The Regulation of Peace River
The Regulation of Peace River
A Case Study for River Management

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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 Baraclough, 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
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 pre-existing 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 pre-regulation 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

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$^1$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.
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$^3$s$^{-1}$ at Hudson’s Hope (and were normally less than 2000 m$^3$s$^{-1}$), the river was subject to release flows of more than 4000 m$^3$s$^{-1}$ 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,

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**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$^3$s$^{-1}$ (Photo courtesy of M. J. Miles).
when flows exceeding 12 000 m$^3$s$^{-1}$ 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

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**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.
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$^3$s$^{-1}$, 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


CHAPTER 2
The regulation of Peace River

2.1 Introduction

Peace River drains approximately 293,000 km² 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 1,300 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 9,800 m³s⁻¹, but it was already 6,000 m³s⁻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
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.
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.
The regulation of Peace 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 midwinter 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 2.4 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.
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.