35%)*
AB1	Pre-reg.	263	368	404	439	1140
	Post-reg.	237	333	377	421	649
	(Difference)	*(–9%)*	*(–9%)*	*(–9%)*		*(–43%)*
AB2	Pre-reg.	217	435	478	544	826
	Post-reg.	326	424	478	576	1000
	(Difference)	*(+50%)*			*(+6%)*	*(+22%)*
AB3	Pre-reg.	383	575	683	905	1692
	Post-reg.	375	483	567	683	1133
	(Difference)		*(–16%)*	*(–17%)*	*(–25%)*	*(–33%)*
AB4	Pre-reg.	346	606	779	1055	2000
	Post-reg.	308	500	586	851	1942
	(Difference)	*(–11%)*	*(–18%)*	*(–25%)*	*(–19%)*	

Note: only changes larger than 5% of the pre-regulation value are identified in the table.

the single-thread width distributions do not change by more than 6% of their original values, but all other metrics (i.e., median, upper and lower quartiles, and the maximum) have been reduced by more than 10% since regulation. Furthermore, the wider-than-average channels generally have experienced larger proportional changes, resulting in more symmetrical distributions of width about the median value (see Figure 11.2). Reaches 1 and 2 in Alberta have been relatively unaffected by regulation. While changes of greater than 10% have been recorded for distribution minima and maxima, the more reliable estimates of the distribution quartiles have remained virtually unchanged. In contrast, Alberta Reaches 3 and 4 clearly have changed since regulation. The median and the quartiles have all declined. The reductions in the median total width are largest in the BC reach (at 25%), and they decline downstream, with values in Alberta Reaches 3 and 4 estimated to be 21% and 14%, respectively.

11.3.2 Observed changes in channel pattern

Using the data collected for each reach from the two sets of maps of Peace River, we calculated the proportion of the cross-sections within the reach having one, two, three, or four active channel threads (none had more than four anabranches), which provides us with estimates of the proportion of each reach with a particular channel pattern. Table 11.4 compares the pre- and post-regulation values for each reach. The British Columbia reach has a single-thread pattern for just under half of the reach length before and after regulation—most of that above the confluence with Pine River. Since regulation, the percent of the British Columbia reach exhibiting two active channels has increased from 32% to 41%, while the percent of the reach exhibiting more than two channels has declined from 21% to 13%. The two sets of numbers are largely reciprocally related, reflecting the reduction of multithread sections to ones with just two remaining branches.

Alberta Reach 1 has a single-thread pattern for most of its length (about 84%), reflecting the confined nature of most of the reach, and the distribution of channel patterns has not changed much, although there has been 3% increase in the frequency of sections with two channels at the expense of single-thread section frequency where sedimentation has occurred at Many Islands and Montagneuse River. Alberta Reach 2 was similarly unaffected by regulation, exhibiting a single-thread pattern about two-thirds of the time and most of the channel splits occurring about major islands. Alberta Reach 3 has single-thread sections (for about 50% of its length), sections with two anabranches (about 44%), and occasionally sections with three anabranches (about 6%), but the distribution of channel patterns does not seem to have been affected by regulation. Again, most of the

Table 11.4 Changes in observed frequency of single-thread and anabranched sections of Peace River

Reach		1 Channel	2 Channels	3 Channels	4 Channels
BC	Pre-reg.	0.47	0.32	0.18	0.03
	Post-reg.	0.46	0.41	0.12	0.01
	(Difference)		*(+0.09)*	*(−0.06)*	
AB1	Pre-reg.	0.85	0.11	0.02	0.02
	Post-reg.	0.82	0.14	0.03	0.01
	(Difference)	*(−0.03)*	*(+0.03)*		
AB2	Pre-reg.	0.67	0.32	0.01	
	Post-reg.	0.68	0.31	0.01	
	(Difference)				
AB3	Pre-reg.	0.48	0.44	0.07	0.01
	Post-reg.	0.51	0.43	0.06	
	(Difference)	*(+0.03)*			
AB4	Pre-reg.	0.53	0.35	0.10	0.02
	Post-reg.	0.55	0.39	0.05	0.01
	(Difference)		*(+0.04)*	*(−0.05)*	

Note: only changes larger than 0.02 are identified in the table.

divided channels in this reach are divisions about major islands in meander bends. Alberta Reach 4 is similar to Reach 3, but there has been a decline in the frequency of sections with three anabranches (from 10% to 5%) and a corresponding increase in the frequency of sections with two anabranches (from 35% to 39%). With the exception of the results from this last reach, it appears that channel pattern changes are concentrated in the British Columbia reach, which has had the greatest frequency of multiple thread sections both before and after regulation and which has exhibited the greatest changes in the frequency of the different channel patterns.

11.3.3 Predicted channel changes: single thread widths

The UBCRM was calibrated to the pre-regulation channel dimensions for the single-thread sections by varying the bank strength parameter (φ') to produce the best agreement between model predictions and observed widths for each reach in Alberta and for each sub-reach in BC. Then, the estimates of the post-regulation flows were used to make predictions of the post-regulation regime condition. Since the UBCRM runs numerous Monte Carlo simulations for each reach, in which input parameter sets are chosen randomly from a distribution of input values representing the uncertainty associated with each input parameter, the predictions are best represented as distributions; we used a Gaussian kernel function to estimate the probability density at 100 equally distributed points that cover the range of the predictions, which produces a smooth, continuously varying representation of the distribution.

Figure 11.3 presents the analysis of the single-thread sections in the six sub-reaches in British Columbia; in this analysis no consideration was given to channel pattern. The predictions of the post-regulation widths are all very different from the pre-regulation conditions, with virtually no overlap of the range of predictions. Generally, the predicted post-regulation mode is about half the pre-regulation mode (Table 11.3)—smaller than empirically predicted. The observed post-regulation widths are more consistent with the pre-regulation predictions in sub-reaches 1 to 5; only sub-reach 6 exhibits a distribution of widths that is more similar to the post-regulation UBCRM predictions than to the pre-regulation predictions. Generally speaking, the relative degree to which single-thread

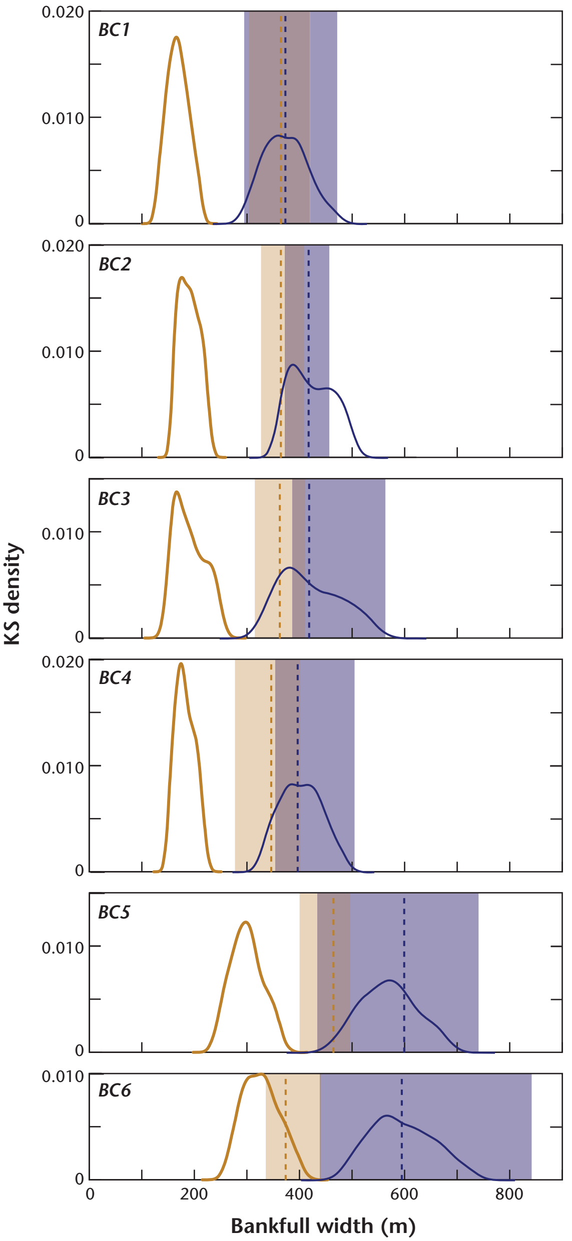

Figure 11.3 Single-thread regime predictions for six sub-reaches in the BC reach of Peace River. The distribution of post-regulation single-thread channel widths predicted by the UBCRM is displaced to the left of the measured pre-regulation distribution. The distributions are shown as smoothed density plots while the medians and interquartile ranges are shown as vertical lines (median value) and shaded regions (interquartile range): the post-regulation predicted range is cross-hatched.

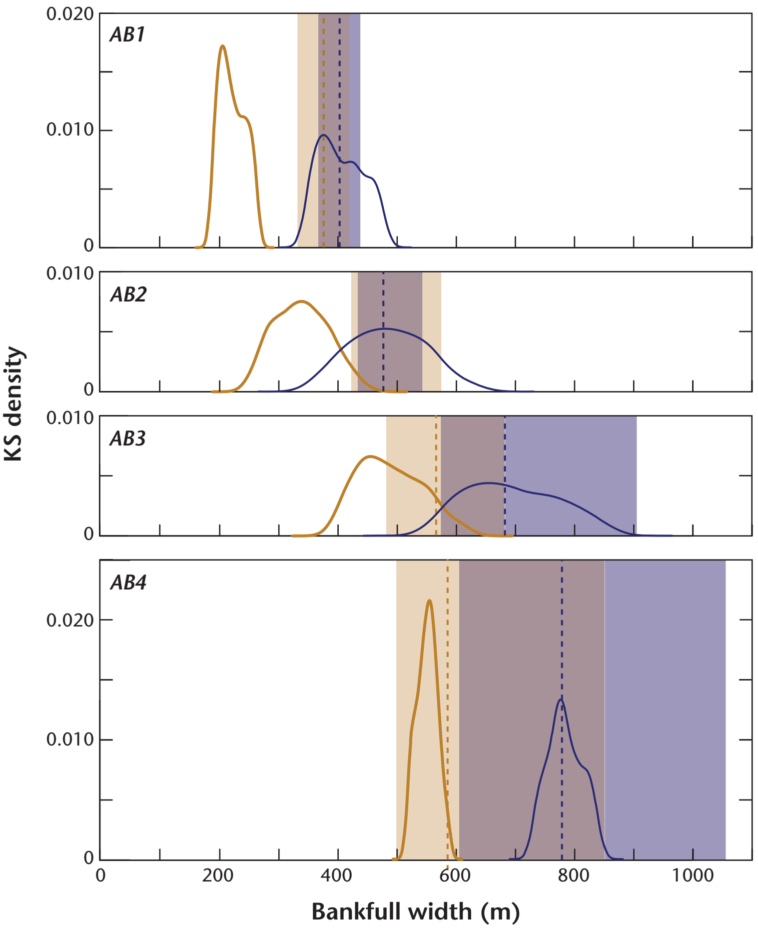

Figure 11.4 Single-thread regime predictions for four Alberta reaches of Peace River. The distribution of pre-regulation measured and post-regulation predicted single-thread widths are shown as smoothed density plots. The median and interquartile ranges of pre-regulation width distributions for single-thread sections measured from maps and post-regulation predictions are shown using the same conventions as in Figure 11.3. Post-regulation values are displaced to the left of pre-regulation ones.

channel width has shifted from the pre-regulation conditions towards the post-regulation UBCRM prediction increases with distance downstream from the Peace River Dam.

The results of this analysis for the reaches in Alberta are shown in Figure 11.4. For all of the reaches, the UBCRM predicts a significant change in the channel dimensions for single-thread sections following regulation. The post-regulation predicted widths for Reaches 1 and 4 do not overlap at all with the pre-regulation predictions, and the post-regulation distribution modes are about 40% smaller than the pre-regulation modes in both cases (in accord with empirical predictions). Both the observed pre- and post-regulation width distributions are represented in Figure 11.4. The widths in Reach 1 have changed very little, and in fact the post-regulation observations are still consistent with the pre-regulation predictions. In contrast, the observed widths in Reach 4 have shifted somewhat toward smaller values, and are consistent with the higher estimates of the regime width from the UBCRM. Nevertheless, there is no suggestion that either reach has returned to regime conditions.

UBCRM predicts smaller reductions in width for Reaches 2 and 3, and the range of the pre- and post-regulation width predictions overlap substantially. The post-regulation modes are about 30% smaller than the pre-regulation ones. The observed widths indicate that there has been almost no post-regulation adjustment in Reach 2, and that the changes in Reach 3—while significant—are not consistent with that reach having attained a regime configuration.

11.3.4 Predicted channel changes: channel pattern

In order to assess potential changes in channel pattern, we imposed a channel bifurcation threshold (associated with a critical *W/d* ratio of 60), and used the UBCRM to predict the minimum number and dimensions of stable anabranches for the Monte Carlo simulations. These simulations provide estimates of the channel pattern frequency and of the total channel width. In Figure 11.5, the results of the analysis are compared with the range (and median) of the pre-regulation observed total channel width for each of the British Columbia sub-reaches. Each of the peaks in the pre-regulation predicted distributions correspond to a pattern with a different number of anabranches. For the pre-regulation conditions, the analysis commonly predicts single-thread and double-thread patterns, while three anabranches are predicted somewhat less commonly; this generally agrees with the observed pre-regulation channel pattern frequency (see Table 11.4). The range of channel widths predicted by the UBCRM using this approach also agrees tolerably well with the range of observed total widths, lending additional support to this approach.

For post-regulation conditions, the UBCRM predicts that channel pattern should change dramatically. The analysis predicts that, at regime, the river should exhibit a dominantly single-thread pattern in sub-reaches 1 to 4. For sub-reaches 5 and 6, the dominant pattern is predicted to be single-thread, with occasional sections with two anabranches. For all sub-reaches, the post-regulation total widths are predicted to be much reduced, generally falling below the range of the pre-regulation total widths. The relatively minor changes to the channel pattern that have been documented in the British Columbia reach suggest that channel pattern has not adjusted to the post-regulation regime state predicted by the model.

The predicted new equilibrium channel widths are given in Table 11.5, showing ultimate predicted adjustments varying from 55% immediately below the dams to 30% in the most distal reaches.

11.3.5 A test for consistency

The UBCRM returns estimates of bedload transport in the river based on the assumption of hydraulic capacity. Estimates of bedload delivered by various tributaries and of bedload caliber material transported at TPR have been made by independent means (Chapter 2), with which UBCRM predictions may be compared. Table 11.6 displays the data. For purposes of analysis we have chosen the computed transport for the median of the distribution of single-thread channels. Those values are reported as transport rate in mineral volume measure.

The comparison of estimated tributary contributions with the estimated transport capacity of the river is not exact since the former takes account of the annual distribution of flows, whereas the latter is computed for steady flow at the selected dominant discharge, which is MAF in both the natural and regulated regimes. The transport rate has been multiplied up to an annual volume transported by the fraction of time during which flow in each reach exceeds 1000 m^3s^{-1}, which is a flow capable of mobilizing material of at least two millimeter diameter in all reaches, hence sand at least will be moved. Fine gravel is apt to be moved at that flow as well if it is available in the channel, but most of the bedload transport will occur when flow approaches the MAF value. Computed tributary inputs of bedload are compared with the computed transport in the reach into which they flow. None of the figures can be regarded as precise, but the comparisons correspond with observed experience along the river.

In the natural regime, the indicated bedload transport capacity of Peace River above the Pine River junction matches or exceeds computed tributary inputs, consistent with the indication of historical air photos. Indeed, below the Moberly confluence the sum of the two principal tributary inputs just matches the estimated transport capacity of the mainstem river. However, Pine and Kiskatinaw Rivers appear to deliver more material than Peace River was able to move away, consistent with the appearance of substantial sediment deposits in Sub-reaches BC5 and BC6, where the channel was (and is) frequently multithread. At the Alberta border, the bedload transport estimated from UBCRM results is commensurable with the independently calculated value, within a reasonable margin for the comparison. In the Alberta reach, the estimated transport capacity below Smoky River is commensurable with the estimated bedload fraction of the Smoky River sediment contribution (this derived from sediment budget considerations, not from independent bedload calculations), and estimated transport in the lower river remains commensurable with that quantity.

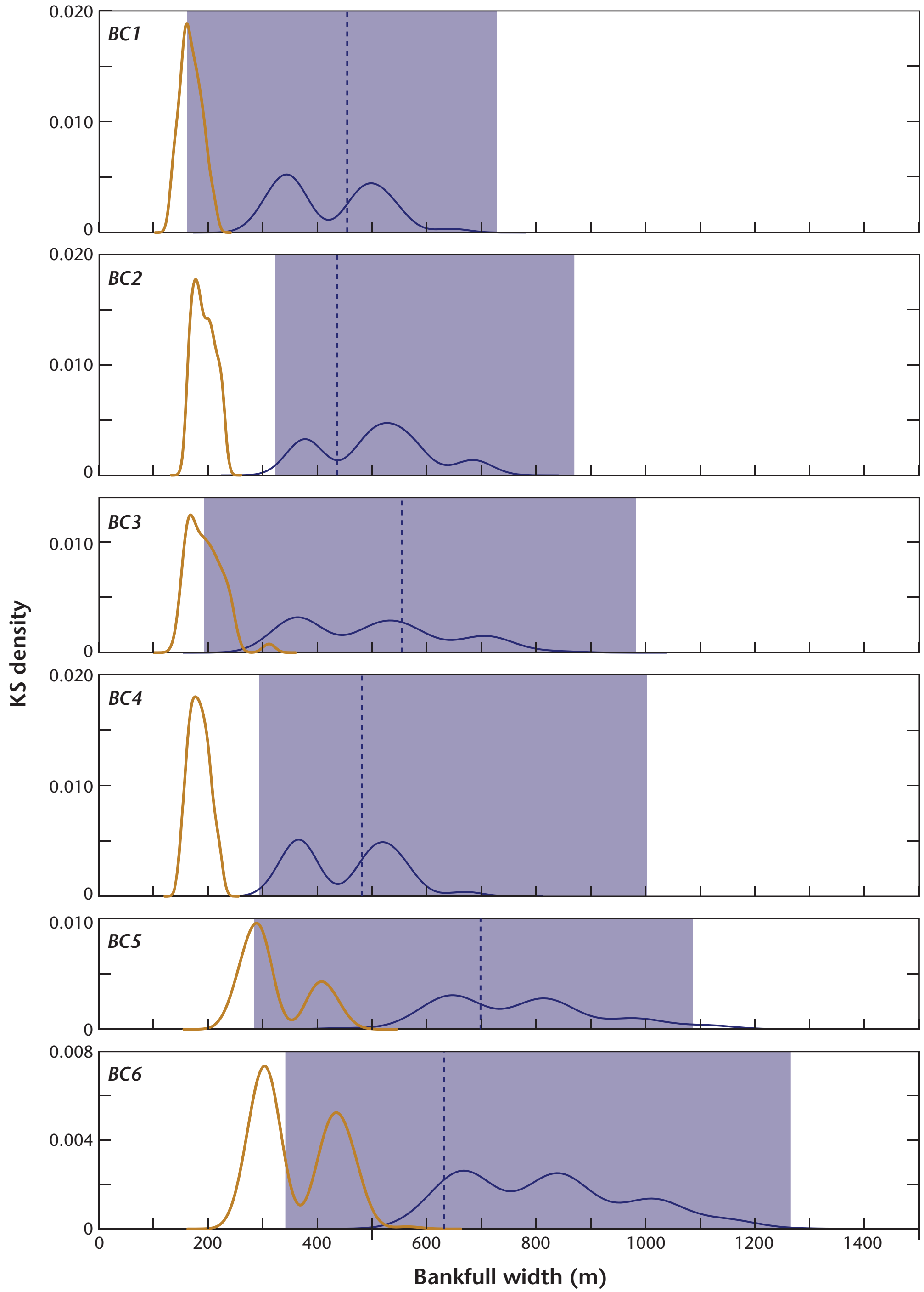

Figure 11.5 Regime-based predictions of channel pattern and total channel width for six sub-reaches in the BC reach of Peace River. The distribution of pre-regulation measured and post-regulation predicted widths (dashed line) are shown as smoothed density plots. The median and interquartile range of the total pre-regulation channel width distribution are shown using a line and shaded area, respectively.

Table 11.5 Modeled changes in equilibrium widths for single-thread sections of Peace River

Reach		Single-thread channel width predictions (m)		
		1st Quartile	Median	3rd Quartile
BC1	Pre-reg.	340	371	401
	Post-reg.	153	168	183
	(Difference)	*(–55%)*	*(–55%)*	*(–54%)*
BC2	Pre-reg.	388	419	458
	Post-reg.	175	189	206
	(Difference)	*(–55%)*	*(–55%)*	*(–55%)*
BC3	Pre-reg.	374	411	467
	Post-reg.	166	187	214
	(Difference)	*(–56%)*	*(–55%)*	*(–54%)*
BC4	Pre-reg.	373	402	433
	Post-reg.	169	181	197
	(Difference)	*(–55%)*	*(–55%)*	*(–55%)*
BC5	Pre-reg.	529	568	607
	Post-reg.	278	299	319
	(Difference)	*(–47%)*	*(–47%)*	*(–47%)*
BC6	Pre-reg.	551	589	639
	Post-reg.	300	325	351
	(Difference)	*(–46%)*	*(–45%)*	*(–45%)*
AB1	Pre-reg.	375	402	437
	Post-reg.	206	221	242
	(Difference)	*(–45%)*	*(45%)*	*(–45%)*
AB2	Pre-reg.	438	486	536
	Post-reg.	305	340	374
	(Difference)	*(–30%)*	*(30%)*	*(–30%)*
AB3	Pre-reg.	634	687	755
	Post-reg.	447	485	531
	(Difference)	*(–30%)*	*(–29%)*	*(–30%)*
AB4	Pre-reg.	763	781	805
	Post-reg.	540	553	563
	(Difference)	*(–29%)*	*(–29%)*	*(–30%)*

After regulation, transport in the upper river is reduced to near-zero, consistent with the observed accumulation of bed material at all confluences. Local degradation—signifying movement of bed materials has been recorded, however, in exceptional flows (Chapter 10). Below the Smoky River confluence the decline in the transporting capacity of Peace River is significantly modulated both by the increased freshet flows and the declining size of the bed material, such that a substantial portion of the material delivered by Smoky River can be moved on. Indeed, most of that material is relatively fine and nearly all of it is redistributed along the river beyond the confluence.

The very approximate nature of this comparison notwithstanding, the results lend confidence that the UBCRM has reasonably diagnosed the eventual equilibrium geometry of the regulated river.

11.4 Time scales for channel adjustment

All evidence, consistent with what has been found in previous chapters, is that the channels of Peace River have not adjusted to the regulated regime of flow. What, then, may be the time scale for full adjustment of Peace River to the regulated regime? This question may be considered from the perspective of the time scale for riparian vegetation to colonize and stabilize exposed channel banks and bar surfaces, from the time scale for

Table 11.6 Comparison of bedload transport estimates in Peace River

Reach/ sub-reach	Tributary	Tributary input (m^3a^{-1} mineral)	UBCRM natural	Transport (Q_{b50})[a] regulated	Ratio reg./nat.	Ratio trib./reg.
			British Columbia			
1			1400	40	0.028	
2			700	25	0.036	
3	Halfway	1530	2600	100	0.038	15
4	Moberly	8230	9800	250	0.026	33
4	*BCR bridge*			*0*		
5	Pine	1010	10	0	0.00	inf.
6	Kiskatinaw	3110	395	40	0.10	78
6	Alberta border	*625*	395	40	0.10	*16*
			Alberta			
AB1			130 000	18 000	0.14	
AB2	*TPR*	*1 700 000*	1 500 000	990 000	0.39	*1.7*
AB3			2 100 000	1 800 000	0.86	
AB4			2 200 000	2 200 000	1.0	

Results in italic are based on transport in Peace River mainstem.

[a]Based on bedload at hydraulic capacity as computed in UBCRM for the prescribed "dominant" flow, multiplied up by the time during the year when, on average, flows exceed 1000 m^3s^{-1}. At this flow level, the river is everywhere capable of moving grains of at least two millimeter diameter. See text for further discussion.

sufficient sediment recruitment to effect the indicated shrinkage of the channel section, or from the perspective of transfer of sediments through the length of the river to accomplish gradient adjustments as well as section reshaping.

Vegetation succession might ordinarily be expected to operate on a time scale of about a century for development of a mature, cottonwood-dominated riparian forest. Along Peace River, however, the process is observed to be substantially hindered by winter ice action, most dramatically in Alberta Reach 2 (see Chapter 6). In the British Columbia reach, ice cover and ice action have been limited by virtue of the schedule of winter flow releases, deliberately manipulated to limit ice effects. Nevertheless, succession remained slow through the first quarter century of "normal" regulated flows. One reason for that might be the arid nature of the gravel bar surfaces. The 1996 flood thoroughly soaked these surfaces for the first time and that event was followed by the appearance of significant seed germination, but the 2005 mapping of riparian vegetation does not bear out a significant acceleration in vegetation establishment. It is estimated (Chapter 7) that rates of channel width reduction, effected almost entirely by vegetation progression have varied by between 1% and 5% per annum. This proportional figure gives rise to an equation for the approach to the new equilibrium width

$$w_{eq}/w_{in} = \exp[-pt_{eq}], \qquad (11.1)$$

in which w_{in} is the initial width (width at the inception of regulation), w_{eq} is the predicted equilibrium width under regulation, p is the proportional rate of width reduction (expressed as a fraction), and t_{eq} is the expected time to equilibrium. In the upper river, width is expected to decline to about 50% of its pre-regulation value (Table 11.5), that is, $w_{eq}/w_{in} = 0.5$, and in the lower river by about 30%. For the estimated values of p, t_{eq} in the upper river varies between 14 and 70 years; in the lower river it varies between 7 and 36 years.

A second approach to width equilibrium after regulation stems from the observation that, from the time of establishment of "normal" regulation flows (1973), the rate of progression into the channel zone of riparian vegetation has been approximately linear (see Figure 7.10). Applying the observed linear rates to the median estimates of expected change in width (Table 11.5) yields the results given in Table 11.7. Time scales are similar to the 70-year value calculated above except in Reaches

Table 11.7 Time to equilibrium regulated width (linear rate)

Reach	Δw (m)	dw/dt (m a^{-1})	t_{eq} (a)
BC	235[a]	3.5	67
AB1	181	1.4	129
AB2	146	0	–
AB3	202	4.0	51
AB4[b]	228	2.6	87

[a]Mean of six sub-reaches; variance is small.

[b]Based on progression rate in AB4a. Rate is smaller in AB4b but data are incomplete.

AB1 and AB2, where they are longer—essentially no actual change occurring in the second case—due to ice effects. We conclude that the time scale for width adjustment through riparian vegetation succession will be on the order of a century.

Sedimentation as an agent of morphological adjustment must accommodate both lateral change in the channel cross-section (in part an adjunct of riparian succession) and longitudinal adjustment of the river gradient. The latter, which encompasses redistribution of sediments along the entire length of the channel, will dominate the time scale for morphological adjustment. Strictly assessed, this would involve a morphodynamic model of the river operated on a long time scale: sediment transport formulations are insufficiently precise for this to be feasible. An alternative is an approximate formulation due to deVries (1975). He proposed the criterion

$$t_{50} = L^2/Y \quad (11.2a)$$

$$Y = bQ_b/3wS \quad (11.2b)$$

wherein t_{50} is the time for channel bed adjustment to be 50% complete, S is channel gradient, Y is a sediment diffusivity coefficient, b is the exponent of a bed sediment transport relation, Q_b is the mean annual *bulk* volume of the bed material transported (about 1.6 times the mineral volume), w is river channel width. Subsequent investigators (Dade and Friend, 1998; Métivier, 1999) have proposed variations on this formulation, while DiSilvio and Nones (2014) have recently abstracted similar approximations from simplified analyses of long profile adjustment to a sediment supply perturbation. Depending on the exact time scale selected (the diffusive effect is asymptotic, so no final time can be given), differences of $O[1]$ are observed amongst the formulations, but they do not materially affect the order of magnitude results, considering that they are all gross approximations. Here, we adopt deVries's original formulation.

Data for the calculations are given in Table 11.8. The results imply that the river, through Reach AB2, will never achieve the estimated equilibrium geometry, while in the distal, sandy reach of the river, the time to equilibrium is the order of 10^4 years. These results hold qualitatively even if the 1D equations are in error by as much as an order of magnitude. The reason for the failure to approach equilibrium geometry in the upper river is simply the lack of sediment transporting capacity, an issue that might be resolved if a "flushing flow" strategy were to be adopted to episodically pass significant flood flows through the river. (Note that sediment transport appears in the numerator of Equation 11.2b, which places it in the denominator of Equation 11.2a, accordingly it has an inverse effect on time scale.) More generally, the effectively infinite time scale for the upper river quantifies the implications of "passive response," as defined by Petts (1984), for the river system. The surprisingly long time scale, even in the distal portion of the river—least affected by regime change—is in fact supported by estimates of adjustment times the order of 10^3 to 10^5 years in other major rivers (deVries, 1975; Williams and Wolman, 1984; Dade and Friend, 1998; Métivier and Gaudemer, 1999; Castelltort and Van Den Driessche, 2003). The effect arises simply in view of the large distances over which the adjustment must be distributed.

These results reinforce the lesson that the river response to regulation, except in the most distal reaches, is largely passive, because of the reduction in bed material transport capacity in the normal regulated regime. Practically, vegetation succession on the timescale of 10^2 years will dominate the visible response. After a century, further modification of the channel will slowly continue but the signal of flow regulation will be lost in the overall effect of changing environmental conditions predicated on human activity and regional hydroclimatic change.

11.5 Conclusions

We have employed a rational regime model, UBCRM, to predict the equilibrium width of the regulated river. It indicates that reduction of channel width of about 50% might be expected in the upper river and of about

Table 11.8 Data of river equilibration problem

Parameter	Dimensions	Upper river		Lower river	
		BC1/4	BC5/6 AB1	AB2	AB3/4
Bed material		Cobble	Cobble	Sandy gravel	Sand
L^a	m 101 000	125 000	267 000	481 000	
b^b	–	3	3	1.5	1.5
Q^c	m^3s^{-1}	1940	3000	5940	5950
S^d	–	0.00055	0.00040	0.00030	0.000060
w^e	m	374	411	478	575
$Q_b{}^f$	m^3a^{-1}	250	60	1.5×10^6	2.8×10^6
Y	m^2a^{-1}	1215	365	5×10^6	4×10^7
t_{50}	a	$O[10^7]$	$O[10^7]$	$O[10^4]$	6×10^3

Results in this table are different in detail from earlier results in Church (1995), as a result of more detailed data of expected changes along the channel, but the qualitative conclusions that may be drawn from the data are not changed.

[a]Reach length considered: the total distance considered excludes some gaps between the study reaches.

[b]Exponent in a bed material transport relation: in the upper river, the exponent is increased beyond the customary "full mobility" value in view of the coarse material, on the assumption that transport is always restricted to conditions near threshold.

[c]MAF in the regulated regime: some averaging is employed where more than one study reach is included.

[d]Reach average gradient: further averaging employed where more than one study reach is included.

[e]Observed width in the regulated regime (Table 11.3): averaging employed where more than one reach is included.

[f]Bed material transport as bulk value: adapted from Table 11.6.

30% in the lower river. The results are in general accord with predictions made from empirical hydraulic geometry (Chapter 5), implying that no change in regime type is expected to occur. However, only half or less of the expected adjustment has been observed in the first 40 years of regulated flows. Because the regulated flows lack the capacity to move the bed material of Peace River in significant quantity, the observed adjustment is largely the passive consequence of a shrinking active channel within the channel zone by the progradation of riparian vegetation across the former bar surfaces of the channel. Adjustment is even more constrained in Alberta Reaches AB1 and AB2, where seasonal ice scour effects further inhibit regime adjustment.

Overall equilibration of the long profile is projected to require a period comparable with the length of Holocene time in the distal, sandy portion of the river, and not to be practically achievable in the more proximal gravel-bed reaches. The reason is the relative lack of sediment transporting capacity of the river in the regulated regime. The major tributaries continue to deliver significant loads of bed material that accumulate near the confluence, contributing to the development of a stepped longitudinal profile (Chapter 3) that will come to characterize the river in the future.

Acknowledgments

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References

Brandt, S. A. (2000) Classification of geomorphological effects downstream of dams, *Catena*, 40, 375–401.

Castelltort, S. and Van Den Driessche, J. (2003) How plausible are high-frequency sediment supply-driven cycles in the stratigraphic record? *Sedimentary Geology*, 157, 3–13.

Chang, H. H. (1979) Minimum stream power and river channel patterns. *Journal of Hydrology*, 41, 303–327.

Church, M. (1995) Geomorphic response to river flow regulation: case studies and time scales. *Regulated Rivers: Research and Management*, 11, 3–32.

Church, M. (2003) What is a geomorphological prediction? in *Prediction in Geomorphology*, edited by P. R. Wilcock and R. M. Iverson. Monograph Series, vol. 135. American Geophysical Union, pp. 183–194.

Dade, W. B. and Friend, P. F. (1998) Grain-size, sediment-transport regime, and channel slope in alluvial rivers. *Journal of Geology*, 106, 661–675.

Davies, T. R. H. and Sutherland, A. J. (1983) Extremal hypotheses for river behavior. *Water Resources Research*, 19, 141–148.

deVries, M. (1975) A morphological time scale for rivers. *Proceedings of the 16th International Association for Hydraulic Research World Congress*, 2, 17–23, Jul 27–Aug 1, São Paulo, Brazil.

DiSilvio, G. and Nones, M. (2014) Morphodynamic reaction of a schematic river to sediment input changes: analytical approaches. *Geomorphology*, 215, 74–82. doi:10.1016/j.geomorph.2013.05.021

Eaton, B. C. (2006) Bank stability analysis for regime models of vegetated gravel bed rivers. *Earth Surface Processes and Landforms*, 31, 1438–1444.

Eaton, B. C. and Church, M. (2007) Predicting downstream hydraulic geometry: a test of rational regime theory. *Journal of Geophysical Research*, 112, F03025. doi:10.1029/2006JF000734

Eaton, B. C., Church, M., and Millar, R. G. (2004) Rational regime model of alluvial channel morphology and response. *Earth Surface Processes and Landforms*, 29, 511–529.

Eaton, B. C., Millar, R. G., and Davidson, S. (2010) Channel patterns: braided, anabranching, and single-thread. *Geomorphology*, 120, 353–364.

Ferguson, R. I. (2007) Flow resistance equations for gravel- and boulder-bed streams. *Water Resources Research*, 43, W05427. doi:10.1029/2006WR005422

Fenton, J. D. and Abbott, J. E. (1977) Initial movement of grains on a stream bed: the effect of relative protrusion. *Royal Society of London Proceedings, A. Mathematical and Physical Sciences*, 352, 523–537.

Kirkby, M. J. (1977) Maximum sediment efficiency as a criterion for alluvial channels, in *River Channel Changes*, edited by K. J. Gregory. John Wiley & Sons, Ltd, Chichester, UK. pp. 429–442.

Métivier, F. (1999) Diffusive-like buffering and saturation of large rivers. *Physical Review E*, 60, 5827–5832.

Métivier, F. and Gaudemer, Y. (1999) Stability of output fluxes of large rivers in South and East Asia during the last 2 million years: implications on floodplain processes. *Basin Research*, 11, 293–303.

Millar, R. G. (2005) Theoretical regime equations for mobile gravel-bed rivers with stable banks. *Geomorphology*, 64, 207–220.

Millar, R. G. (2000) Influence of bank vegetation on alluvial channel patterns. *Water Resources Research*, 36, 1109–1118.

Millar, R. G. and Quick, M. C. (1993) Effect of bank stability on geometry of gravel rivers. *Journal of Hydraulic Engineering*, 119, 1343–1363.

Millar, R. G. and Quick, M. C. (1998) Stable width and depth of gravel-bed rivers with cohesive banks. *Journal of Hydraulic Engineering*, 124, 1005–1013.

Parker, G. (1990) Surface-based bedload transport relation for gravel rivers. *Journal of Hydraulic Research*, 28, 417–436.

Petts, G. E. (1984) *Impounded Rivers: Perspectives for Ecological Management*, John Wiley & Sons, Ltd, Chichester, UK. 326 p.

Van Rijn, L. C. (1984) Sediment transport, part I: bed load transport. *Journal of hydraulic engineering*, 110, 1431–1456.

Yang, C. T. (1976) Minimum unit stream power and fluvial hydraulics. *Journal of the Hydraulics Division-American Society of Civil Engineers*, 102, 769–784.

White, W. R., Bettess, R., and Paris, E. (1982) Analytical approach to river regime. *Journal of the Hydraulics Division* [American Society of Civil Engineers], 108, 1179–1193.

Williams, G. P. and Wolman, M. G. (1984) Downstream effects of dams on alluvial rivers. *United States Geological Survey, Professional Paper*, 1286, 83 p.

CHAPTER 12
Implications for river management

Peace River is a northward flowing, boreal river that rises in the Rocky Mountain Trench of British Columbia and flows more than 1600 km east and north to the Peace–Athabasca delta, beyond which it becomes Slave River. It is a major tributary of Mackenzie River. In 1967 it was dammed for the generation of hydroelectric power at the front ridge of the Rocky Mountains in northeastern British Columbia. A second dam was subsequently constructed 20 km downstream in Peace Canyon. The 1200-km river course below the dams has consequently been subjected to a radically altered flow regime. This chapter presents a summary of the main lessons learned from a 55-year longitudinal study of the downstream river commencing 17 years before dam closure using air photographs and hydrological records, and field data collected from the early 1960s to present.[1]

Immediately below the dams the hydrological regime has been inverted, with high flows in winter varying around 2000 m^3s^{-1} for electricity generation, and low flows in summer in the range 350 to 700 m^3s^{-1} (Figure 12.1). Pine River, the first significant tributary 101 km downstream from the lower dam, reestablishes a weak, late spring freshet but it is not until the confluence with Smoky River, 368 km downstream, that a major freshet is reestablished. Yet at Peace Point, 1116 km from the dams, the mean annual flood is now only about 55% of its former value. However, there still remains the possibility for exceptional weather events to generate flows comparable with the highest ever recorded in the river. Figure 12.1 presents a summary comparison of the natural and regulated flow regimes of the river at key gauging stations along the river.

The river flows on bedrock immediately below the dams but, after about 20 km becomes a cobble-gravel bed river, a characteristic that continues to the Smoky confluence. That tributary introduces a large sand load to Peace River so that the bed becomes sandy gravel. Transition to a sand bed occurs near Carcajou, 650 km below the dams. An interesting aspect of the project is that the headwater region above the dams, which supplies half of the basin runoff from 24% of the basin area, features rocks that contribute relatively little sediment, while the plateau region east of the mountains and downstream from the dams lies in the Western Canada sedimentary basin where Mesozoic to Cenozoic rocks are mainly weakly lithified and highly erodible. The river, entrenched below the plateau surface along much of its course, is directly subject to valley side landslides, as are its tributaries. Hence, of the two principal governing conditions of river character, the water regime of the river has been severely altered, while the sediment regime, dominated by below-dam inputs, is little modified.

Because there is a major hydrological and sedimentological change in Peace River at the Smoky confluence, it is informative to consider the effects of river regulation in terms of the cobble-gravel "upper river"—upstream of the Smoky confluence—and the sandy "lower river" downstream.

In the cobble-gravel upper river, Kellerhals and Gill (1973) predicted that there would be no degradation because the dramatically reduced flows (the regulated mean annual flood immediately below the dams being only 33% of its unregulated value) would be unable to mobilize the bed material. This prediction has been confirmed: the river bed today is essentially immobile and the river is non-alluvial in the normal regulated flow regime. They further predicted that sediments injected

[1]The writer's field activity commenced in 1979. Earlier work was conducted by crews from British Columbia Hydro and Power Authority and their contractors.

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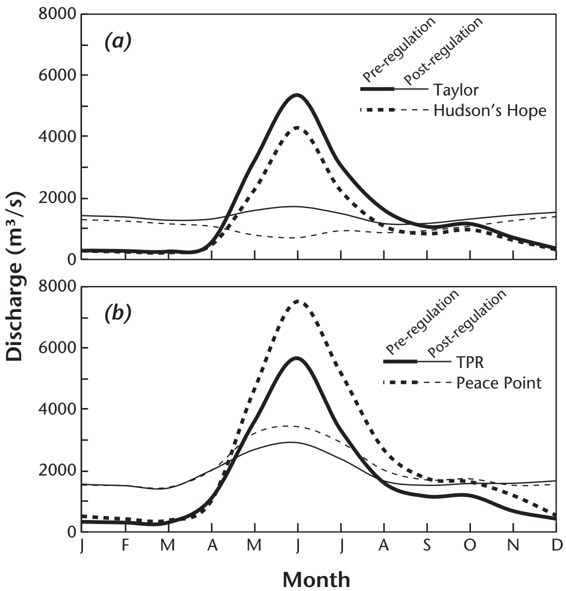

Figure 12.1 Natural and regulated flow regimes represented as monthly mean flows (a) for Hudson's Hope (immediately below the dams) and at Taylor (below the Pine River confluence) in the upper river, and (b) at TPR (below the Smoky River confluence) and at Peace Point in the lower river.

by significant tributaries would accumulate near the tributary junctions, leading to the development of a stepped long profile. We also observe this phenomenon in the upper river, with the additional occurrence of aggradation below major landslides—that is, immediately downstream from any significant sediment input. The response of the river can be described, then, as passive to mildly aggradational near tributary junctions, one of several possible outcomes enumerated by Petts (1984), but much less common than the downstream degradation that usually follows the interruption of sediment passage by a reservoir.

The river has not, however, become entirely passive. Exceptional flows, such as the weather-generated flood of 1990 and the reservoir drawdown flood of 1996, showed that gravels can still be moved within the channel. In 1990, injection of sediment from flooding tributaries led to a mainly aggradational response, not dissimilar to the normal response to regulation. However, the clearwater flood of 1996 effected significant degradation, largely in areas of the channel where aggradation had been the norm ever since regulation, as accumulated sediment was remobilized and moved downstream. This observation suggests that the regrading of the upper river will, in the long term, depend to a major degree on the occasional occurrence of exceptionally high flows—ones outside the range of normal regulated flows.

Aside from episodic, localized channel gradation, the main adjustment of the channel is the progression of riparian terrestrial vegetation onto former bar surfaces and abandoned channel edges. This phenomenon is pervasive along the river, but it is proceeding more slowly than might be expected from simple consideration of riparian vegetation dynamics because of the occurrence of high flows in winter accompanied by damage inflicted on young vegetation by rafted river ice. The result is to hold the succession in an earlier stage than it otherwise might have attained after 40 years of regulated flows.

A related issue is the maintenance of some secondary channels along the river that are dry under all open water regulated flows yet may carry water in winter, particularly when ice reduces conveyance in the main channel. The persistence of these channels has been an important factor in the passage of the major post-regulation floods along the river. There has nevertheless been a reduction in the number and length of secondary channels in the river, much of which was achieved at the time of initial regulation simply by the elimination of flows large enough to flood them.

The lower courses of tributaries (extending 1 to 10 km upstream at present) joining within at least the first 150 km below the dams have been affected by the flow regulation. Lower water levels in Peace River at the time of the main tributary freshets (snowmelt in April to May and summer rainstorm runoff) mean that they are flowing to an effectively lower base level than before, so that a knick point has progressed upstream from the confluence. Degradation is on the order of a meter, which is commensurate with the stage change that has occurred in Peace River at the time of tributary freshets. However, tributary degradation may be reduced or even eliminated by high sediment delivery, leading to the progradation of a fan delta from the tributary into Peace River. Such fans have developed at the mouths of many tributaries beyond the first 150 km and at the major gravel-yielding tributaries within that distance, and in some instances they existed before regulation. At these places the channel of Peace River has been constricted: width contractions may be as great as 50%. This is approximately the expected contraction that the entire channel will eventually undergo when fully adapted to the regulated flow regime. It is possible that the new equilibrium channel of upper Peace River is first becoming evident at tributary junctions where active sedimentation accelerates the normally passive process of adjustment.

The lower river has experienced a comparatively less radical change in the flow regime than the upper river; one may assert that basin-scale runoff generation rather than flow releases from the dam still dominate the hydrograph. Nonetheless, normal high flows have shrunk to 45 to 50% of their former magnitude. Smoky River reestablishes a significant annual snowmelt freshet and Peace River downstream remains competent to wash the substantial load of sand and fine gravel delivered from this tributary and mainstem through the immediate downstream reach. Beyond Carcajou and the gravel–sand transition, however, where channel gradient declines by a factor of about five, there is substantial sand deposition and shoaling of the channel. In this reach, lateral accretion of bars is prominent and riparian vegetation has prograded into parts of the channel zone, but the relative responsibility of real sedimentation and lower flows cannot be decisively determined with the information (derived entirely from planimetric maps) to hand.

The evolving hydraulic geometry of the river is consistent with the concept of a mainly passive response to flow regulation. The river everywhere remains wider and shallower than it should be, implying that flows have simply contracted into the bottom of a wide channel. Nor does the pattern of adjustment along the river follow the downstream hydraulic geometry (the scaling rules for channel regime) for Albertan gravel-bed rivers with which the pre-regulation river conformed, implying that the river is not "in regime" (or "at equilibrium") for the current flows. Overall, the channel has remained remarkably stable within the pre-regulation channel zone, extension of the channel zone being restricted to local bank erosion in some places where the river main current sets directly toward the bank, much as occurred before regulation. The occurrence and number of multithread channels has been reduced mainly by simple abandonment of secondary channels with high entrances; often the downstream end of such channels remains open and the resultant backwater represents significant habitat for rearing fish and for amphibians.

The effects of winter ice, already invoked above, are important along this northward flowing river. Normally, freeze-up occurs first downstream while breakup occurs first upstream so that, at both ends of the winter season (and possibly during mid-winter thaws), open stretches of the upper river may flow into fast ice downstream. The open river may carry frazil ice or ice floes into fast ice and create jams that cause significant stage rises and winter flooding. At spring breakup successive jams and the ice drives that follow the breakup of a jam create the highest water stages experienced along the river, and may cause major ice scour of the channel banks and bed. Release of water from the dams has created a reach of persistently open water below the dams: ice cover may begin anywhere between Taylor, British Columbia (km 102) and Dunvegan Bridge, Alberta (km 275), according to the severity of the winter. Within this reach, winter ice effects have been significantly diminished. Farther downstream, however, where the river runs due north, there appears to have been little change in the ice regime apart from a minor contraction of the ice season that may be due to ameliorating autumn and spring temperatures. Below Smoky River, a southern tributary that delivers a relatively early spring freshet to Peace River, the river is semiconfined within a series of major meander loops. The most significant ice jams and the greatest ice damage occur along this reach. Post-regulation ice damage is observed as much as 10 m above mean summer water level and the channel has contracted in width not at all since regulation: ice scour along the banks is the evident reason. This presents perhaps the most substantive evidence available that ice may maintain river channels larger than their regime type would predict (see Smith, 1979).

The common riparian vegetation succession along the river consists of the establishment of balsam poplar (*Populus balsamifera*) on gravelly substrates, or a mixture of poplar, willow and alder on sandy-silty sites, succeeded by growth to dominance of the poplar, subsequent infiltration of white spruce (*Picea glauca*) where seed is available, and dominance by spruce after 100 to 150 years. On the channel edge of the riparian forest, however, the succession is often held at the relatively early shrub stage of poplar–alder–willow dominance due to the occurrence of winter high water and repeated ice damage. The ability of these species to resprout from damaged tissue creates a thick tangle along the shore that is remarkably persistent. On the former floodplain, now a low terrace, the lowering of the river-controlled water table has led to premature decadence and death in pre-regulation poplar forests with no obvious succession, and a reversion to shrub species. While there has been measurable succession in floodplain forests consisting of young to mature cottonwoods, the most dramatic change post-regulation has been the significant expansion of the early shrub stages along the river edge. The net result of these processes is not an evident evolution, after 40 years of regulation, toward a more uniform terrestrial forest, as one might expect (Marston *et al.*, 2005), but the persistence of a high degree of evenness in the proportional occurrence of the riparian vegetation types and the continuation of the palimpsestic distribution formerly established by river erosion and sedimentation, such that successional sequences are frequently not evident.

The outcome of the two "experiments" embedded within this study are clear. The first experiment is the radical manipulation of the flow regime—one of the two principal governing conditions of river character and process—while the sediment regime, the second major condition, has remained relatively unchanged. The flow regime has been manipulated to the extent that the upper river is incompetent to move the gravel load delivered from the tributaries during normal regulated flows (even though the total annual water volume has changed only insofar as climate dictates). The result is aggradation focused near tributary junctions and major landslides that impinge on the river. Degradation has occurred only under the influence of an exceptionally prolonged high flow, and that mainly in locations subject to aggradation under normal flows. The supply of gravel is quite limited so that, along most of the channel, the response to regulation so far has been passive shrinkage of the active channel within the former channel zone. In the lower river, the large but mainly fine sediment load introduced by Smoky River is, with the help of Smoky River inflows, mainly transported through the immediately downstream reach, but significant aggradation has occurred beyond the transition to lower river gradients. Lateral deposition of sand is a general feature along the river everywhere below the confluence of Pine River.

The second "experiment" entailed the subjection of the channel to exceptionally high flows after more than 20 years of regulated flows. The high flows comprised a severe storm in June 1990 that delivered the flood of record to the lower river, and a reservoir drawdown flood in 1996 that emulated a moderate pre-regulation freshet. The channel conveyed these flows surprisingly well—that is, without major morphological changes—the consequence of the limited adjustment of channel capacity during the years of normal flow due to the passive nature of the response to flow regulation in the upper river and the persistence of ice effects in maintaining channel geometry in the lower river.

Considered together, the two experiments emphasize the key role played by the sediment supply to the river. It is sufficiently limited in the upper river that a complete regime adjustment of the river to the new flow regime—entailing the regrading of the river along its entire length—is unlikely to be achieved. Even in the lower river, such an adjustment is estimated to require on the order of 10^4 years. Startling though the result may be, it is not inconsistent with other recent estimates of regrading time for large rivers. Meanwhile, the time scale for lateral adjustment of channel width, largely determined by riparian vegetation succession, is expected to require on the order of 10^2 years.

Recognition of the inability of the upper river to move its bed under normal regulated flows and concerns for aquatic habitat maintenance raise the question what might be the magnitude of flushing flows required to turn over and clean the bed of infiltrated fine sediments. In Peace River abundant summer growth of aquatic macrophytes on the streambed traps silt and creates a bed surface that is discouraging to salmonid fishes; silt accumulation on the bed is pervasive in summer as far downstream as Pine River. Bedload transport calculations suggest that bed movement may begin at ca. 3000 m^3s^{-1} in the upper river, although sand and fine gravel may be moved at flows as low as 1000 m^3s^{-1}. However, significant scour has been observed along the reach only when flows have exceeded 5000 m^3s^{-1}, which has occurred in 1972, 1990, and 1996. In these events flows exceeded that value at Hudson's Hope (except 1990), approached or exceeded 6000 m^3s^{-1} at Taylor and 7500 m^3s^{-1} at Dunvegan Bridge. Even at these flows disturbance was not great and it is doubtful that all of the bed was moved. There remains also the question for how long such a flow need be maintained to be effective. The 1996 clearwater release from the dam is the only flow known to have had significant scouring effect, but the effects were not dramatic even though high flow was maintained for weeks (mean flow 4100 m^3s^{-1} at Hudson's Hope; 4800 m^3s^{-1} at Taylor; 5500 m^3s^{-1} at Dunvegan Bridge). The flow of equivalent magnitude in 1972 was maintained for only hours and its summary effect is not known, but no major scour is recorded between the 1968 and 1975 surveys. As best current guidance it appears that a flow at Hudson's Hope the order of 5000 m^3s^{-1} is required and should be maintained for a period of at least days to effect significant gravel turnover and streambed flushing, but the prescription should be recognized as extremely tentative.

What implications for the management of regulated gravel-bed rivers may we draw from this experience?

1. Gravel-bed rivers transport bed material at rates that exceed the threshold for sediment entrainment only modestly. Any such river regulated for hydroelectric power generation is almost certain to reduce flows below the threshold for bed material entrainment, at least in the reaches immediately below the point of regulation: hence significant degradation of the bed should not be expected.
2. On the contrary, aggradation should be expected in the vicinity of gravel-bearing tributaries, leading to the development of a stepped long profile and possible water level problems in the vicinity of tributary confluences that might compromise water offtakes and outfalls and other river-oriented infrastructure.
3. Within tributaries delivering moderate or modest sediment loads, degradation should be expected in the lower course consequent upon the effective lowering of water levels in the main river with possible consequences for bridge footings and other streambank infrastructure.
4. Upstream of tributary delivery of abundant sediment transportable in the mainstem, the river adjustment to regulated flows will be passive, dominated by riparian vegetation progression onto abandoned bar surfaces and channel margins: this circumstance will preserve a high capacity to convey flood flows for many years following the inception of regulation.
5. In light of the above, for gravel-bed rivers with significant ecological values, the design of a "flushing flow" regime is an essential concomitant of flow regulation.

   For boreal rivers, additional lessons include the following:

6. The annual hydrograph will become "inverted" near the dam, with high flows in winter and lower flows in summer, with possibly significant consequences for seasonal activity in the aquatic ecosystem.
7. Winter ice activity will be diminished for some distance below the dam, but will still be forceful far downstream from the dam.

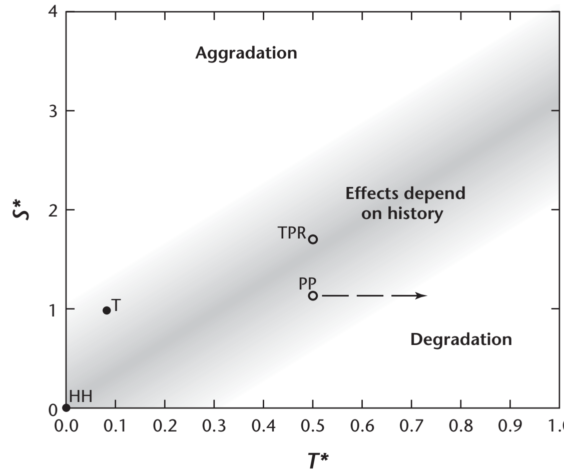

Figure 12.2 Diagram of Grant *et al.* (2003) for river response to regulation. $T*$ = (incidence of competent flows after regulation)/(incidence of competent flows before regulation); $S*$ = sediment transport below the dam/sediment transport above the dam. The original diagram is not fully scaled, so the present diagram differs slightly in that the scale of $T*$ is continued to zero without a break. The transport above the dam is estimated to be five million tonnes a^{-1} (see text for details of this estimate). For the lower river antecedent upstream transport is this figure plus the contribution from upstream tributaries. Data for Peace Point indicate a range for competent flows since the true change in competent frequency there for the sand-sized sediments is not known.

8. Ice activity will delay riparian progression and succession by seasonally damaging river edge vegetation, possibly maintaining a permanent shrubby fringe that will create a particular kind of riparian habitat, superior for riparian birdlife but possibly discouraging for large animals: organic matter contribution to the river may be less than would be produced from a maturing riparian forest.
9. Ice activity may maintain the channel in a state near that of the pre-regulation condition which will favor conveyance of unusually high open water flows.

To conclude, we situate Peace River in a scheme put forward by Grant *et al.* (2003) to give a qualitative prediction of the response of a river to regulation (Figure 12.2). The diagram considers the ratio of time during which competent flows occur after and before regulation and the ratio of sediment flux below and above the dam. In the present case, the sediment load above the dams is estimated to be five million tonnes a^{-1} on the basis of regional sediment yield analysis (Church and Slaymaker, 1989). Below the Smoky confluence, the upstream load is estimated from Dunvegan Bridge. The diagram places Peace River just on the aggradational side of equilibrium response, in conformity with the experience reported in this study, except at Peace Point, where the result is marginally for degradation. All estimates fall within the range said to depend on flow history, which we might regard the 1996 flood event as confirming.

Peace River represents an ongoing experiment in the relative influence of water and sediment as governing conditions of river form and process. Within the regulated flow regime, the sediment influx to the river appears to be the most significant condition controlling the morphological response, but its effect is substantially modulated by the degree to which the flow regime can or cannot redistribute sediment within the river. Future years and studies of other regulated northern rivers will further test this and other conclusions reported in the present study.

Acknowledgment

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References

Church, M. and Slaymaker, O. (1989) Holocene disequilibrium of sediment yield in glaciated British Columbia. *Nature*, 337, 452–454. doi:10.1038/337452a0

Grant, G. E., Schmidt, J. C., and Lewis, S. L. (2003) A geological framework for interpreting downstream effects of dams on rivers, in *A Peculiar River*, edited by J. E. O'Connor and G. E. Grant. Vol. 7: Water Science and Application. American Geophysical Union, Washington, DC. pp. 203–219. doi:10.1029/007WS13.

Kellerhals, R. and Gill, D. (1973) Observed and potential downstream effects of large storage projects in northern Canada, in *Proceedings of the 11th ICOLD Congress*, 1, 731–754.

Marston, R. A., Mills, J. D., Wrazien, D. R., Bassett, B., and Splinter, D. K. (2005) Effects of Jackson Lake Dam on the Snake River and its floodplain, Grand Teton National Park, Wyoming, U.S.A. *Geomorphology*, 71, 79–98.

Petts, G. E. (1984) *Impounded Rivers: Perspectives for Ecological Management*. John Wiley & Sons, Ltd, Chichester, UK. 326 p.

Smith, D. G. (1979) Effects of channel enlargement by river ice processes on bankfull discharge in Alberta, Canada. *Water Resources Research*, 15, 469–475. doi:10.1029/WR015i002p00469.

Appendix: data files online

Supporting data files, as follows, are located online at http://blogs.ubc.ca/peaceriver/

Folder title	File title	File type
Air photo flight lines	Air photo flight lines	pdf
Contains flight-line numbers and photo number ranges for all photos used in the construction of the morphological and vegetation maps along Peace River, with photo scale and Peace River flow at principal gauges nearest the flight line.		
Cross-section surveys	32 files by code + xs number	Excel
	cross-section images	pdf
Contains files giving x–z data for all surveys by cross-section, with an image of superimposed xs plots. The images are separately repeated in a pdf file.		
BC Peace surface grain size	BC Peace surface grain size	Excel
Contains D_{50} and D_{90} data of surface grain sizes collected in the BC Peace River in 1978, and means and standard deviations for subsets of samples as used in Chapter 3.		
At-a-station hydraulic geometry principal stations	At-a-station hydraulic geometry principal stations	Excel
Contains gauging data from which hydraulic geometries were constructed in Chapter 5; ice-period data are separately listed.		
Peace River morphology	BC Peace morph areas and stats	Excel
	AB Peace morph areas and stats	Excel
Contains cumulative areas by sub-reach of individual mapped morphological units and derived statistics reported in Chapter 7.		
Peace River vegetation	BC vegetation area stats	Excel
	AB1 vegetation area stats	Excel
	AB2 vegetation area stats	Excel
	AB3 vegetation area stats	Excel
	AB4A vegetation area stats	Excel
	AB4B vegetation area stats	Excel
Contains vegetation area statistics by sub-reach within files for each study reach, as analyzed in Chapters 8 and 9.		

(*continued*)

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Folder title	File title	File type
Vegetation stats and ratios	BC veg stats and ratios	Excel
	AB1 veg stats and ratios	Excel
	AB2 veg stats and ratios	Excel
	AB3 veg states and ratios	Excel
	AB4A veg stats and ratios	Excel
	AB4B veg stats and ratios	Excel
Contains derived statistics, including transition ratios, as reported in Chapters 8 and 9.		
Vegetation field studies	Vegetation plot field data	Excel
	Veg stats field islands	Excel
"Vegetation plot field data" contains the plant enumerations for the field plots, reported in Chapter 8. "Veg stats field islands" reports photo-interpreted type areas for the islands on which the field plots were located.		
Peace River Maps		
Peace BC	53 maps	pdf
Peace Alb reach1	54 maps	pdf
Peace Alb reach 2	54 maps	pdf
Peace Alb reach 3	54 maps	pdf
Peace Alb reach 4A	25 maps	pdf
Peace Alb reach 4B	35 maps	pdf
Contains maps in subfolders for all study reaches. Maps are identified by date and map number. Maps correspond with Terrain Resource Information Mapping quadrangles, not with study sub-reaches. Maps display morphological units and vegetation types, statistics for which are given in files contained in the preceding folders. These maps constitute the basic data source for the reach-length studies of morphological and vegetation change. Original maps were constructed at the scale 1:20 000 using ESRI ARCmap® Version 10: working files are available from the author. Details of map construction are given in Chapter 7.		

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