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Date 18/12/01
Abstract

River regulation imposes direct changes on flow and sediment delivery, producing a suite of downstream responses in channel morphology. On the Peace River in northern British Columbia and Alberta, the W.A.C. Bennett hydroelectric dam has reduced peak flows while leaving sediment load effectively unchanged. My research aims to identify systematic, regulation-induced patterns of channel gradation in the mainstem Peace and its tributaries below the dam. The significance of regulation within the natural variability of basin hydrology is assessed by comparing actual regulated river flows to simulated flows based on reservoir level fluctuations. Mainstem bed elevation changes are assessed from repeatedly surveyed cross-sections and specific gauge records, supplemented by analysis of channel planform change. Results show degradation to be minimal, due to the naturally armoured gravel bed and elimination of competent flows. The predominant pattern in the upper regulated reaches is one of aggradation below tributary confluences and other sediment sources. In the long term, the Peace River may be raising its proximal bed to compensate for a loss of sediment transport capacity since regulation. Backchannel abandonment and other planform changes appear to be occurring more slowly, and may be less important to river slope adjustment. Data from the lower river are few and inconclusive. Tributary gradation was investigated by means of air photo, field surveys and dendrochronology of young floodplains. These methods reveal a range of responses to regulation, including degradation, aggradation and no apparent change. Degradation due to reduced tributary base level appears to attenuate downstream as the Peace River flood is restored by unregulated tributary flows, though this trend is complicated by other factors such as tributary sediment supply, flood timing between tributary and mainstem, and ice activity. Aggradation due to tributary fan growth may mitigate degradation; it is a less prominent response, though it appears to predominate in the lower Smoky River. Regulation is a secondary effect in the tributaries, and its influence on gradation has been limited. On the mainstem, however, it is a primary change, and the resulting channel gradation will take a long time to complete.
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1. INTRODUCTION

River regulation is a common and important form of human intervention in the natural environment. The 20th century was marked by a proliferation of large dams, with the worldwide number increasing sevenfold to about 39,000 between 1950 and 1986 (Dynesius and Nilsson, 1994). Today, that number is over 45,000, and over 800,000 if small dams are included (Høeg, 2000). Regulation projects have been pivotal in the settlement and development of the American west (cf. Reisner, 1993), and over 20% of total stream runoff is regulated in North America and Africa (compared to Europe's 15%). Large dams are currently being constructed at a rate of over 200 per year (Knighton, 1998). These are generally large, publicly funded projects with far-reaching effects across space (upstream, downstream, along transmission lines and throughout irrigation networks) and spheres of interest (biophysical, engineering, socioeconomic, political, cultural). While public attention lately has been centred on the ecological and socioeconomic impacts of dams, their primary effects on rivers are hydrological and morphological. These are the focus of my research.

River regulation is commonplace in British Columbia, where the mountainous landscape and wet climate provide a wealth of potential dam sites. Over 2500 dams of all sizes have been built throughout the province, and nearly 95% of British Columbians obtain their power from the 32 large hydroelectric facilities of BC Hydro (Hume, 2001). Future developments, however, can expect intense public scrutiny as riverside population and land pressure continue to grow. This makes rivers in the thinly populated northern regions of British Columbia the most likely candidates for future dam sites, and it is therefore critical to understand how these rivers may respond to regulation. In general, there have been very few studies of regulated northern rivers, and only one (to the author's knowledge) of a large northern gravel-bed river. That exception is the Peace River in northeastern British Columbia and Alberta.

The Peace River has been regulated since 1968, when the W.A.C. Bennett Dam was closed upstream of Hudson's Hope, British Columbia, impounding the Williston Reservoir as part of a major hydroelectric development. The smaller Peace Canyon Dam, a run-of-the-river project, was completed about 23 km downstream in 1980. The presence of Bennett Dam has significantly altered the river's flow regime and this, in turn, has produced downstream changes in channel morphology. The Peace is a rare case where a substantial amount of morphological
data has been collected since its damming, permitting detailed study of the river's response to flow regulation. Although some preliminary results have been reported (see Section 1.2 below), the present work is the first systematic analysis of downstream post-regulation channel gradation in the Peace River basin. The focus will be on change in the channel elevation. This represents an important mechanism by which rivers strive toward an equilibrium between flow, sediment transport and channel form, particularly in a frequently confined system such as the Peace (Knighton, 1998). Reference will also be made to changes in river planform, as morphological adjustment must ultimately be considered in three dimensions. The project encompasses the entire regulated drainage basin of the Peace River, including the mainstem river and several of its unregulated tributaries. The emphasis, however, will be on the proximal regulated basin between the dam site and Dunvegan, Alberta, as regulation effects are generally strongest near the dam, and most available data come from this reach.

The introductory chapter of this report continues in three major sections:

- a review of the scientific literature on regulated river morphology;
- an overview of the Peace River basin, including its physiography, climate, regulated hydrological regime, and a survey of past studies on the Peace; and
- an explanation of the hypotheses and operating questions which underpin my research.

This is followed by chapters on post-regulation channel gradation of the Peace mainstem, channel gradation in tributary channels, and conclusions of the research. It is hoped that this study will elucidate the particular reactions of the Peace River to flow regulation, and contribute to the general knowledge of regulation effects on fluvial morphology, particularly in gravel-bed rivers.

1.1. Morphological Changes in Regulated Rivers

This section reviews previous research on dam-related changes in river channel morphology. The literature is summarized in two major sections: primary effects of flow regulation, and subsequent channel responses. The section closes with a brief appraisal of the current state of knowledge. Studies of the Peace River are reviewed in Section 1.2 as part of a description of the river and its regulated regime.
Considering the prevalence and societal importance of river regulation projects, it is no surprise that a wealth of research has been conducted on the effects of dams on rivers. The present literature review focuses on effects downstream of dams. Particular attention is paid to a number of summary papers (e.g. Petts, 1979; Williams and Wolman, 1984) which compile the findings and data of numerous more specific studies.

1.1.1. Primary Changes: Flow and Sediment Supply

When a river is dammed, two of its most basic governing factors are altered: flow regime and sediment load. These primary changes initiate the suite of observed channel-form responses. The following section describes the documented range of flow and sediment supply changes in regulated rivers.

**Altered Flow Regime**

The particular effects of regulation on a river’s flow regime vary from project to project. In their study of 21 primarily sand-bed regulated rivers in the U.S., Williams and Wolman (1984) stated, “Because of the various purposes for which dams are built, there are large variations from one dam to another in the magnitude and duration of flow releases.” It was found that dam operation could cause mean daily discharge to increase or decrease, but in most cases led to reduced peak flood magnitude, an important control on channel size and the location and composition of riparian vegetation. This type of response was also described by Petts (1979), who reported flood peak reductions of 20% to 75% in previous studies. In general, impoundment by a dam has the effect of smoothing a river’s downstream annual hydrograph: flood peaks and low flows are absorbed in the reservoir and flow releases are more uniform (Williams and Wolman, 1984), though regulated flows may be quite erratic on diurnal or synoptic scales.

Flow may be nearly or completely eliminated, especially in the case of irrigation reservoirs. For example, the Colorado River loses 64% of its runoff to irrigation and 32% to evaporation from reservoirs, leaving only 4% of the natural flow reaching the Gulf of California (Dynesius and Nilsson, 1994). In contrast, extreme flows in the River Mersey in Tasmania are actually augmented during occasional dam overspills, though flood frequency is reduced overall (Knighton, 1988). In Canadian regulated rivers, peak flows generally tend to be reduced, but winter flows typically increase (Kellerhals, 1982) due to high demand for hydroelectricity during
cold months. In the South Saskatchewan River downstream of the Gardiner Dam, the year's highest flows now occur in winter (Rasid, 1979). Another important aspect of Canadian rivers is their ice regime. Interactions between river ice and regulated flow during winter and spring are highly variable from system to system (Kellerhals and Gill, 1973), and not well documented (Uunila, 1999). There is some evidence, however, that reduced spring flooding on regulated rivers may discourage the occurrence of severe mechanical river ice breakup and consequent ice jam flooding (Prowse and Conly, 1998).

The hydrological impact of regulation generally fades with distance downstream of the dam due to flow contributions from unregulated tributary rivers (cf. Church, 1995). Long-term regulated flow patterns are made unpredictable by changing uses and limited life span of dams. This is underscored by the case of the lower Yellow River, China, which was dammed in 1959. Initially the reservoir was used for water storage, but after excessive siltation it was relegated to a flood retention role, resulting in another change in flow regime (Xu, 1990 and 1996b) and two distinct periods of morphological response. Clearly, flow regimes and downstream channel adjustment of regulated rivers depend in large part on human decisions.

**Altered Sediment Load**

Reservoirs are highly effective sediment traps, catching all but the finest incoming sediment supply in most cases (cf. Kellerhals and Gill, 1973; Taylor, 1978; Petts, 1979; Galay, 1983; Williams and Wolman, 1984). An elementary upstream result of this is the gradual filling of reservoirs. Downstream, the degree and importance of sediment supply interruption varies with distance from the dam and from river to river. Williams and Wolman (1984) found that suspended sediment loads were reduced by regulation in most cases. In some rivers, sediment load recovered to near pre-regulation levels at some distance downstream due to inputs from unregulated tributaries; in others, levels never recovered. Suspended load in the South Saskatchewan River at Saskatoon has dropped over 90% since closure of the Gardiner Dam (Rasid, 1979), and a significant decline in sediment delivery has been observed in the Colorado River since closure of the Hoover Dam (Knighton, 1998). Grimshaw and Lewin (1980) described the sediment supply to the regulated lower River Rheidol in Wales as "severely curtailed," and stated that "the lower, unaffected part of the catchment appears to have produced proportionately only a smaller part of the total suspended sediment yield." This contrasts with
the Peace River, where most sediment enters downstream from the dam, and the reduction of sediment supply to the lower river has been minor (Church, 1995).

1.1.2. Secondary Changes: Morphology

It is intuitive and widely reported that dams influence downstream morphology via the primary changes described above. Yet an important point was raised by Williams and Wolman (1984): not all observed change downstream from a dam need be caused by the dam, since natural processes and responses are not eliminated from the regulated river. To establish causality in morphological change over space and time, that change must be outside the natural variability of the river. Williams and Wolman described several qualitative techniques to assess whether change is attributable to a dam, including proximity of change to the point of regulation, comparison of changes before and after regulation, and extrapolation of post-regulation rates of change back to pre-dam times. Frequently, this type of assessment is hampered by a lack of pre-regulation data (Williams and Wolman, 1984).

Williams and Wolman divided their observations of downstream morphological effects into several categories. Their categorization is used here, in modified form.

Bed Degradation and Aggradation

Degradation is the most common and immediate channel response to flow regulation. Due to reservoir trapping of upstream sediment, the riverbed immediately below the dam scours without compensating deposition of incoming sediment (Galay, 1983). The effect may be dramatic: after closure of the Hoover Dam, the Colorado River degraded up to 7.1 m within a 130 km reach (Galay, 1983). Degradation reduces the local channel gradient, helping to restore equilibrium between post-regulation flow, sediment supply and channel form. A new graded condition may not be reached, however, if degradation is halted by the formation of an armoured bed through preferential entrainment of the finer bed material (Church, 1995). Armouring resulted in far less degradation than predicted below the Aswan High Dam on the Nile River (Schumm and Galay, 1994). Initial degradation is contingent upon the regulated flow being competent to entrain local bed material; in gravel-bed rivers, the bed is often naturally armoured and high flows are curtailed, so that degradation is not seen at all (Kellerhals, 1982). Inbar (1990) presented the extreme case of eleven regulated mountain streams in the Golan Heights, Israel. These have
bedrock, boulder and cobble beds, and they show no evidence of dam-induced degradation. Degradation may also be arrested by exposure of a relict gravel layer (Xu, 1996a). Armouring effects have also been observed in scale-model laboratory work (e.g. Begin et al., 1981).

The downstream extent of degradation is highly variable. Most degradation is 'wedge-shaped' - most severe immediately below the dam and tapering downstream. Williams and Wolman (1984) found that degradation zones may be anywhere from a few to hundreds of kilometres in length, and may continue growing beyond the time scale of most current studies. In the case of the Nile, a shallow, more uniform style of degradation is seen, extending 600 km downstream following construction of the Aswan High Dam (Schumm and Galay, 1994). Reasons for this phenomenon are unclear, but it may be related to a general mobilization of fine sediments from the lower bed and banks all along the river.

Aggradation - the raising of the riverbed by deposition of sediment - downstream of dams has been noted in some systems. Marked aggradation is common below the confluence of unregulated tributaries contributing bed material no longer transportable by the enfeebled mainstem. Local aggradation then occurs in the form of in-channel alluvial fans, bars, benches or the choking of coarse beds with finer material (Petts, 1977 and 1979; Kellerhals, 1982). Periodic inputs of sediment by valley wall mass wasting can have a similar effect (Kellerhals, 1982). Aggradation is a passive and often slow process, particularly if sediment supply is reduced (Petts, 1979).

Most authors caution that observed degradation and aggradation are likely only the first stages in a series of long-term morphological changes (cf. Petts, 1979). The long-term response of the channel to its new flow and sediment regime may be complex and unpredictable. Petts listed potential factors in these complex responses, including frequency of competent discharges, sediment from non-regulated sources, constraints on channel migration and specific local channel form. Xu (1996b), however, reminded us that in regulated rivers, people continue to play a major, if unpredictable, role. He cited the Yellow River below Sanmenxia Dam, where a degraded zone promptly re-filled with sediment when the pattern of flow and sediment release from the reservoir was changed.
Variations in Bed Material Calibre

Less information is available on bed material composition changes downstream of a dam. As mentioned above, degradation followed by armouring is common, implying a coarsening of the local bed. This has been statistically supported by bed material analysis in the South Saskatchewan River (Rasid, 1979), and also observed in Bear Creek near Denver, Colorado (Hadley and Emmett, 1998). Petts (1979) asserted that downstream aggradational features may be finer than the natural local bed material due to reduced flows and the abstraction of coarse sediment supply by the reservoir. The most systematic examination of bed material change was conducted by Williams and Wolman (1984). They found that at a cross-section in the degradation zone, bed material tended to coarsen and become less sorted with time. Downstream, they found some evidence of bed material fining with distance from the zone of maximum scour, but no strong pattern was identified.

It seems counter-intuitive that a reduction in flow should produce a generally coarser bed, yet, in the literature, both degradation and aggradation are associated with relatively coarse bed material. These patterns may eventually change as regulated rivers approach new graded conditions, but observations of such long-term morphological responses are completely absent from the literature.

Channel Width Changes

With peak flows generally reduced below a dam, it is expected that channel cross-sectional area should shrink to appropriate equilibrium dimensions (Kellerhals, 1982). Indeed, the most commonly reported change in channel width is narrowing (e.g. Rasid, 1979; Schumm and Galay, 1994). This occurs through a variety of mechanisms, including bank slumping, accumulation of windblown sediments, and prograding deposits at tributary mouths (Petts, 1979; Williams and Wolman, 1984). Such depositional changes can be very slow, especially in armoured gravel-bed rivers (Kellerhals, 1982). Multi-channel rivers commonly reduce their width through the abandonment of small braid channels or backchannels which are occupied only at higher flows (cf. Xu, 1996b; Friedman et al., 1998). In most of these situations, initial narrowing coupled with reduced flood frequency opens new portions of the channel to colonization by pioneer riparian vegetation. These plants then promote increased local sedimentation and substrate stability, reinforcing the conversion from channel to floodplain.
Post-regulation channel narrowing is not universal, however. Cases of unchanged width have been reported on rivers where degradation is the predominant response (Williams and Wolman, 1984; Hadley and Emmett, 1998). Channel widening may also occur through such mechanisms as:

- clear water scouring of bed and banks;
- reduced sedimentation due to reduced sediment supply;
- undermining of vegetated banks due to degradation below root level; and
- irregular erosion without compensatory deposition due to sporadic flow releases (Williams and Wolman, 1984).

In gravel-bed, bedrock-floored or armoured channels, relatively weak banks may erode instead of the bed, leading to channel widening (Xu, 1990 and 1996b).

Changes in channel width may be observed well beyond the degradation zone, and a river may exhibit complex combinations of narrowing, widening and stability. No clear correlation of width with bank material or downstream trends in magnitude of change has been reported (Williams and Wolman, 1984).

**Channel Pattern Changes**

Besides degrading, a regulated river may lower its gradient by increasing its sinuosity. In meandering rivers this may occur if degradation leads to undercutting and bank failure at the outside of bends. Observed reactions of meandering rivers to regulation are highly variable. For instance, Petts (1979) found increased rates of channel migration due to frequently recurring, competent regulated flows in sand-bed rivers. The Nile, which naturally has a relatively straight channel, has exhibited slowed bank erosion rates since regulation, without clear consequences to meandering and channel pattern (Schumm and Galay, 1994). Kellerhals and Gill (1973) suggested that meander bends may widen due to continued erosion but insufficient deposition due to reduced sediment supply. Friedman et al. (1998) cited reduced meandering rates after regulation, while others observed meandering to stop altogether (Hadley and Emmett, 1998; Johnson, 1998). Zones of altered meandering activity may migrate downstream with time, leading to an even more complex pattern of response (Petts, 1979).
Regulated multi-thread streams may increase their sinuosity by abandoning high-stage secondary channels, forcing the flow to follow a less direct course. Braid abandonment tends to create a narrower channel (e.g. Johnson, 1998; Xu, 1996b), especially once vegetation begins to encroach. Increased sinuosity in a braided river may later reverse itself (Xu, 1996b), or progress to the point where a single channel is entrenched in a new meandering pattern (Kellerhals and Gill, 1973; Galay, 1983). In some cases, however, braided streams simply remain braided (Xu, 1996b) while undergoing other changes.

Changes to Riparian Vegetation
Morphological change in a regulated river is often mediated by changes in riparian vegetation. The most common case is the colonization of bar and floodplain surfaces which, under natural flow conditions, were regularly scoured or flooded. This almost invariably contributes to reduced cross-sectional area (e.g. Taylor, 1978; Petts, 1979; Kellerhals, 1982). This effect appears to be most marked in braided systems where a larger amount of bar surface area is available (Johnson, 1998; Williams and Wolman, 1984). On the other hand, in a single-channel system characterized by degradation, Hadley and Emmett (1998) noted a change in species composition rather than in vegetated area, with woody plants replacing grassy species along the channel since regulation. The deeper and more complex root structure of these shrubs has likely increased bank stability, contributing to the observed stability in channel width. Williams and Wolman (1984) noted other potential effects of increased riparian vegetation, including faster thalweg flow velocities at high stages (due to increased flow resistance on the vegetated surface) and higher water loss to evapotranspiration.

Effects on Downstream Tributaries
In addition to continuing their role as (probably unregulated) contributors of flow and sediment, tributaries downstream from a dam may undergo significant morphological changes themselves. Damming the mainstem often changes the effective tributary base level, either through 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 a steepening of the tributary slope near the mouth, leading to upstream-progressing channel degradation (cf. Taylor, 1978; Petts, 1979). Although studies in natural streams suggest such base level effects should not extend far upstream (Leopold and Bull, 1979), research on dammed
streams indicates the effect can be significant and extensive. Channel depths on the North Donets River in Russia, a tributary to the dammed Don River, have reportedly doubled and tripled, leading to extensive deposition in the mainstem (Petts, 1979). Reduced stage in the regulated Missouri River caused upstream-progressing degradation and the collapse of a bridge in an unregulated tributary, the Big Sioux River, during a flood in 1962 (Galay, 1983). Degradation, channel widening and headward stream extension have been observed in lower-order tributaries to the Osage River, Missouri, which has degraded due to regulation (Germanoski and Ritter, 1988). Tributary steepening due to base level drop may also accelerate bank erosion and channel instability; several tributaries to the Peace River have been cited as possible examples of this (BC Hydro, 1976).

**Predicting Future Change**

A few qualitative models for the channel morphological response to regulation have been put forth. Some of these consist of simplified flowcharts showing potential consequences of various scenarios (cf. Petts, 1979). On the basis of flume and field work, Xu (1990 and 1996b) proposes a descriptive three-stage model for braided and wandering rivers. The stages are:

1) initial narrowing, slope reduction and increased sinuosity due to degradation and braid abandonment;

2) intensified bank erosion leading to increased width and decreased sinuosity, and stabilized slope; and

3) achievement of equilibrium to new flow and sediment conditions.

A considerable literature exists on quantitative modeling of degradation below dams. Approaches have included numerical analysis based on bedload transport formulae (cf. Komura and Simons, 1967; Galay et al., 1988) and kinematics (cf. Karim and Kennedy, 1988), as well as flume experiments (cf. Ashida and Michiue, 1971). These efforts have produced relatively good scour predictions for sand-bed rivers, but offer less promise in gravel-bed rivers, where sediment transport computation is seriously complicated by natural bed armouring and irregular bedload transport (Gomez and Church, 1989).

Little has been done to model other morphological changes quantitatively. Williams and Wolman (1984) made an initial attempt, using 287 surveyed cross-sections, to produce
hyperbolic regressions of both degradation and narrowing versus time since regulation. While reasonable relations were produced, the input data were rather carefully selected: non-degrading and non-narrowing cross-sections were discarded. Their results are purely empirical, and only applicable to other degrading or narrowing regulated rivers. In addition, to apply their relations to specific sites, prohibitively high-quality information on such variables as bed and bank material and future flow release patterns are required (Williams and Wolman, 1984). Hydraulic geometry (cf. Leopold and Maddock, 1953) provides a potentially powerful tool in predicting magnitude and extent of morphological changes due to regulation. In this vein, Church (1995) used the ratio of discharge before and after regulation to predict final post-regulation channel width, mean channel depth, flow velocity and meander wavelength at various points along the Peace River. Such predictions may be applied specifically to any channel location where the at-a-station hydraulic geometry is well defined, or more generally at reach scale using regional regime equations, as Church did.

It is unclear from the literature how far downstream the influence of a dam may be felt. Far-reaching effects have been documented. For example, coastal erosion in Louisiana has been partly attributed to sediment starvation by upstream reservoirs on the Mississippi River, and erosion of the Nile delta has been linked to the influence of the Aswan High Dam, nearly 1000 km upstream (Knighton, 1998). Downstream hydraulic geometry can provide an estimate of downstream changes provided that channel form and flow are well documented. In general, however, predictive ability can only be expected to decrease with distance from the point of flow regulation, as more and more external influences are introduced.

1.1.3. Assessment of the Literature
The literature on downstream effects of dams on river channel morphology is large and replete with case studies from a wide range of systems and regulation scenarios. Within these, the spectrum of primary (flow and sediment supply) and secondary (morphological) effects appears to be well-documented. Still, only a few papers strive to draw this disparate body of work together. A synthesis of all observed types of flow, sediment and channel morphology responses to damming, perhaps in the form of a detailed flow chart (e.g. Petts, 1979, Figure 1), would be a valuable addition. Further, only Williams and Wolman (1984) and Church (1995) appear to have tried to quantitatively model any post-regulation channel response other than degradation. This
may result in part from the unpredictability of long-term regulated flow regimes, influenced as they are by such factors as reservoir siltation and hydroelectric market conditions. Nevertheless, improved quantitative modeling might be of value to anyone concerned with the effects of proposed or existing dams. Finally, the general literature does not offer many cases parallel to the Peace River:

- most reported cases of regulation involve changes to both flow and sediment supply regimes, while in the Peace the former is dominant;
- most studied rivers have sand beds, while the Peace has cobble-gravel-bed reaches extending over 400 km below the point of regulation; and
- no other studies consider sites where seasonal ice effects are of potential significance.

The Peace River may therefore offer answers to some important, open questions.

1.2. Study Site

1.2.1. Peace River: Physiography and Climate

The Peace River (Figure 1.1) originates in the northern Rocky and Omineca Mountains of British Columbia. Since closure of Bennett Dam in 1968, its headwaters have flowed into Williston Reservoir, which extends from the Rocky Mountain Trench to just upstream of Hudson’s Hope, where the river leaves the mountains. From there, the Peace runs east and then northeast across the high plains of British Columbia and northern Alberta to the Peace-Athabasca Delta, an extensive freshwater marsh complex at the junction of the Peace, Athabasca and Birch Rivers. Here, some 1200 km below its dams, the Peace is renamed the Slave River and runs north to Great Slave Lake, Northwest Territories, which in turn drains to the Arctic Ocean via the Mackenzie River. In total, the Peace River basin occupies approximately 293,000 km².

Over most of its course downstream of Hudson’s Hope, the Peace River is deeply entrenched within its valley, leading to frequent confinement of the channel (Uunila, 1999); it is not truly alluvial until it approaches the Peace-Athabasca delta (Kellerhals and Gill, 1973). The riverbed is dominated by gravel from Hudson’s Hope to a point upstream of the Smoky River confluence. From here to just upstream of Carcajou, Alberta, the bed is a mixture of sand and gravel, and from Carcajou to the Peace-Athabasca delta it is primarily sand (Church, 1995; see Figure 1.1).
Figure 1.1  Map of Peace River basin showing locations of physiographic divisions, major tributaries and Water Survey of Canada hydrometric stations. (after Church, 1995). Inset shows Peace basin within Canada.
Most bedload is gravel except in the sand reach below Carcajou, and the suspended load is much greater than the bedload in terms of total sediment yield (Kellerhals and Gill, 1973). The river in its cobble-gravel reaches has a wandering channel pattern, with shallow, irregular bends and frequent islands; as it enters its sandy reaches, the river becomes more sinuous with fewer islands. Major tributaries below the dams include the Halfway, Moberly, Pine, Beatton and Kiskatinaw Rivers in British Columbia, and the Pouce Coupe, Burnt, Smoky, Whitemud, Boyer and Wabasca Rivers in Alberta. Among these, the Smoky is by far the largest river, and it contributes a substantial flood and sediment load to the Peace. The Pine is the largest British Columbia tributary, and the second largest in the Peace basin.

The mountain and lowland regions of the Peace basin differ strongly in their geology and climate. The mountains upstream of Hudson's Hope account for only 24% of the total catchment area, yet contribute over 50% of total flow at Peace Point, near the terminus of the river (Xu and Church, 1996). This disproportionate runoff contribution is explained by the relatively wet climate and lack of secondary runoff storage in the upper basin (Uunila, 1999). By contrast, the lower basin lies in the rain shadow of the mountains, receiving less precipitation and experiencing greater evaporation losses. Most of the Peace River's sediment load appears to derive from these lower reaches. The headwaters flow primarily over carbonate bedrock which yields relatively little clastic sediment, while the lower reaches flow through thick, poorly consolidated glacial and post-glacial deposits and poorly lithified rock (mostly shale and sandstone of Cretaceous age (Mathews, 1963; Holland, 1976)). These provide ready sediment supplies, as evidenced by the frequent valley-wall landslides seen along the Peace Valley. Thus, unlike most of the world's rivers, the sediment yield per unit area of the Peace River actually increases with drainage area (Church et al., 1997) – a pattern characteristic of Church and Slaymaker's (1989) second phase of post-glacial fluvial adjustment in western Canada. Due to this separation of main water and sediment sources, the damming of the Peace above Hudson's Hope has significantly altered the flow regime without commensurate effect on sediment supply.

The Peace River has a mean annual flow of 1101 m$^3$/s at Hudson's Hope and 2118 m$^3$/s at Peace Point$^1$. The annual hydrograph of the unregulated Peace was dominated by the snowmelt freshet in late spring, with lesser flood peaks due to rainstorms (Uunila, 1999). Much of the river is ice-

$^1$ Flow figures quoted in this report were obtained from the federal government’s Hydat 2000 database of Water Survey of Canada hydrometric data.
covered in winter, and ice jams following spring breakup of the river ice are the cause of the river's highest water levels (Prowse and Conly, 1998).

1.2.2. Regulated Hydrologic Regime

The W. A. C. Bennett Dam (Figure 1.2) is one of the largest earth-fill structures in the world, with dimensions of 2 km wide, 850 m thick at base, and 183 m high. It was constructed between 1962 and 1967 of materials taken from a local moraine, and impounds the 1773 km$^2$ Williston Reservoir (BC Hydro, 1996). The smaller Peace Canyon Dam, constructed from 1975 to 1980, measures 534 m wide and 50 m high, and is made of concrete. A run-of-the-river project, this dam generates power according to the pattern of releases from Bennett Dam. Its reservoir (Dinosaur Lake) is much smaller, covering 21 km of the narrow Peace Canyon (BC Hydro, 1993), and its impact on Peace River flow patterns is negligible compared to that of Bennett Dam. Consequently, Bennett Dam is considered the chief source of regulation, and the Peace Canyon Dam is seldom referred to in this paper.

Figure 1.2  W.A.C. Bennett Dam (source: BC Hydro, 1999).
In terms of impact on river morphology, the most important effect of Bennett Dam has been the reduction of peak flood discharges. Prior to regulation, spring meltwater floods gave a strongly seasonal character to the annual hydrograph of the Peace River (Kellerhals, 1982). Reservoir storage dampens these peak flows significantly, as releases are governed by demand for hydroelectricity. The post-regulation mean annual flood at Hudson’s Hope is now approximately 2024 m$^3$/s, down from 6089 m$^3$/s before dam closure. Downstream, flow contributions from unregulated tributaries gradually dilute the effects of regulation. Even at Peace Point, however, the mean annual flood has declined from 10,088 m$^3$/s to 6109 m$^3$/s. Since closure, there have been only two notable flood releases from the dam. The first, in June, 1972, was a test of the dam’s spillway, and lasted roughly a week. The second, from late June to mid-August, 1996, was an emergency release to draw down the reservoir after sinkholes were found in the dam; it lasted over six weeks, with geomorphic consequences discussed later in the paper.

Flood curtailment has reduced the overall range of flow variability in the river. Due to peak power-generation requirements during winter, post-regulation winter flows in the Peace are augmented (Kellerhals, 1982), though they do not approach flood levels.

The persistence of post-regulation flood reduction is best illustrated by cumulative departures analysis (cf. Buishand, 1982). This consists of calculating the difference between individual flow data points and the mean of the entire time series, and plotting the running total of these ‘departures’ versus time. In these ‘residual mass curves’, periods of higher-than-average flow have a positive slope, while low-flow periods have a negative slope. Cumulative departure plots of mean annual flow and mean annual flood for selected hydrometric stations along the regulated Peace River are presented in Figure 1.3. The effect of regulation is dramatic: at Hudson’s Hope (Figure 1.3a), mean annual flood departures before regulation are uniformly positive; since regulation, mean annual flood has been consistently below average except for the emergency release flood of 1996. At Peace River town (Figure 1.3b), Alberta, downstream of the largest tributaries, and at Peace Point, (Figure 1.3c), the pattern is somewhat weakened, but there is still a clear trend of lower-than-average floods since regulation. The residual mass curves for mean annual flow, however, show no distinct change of pattern around the time of regulation, though the Peace Point data are consistently low from 1980 to 1995.

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2 Mean annual flood is calculated by averaging the maximum daily flows for all applicable years.
The hydrological effects of regulation may be confounded with natural fluctuations driven by climate cycles. Of particular concern is the Pacific Decadal Oscillation (PDO), which operates at inter-decadal frequency (cf. Trenberth and Hurrell, 1994; Mantua et al., 1997). Correlations between the PDO and North American weather and river flow have begun to be identified, though the patterns are complex. For instance, there has generally been less snow in southern British Columbia between 1977 and 1988, while northern British Columbia has had more snow since the late 1970s (Moore, 1996; Moore and McKendry, 1996). PDO-scale shifts in mean annual flow are suggested by the residual mass curve at Peace River town (Figure 1.3b), particularly a downturn in the 1920s and an upturn in the 1960s. From a geomorphic standpoint, however, oscillations in mean annual flow may not matter; of greater concern is the incidence of geomorphically effective flows. To determine whether climatic cycles have contributed significantly to the river’s diminished floods, ‘naturalized’ daily flow data were obtained from BC Hydro. These data, based on monitored reservoir water volumes, simulate what Peace River flows would have been in the absence of Bennett Dam. The accuracy of the naturalized flows on a time scale of days is highly suspect, as they are sensitive to water level measurement errors projected over the large area of Williston Reservoir. Nevertheless, the simulated data should suffice for the analyses performed here.

Figure 1.4 shows the hydrographs of actual and naturalized daily flows for all available post-regulation years at two hydrometric stations. At Hudson’s Hope (Figure 1.4a), the reduction in flood peaks is clear; in most years, the snowmelt freshet is eliminated, and only in 1996 do actual peak flows approach those simulated by BC Hydro. The increase in winter flow rates is also evident, and these flows are generally the highest of the year. At Peace River town (Figure 1.4b), the effect is muted: actual flood peaks are less dramatically reduced, and in some years – 1972 (the year of the spillway test), 1974, 1982, 1987, 1990 – they approach the simulated maxima. Importantly, however, the simulated floods remain consistently higher at this station, and there is no suggestion of a natural reduction in flood levels coincident with the onset of regulation.

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3 Notably, the flood of record at Peace River town occurred in 1990, largely due to flow contributions from the Smoky River basin (Church et al., 1997).
Figure 1.3 Cumulative departure plots for Peace River mean annual flow and mean annual flood at Hudson’s Hope, Peace River town and Peace Point. Years of reservoir filling are omitted.
Figure 1.4  Hydrographs showing actual and naturalized daily Peace River flows at Hudson’s Hope (a) and Peace River town (b) for the post-regulation period.
Peak flows alone do not suffice to assess the effect of regulation on Peace River hydrology, and it is desirable to explore other geomorphically meaningful flow indices. There is no consensus on what flow level dominates a river’s sediment transport and channel form (Knighton, 1998). One popular approximation is bankfull flow, based on Wolman and Miller’s (1960) premise that this discharge has the magnitude and frequency to do the most geomorphic work over the long term. In many rivers, bankfull discharge has been calculated to have a return period of one to two years, which corresponds roughly to the mean annual flood. For the Peace River, I have analyzed the frequency of occurrence of daily flows greater than one-half the mean annual flood. Flows at this threshold may not be competent to mobilize the gravel bed of the Peace River, but serve to illustrate inter-annual frequency patterns of relatively high discharges. Figure 1.5 shows histograms for the occurrence of these flows for the actual and naturalized daily flow records at Taylor, British Columbia, and Peace River town. These charts show a severe reduction in the occurrence of high flows; only in 1996 does the number of actual high-flow days approach that predicted by the naturalized time series. At Taylor, the total actual number of high-flow days is only 8% of the number predicted by the naturalized flows; this figure rises to 18% at Peace River town, and 24% at Peace Point (not shown). This is probably the clearest illustration of the negative impact of Bennett Dam on the Peace River’s potential for sediment transport and suggests that, with respect to morphological adjustment, regulation has been a far more important forcing agent than natural climate shifts over the past three decades.

1.2.3. Effects of Regulation: Peace River Literature

A considerable body of work exists on the regulated Peace River. Some of the more pertinent papers are reviewed here, in roughly chronological order.

Much of the early research on Peace River morphology was done by Kellerhals. One paper (Kellerhals, 1971) examined the influence of regulation on water levels in Lake Athabasca, which is connected to the river via several outlet channels in which flow direction depends on relative water levels in the two main water bodies. More relevant to the present study is an overview of Canadian regulated rivers, including a case study of the Peace (Kellerhals and Gill, 1973). Here, the authors supplied the first morphological predictions of the effects of regulation. They expected reduced annual variation of flows and stages, with potential flooding due to ice jams. Degradation was considered improbable below Bennett Dam due to the naturally
Figure 1.5  Histograms showing the number of days when flow (actual and naturalized) exceeded half the pre-regulation mean annual flood discharge at Taylor (a) and Peace River town (b) for the post-regulation period.
armoured cobble-gravel bed in this reach. Predicted and/or observed morphological changes included:

- aggradation at downstream tributary mouths, causing steps in the long profile;
- reduced channel capacity via slow filling of scour holes and bar abandonment and colonization by terrestrial plants;
- degradation of downstream tributaries; and
- lower water levels in Lake Athabasca and potential permafrost encroachment in the Peace-Athabasca delta region.

In a later summary paper (Kellerhals, 1982), two examples of likely tributary degradation were elaborated: Farrell Creek, a small gravel-bed river, has degraded 1 m for a distance of 300 m upstream of its mouth; and the Pine River, the largest British Columbia tributary, has undergone rapid bank erosion above the confluence. The Pine was also cited as an example of tributary-mouth aggradation. According to Kellerhals, bed elevation changes at locations away from tributary mouths have been small and irregular during the regulated period. He also speculated that higher winter flows create more potential for ice jamming.

BC Hydro (1976) commissioned a report in anticipation of potential new hydroelectric developments on the British Columbia reach of the Peace River: Site C, near the mouth of the Moberly River, or Site E, at the British Columbia-Alberta border. It was a detailed investigation of hydrology, morphology, bed material and sediment transport on this segment of the Peace and five of its major tributaries. While this report did not assess comprehensively the effects of Bennett Dam, post-regulation channel instability in the Halfway, Moberly and Pine Rivers was attributed to the regulation-induced lowering of mainstem water levels. Degradation of distal Lynx Creek, a small tributary upstream of Farrell Creek, was also noted. The report contains valuable baseline data on the Peace and its tributaries, some of which I used in my research.

Church has inherited from Kellerhals the role of principal investigator of morphological changes along the Peace River. An unpublished report (Church and Rood, 1982) for the BC Energy Commission provided initial observations from surveys of Peace River cross-sections between Hudson's Hope and the British Columbia-Alberta border. The report also included a vegetation survey of the islands and bars between the Moberly and Beatton Rivers (Teversham and North, 1982). The authors indicated that no consistent degradation was seen in any of the cross-sections. Deposition at the mouth of the Pine River has resulted in flow deflection and bank
erosion 1 km downstream on the Peace. Only minor or "natural" aggradation was reported for the rest of the study reach. Church and Rood noted that abandonment of old bars and backchannels has increased channel sinuosity. It was predicted that future floodplain accretion will be slower, controlled mainly by ice jam floods, and will reach a final elevation below the old floodplain, which has become a low terrace. Most of the vegetation succession pattern changes observed by Teversham and North were related to peak flow curtailment, silt deposition in low abandoned areas, reduced erosion, and various ice jam effects.

In his most important paper on the subject, Church (1995) described the Peace River as a full-scale study of the effects of flow regulation without confounding change in sediment supply, since most of the Peace bed material load enters the system downstream of the dam. Church used hydraulic geometry to predict, at reach scale, the final width, depth, average velocity and meander wavelength which should develop under the regulated flow regime. All were predicted to decrease in the long term, and field evidence suggests most of these predictions are in gradual progress. In the gravel reaches, capacity was reported to be reduced via bar and back channel abandonment, channel-edge bar accretion, and primary plant succession in these areas. The same processes were also seen in the lower sandy gravel and sand reaches, with channel-edge accretion enhanced by an increased fine sediment load supplied by the Smoky River. Church predicted that long-term aggradation may occur here due to a combination of backchannel abandonment (leading to higher sinuosity and lower gradient) and increased concentration of fines in reduced flows. This aggradation may cause shoaling and renewed island formation, leading to the predicted reduction of meander wavelength. He also noted that tributary fan growth has constricted river flow, producing backwater reaches upstream and giving the long profile of the river the beginning of a stepped appearance. The time scale for completion of these changes was projected to be thousands of years.

In a report for the Canada / Alberta / Northwest Territories Northern River Basins Study, Church et al. (1997) assessed regulation-induced channel pattern changes using detailed maps of channel and riparian vegetation patterns in the Alberta reaches of the Peace. Substantial channel narrowing was reported for two of the study reaches, primarily due to plant succession. Little change in width was observed in a confined reach, while the most distal study reach showed a much slower rate of narrowing, primarily via silt accretion to the channel edges. Backchannel abandonment has reportedly increased sinuosity in many locations, leading to reduced gradient,
but this may be offset by reduced flow resistance due to concentration of flow in a single channel. Island reaches, which are historically the least stable, were predicted to ultimately remain unstable in the regulated regime. Another unpublished volume (Xu and Church, 1996) compiled three reports on the regulated Peace River: one on the new hydrological regime, a second on morphological change in the Alberta reaches, and a third examining probabilities of change between various morphological units along the river. Many of the effects already described were elaborated by means of quantitative indices and their downstream patterns of change.

Uunila (1999), in a thesis supervised by Church, focused on the ice regime of the Peace River and its effects on river channel morphology. Field evidence indicated that ice jam flooding is most frequent and severe between Peace River town and Carcajou, a confined, sinuous reach with many islands. Ice processes appear to be minor contributors to the channel morphology of the Peace River, with ice scour features small and short lived, and ice sedimentation quite localized. Narrow, irregular benches which line some reaches of the channel may be formed by ice shove and ice-jam sedimentation. Ice damage to riparian plants is common, and the elevation of riparian vegetation communities appears to be related to the local intensity of ice processes.

Prowse and Conly (1998) also discussed Peace River ice in revisiting the issue of reduced water levels in Lake Athabasca. The open-water flood of record in the lower Peace River occurred in 1990, largely due to flow from the unregulated Smoky River. This flood failed to inundate the Peace-Athabasca delta, indicating water levels in the system must be dependent upon ice-jam flooding. An analysis of Peace River ice and flow records suggested that regulation has had little effect on river ice mass, ice strength or flow at the time of spring break-up, but has tended to cause ice to form at a higher level. Since a higher ice surface can pass a larger spring flood, this reduces the chances of mechanical ice break-up, jamming and severe flooding. The trend was reinforced in the 1970s and 1980s by the absence of large spring floods in the lower tributaries, likely due to reduced precipitation associated with the PDO (see Section 1.2.2).

The work of Kellerhals, Church and others has supplied a good base of site-specific information on the post-regulation Peace River, including:

- pre-regulation physiography, climate, hydrology and morphology;
• main processes and trends of channel width and pattern, and riparian vegetation change;
• initial observations of bed degradation and aggradation along parts of the regulated river; and
• preliminary information on ancillary effects of regulation, e.g. erosion in downstream tributaries, interactions with the ice regime, and water level changes in the Peace-Athabasca delta region.

Collected knowledge of morphological adjustment falls short of complete, however, and many open research questions remain. I have chosen to explore the topic of channel gradation in the Peace River and its tributaries. The rationale and hypotheses for my work will now be reviewed.

1.3. Project Rationale and Hypotheses
The reduction in peak flows on the regulated Peace River implies a loss of sediment transport competence below Bennett Dam. Most of the river's sediment load enters the channel downstream of the dam, delivered by valley wall failures and unregulated tributaries; this supply is essentially unaltered by regulation. For the regulated river to establish equilibrium transport of its unregulated sediment load, channel gradient must increase, or flow resistance must decrease. Channel narrowing and abandonment appear to have contributed to these adjustments (Church et al., 1997) but, in a confined river like the Peace where channel migration is constrained, channel gradation must play an important role. Although degradation and aggradation have been touched upon in previous research, no comprehensive study of channel gradation throughout the regulated Peace River basin has been made. By extension, the interaction of channel gradation and channel pattern change within long-term river gradient adjustment remains unclear. These problems are central to understanding the response of the Peace River to flow regulation, and their resolution is the goal of this project.

My research seeks to test two general hypotheses:

1. Through aggradation and channel pattern change, the Peace River is steepening its course to compensate for its reduced post-regulation capacity for sediment transport.
2. Peace River tributaries downstream of Bennett Dam have systematically degraded in response to reduced mainstem water levels.

To test these hypotheses, three more specific operating questions have been devised:
i. Are systematic patterns of degradation and/or aggradation evident in the mainstem channel since regulation?

ii. Are identified gradation trends reinforced by post-regulation planform changes in the river channel?

iii. Can systematic post-regulation channel degradation be identified in the distal reaches of downstream tributary streams?

A complicating factor in this study is the sheer scale of the problem: the subject reach is over 1000 km long, and no simple picture of the behaviour of the regulated Peace River as a whole is available. My arguments, therefore, rely on inference based on detailed observations at numerous locations along the river.

The first two operating questions are explored in Chapter 2, which considers post-regulation channel gradation in the mainstem Peace River. Chapter 3 deals with the second hypothesis on tributary gradation.
2. **Mainstem Channel Gradation**

In this chapter, patterns of post-regulation channel gradation are considered along the Peace River mainstem from the dam site to Peace Point. The ideal information source for tracing river-length gradation patterns would be a sequence of longitudinal profiles over time. Regrettably, no such resource exists, requiring that data be compiled from multiple locations along the river to interpret large-scale patterns of change. Three main analytical techniques are employed: comparison of repeatedly surveyed cross-sections, specific gauge analysis of historical rating curves, and analysis of changes in sinuosity and braiding index using morphological change maps. The following sections will describe these methods and their error sources, present their respective results, and integrate the findings in a discussion.

2.1. Methods

A variety of data are called upon in this study, each with a variety of error sources. Where possible, error factors are calculated; otherwise, potential error sources are discussed qualitatively. Formal statistical tests for significance are not applied in this project, as they are generally not suited to the structure and quantity of my data. For instance, degradation or aggradation over time at one cross-section cannot be statistically tested; one can only assess whether observed change exceeds the error margins. As a second example, in determining reach-scale gradation trends, the number of available cross-sections is insufficient for a statistically representative sample unless the entire set is considered a homogeneous population, which is unlikely given the variability of local conditions along the river. In the absence of statistics, conclusions are based upon the consideration of all available evidence in light of known error margins.

2.1.1. Cross-Sections

The comparison of successive surveyed river cross-sections reveals net erosion and deposition through time at a location, suggesting net local gradation. Beginning in 1968, and continuing in 1975, a total of 35 monumented cross-sections were established and surveyed along the Peace mainstem from Hudson’s Hope to the British Columbia-Alberta border on behalf of the British Columbia Hydro and Power Authority (BC Hydro). No cross-sections were established prior to
regulation. The sections were re-occupied and surveyed under the direction of Dr. Michael Church of the University of British Columbia in 1979, 1981, 1986, 1991 and 1998. The resulting elevation profile data were analyzed in the present study. Survey data are sparser in the Alberta reaches of the Peace. Cross-sections were established on the river near Dunvegan by a variety of contractors and agencies, and three historical sets were considered suitable for analysis. Thirty additional cross-sections were surveyed in the Fort Vermilion area in the 1970s (McLean and Anderson, 1980), and others are known to exist between Peace River town and Carcajou, and near Peace Point, but these have never been re-occupied. The locations of analyzed cross-sections are presented in Figure 2.1.

In the field\(^4\), cross-sectional surveys were performed in two components: the banks and the channel. Bank surveys were done with a level, theodolite or geodimeter, depending on the year and the section. Permanent benchmarks of driven rebar or iron rod were established on both banks at most sites, and their elevations surveyed to geodetic datum. These have been updated, supplemented or replaced as necessary through the years, so that surveys from all years can be compared at most sites. Bank surveys have generally included all major breaks in slope and vegetation type. Since 1991, many of the bank surveys have been shortened as the upper banks are no longer active under the regulated hydrologic regime.

Channel surveys were performed by boat using a fathometer. Vertical control was achieved by surveying the water surface elevation during the bank survey. Horizontal control was established by two different methods. In the earlier surveys, the rod or prism was carried on the boat and periodically surveyed from the bank. These horizontal ‘fixes’ were simultaneously marked on the fathometer traces, allowing the positions of intervening points on the river bottom to be estimated by interpolating between fixes. In 1998, the boat’s position was tracked by differential global positioning system (DGPS). A roving GPS unit was kept aboard to log the boat’s position, while a stationary base unit (either the permanent Fort St. John station or a handheld unit placed on a local benchmark) ran for the same time period. These two records could then be used to correct for ‘selective availability’ scrambling of the GPS signal, improving positional accuracy. In both methods, the boat was kept on the survey line by sighting along parallel range

\(^4\) Described methods were used in the British Columbia reach surveys of M. Church; methods used at other sites may have varied somewhat, but the level of precision should be similar.
poles and targets installed on the line. Channel surveys were generally repeated at least twice. Further details of the survey methodology are provided by Church and Rood (1982).

Several analyses were performed on the survey data. First, for each section, all available years of data were plotted together. Local temporal patterns of cross-sectional change were qualitatively assessed, and the sections were classified into five general gradation response types. To qualify as unstable, the channel needed to exhibit consistent change in form beyond the limits of survey error (see below). Changes in cross-sectional channel form were quantified by two means (Figure 2.2). In the first method, cross-sectional areas below a common elevation were subtracted from year to year. Area change was then divided by channel width, as determined from morphological maps of the river (see Section 2.1.3), to yield net gradation. The second technique was designed to capture gross change, even where net cross-sectional area was unaltered (e.g. compensating scour and fill, or lateral bar migration). This involved importing the sections into a geographic information system (GIS) and performing union overlays between years. This operation generated three polygon types: the channel area common to both years, and the areas occurring in only one of the years. Summing the areas of the latter two polygon types yielded gross cross-sectional ‘activity’. Both methods required that all surveys of a given section be truncated at a common water level. This level was subjectively chosen to remove the

![Figure 2.2](image.png)

**Figure 2.2:** Illustration of cross-sectional change measurement techniques. Cross-sections from different years are truncated below a common water surface.
upper river banks, with the goal of excluding changes caused by non-fluvial processes (e.g. construction, slope failure, ice scour). To highlight long-term patterns of change, net gradation was calculated over the longest possible period at each section. To avoid bias arising from unequal numbers of survey years, cross-sectional activity comparisons were made between the 1975 and 1991 surveys, or the nearest available years. Change observed in survey years later than 1996 was considered separately, due to the exceptional effects of the extended emergency release flood of that year.

The cross-sectional survey data have variable margins of error, depending on the particular methods used in a given year and the local flow conditions and channel configuration at a section. During the bank surveys, vertical and horizontal error increase with distance between instrument and rod. Operator errors, such as misread numbers or a tilted stadia rod, are inevitable and can propagate throughout a survey; many of these were caught during data reduction, as they often result in visible anomalies in the survey plot. During the channel survey, the fathometer cannot resolve depths less than 1 m, and its accuracy is susceptible to air bubbles and waves. Positional error depends upon the skill of the boat driver, as the boat must be kept on-line and its speed must be consistent between positional fixes. This is somewhat controlled by the replication of channel runs. Additional sources of error include measurement of depths and distances on the fathometer traces (± 0.05 m vertical, approximately ± 1 m horizontal), and the assumption of a flat water surface. This latter is likely negligible at most locations due to the low sinuosity of the Peace River, but the survey notes suggest that at a couple of sections, the water surface superelevation may be as high as 0.2 m. All of these error sources are mitigated by the fact that in a river the size of the Peace, channel geometry and features are relatively large, and can be expected to change relatively little within short distances of the true cross-section location.

Church and Rood (1982) provide a more detailed discussion of methods and error in the cross-sectional surveys; they estimate that in the worst case, channel survey techniques may produce error of ± 0.2 m vertically and ± 9 m horizontally. At the scale selected for the cross-section plots (Appendix A), this amounts to a vertical range of ± 1 mm. Horizontal error is mostly of concern near the riverbanks, where it might combine with relatively high bed slopes to produce

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5 Horizontal error in the channel survey should be considerably improved in the 1998 data, due to the use of GPS to track boat position.
false changes in bed elevation. For this reason, anomalous cross-sectional changes near the water’s edge are treated with suspicion. Extending the vertical error term systematically over a typical cross-sectional width of 300 m (i.e. assuming that the error is a bias) yields an areal error term of roughly ± 60 m². Cross-sectional activity values less than this magnitude are, therefore, considered insignificant.

2.1.2. Specific Gauge

Historical stream gauging notes, rating curves and rating tables are available for the Peace River at the following Water Survey of Canada gauging stations: above the Pine River, Taylor and above the Alces River in British Columbia; and Dunvegan bridge, Peace River town, Carcajou, Fort Vermilion and Peace Point in Alberta. The records from individual stations vary in length, dating as far back as 1915 (at Peace River town) (Table 2.1). New rating curves are drawn when discharge measurements begin to plot substantially off the old curve, suggesting a change in regime or channel morphology. Estimations of local degradation or aggradation can be derived by comparing the stage for a given discharge on successive rating curves at a station, a procedure known as specific gauge analysis. In some instances, consecutive rating curves are not comparable due to changes in the gauge location or datum. Otherwise, all possible comparisons have been made. The length of the Peace River gauging history allows the comparison of pre- and post-regulation specific gauge trends at some locations.

<table>
<thead>
<tr>
<th>Gauge Location</th>
<th>Approximate Distance Below Dam (km)</th>
<th>Records Available*</th>
<th>Pre-Regulation Mean Annual Flood (m³/s)</th>
<th>Post-Regulation Mean Annual Flood (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above Pine R.</td>
<td>117</td>
<td>1979 – pres.</td>
<td>na</td>
<td>2426</td>
</tr>
<tr>
<td>Taylor</td>
<td>122</td>
<td>1945 – pres.</td>
<td>7525</td>
<td>3082</td>
</tr>
<tr>
<td>Above Alces R.</td>
<td>167</td>
<td>1974 – pres.</td>
<td>na</td>
<td>3430</td>
</tr>
<tr>
<td>Dunvegan Bridge</td>
<td>297</td>
<td>1960 – pres.</td>
<td>8275</td>
<td>3801</td>
</tr>
<tr>
<td>Peace River Town</td>
<td>402</td>
<td>1915 – pres.</td>
<td>9157</td>
<td>6000</td>
</tr>
<tr>
<td>Carcajou</td>
<td>662</td>
<td>1961 – 1966</td>
<td>9997</td>
<td>na</td>
</tr>
<tr>
<td>Fort Vermilion</td>
<td>827</td>
<td>1917 – 1977</td>
<td>9783</td>
<td>5086</td>
</tr>
<tr>
<td>Peace Point</td>
<td>1162</td>
<td>1962 – pres.</td>
<td>10088</td>
<td>6109</td>
</tr>
</tbody>
</table>

Table 2.1: Summary of available Peace River specific gauge records; * Some discontinuities exist in the gauging records; na = not available.
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 of 0.8 times the pre-regulation mean annual flood\(^6\), which should be slightly less than bankfull. This relatively high flow was chosen to avoid spurious gradation effects due to changing bed topography (which are significant at low flows), as well as breaks in the rating curve at overbank flows. At the three uppermost stations, incomplete high-flow records forced the use of lower flows: 0.4 MAF above Pine River, and 0.6 MAF at Taylor and above Alces River.

Error in stream gauging is variable due to diverse measurement methods (e.g. from bridges or moving boats) and meteorological conditions (e.g. wind, ice, slush). The exact form of the rating curves used in this analysis is quite subjective and dependent on the technician who drew the curve. In general, though, the Peace River curves have a consistent, logarithmic form from year to year, suggesting that between-year comparisons should be valid. Stage measurements conducted by the Water Survey of Canada are comparatively precise, as water levels are recorded in stilling wells and gauge elevations are frequently verified against geodetic datum, with an error tolerance of millimetres (R.D. Moore, pers. comm.). According to Pelletier (1988), who conducted an extensive literature review on error in stream gauging, most flow measurements have a precision of approximately ±6%. To illustrate, a measured flow of 5846 m\(^3\)/s (the post-regulation mean annual flood at Peace River town) may lie anywhere in the range of 5495 m\(^3\)/s to 6197 m\(^3\)/s. Using a recent rating table (#10, dated October 29, 1990), this represents a 0.32 m range in stage. This rough analysis suggests an error term of approximately ±0.2 m for specific gauge analyses.

2.1.3. Planform Analysis

Channel gradation and planform change are intimately linked, as sinuosity adjustment is the easiest means for a river to alter its slope (Church, 1995), and may suggest gradient adjustments undetectable by analysis of vertical changes alone. Mainstem bed gradation must therefore be compared with planform changes to gain a complete view of channel response to regulation.

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\(^6\) The mean annual flood was rounded off for the sake of convenience; in some cases, the same flow was used at successive stations. This should not affect the results, as the same flows were used from year to year at a station.
My principal information source is a series of 1:20,000 maps depicting morphological and riparian vegetation changes along the Peace River. These were produced at UBC under the supervision of M. Church. The maps are based on medium scale (mostly 1:30,000 to 1:50,000) aerial photographs from 1953, 1968, 1977, 1986 and 1996 in British Columbia, and from 1950, 1966, 1976, 1988 and 1993 in Alberta; these are referred to as Periods 1 through 5, respectively. Coverage includes the entire British Columbia reach downstream of Hudson’s Hope, and four extended reaches in Alberta (see Church et al., 1997, Figure 3). The maps classify the channel area into major morphological units, including water, vegetated and unvegetated bars, islands, floodplain, and alluvial fans. Each of the mapped reaches was divided into relatively uniform sub-reaches according to morphological features and position relative to major tributary rivers (Figure 2.1). All surveyed cross-sections and gauging sites of interest (except Carcajou and Peace Point) fall within mapped reaches.

Channel pattern change was assessed by calculating channel sinuosity and braiding index (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. Braiding index was derived by counting the number of channels crossed by a transect line. To avoid error from varying water levels between map dates (see below), channels were considered to include all morphological units classified as either water or bar. This is an important definition, as it includes recently vegetated bar and backchannel surfaces. It is a conservative measure of braiding index aimed at capturing channel pattern changes with a significant effect on river slope, and it will likely miss early stages of backchannel abandonment which may be ecologically significant. Braiding index transects were digitized at approximately 1 km intervals along the river, and individual results were averaged within sub-reaches. Changes in sinuosity and braiding index were derived for the sub-reaches containing cross-sections and gauge sites. Local braiding index was also measured at each of the data sites.

Error sources and magnitudes in the Peace River mapping project are carefully documented and reported 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. Measurements of channel and valley length are subject operator error, but after

7 The 1960s British Columbia and Alberta maps are composites based on photos from 1961 to 1970, though most were from 1966-69. This was necessitated by limited photographic coverage in the target period near dam closure.
repeat measurements of the same reach, this was found to be insignificant if sinuosity is reported to two decimal places. Braiding index is 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. This is a distinct problem for the most recent maps of the British Columbia reach (Period 5), which are based on air photos from July, 1996, at the height of the emergency release flood. Flows in the British Columbia reach during this period were on the order of 5000 m$^3$/s versus a rough average of 1000 m$^3$/s in the previous four periods. Using the 1992 rating curve at Taylor, this amounts to a 2.4 m disparity in stage, which could have a strong effect on the apparent braiding index. Though incompatible flow levels are less of a problem in the Alberta reaches considered in this report (Church et al., 1997), mapped flows in sub-reach AB3-6 (containing the Fort Vermilion gauge) ranged from 878 m$^3$/s to 3140 m$^3$/s, indicating some potential for error. Visual inspection of the channel maps used in the braiding index calculations suggests that the inclusion of both bar and water surface areas largely compensates for these concerns, though the high 1996 stage obviously activated some high backchannels (cf. Figure 2.3). 1996 planform results are therefore reported, but should be accepted only with caution. There is no measurement error factor in computing braiding index, as the same transects were used each year.

2.2. Results

Mainstem channel gradation results are presented in three sections: cross-sections, specific gauge and planform analysis. These are followed by a section devoted to the effects of the 1996 emergency release flood.

2.2.1. Cross-Sections

The first step in analyzing the Peace River cross-sections is to classify them according to their pattern of post-regulation gradation response. These responses have been highly varied, reflecting the local conditions at each site. Nevertheless, it is possible to group the sections into five general response types: stability, aggradation, fan progradation, degradation, and scour / fill. In addition, at two locations, the river has shown a complex behaviour involving two distinct phases of gradation response. Classification is complicated by the effects of the 1996 flood: at
many locations, this anomalous flow event produced a distinctive imprint on the channel form. These changes seem unrepresentative of the river's overall adjustment to regulation and, accordingly, the cross-sections have been classified based on their pre-1996 response.

The following subsections describe each of the pre-1996 response types, illustrated by examples. Broader gradation patterns revealed by the cross-sections are then presented, followed by the results of the net gradation and cross-sectional activity analyses. Post-1996 changes are noted where applicable, but discussed separately in Section 2.2.4. The complete set of historical cross-sections is provided in Appendix A.
Stability
Stable cross-sections exhibit no particular gradation pattern. In some instances, the section has remained virtually fixed over the past 30 years; one such case is Section 23 (Figure 2.4a), located in an island reach upstream of Farrell Creek, British Columbia. 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 lines. The right channel has been even more stable, and the island form remained virtually constant from 1975 to 1998, the last survey date. 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. An example is Section 127 (Figure 2.4b), located 6.8 km below the Pine River confluence. At this site, as much as 0.5 m of vertical erosion occurred on the right bar surface from 1975 to 1981, but this was offset by fill in other parts of the section. In later years, changes were less dramatic and have not produced any significant net change in bed elevation. The 1998 survey shows slight aggradation in the main channel, and extensive deposition on the bar surface in the wake of the 1996 flood.

Aggradation
Aggrading cross-sections have displayed a consistent depositional trend since regulation. This class includes sections characterized by gradual, general aggradation across most of the channel. An example is Section 119 (Figure 2.5a), located upstream of the BCR railway trestle, approximately 6.1 km upstream of the Pine River confluence. This site showed aggradation across most of its width from 1975 to 1986. From 1986 to 1991, the channel appears to have stabilized. This is a common occurrence throughout the sections: regulation-induced changes appear to have been slowing by the early 1990s. From 1991 to 1998, the channel degraded slightly. In some cases, aggradation is more localized within a cross-section. A good example is provided by Sections S10 and 125 (Figure 2.5b and c), located at and just downstream of the Taylor bridge, 1.7 km and 3.1 km below the Pine confluence. At S10, there was dramatic aggradation (up to 3.2 m) in the main channel from 1968 to 1975. This deposition continued at a slower pace through 1986, and appeared to have stabilized by 1991. At 125, the aggradation began more slowly, accelerated between 1981 and 1986, and continued through 1991. Together, these sections reveal the downstream growth of a new bar composed of Pine River sediment; this interpretation is supported by air photos (Figure 2.6) and field observations of shoaling in the

8 A false aggradation signal at the far right of the section from in 1986 was caused by the deposition of floated logs.
Figure 2.4: Examples of stable cross-sections: (a) Section 23, upstream of Farrell Creek (km-41.8 below Bennett Dam), and (b) Section 127, 6.8 km downstream of the Pine River (km-127.2).
Figure 2.5: Examples of aggrading cross-sections: (a) Section 119, upstream of the BCR trestle (km-114.3), (b) Section S10, at the Taylor bridge just below the Pine River (km-122.1), and (c) Section 125, located just below S10 (km-123.5).
reach below the bridge (M. Church, pers. comm.). The post-1996 response of these sections was scour / fill at S10, and accelerated aggradation at 125. In 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; see Appendix A).

**Figure 2.6:** Aerial photographs from 1970 and 1997 showing bar growth below the Pine River confluence. Sections S10 and 125 are shown. At 125, the bar is sub-aqueous.

**Fan Progradation**

Fan progradation is a specific type of aggradation resulting from the buildup of tributary sediments in the main channel of the Peace River. It is treated separately from other types of aggradation because of its distinctive style and the fact that it may be accompanied by compensating erosion. Section Y (Figure 2.7a), located on the fan of the Halfway River, is a particularly severe example. At this site, massive deposition occurred between 1968 and 1975,
filling the entire channel with up to 6.3 m of sediment. The primary source of this sediment was the large Attachie landslide of 1973, which temporarily dammed the Peace River just 1 km upstream (cf. Fletcher and Hungr, 2000). A more typical phase of fan growth followed, with most aggradation between 1975 and 1991 occurring on the left bank, and the thalweg being progressively raised and forced toward the right bank. An unexplained period of fan erosion seems to have occurred from 1981 to 1986; survey notes from 1986 indicate possible ice disturbance high on the right bank. The 1996 flood initiated as much as 2 m of degradation across the entire channel at this site. Fan progradation has also been observed as far downstream as Section U1 (Figure 2.7b), located on the Hines Creek fan just upstream of Dunvegan. Though only two survey years are available at this site, the delta front has clearly pushed into the main channel from the left. In response to this flow constriction, the right bank has eroded. This is typical of several tributary confluences, and demonstrates that in some places, initial aggradation may trigger compensating degradation in another part of the channel.

Degradation
General degradation, the classic response of a river channel to regulation, is seen at only two locations along the 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 (Figure 2.8a), resulting in the destruction of a survey benchmark on the bar surface. The channel appears to have stabilized between 1986 and 1991. No 1998 survey data were available. The second example is provided by Section S2 (Figure 2.8a), located 7.2 km downstream of the Halfway River confluence. At this section, a mid-channel bar steadily eroded from 1968 through 1986, and the bed apparently stabilized by 1991. With the rest of the channel essentially stable, the net effect is a lowering of mean bed elevation. The pattern was reversed after the 1996 flood, with the 1998 survey showing reconstruction of the eroded bar. Both degrading sites are relatively proximal, located 55.9 km and 72.9 km below Bennett Dam, respectively, and both are.

Changes near the far left bank of U1 should be ignored, as the 1968 and 1987 surveys were not taken at the exact same location. According to M. Miles and Associates Ltd. (2000), the channel comparison is valid, but the left bank and upper fan diverge significantly in position.
Figure 2.7: Examples of cross-sections exhibiting fan progradation: (a) Section Y, on the Halfway River fan (km-65.7), and (b) Section U1, on the Hines Creek fan (km-299.6).
Figure 2.8: Examples of degrading cross-sections: (a) Section S1, located 13.1 km below Farrell Creek (km-55.9), and (b) Section S2, below the Halfway River confluence (km-72.9).
Scour / Fill
Sections in this category have shown significant cross-sectional activity over the period of record, but have been characterized by compensating scour and fill, with little apparent change in mean bed elevation. These sites are distinct from the stable cross-sections in that scour and fill have been progressive, rather than random fluctuations about some mean bed level. They also differ from the fan progradation sites in that their behaviour has not clearly been initiated by local aggradation. One typical scour / fill scenario is depicted by Section S5 (Figure 2.9a), 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, the scarped face of a fluvial terrace. Compensating bar growth has occurred at the left side of the channel, next to an island. The period from 1968 to 1981 was especially active, and again, the channel appears to have stabilized by 1991. The 1996 flood re-activated the pattern, as the 1998 survey shows renewed right bank attack and a rightward shift in the mid-channel bar. Another type of scour / fill is illustrated by Section 107 (Figure 2.9b), located in a backwater reach 3.6 km upstream of the Moberly River confluence. Here, the dominant change has been a progressive leftward shift of a large mid-channel bar. Again, the mean bed elevation of the section is unchanged despite the highly active nature of the cross-section. At this site, the 1996 flood caused some erosion of the bartop.

Complex Response
While rates of change have varied, most of the cross-sections have featured a single general response type. Two, however, have exhibited two distinct gradation phases. These ‘complex’ responses are not unlike those seen at fluctuating but stable sections; they simply have shown a greater degree of consistency within each phase. The first, Section 113 (Figure 2.10a), is located 3.6 km below the Moberly River. It underwent aggradation in the thalweg from 1975 to 1981, followed by degradation from 1981 to 1991. The shallow left portion of the channel was generally stable. The 1996 flood caused degradation of up to 1 m across most of the channel here. The second example is Section 123 (Figure 2.10b), located on the Pine River fan. The river experienced general aggradation here from 1975 to 1979. The thalweg essentially stabilized by 1981, while the delta front began to retreat through 1986, stabilizing in 1991. The 1996 flood caused accelerated erosion of the delta front and substantial bar growth in the former thalweg.
Figure 2.9: Examples of scour/fill cross-sections: (a) Section S5, upstream of Wilder Creek (km-88.9), and (b) Section 107, in a backwater reach upstream of the Moberly River (km-100).
Figure 2.10: Cross-sections exhibiting a complex response: (a) Section 113, downstream of the Moberly River (km-107.2), and (b) Section 123, on the Pine River delta (km-120.9).
Summary of Cross-Section Responses
Table 2.2 lists the post-regulation changes at all cross-sections. It includes a very brief description of principal changes at each section, and indicates the response type both before and after the 1996 flood. Table 2.3 summarizes the frequency of occurrence of the different response types. Looking at the pre-1996 responses in these tables, it is clear that the river, from Hudson’s Hope to Dunvegan, was predominantly stable or aggrading (including fan progradation), with degradation or scour / fill responses occurring at only 6 of 40 cross-sections. Five of these six, it should be noted, are located in the upper half of the British Columbia reach, between Hudson’s Hope and the Moberly River. As the Peace approaches the Moberly confluence, the pattern of change becomes dominantly aggradational, with intermittent stable sections. This remains true at Dunvegan, though nothing can be said of the intervening upper Alberta reaches.

The following sub-section explores the observed gradation patterns quantitatively.

Net Gradation and Total Cross-Sectional Activity
Net gradation, based on measured change in cross-sectional area between survey years, provides an objective assessment of post-regulation channel adjustment, and allows direct comparison with the specific gauge analysis (Section 2.2.2). These results are displayed in Figure 2.11, with bars showing the cumulative net gradation from the earliest survey up to 1996, and circles indicating the post-1996 response. Major tributaries, sediment sources, and the British Columbia-Alberta border are also shown. Considering only the pre-1996 data, the most dramatic feature of this plot is the aggradational spike at Section Y. Bar growth due to Pine River sediment at Sections S10 and 125 is also clearly represented by consecutive positive bars on the chart. At these and lesser deposition zones, local gradation trends are apparent, with relatively stable sections interspersed among the spikes (e.g. Sections S7 through 123) over a scale of several kilometres.

Additionally, there is an apparent change in response from the upper half of the British Columbia reach (20 to 95 km below the dam) to the lower half (km-95 to the British Columbia-Alberta border, or km-168.4). Except for Section Y, the upper reach has been generally stable over the
<table>
<thead>
<tr>
<th>Response Type</th>
<th>Pre-1996 Total</th>
<th>Post-1996 Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>Aggradation</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>Fan Progradation</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Degradation</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Scour / Fill</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Complex</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2.3: Frequency of occurrence of cross-sectional gradation response types.

years, with a few instances of slight degradation. Starting at Section C, however, the lower British Columbia reach is dominated by aggradation. This effect may be exaggerated due to undersampling of the upper reach (it contains only 11 sections, compared to 24 in the lower reach), but even if half of the lower sections were erased the trend would remain. The aggradation may weaken between Sections Z and S8, but this cannot be stated with confidence due to the absence of data in this 16-km reach, as well as significant aggradation at E6 just below the Alces River.

At Dunvegan, sections U1 and G show fan growth at the mouth of Hines Creek, though U1 has had enough compensatory erosion to produce slightly negative net gradation. The most distal cross-section (D1) is stable. The 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 site may not fairly represent overall local channel behaviour. This must be borne in mind when interpreting the sections.

A different perspective is provided by Figure 2.12, which shows total cross-sectional activity between 1975 and 1991 (or the nearest possible comparison), and after the 1996 flood. This parameter, which adds total erosion and deposition between survey years, emphasizes the gross amount of sediment transport occurring at a section, irrespective of whether this led to a net

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10 Though many of the sections in the upper British Columbia reach show net degradation before 1996, close examination of the historical surveys suggests most are stable, though fluctuating. Only Sections S1 and S2 have been classified as truly degrading.
Figure 2.11: Net post-regulation channel migration at surveyed cross-sections. Dots show net migration up to the most recent post-1999 survey. Circles indicate net migration for post-1999 data, where applicable.
change in bed elevation. In this plot, the dominant spikes are at Sections S5 and 107, both of which fall into the scour / fill response type. The other scour / fill sites (B and S11) are also quite active. The response of Section Y is muted because the Attachie landslide occurred before 1975. Most of the remaining aggradation sites (e.g. 117, 119, S10, 125, Z) are relatively active, but a few (e.g. 23, S9) appear in this plot as relatively inactive. Though the disparity is less pronounced than in the net gradation data, the upper British Columbia reach shows less channel activity than the lower. The Dunvegan plot echoes the results shown in Figure 2.11 (inset), with most activity concentrated at the Hines Creek fan.

2.2.2. Specific Gauge

Table 2.4 presents the net gradation results derived by specific gauge analysis. The results are broken into pre-regulation, post-regulation (to 1996), and post-1996 periods. Again, post-1996 changes are mentioned, but detailed discussion is left for Section 2.2.4. Within each period, the longest possible comparison between years was made, in order to emphasize long-term gradation trends; in some instances this has smoothed over a certain amount of shorter-term variability in mean bed elevation. Considering the ± 0.2 m error tolerance calculated for this analysis, several of the stations (Dunvegan, Peace River town, Peace Point) show no significant change before or after regulation. At Dunvegan, this outcome belies the dynamic cross-sectional activity noted in Section 2.2.1. At Peace River town, gauging notes from the earliest available pre-regulation record (1915 to 1922) indicate that the 1922 curve may be of suspect quality, so the early results here are questionable. This site is essentially on bedrock, so the non-significant gradation is reasonable and provides confidence in the method. At Peace Point, the most distal available data site, the same rating curve was used from 1970 through 1993. This suggests that despite some fluctuation below the significance level, the channel has been highly stable for most of the post-regulation period.

The gauge above Pine River indicates degradation of 0.31 m from 1983 to 1992, with a lesser amount of aggradation after the 1996 flood. Interestingly, this gauge is located just downstream of Section D, where the cross-sectional surveys revealed the opposite pattern: aggradation before 1996, and degradation after. The gauge at Taylor, however, supports the cross-section results

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11 Figure 2.11 does not clearly show the aggradation at Section D because the aggrading left bar has not been surveyed since 1975; see annotated cross-section plot in Appendix A.
at S10: it was stable before regulation, aggraded 0.57 m after regulation, and has been stable since the 1996 flood. The station above the Alces River recorded stage only until the early 1990s. It appears to have been stable prior to 1996, with degradation of 0.29 m after the emergency release flood.

In Alberta, at Carcajou, there is evidence of net degradation before regulation. This station was decommissioned after 1966, however, preventing any analysis of post-regulation trends. Farther downriver at Fort Vermilion, the results show significant degradation (0.32 m) before regulation, with marginal degradation (0.20 m) in the post-regulation period up to 1977. These numbers suggest this was a naturally active reach, but the post-regulation results may be corrupted by effects from the construction of the Fort Vermilion bridge between 1972 and 1973. A consultant’s report (McLean and Anderson, 1980) indicates there was substantial erosion and deposition associated with the bridge footings during this period.

<table>
<thead>
<tr>
<th>Location</th>
<th>Net Gradation (m)</th>
<th>Pre-Regulation</th>
<th>Post-Regulation / Pre-1996</th>
<th>Post-1996</th>
</tr>
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<tbody>
<tr>
<td>Above Pine River</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>-0.31</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>0.00</td>
<td>0.57</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
<td>-0.29</td>
</tr>
<tr>
<td></td>
<td>-0.18</td>
<td>0.00</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>0.11</td>
<td>0.18</td>
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<tr>
<td></td>
<td>1964 – 1968</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>-0.11</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Carcajou</td>
<td>1963 – 1966</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>-0.28</td>
<td></td>
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<tr>
<td></td>
<td>-0.32</td>
<td>0.20</td>
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<tr>
<td></td>
<td>0.20</td>
<td>-0.18</td>
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**Table 2.4:** Net gradation derived by specific gauge analysis. Values are based on a flow of 0.8 times the pre-regulation mean annual flood, except above Pine River (0.4 MAF), at Taylor and above Alces River (0.6 MAF). Significant results are in bold; positive values indicate aggradation, negative values indicate degradation.

The specific gauge results at Pine River and Taylor are well illustrated by superimposing the consecutive rating curves (Figure 2.13). 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 the channel form may be changing without effect on mean bed elevation. These effects can be seen at Peace River town (Figure 2.14), where the 1964 and 1969 curves cross around 3500 m$^3$/s and are generally

![Figure 2.13: Historical rating curves for Peace River above Pine River (a) and at Taylor (b).](image)

Figure 2.13: Historical rating curves for Peace River above Pine River (a) and at Taylor (b).
2.2.3. Planform Analysis

The planform analysis in this project focuses on the mapped reaches containing channel gradation data sites. These include the entire British Columbia reach (divided into sub-reaches BC-1 through BC-6 in the morphological maps) and three sub-reaches in Alberta (AB1-8, containing the Dunvegan sections and gauge; AB2-3, containing the Peace River town gauge; and AB3-6, containing the Fort Vermilion gauge). Figure 2.15 summarizes the downstream variability in planform complexity in the study reaches, based on these two parameters and the 1953 maps. In this plot, sinuosity and braiding index generally track each other quite faithfully. Only in sub-reach BC-2 do they diverge significantly, as the main channel here happens to follow the shape of the valley quite closely, producing low sinuosity despite the frequent occurrence of islands. The most complex sub-reaches are BC-5 and BC-6, with high sinuosity and braiding index. AB2-3 has high sinuosity, but a moderate braiding index. All three of these sub-reaches are characterized by frequent islands and backchannels; these features are less frequent in the less complex sub-reaches.

A summary of historical channel sinuosity is presented in Table 2.5. Sinuosity is essentially unchanged across all map periods and sub-reaches, with the difference in sinuosity never greater than 0.02 for any comparison. Braiding index has also been quite stable at most sub-reaches.
Downstream variability in sinuosity and braiding index for sub-reaches containing cross-sections or specific gauge sites. Data are from 1953 for BC and 1950 for Alberta.

(Figure 2.16), rarely varying by more than 0.10 over the entire period of record. This reflects both the chosen technique for braiding index measurement and the primary style of planform adjustment on the Peace River: gradual vegetative succession and siltation on high bars and in backchannels (cf. Church et al., 1997). This is a slow process which may progress for some time before a backchannel finally overgrows completely with floodplain species, leading to a change in braiding index by my method. Two exceptions are sub-reaches BC-4 and BC-5; the former has shown a steady decline in braiding index over the mapping period, while the latter has had a rather erratic history (Figure 2.16). These sub-reaches mark the beginning and middle of the lower British Columbia reach referred to in Section 2.2.1. The braiding index changes in sub-reach BC-4 are principally the result of the abandonment of two right-bank backchannels just upstream of the Pine River confluence (Figure 2.17) in 1986 and 1996. In sub-reach BC-5 (Figure 2.18), some backchannel infilling near the distal end accounts for the reduced braiding index from 1953 to 1967. The index then rose from 1967 to 1977, apparently because of the formation of some small islands and a minor channel avulsion just upstream of Section 127. Braiding index again fell in the two periods after 1977 as backchannels on the Pine delta and the bar complex of Sections 127 and 128 filled.
### Table 2.5: Historical sinuosity changes in sub-reaches containing cross-sections or specific gauge sites.

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<td>1.04</td>
<td>1.02</td>
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<td>1.03</td>
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<td>1.05</td>
<td>1.06</td>
<td>1.06</td>
<td>1.05</td>
</tr>
<tr>
<td>BC-6</td>
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<td>1.05</td>
<td>1.06</td>
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<td>1.01</td>
<td>1.01</td>
<td>1.01</td>
</tr>
<tr>
<td>AB2-3</td>
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<td>1.06</td>
<td>1.06</td>
<td>1.06</td>
<td>1.07</td>
</tr>
<tr>
<td>AB3-6</td>
<td>1.04</td>
<td>1.05</td>
<td>1.04</td>
<td>1.04</td>
<td>1.03</td>
</tr>
</tbody>
</table>

### Figure 2.16: Historical braiding index changes in sub-reaches containing cross-sections or specific gauge sites.
Figure 2.18: Historical morphological maps of sub-reach BC-5, downstream of the Pine River confluence. Shaded areas represent bar or water surfaces.
Table 2.6: Historical local braiding index changes at gradation data sites. Results showing change are in bold type.

occurred at cross-sections in sub-reaches BC-4 and BC-5. In almost all cases, the trend has been toward reduced braiding index. The only exception is Section 126, whose index dropped from 3 to 2 in 1986, only to return to 3 in 1996. Examination of the maps (Figure 2.18) suggests this may be a mapping artifact associated with the gradual infilling of a central island backchannel.
It is interesting to note that braiding index at the Peace River town gauge has remained constant at 1, despite being located in a relatively braided sub-reach (Figure 2.15). This gauge is positioned in a single-thread, bedrock-controlled reach (M. Church, pers. comm.), and the overall behaviour of sub-reach AB2-3 may not coincide with that of the channel at the gauge location.

2.2.4. Effects of the 1996 Emergency Release Flood

During the emergency release flood of 1996, Peace River flows at Taylor were on the order of 6000 m$^3$/s; this is twice the post-regulation mean annual flood of 3040 m$^3$/s, and approaches the pre-regulation mean annual flood of 7525 m$^3$/s. Considering its 6-week duration, this flood obviously constituted an episode of exceptional sediment transport competence for the regulated Peace River.

In most of the cross sections and summary data presented, there is a distinct change in channel response after 1996. In the most recent data, only 5 surveyed cross-sections remained stable (Table 2.3); notably, all of these are in the upper British Columbia reach (Table 2.2). Among the rest, the most dramatic effect was widespread erosion: after 1996, 15 sections fell into the erosive response types (8 degradation and 7 scour / fill), compared to only 6 in the preceding post-regulation period (Table 2.3). While degradation was pronounced at some formerly aggrading sites (e.g. Sections Y and 117), previously stable sites such as Section D were also eroded (see Figures 2.1 and 2.11). Conversely, only 9 sites showed aggradation after 1996, compared to 18 (including fan progradation) prior to that year. Of these, 6 were previously stable or degrading, while 3 were already aggrading. The sites which aggraded after 1996 are all located downstream of significant sediment sources, though sometimes at considerable distances:

- Section S2 is 7 km below the Halfway River;
- Section 113 is 3.6 km below the Moberly River, and 1.3 km downstream of an eroding bluff on the left bank of Section 112; and
- Sections 125 through 128 are all within 8 km of the Pine River confluence.

In other aggrading sections, the sediment source may be degrading sites upstream (e.g. Sections S7 and S9). Section 108 appears to be aggrading because it lies in the Moberly River backwater; the source of this sediment is a series of slumping terraces on the left bank, extending throughout the bend containing Sections C through 108.
The effects of the 1996 flood can also be seen in some of the specific gauge data. According to Table 2.4, the gauging site above the Pine River confluence (between cross-sections D and 117) has aggraded since 1996. The Taylor gauging site (in the same position as Section S10) has remained stable, though cross-section S10 shows that the 1996 flood caused a considerable redistribution of sediment (Figure 2.5b). There was 0.29 m of degradation at the Alces River gauge, which is in line with the scour / fill response seen in the 1998 survey at Section E6 (Table 2.2). The Dunvegan gauge shows slight aggradation, but not above the 0.2 m threshold for significance. At the two remaining gauges with post-1996 records (Peace River town and Peace Point), the rating curves have not been updated since 1996, indicating the channel remained stable despite the emergency release flood.

In the British Columbia reach, the latest maps used in the planform analysis are based on photos taken at the height of the 1996 emergency releases, while the latest Alberta maps are based on 1995 photos. For this reason, the planform results offer little insight into the effects of the 1996 flood, though the maps do show that the flood re-activated many abandoned backchannels. Most of the post-1996 cross-sectional changes occurred within the active channel, with few instances of 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 some fine sediment or vegetation in backchannels may have been scoured away.

The sediment redistribution achieved by the 1996 flood is clearly extraordinary under the new hydrological conditions of the Peace River. Figures 2.11 and 2.12 both demonstrate that the degree of net gradation and cross-sectional activity in the two-year period after the emergency release flood was commensurate with the geomorphic work done during the entire previous 28 years of the regulated period. In fact, the recorded changes may be conservative, since they are mostly based on the 1998 channel surveys, two years after the flood. It may be that the channel counteracted some of the flood effects during this time.

2.3. Discussion

The previous sections have presented various lines of evidence for the post-regulation adjustment of the Peace River mainstem channel. These are brought together in Figure 2.19, which maps the net gradation response from each data site (pre-1996), as well as summary planform
information by sub-reach and major sediment sources such as tributaries and landslides. This map forms the basis for the following discussion.

2.3.1. Absence of Channel Degradation

The first important aspect of Figure 2.19 is the near absence of degradation; it is restricted to two cross-sections (S1 and S2) and the gauge site above Pine River. This is remarkable within the general literature on regulated rivers, where degradation below the dam is a nearly universal outcome (cf. Williams and Wolman, 1984). The lack of degradation was predicted for the Peace River very early on (cf. Kellerhals and Gill, 1973) due to its resistant cobble-armoured bed and its weakened flow regime, possibly assisted by the fact that sediment supply from the upper Peace was naturally small (Church, 1995).
Degradation at S1 and S2 is related to mid-channel bar erosion rather than general downcutting. These relatively active surfaces may not have had such well-developed armour as the majority of the channel. The gauge site above Pine River is located just upstream of a tight bend, amidst considerable bar activity (Figure 2.17). It may be that the channel at the gauge site has been forced to degrade to maintain channel capacity in the face of nearby bar growth. At Dunvegan, some erosion has occurred opposite the prograding Hines Creek fan (Sections U1 and G), but this has not produced net degradation. This process may be pronounced at Hines Creek because the river’s bed material is somewhat finer here, nearly 300 km below the dam. Additionally, it is possible that at this location a certain amount of sediment starvation is being felt due to the Peace River’s inability to deliver bedload from the proximal tributaries. On the other hand, a similar pattern is seen at the Farrell Creek fan, 250 km upstream (see Section S3 in Appendix A). Specific gauge analysis at Fort Vermilion and Peace Point suggest there may have been slight post-regulation degradation at these sites, but the results are too small to be accepted as significant (Table 2.4). In any case, these distal gauges are located over 800 km downstream of the dam, in a fine-grained reach. Any downcutting this far downstream is unlikely to be due to regulation, as the river is still capable of supplying sand-size bed material.
2.3.2. Spatial Variability of Channel Gradation

Figure 2.11 suggests that net channel gradation in the post-regulation Peace River varies at both local and reach scales. Locally, aggradation sites are interspersed with more stable sites, with deposition zones rarely exceeding 5 km in length. This effect is especially striking in the upper British Columbia reach, where massive aggradation at the mouth of the Halfway River (Section Y) apparently has not reached Section S2, a mere 7 km downstream. The pattern is repeated near the Moberly and Pine River confluences. This suggests that contemporary sediment inputs to the Peace River remain essentially stationary, with the regulated river lacking the power to efficiently move the material downstream. This conjecture is reinforced by the distribution of major sediment sources, shown in Figures 2.11 and 2.22. Each aggradation site is located a short distance downstream of an identifiable sediment source and, nearly every sediment source is followed by an aggrading site. A notable exception is Section S6, a stable cross-section with a poor survey record (Appendix A). It is likely, however, that the right channel here has continued to aggrade since the last reliable survey in 1975, due to material deposited by the prolific Moberly River. New backwater reaches above constricted tributary junctions (e.g. cross-sections 108, 122, Z) are probably especially efficient at trapping sediment, though this does not seem to be a prerequisite for aggradation. This scale of variability in channel gradation supports the observation of Church (1995) that the Peace River is taking on a stepped longitudinal profile in response to localized sediment inputs and weakened flood regime.

Post-regulation channel gradation also seems to vary at a scale of roughly 100 km, with the lower British Columbia reach (from Section C to the British Columbia -Alberta border) showing more consistent aggradation than the upper British Columbia reach. Two possibilities may explain this pattern. First, it is generally the upper reaches which degrade in regulated rivers, with the effect eventually weakening due to downstream sediment inputs. While the regulated Peace is generally incapable of mobilizing its cobble armour layer, it may be that the river partly compensates for its interrupted sediment supply by redistributing sediment inputs in the upper British Columbia reach, spreading aggradation too thinly to be detected. This hypothesis is undermined, however, by the sharp, localized aggradation seen at the Halfway River mouth.

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12 Aggradation occurred at S2 after the 1996 emergency release flood (Figure 2.8b); this sediment may have been eroded from the Halfway fan.
This sediment has made little discernible progress to the cross-sections below in the past 30 years.

A second, more convincing theory is that the lower British Columbia reach simply contains more sediment sources, leading to more pervasive aggradation. Again, Figure 2.19 supports this notion, indicating very few sediment sources in the upper reach other than the Halfway River, the Attachie landslide, and a handful of smaller tributaries. Though the lack of data below Lynx and Wilder Creeks may bias these results, the smaller creeks seem to be relatively unimportant sediment contributors, as evidenced by the relatively slow fan progradation at Cache Creek (Section B) and the negative net gradation at Farrell Creek (Section S3). Non-tributary sources in the upper reach are rare, as the river is bounded primarily by bedrock upstream of Section 16, and by stable terraces for most of the reach between Sections 16 and C. In contrast, from Section C downstream, productive tributaries such as the Moberly, Pine and Beatton Rivers are supplemented by frequent eroding and slumping banks, terraces and bluffs. This section of the river has a complex morphology (cf. Figures 2.17 and 2.18), with extensive islands, bars and backchannels, suggesting the long-term development of the river form is also spatially linked to sediment supply. This is especially true of sub-reaches BC-5 and BC-6 (as demonstrated by the planform data in Figure 2.15), downstream of the Pine and Beatton Rivers, the two largest tributaries in the British Columbia reach. Based on this analysis, and the behaviour of Section Y, it seems possible that if only there were more sediment sources in the upper reach, the entire British Columbia portion of the regulated Peace River might be dominated by localized aggradation.

Farther downstream, data are sparser and the spatial pattern of channel gradation cannot be outlined in detail. The Dunvegan sections show a mixture of fan progradation and compensatory erosion, quite similar to the response at Farrell Creek. The offsetting activity at U1 gives way to stronger aggradation directly beneath the Dunvegan bridge (Section G). Section D, just 2 km downstream of Hines Creek, has been perfectly stable, as has the Dunvegan reach in general, according to the specific gauge results (Table 2.4). The channel in this area again shows localized aggradation at sediment sources, and the development of a stepped profile. The pattern is repeated 394 km below the dam, where the Smoky River delta has reportedly prograded substantially into the mainstem since regulation (M. Church, pers. comm.). Yet again, any aggradation has been limited in extent, with no evidence of bed elevation change at the Peace
River town gauging site 8 km downstream (Table 2.4). There are reports of shoaling as far downstream as Carcajou, 654 km below Bennett Dam (Church, 1995), suggesting aggradation may also be occurring there. At Fort Vermilion (821 km below the dam), however, there is no solid evidence of post-regulation channel gradation (Table 2.4), but neither are there any major sediment sources in the immediate upstream reach. By this point, however, the hydrological effects of regulation are considerably diminished and the bedload is primarily sand (Church, 1995). In these lower reaches, including the stable Peace Point gauge site, connections between channel behaviour and river regulation become rather tenuous.

2.3.3. Channel Gradation and Planform Change: Implications for Slope

Channel gradation and planform adjustment in the Peace River are intimately linked, as both are mechanisms for slope adjustment, through which the river may adapt to its new hydrologic regime. The connection between these two aspects of channel form is sediment supply: both require sediment, and the main loci of channel gradation and planform complexity occur where sediment supplies are abundant and productive (Figure 2.19). As the preceding discussion emphasizes, channel gradation began promptly after closure of the Bennett Dam, primarily in the form of aggradation below sediment sources. In fact, prior to the 1996 emergency release flood, it appears in many of the surveyed cross-sections that gradation had begun to slow (see examples in Section 2.2.1 and Appendix A).

According to previous studies (e.g. Church et al., 1997), gradation has been accompanied by the steady succession of floodplain vegetation on upper bar surfaces and in backchannels no longer regularly occupied by river flow. This is ecologically significant, as backchannel flooding is important to maintaining riverine biodiversity and food chains (cf. Power et al., 1996). My analysis, however, suggests these planform changes are progressing slowly (see Section 2.2.3). Some loss of backchannels is apparent in sub-reaches BC-4 and BC-5, but the pattern is not overwhelming, absent in all other studied reaches, and accompanied by the remarkable stability of mainstem sinuosity. Topographically, the backchannels still exist: they were extensively re-occupied by the 1996 flood, and historical cross-sections show they have been slow to fill (e.g. S4, 23, S2, S5, E6; see Appendix A). In fact, my conservative measure of braiding index may exaggerate the rate of disappearance of these features: even when they are thoroughly overgrown with trees, their complete siltation may take a long time since they are so rarely flooded.

Gradation changes have undoubtedly produced some local planform responses (e.g. bank erosion
due to flow deflection around prograding tributary fans). On the whole, however, planform adjustment and gradation seem to operate on different time scales, and largely independently of one another.

The implications of these changes for the slope of the Peace River are complex. With respect to gradation, it seems clear that the channel is taking on a stepped longitudinal profile. This is illustrated in Figure 2.20, a different rendition of the pre-1996 net gradation results from the British Columbia cross-sections. The question is whether this represents progress toward some new equilibrium between the Peace River’s channel form, sediment supply and regulated hydrologic regime.

![Figure 2.20](image)

**Figure 2.20:** Schematic of development of stepped longitudinal profile in the British Columbia reach of the regulated Peace River. Note exaggerated backwaters and oversteepened sections at aggradation zones.

As the first of my research hypotheses implies (Section 1.3), equilibrium demands an overall steepening of the channel slope to restore the river’s sediment transport competence. Although its bed elevation at the dam and at the Peace-Athabasca delta are essentially fixed, such an adjustment should still be possible below the first significant sediment supply. This would take the form of downstream-weakening aggradation to a point, probably somewhere in the sand-bed reach below the Smoky confluence, where tributary floodwaters and bedload fining compensate
sufficiently for flood reduction. So far, most observed aggradation seems too localized to represent such a master plan, and the resulting local channel steepening is generally offset by reduced slope in an upstream backwater reach. In the long term, however, locally increased slopes should promote the downstream progression of aggradation zones. 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. This process could eventually reach and fill the intervening backwater reaches, producing the required general aggradation.

In previous literature it has been posited (cf. Church et al., 1997) that the Peace River is adopting a more consistently single-thread channel pattern due to backchannel abandonment. This may misrepresent the fact that the backchannels continue to exist, but are no longer occupied by the usual range of regulated flows. Secondary channels still occupied at moderate flows, however, may not be scoured as effectively as before regulation. If these gradually become overgrown and choked with fines, their flow resistance will increase, which might lead to the concentration of more flow in the main-thread. If flow concentration is sufficient to increase bank erosion, the river may even become measurably more sinuous. The outcome would be reduced channel slope, counteracting the general aggradation hypothesis. An alternative scenario is increased braiding near sediment sources as local aggradation proceeds. This might cause a complimentary increase in slope and reinforce, at a smaller scale, existing channel patterns in complex reaches, rather than promoting a single-thread pattern. At this point, however, only the mid-channel bar growth below the Pine River confluence suggests itself as a possible example of such a mechanism. In sum, then, it is unclear whether ongoing planform changes complement the river’s progress toward a new equilibrium.

2.3.4. Role of the 1996 Flood

In six weeks of near-bankfull flow, the 1996 emergency release flood transformed the British Columbia reach from predominantly aggrading to degrading, with much of the eroded sediment deposited in previously stable areas. The final result was a major rearrangement of sediment which had been stuck near tributary confluences and other sources. While the resulting longitudinal profile may not be substantially smoother (Figure 2.20), the development of the stepped post-regulation profile was certainly disrupted. In the wake of this event, can the Peace...
River be expected to simply revert to its previous pattern of post-regulation adjustment, or has the pattern of change been fundamentally altered?

The redistributed sediment may be expected to have some lasting morphological impact, as it could form the basis of new bars and islands (e.g. Section S2, below the Halfway River), or generate new points of bank attack through flow deflection (e.g. the left bank of Section 121, below the BCR bridge). However, the preceding analysis has pointed to sediment sources as the driving force behind the pre-1996 gradation response, and these should mostly be unchanged. 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 continuing superimposed. This exceptional flow event may not have pushed the river any closer to a new equilibrium channel form, as it simply redistributed sediment which had already accumulated. Sediment was likely introduced to some areas prematurely, but this has set back the pattern of stepped aggradation which is necessary to sustain this redistribution in the long term.

The 1996 flood challenges the widely-held perception that, since regulation, the Peace River has essentially become static, bound by so-called 'lag' deposits and bed armour (cf. BC Hydro, 1976). Despite the general prevalence of stable or aggradational conditions at most data sites on the regulated Peace, some instances of erosion were observed even before the 1996 event, including:

- channel incision provoked by tributary fan growth (e.g. Farrell Creek, Hines Creek);
- bar instability (e.g. Section 107 upstream of the Moberly River);
- bar erosion (e.g. Section S2 below the Halfway River); and
- bank erosion (e.g. Section S5 upstream of Wilder Creek).

Although most of the regulation-induced changes in the Peace River channel have been passive in nature, it should be realized that erosive processes do still occur under the right conditions. This point was dramatically reinforced by the emergency release flood, and although such an event is surely rare in the regulated hydrologic regime, a repeat depends only on recurrence of the need to draw down the reservoir rapidly. The post-1996 results provide a critical precedent for understanding the consequences of such flow events.
3. Tributary Channel Gradation

Tributary response to regulation in the Peace River system has received almost no attention. Yet at least two cases of post-regulation tributary degradation have been documented, requiring engineering works to protect bridge footings at Lynx Creek and Farrell Creek (BC Hydro, 1976). Also, severe post-regulation channel instability at the mouth of the Pine River has been cited as a possible indicator of degradation in that river (Kellerhals, 1982). The present chapter documents post-regulation channelgradation in several tributaries in the upper Peace basin.

In their distal reaches, the selected Peace River tributaries (Figure 3.1) have many similarities. All are cobble-gravel-bed rivers deeply incised into the surrounding landscape (foothills for the uppermost tributaries, and high plains for the rest), having cut through layers of post-glacial sediments and shale and sandstone bedrock. Their valleys are narrow, and within these confines the rivers frequently run against high bluffs and various fluvial terraces. Contemporary floodplain development is therefore highly constrained, producing generally narrow and discontinuous surfaces. The tributaries have generally been degrading in post-glacial times, though occasional braided reaches (especially in the Moberly River) suggest they experience localized, transitory episodes of aggradation. All have built fans of varying size into the main channel of the Peace, a process accelerated by regulation. The Peace basin’s drainage density declines as the river leaves the mountains and enters the drier Alberta Plateau, and tributaries become less frequent. This large-scale climate gradient is also evident in the flow regimes of the tributaries: distal tributary basins lie entirely in the dry plains, and their discharge per unit of drainage area is less.

My tributary work consists primarily of air photo interpretation and field investigation of recent morphological changes near tributary mouths. At two sites, these efforts were supplemented by a computational analysis of bed material transport rates; this study is attached in Appendix C, and its results are occasionally referred to in this chapter. The following sections are devoted to an explanation of possible gradation scenarios, a description of methodology, presentation of results for each tributary site, and a discussion of the findings from all sites.
Figure 3.1: Map of Peace River tributary subject sites. Studies were conducted at confluences with the mainstem.
3.1. Tributary Gradation Scenarios

Two opposing gradation mechanisms may be at play in the lower reaches of tributaries to the regulated Peace River. First, upstream-progressing degradation may occur as reduced water levels in the mainstem cause an effective lowering of tributary base level (Figure 3.2a). The resulting increase in tributary slope would enhance sediment transport competence, allowing the tributary to downcut. As Leopold and Bull (1979) demonstrated, stream gradation due to base level change tends not to propagate very far upstream, so this effect would likely be strongest near the mouth. Tributary degradation is most likely to occur during tributary floods. Before regulation, flooding in the Peace and its tributaries was imperfectly synchronized: local rainstorms often generated isolated floods in the tributaries, but snowmelt and synoptic-scale rainfall floods often occurred simultaneously across large portions of the basin (cf. Figure 3.3), producing matching high water levels. Under the regulated regime, however, large flow events in the tributaries consistently encounter lower stages in the main river. During such events, mainstem-tributary stage disparity and the tributary’s ability to erode its bed are maximized.

![Figure 3.2: Schematic illustration of tributary gradations scenarios: degradation due to reduced water levels in the mainstem (a), and aggradation due to tributary fan progradation (b). The Peace River is viewed in cross-section, the tributary in longitudinal section.](image)
Figure 3.3: Example of flood timing between the Peace River at Hudson’s Hope and the Halfway River near Farrell Creek in 1963. Note, however, the isolated major flow event on the Halfway prior to the synchronized main snowmelt floods.

At sites with sufficient flow records, the magnitude of potential degradation was estimated by analyzing the post-regulation drop in Peace River stages during tributary floods. For all tributary floods exceeding the mean annual flood, water levels in the Peace River were compiled for the day when the tributary event peaked. These stages were averaged for the pre- and post-regulation periods, and the difference between the two periods provides an estimated upper limit for degradation. This analysis shows mean post-regulation mainstem stage drops of between 0.5 m and 3.1 m at the various tributary junctions (Table 3.1). There is no clear downstream trend in this figure, despite the progressive downstream restoration of the Peace flood. This outcome may reflect differences in the normal flood timing between the Peace River and its various tributaries. For example, the annual hydrograph of the Kiskatinaw River, which shows very little stage drop, may be naturally asynchronous with the Peace. The analysis has methodological flaws, however. The sites have limited pre-regulation flow records, Peace River gauges are not ideally located above tributary confluences, and flood lag time between mainstem and tributary is a problem where the tributary gauge is located relatively far upstream (i.e. the Pine and Smoky Rivers). Nevertheless, the analysis provides a first appraisal of how much degradation might be expected.
<table>
<thead>
<tr>
<th>Site</th>
<th>Distance Below Dam (km)</th>
<th>Peace Gauge Used</th>
<th>Average Peace Stage During Tributary Floods (m)</th>
<th>Stage Drop / Potential Degradation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pre-Reg.</td>
<td>Post-Reg.</td>
</tr>
<tr>
<td>Halfway</td>
<td>64.5</td>
<td>Hudson's Hope</td>
<td>6.70 (n=4)</td>
<td>4.23 (n=19)</td>
</tr>
<tr>
<td>Pine</td>
<td>120.4</td>
<td>Taylor (- Pine)</td>
<td>4.61 (n=7)</td>
<td>1.53 (n=9)</td>
</tr>
<tr>
<td>Beatton</td>
<td>141.9</td>
<td>Taylor</td>
<td>4.66 (n=4)</td>
<td>3.35 (n=20)</td>
</tr>
<tr>
<td>Kiskatinaw</td>
<td>156.3</td>
<td>Taylor</td>
<td>4.22 (n=3)</td>
<td>3.73 (n=15)</td>
</tr>
<tr>
<td>Smoky</td>
<td>394.1</td>
<td>Peace River (- Smoky)</td>
<td>11.31 (n=5)</td>
<td>9.73 (n=11)</td>
</tr>
</tbody>
</table>

**Table 3.1:** Results of tributary-mainstem stage disparity analysis. Mainstem stages (based on average daily flows) are taken from rating curves for the nearest upstream gauging station. For the Pine and Smoky Rivers, to include contributions from major upstream tributaries, 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.

A second gradation mechanism may counteract tributary degradation (Figure 3.2b). Since regulation, the fans of most Peace River tributaries have prograded into the mainstem. Fan growth may, in fact, have been accelerated if tributary degradation has increased the local bed material load. Tributary fan progradation extends the distance the tributary must travel to reach base level. This reduces tributary slope and stream power, promoting aggradation at the tributary mouth. Depending on the magnitude of base level change and the rates of these processes, tributary mouth aggradation might slow, reverse, or prevent degradation.

The goal of this chapter is to assess whether either or both of these processes have occurred on the unregulated tributaries of the Peace. Methods used to this end will now be described.

### 3.2. Methods

Initially, the tributary component of this project included all unregulated Peace River tributaries below the dam. The final study sites were selected on the basis of air photo interpretation and field visits, a process outlined below. Historical records are available in the form of hydrometric data and aerial photographs, and field work also provided insight into rates on channel gradation. Anecdotal evidence of tributary behaviour was obtained through conversation with Mr. Floyd Erickstad, a 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. A constraint to this study, however, is the absence of historical morphological data. Five monumented cross-sections were established and surveyed across the lower Halfway, Moberly, Pine, Beatton and Kiskatinaw Rivers by Underhill Engineering in 1975. The results and locations of these surveys are available (BC Hydro, 1976) and, during the 2000 field program, attempts were made to relocate them using GPS and a metal detector. Regrettably, the benchmarks were placed precariously close to the channel banks (Figure 3.4), and their reported coordinates are questionable: none of the monuments was found, and the sections were not re-surveyed.

Figure 3.4: Photo of survey benchmark being driven near the left bank of the Halfway River upstream of transect H4 (source: BC Hydro, 1976).

The specific methods used for this portion of the project will now be described.

3.2.1. Aerial Photographs

Air photo interpretation was initially used to seek out examples of post-regulation tributary gradation, and to identify sites for further investigation. Based on the observations of Kellerhals (1982) at Farrell Creek, initial degradation of Peace tributaries may be on the order of 1 m or smaller; this corresponds roughly with the potential degradation estimates described in Section 3.1. Such small vertical changes are at the limit of photogrammetric resolution (D. Ham, pers. comm.), necessitating that the analysis be based on visible planform changes. The primary morphological indicators are channel and bar areas which appear to have 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. Similarly, old floodplains may have become terraces, but this transition is difficult to see on the air photos since both surfaces are forested. Since regulation, the fans of most tributaries have undergone vegetative succession on their upper bar surfaces. This is not, on its own, seen as evidence of degradation, as fan abandonment is partially due to narrowing of the mainstem. 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, the distal reaches of most major tributaries between the dams and the Smoky River were studied on medium-scale aerial photographs. These included Lynx and Farrell Creeks, the Halfway, Moberly, Pine, Beatton, Kiskatinaw and Alces Rivers in British Columbia, and the Pouce Coupe, Clear, Montagneuse, and Ksituan Rivers, Hines Creek, and the Smoky Rivers in Alberta (Figure 3.1). To improve the level of discernible detail, large-scale photos were acquired for all of the British Columbia sites except Lynx Creek. All photos used are listed in Appendix B. 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 be used to guide field efforts, especially site selection and deciding how far upstream to examine in each tributary.

Initial air photo analysis suggested potential degradation at some, but not all, sites. Aggradation appeared possible at the Smoky River, but was not evident at upstream sites. It was therefore decided to investigate only sites above the Smoky, as this largest tributary contributes a significant spring flood, considerably weakening the hydrologic forcing mechanisms which might drive tributary gradation farther downstream.

3.2.2. Field Program

The field program for the tributary investigation took place in July and August, 2000. The objectives of the program were to identify degrading or aggrading sites and quantify observed changes through surveying and dendrochronology of new floodplain surfaces. A secondary objective of the field work was to search for the old BC Hydro survey monuments, but these efforts failed. The remainder if the trip was devoted to site selection, surveying and tree coring.
**Site Selection**

Each site was reconnoitered for signs of gradation. This involved observing identified overgrown bar surfaces and looking for breaks in elevation with adjacent new bars and older floodplains. The distal reaches of all sites between Lynx Creek and Hines Creek were visited, except the Pouce Coupe and Clear Rivers, which were inaccessible. Reconnaissance suggested that degradation had clearly occurred at the most proximal sites, with morphological evidence becoming confusing below the Halfway River. For this reason, detailed field investigation was limited to these sites: Farrell Creek and the Halfway, Moberly, Pine, Beatton, Kiskatinaw and Alces Rivers in British Columbia, and Hines Creek in Alberta. Air photo analysis of the Smoky River is also included in this report, but it was considered impractically large for surveying with limited resources. Although Lynx Creek has degraded, it has been modified by the installation of a boulder rapid to protect its highway bridge from undermining (Kellerhals and Gill, 1973; BC Hydro, 1976). This stream is only 2-3 m wide and appears to lack sufficient stream power to erode this heavily armoured bed, so it was not studied in detail. Basic hydrological characteristics of the selected tributaries are provided in Table 3.2.

<table>
<thead>
<tr>
<th></th>
<th>Farrell Creek</th>
<th>Halfway River</th>
<th>Moberly River</th>
<th>Pine River</th>
<th>Beatton River</th>
<th>Kiskat. River</th>
<th>Alces River</th>
<th>Hines Creek</th>
<th>Smoky River</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distance Below Dam (km)</strong></td>
<td>42.6</td>
<td>64.5</td>
<td>103.6</td>
<td>120.4</td>
<td>141.9</td>
<td>156.3</td>
<td>164.4</td>
<td>299.1</td>
<td>394.1</td>
</tr>
<tr>
<td><strong>Approx. Drainage Area (km²)</strong></td>
<td>637</td>
<td>9400</td>
<td>1900</td>
<td>13,560</td>
<td>15,600</td>
<td>4050</td>
<td>877</td>
<td>1647</td>
<td>51,860</td>
</tr>
<tr>
<td><strong>Gauge Location (km from mouth)</strong></td>
<td>na</td>
<td>4, 21</td>
<td>30</td>
<td>80</td>
<td>28</td>
<td>40</td>
<td>28</td>
<td>18</td>
<td>64</td>
</tr>
<tr>
<td><strong>Mean Annual Flow (m³/s)</strong></td>
<td>5¹</td>
<td>77</td>
<td>12</td>
<td>190</td>
<td>53</td>
<td>10</td>
<td>0.5</td>
<td>3</td>
<td>352</td>
</tr>
<tr>
<td><strong>Mean Annual Flood (m³/s)</strong></td>
<td>49¹</td>
<td>723</td>
<td>73³</td>
<td>1634</td>
<td>781</td>
<td>152</td>
<td>10</td>
<td>30</td>
<td>2724</td>
</tr>
</tbody>
</table>

**Table 3.2:** Hydrological characteristics of tributary sites. Drainage areas were derived by polar planimeter and from gauge notes. For rivers with more than one gauge, the most distal site was used. ¹Farrell Creek is ungauged; its flows are scaled from those of the Halfway River based on drainage area. ³The Halfway gauge was
moved in the early 1980s. The Moberly MAF is relatively low due to the natural regulating influence of Moberly Lake (Figure 3.1).

**Surveying**

At the field sites, vegetated bar and channel surfaces were surveyed to determine if they showed degradation. This involved measuring the relative elevations of young floodplains and their adjacent older floodplains and new bartops (or buried gravel surfaces beneath the young floodplains); if the young floodplain lies between the two in height, the differences can be taken as estimates of degradation (Figure 3.5). Ideally, these surfaces would lie in succession next to the channel, but the fragmented tributary floodplains occasionally left 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 surfaces. Old floodplains appear to provide a more reliable comparison than current or buried bartops, as the latter tend to be quite variable in elevation, while floodplains are relatively flat. Surveys were conducted with standard rod and level, with some distances measured by hip chain.

As with the mainstem bank surveys (Section 2.1.1), tributary surveys are subject to a variable amount of instrument and operator imprecision, particularly for sights over long distances. For efficiency, morphological units were surveyed using spot elevations, rather than mapping the terrain more thoroughly to obtain average elevations. This introduces an unquantifiable amount of error to the elevation comparisons. An important problem is the difficulty in distinguishing old floodplains from low pre-regulation terraces. This is especially troubling on large rivers like

![Figure 3.5: Schematic of technique for measuring tributary degradation by surveying young floodplains. Floodplain surfaces are relatively flat, but young floodplain may still be accreting via sand deposition. Modern and buried gravel surfaces have irregular topography.](image-url)
the Halfway and Pine, 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 spruce (*Picea* spp.) or aspen (*Populus tremuloides*), species which are uncommon on lower floodplains along the Peace River. Silverberry (*Elaeagnus commutata*), a terrace shrub, was not used as an indicator, as there has been enough 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 3.5). 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 suggest that survey results must be interpreted only as an order-of-magnitude estimate of gradation, rather than a precise measure.

**Dendrochronology**

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

Vegetation samples were taken by increment borer or by collecting an entire disc of wood. On older floodplain surfaces, the most common trees are mature black cottonwood (*Populus balsamifera*), a very pulpy species which tended to yield mangled, unusable cores. Fortunately, the smaller cottonwoods, alders (*Alnus* spp.) and willows (*Salix* spp.) which predominate on young floodplains were firmer and provided good samples. Cores were dried, straightened and glued on wooden supports. All samples were prepared by sanding using paper of progressively finer grit. For growth ring counting, samples were wetted, illuminated and placed on the stage of a 20-magnification 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 dendrochronology work is to date the young floodplains, it was not necessary to
obtain a representative sample of tree cores. Some bias may be introduced, however, by the fact that the oldest tree may have been overlooked or misidentified.

3.2.3. Halfway River Specific Gauge

Water Survey of Canada gauges exist on all of the subject tributaries except Farrell Creek (Table 3.2). Their records might potentially be used to assess channel gradation via specific gauge analysis, as described in Chapter 2. 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, located 4 km above the confluence, is close enough to the mouth to be used. 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 being moved 17 km upstream to its current location. The left and right gauges had the same datum and their rating curves can be directly compared (A. Stalker, Water Survey of Canada, pers. comm.). The new upper site, however, must be considered separately, though its flow records are comparable. Rating curves for the Halfway River frequently have been updated; this provides excellent data for specific gauge analysis, as well as being proof of a naturally active channel.

Error factors for the Halfway River specific gauge analysis are calculated as in Section 2.1.2. In this river, the gauging error of ± 6% translates into ± 43 m$^3$/s about the mean annual flood of 723 m$^3$/s, or a range of 680 m$^3$/s to 766 m$^3$/s. Using rating curve #17 (dated October 30, 1981) from the lower station, this would represent a stage range of 3.0 m to 3.11 m. Specific gauge results at this site must therefore exceed ± 0.06 m to be considered significant.

3.3. Results

The results of the investigation into tributary channel gradation are presented in the format of a case study for each site. Table 3.3 summarizes the key results for all sites; it lists young morphological surfaces with reasonable survey comparisons, and gives their estimated age (according to dendrochronological results) and the amount of local gradation revealed by the survey. The locations of the survey lines are shown on maps within each sub-section.
3.3.1. Farrell Creek

Farrell Creek is a relatively small stream which enters the north side of the Peace River approximately 43 km below Bennett Dam. Its 637-km² drainage basin lies almost entirely in the Rocky Mountain foothills. In several locations at its mouth, Farrell Creek runs on shale bedrock. The creek is frequently confined within its valley by post-glacial fluvial terraces or older bluffs (Figure 3.6), and its channel width at the mouth is about 25 m. Along with Lynx Creek, this site is one of two tributaries at which channel degradation has been reported, with the old highway bridge footings being undermined shortly after regulation of the Peace. Although the bridge has been replaced, the old south footing is still in place (Figure 3.7), with the adjacent channel incised 1 m into the shale. Local degradation must be of at least this magnitude, as the footing would originally have been set upon or beneath the thalweg.

Interpretation of low-level air photos of Farrell Creek reveals numerous bars which became forested between 1970 and 1989; these are outlined in green on Figure 3.8. The first area is the Farrell fan. Here, an extensive bar area has been colonized by cottonwood, alder and willow; tree core dating suggests the surface has been a floodplain at least 20 years. 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 3.8), however, the bar would likely have been maintained by Farrell creek, and survey data comparing the young and former floodplain suggest the channel at this location has degraded by 1.4 m (Table 3.3; Figure 3.9).

Similar examples occur at transects F2, F5 and F6, where other young floodplains were found to be 0.8, 0.6 and 0.4 m lower in elevation, respectively, than their adjacent old floodplains. According to the tree ring results, these young floodplains range in age from 16 to 29 years. Another bar on the right bank upstream of F6, just upstream of a power line right-of-way, has also vegetated since 1970, but this site was not surveyed. Above this site, channel morphology appeared to be dominated by a wedge of sediment released by a recently broken large woody debris jam. Although less reliable due to the variability of gravel bar topography, several surveyed bar surfaces (at F2, F4, F5 and F6) also indicate channel degradation 0.4 m to 1.3 m (Table 3.3). Morphological changes at transects F3 and F4 may be misleading, however, as the channel here was created by a meander cutoff in the late 1960s.
<table>
<thead>
<tr>
<th>Site</th>
<th>Surface</th>
<th>Minimum Age (yr)</th>
<th>Comparison</th>
<th>Gradation (m)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farrell</td>
<td>F1: LB YFP (delta)</td>
<td>20</td>
<td>LB OFP</td>
<td>-1.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F2: RB YFP</td>
<td>16</td>
<td>RB OFP</td>
<td>-0.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F3: MC bartop</td>
<td>Base of footing</td>
<td>Thalweg</td>
<td>-0.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F4: RB bartop</td>
<td>-</td>
<td>RB YFP gravel</td>
<td>-0.9</td>
<td>Much of YFP surface still looks like active bar</td>
</tr>
<tr>
<td></td>
<td>F5: LB YFP</td>
<td>29</td>
<td>LB OFP swale</td>
<td>-0.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F6: LB bartop</td>
<td>-</td>
<td>LB YFP gravel</td>
<td>-1.2</td>
<td>YFP has surface gravel; modern bartop poorly defined</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Delta; no reliable comparisons</td>
</tr>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>OFF measured in a swale; generally higher</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>OFF maybe too low (silted in old beaver dam area)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>OFF recently terraced? (very old cottonwood, young spruce)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Modern bartop downstream from site; adjusted for water slope.</td>
</tr>
<tr>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moberly</td>
<td>M1: VYFP north of road</td>
<td>17</td>
<td>OFF north of road</td>
<td>-0.3</td>
<td>OFF is a fragment on delta</td>
</tr>
<tr>
<td></td>
<td>M2: RB YFP</td>
<td>10</td>
<td>RB YFP</td>
<td>0.2</td>
<td>Surface gravel on high bar</td>
</tr>
<tr>
<td></td>
<td>M3: LB YFP</td>
<td>11</td>
<td>RB YFP</td>
<td>-0.8</td>
<td>Surface gravel on front YFP</td>
</tr>
<tr>
<td></td>
<td>M4: LB YFP</td>
<td>10</td>
<td>LB OFP</td>
<td>-0.4</td>
<td>Surface gravel on front YFP</td>
</tr>
<tr>
<td></td>
<td>M5: RB YFP</td>
<td>21</td>
<td>LB YFP</td>
<td>-0.4</td>
<td>Surface gravel on front YFP</td>
</tr>
<tr>
<td></td>
<td>LB bartop</td>
<td>-</td>
<td>RB YFP</td>
<td>-0.7</td>
<td>Surface gravel on front YFP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RB YFP</td>
<td>0.3</td>
<td>Surface gravel on front YFP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pine</td>
<td>P1: Island YFP</td>
<td>17</td>
<td>Island YFP</td>
<td>-2.9</td>
<td>OFF may have been terrace (very high)</td>
</tr>
<tr>
<td></td>
<td>P2: RB YFP</td>
<td>23</td>
<td>RB YFP gravel</td>
<td>-0.8</td>
<td>RB floodplains seem subject to ice activity</td>
</tr>
<tr>
<td></td>
<td>P3: LB YFP</td>
<td>12</td>
<td>LB YFP gravel</td>
<td>-0.8</td>
<td>RB floodplains seem subject to ice activity</td>
</tr>
<tr>
<td></td>
<td>P4: Upper island YFP</td>
<td>14</td>
<td>Upper island OFP</td>
<td>-1.1</td>
<td>OFF may have been a terrace; adjusted for water surface slope</td>
</tr>
<tr>
<td></td>
<td>Bartop b/w islands</td>
<td>-</td>
<td>Upper YFP</td>
<td>-0.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beatton</td>
<td>B1: Delta rear YFP</td>
<td>27</td>
<td>Rear OFP</td>
<td>-0.5</td>
<td>OFF is irregular fringe along base of higher FP/terrace</td>
</tr>
<tr>
<td></td>
<td>B2: RB YFP</td>
<td>-</td>
<td>RB upper OFP</td>
<td>-2.2</td>
<td>OFF may have been a terrace; YFP elevation may be too low</td>
</tr>
<tr>
<td></td>
<td>B3: RB YFP</td>
<td>10</td>
<td>RB upper OFP</td>
<td>-0.7</td>
<td>Adjusted for water surface slope</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>RB lower OFP</td>
<td>-0.4</td>
<td></td>
</tr>
<tr>
<td>Kiskatinaw</td>
<td>K1: RB YFP</td>
<td>13</td>
<td>RB OFP</td>
<td>-1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>K2: LB YFP</td>
<td>9</td>
<td>RB OFP at K1</td>
<td>-1.9</td>
<td>Adjusted for water surface slope</td>
</tr>
<tr>
<td></td>
<td>K3: LB bartop</td>
<td>-</td>
<td>Old channel gravel</td>
<td>-1.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-1.4</td>
<td>Adjusted for water surface slope</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.6</td>
<td></td>
</tr>
<tr>
<td>Alices</td>
<td>A1: -</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>No reliable comparisons</td>
</tr>
<tr>
<td></td>
<td>A2: LB YFP</td>
<td>9</td>
<td>LB OFP</td>
<td>-0.4</td>
<td>No reliable comparisons</td>
</tr>
<tr>
<td></td>
<td>A3: -</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>No reliable comparisons</td>
</tr>
<tr>
<td></td>
<td>A4: -</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Tributary to Alices; no reliable comparisons</td>
</tr>
<tr>
<td>Hines</td>
<td>HC1: -</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>YFP seems ice-controlled; no reliable comparisons</td>
</tr>
<tr>
<td></td>
<td>HC2: LB YFP</td>
<td>42</td>
<td>LB OFP</td>
<td>-0.1</td>
<td>YFP seems ice-controlled; no reliable comparisons</td>
</tr>
<tr>
<td></td>
<td>HC3: -</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Odd: there are spruce on both low floodplains</td>
</tr>
</tbody>
</table>

**Table 3.3:** Results of tributary field work. Ages are based on dendrochronology of the oldest tree on the surface. FP = floodplain, Y = young (post-regulation), VY = very young (< 10 years), O = old (pre-regulation), RB = right bank, LB = left bank, MC = mid-channel. Negative gradation values indicate degradation.
Figure 3.6: Overview of Farrell Creek, looking downstream. Note entrenchment of stream between bluffs of shale and postglacial sediments.

Figure 3.7: Old bridge footing on left bank of Farrell Creek. 1 m of degradation was measured from the base of the footing to the channel thalweg.
Figure 3.9: Transect F1, looking downstream. The young floodplain was an unvegetated bar prior to regulation. This cross-section is typical of degradation at several tributary sites.

3.3.2. Halfway River

The Halfway River has a physiography similar to that of Farrell Creek, draining the Rocky Mountains and their foothills, and entering the Peace from the north, 64.5 km below Bennett Dam. It is a much larger system, however: in the regulated British Columbia reach, it is the third-largest tributary by drainage area (9400 km\(^2\)) and the second-largest by mean annual flow (77 m\(^3\)/s) (Table 3.2), and its channel width at the mouth is about 130 m. The Halfway floodplain is typically discontinuous, though the fragments are relatively large - especially Pig Flat, the large left-bank old floodplain just upstream from the river mouth (Figure 3.10). There is anecdotal evidence of degradation at the Halfway mouth: at an unspecified time after regulation, an ice-breaking device was affixed to the mid-channel pier of the highway bridge over the Halfway. When this device was driven into the bed, it was noticed that the river had scoured away up to several metres of bed gravel and was running near bedrock (F. Erickstad, pers. comm.). The bridge was replaced in the mid-1970s, and an old mid-channel bridge footing remains in place slightly downstream. Due to high flow at the time of the field investigation, however, this footing could not be inspected for signs of degradation.
Low-level air photos of the Halfway (Figure 3.10) reveal a consistent pattern of bars being vegetated between 1970 and 1988, suggesting this site may also have degraded. This is supported by the longer time series of medium-scale photographs (not shown). Only at transect H4 has bar overgrowth been accompanied by noticeable opposing bank erosion, and this seems insufficient to compensate for the lost bar area. On the fan (transect H1), bar afforestation cannot be linked to channel degradation, because of the proximity of the Peace mainstem and a lack of old Halfway River floodplain surfaces for survey comparison. At H2, just upstream of the highway bridge, a large right-bank bar complex was forested around 24 years ago. The distal portion of this young floodplain is 0.3 m lower than the older floodplain at its centre (see 1970 photo in Figure 3.10); the bar survey at this location supports this result, indicating 1.5 m of degradation (Table 3.3). Results are less clear at the upstream end of the transect, where the contemporary bar surface is unusually high despite abundant young floodplain vegetation nearby. Sedimentation in this area appears to be associated with a sharp bend at the apex of the H2 point bar, where the river runs into a high shale bluff at the downstream end of Pig Flat. This bend sharpened considerably between the photo dates in Figure 3.10, apparently backing up the flow and causing bar growth and localized aggradation upstream.

Across the river, the large left-bank point bar complex at the apex of Pig Flat was largely vegetated after 1970. Field work shows that the young floodplain here is around 14 years of age, and 0.8 m lower than an older (32 years) floodplain behind it (Figure 3.11; Table 3.3). This mature floodplain 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 3.10). The young floodplains at H4 and H5 are dated at 20 and 12 years old, respectively, and they indicate degradation of 0.4 m and 1.2 m (Table 3.3). Bartop surveys at H4 and H5 suggest degradation of 1.2 m and 0.4 m, respectively. Several other bars, including one on the right bank upstream of H5 (Figure 3.10), also appear to have converted to young floodplain since regulation, but these sites could not be surveyed during the field investigation due to access problems.
Results of the Halfway River specific gauge analysis are presented in Figure 3.12; the cumulative gradation data are based on 0.8 times the mean annual flow, as in Chapter 2. The Halfway rating curves have been updated almost annually, indicating the cross-section has a history of instability. This is reflected in Figure 3.12, as the bed elevation at the lower station, located 500 m upstream of H4 (Figure 3.10), fluctuated from 1971 to 1976. Between 1976 and 1977, the channel appears to have degraded by nearly 0.1 m, though this result is close to the limit of precision for my analytical method. The gauge was moved from the left bank to the right bank in 1977 due to the main-thread being diverted toward the right bank by a large mid-channel gravel bar (A. Stalker, pers. comm.). Data from the right-bank station show the bed was stable here until the gauge was decommissioned in 1983. At the upper station, used since 1984, no consistent pattern of gradation is revealed, though the mean bed elevation at this site fluctuates as it did at the lower station.
3.3.3. Moberly River

The Moberly River is the first significant tributary to enter the regulated Peace River from the south, 103.6 km below the dam. Its 1900-km² watershed drains primarily mountain and foothill terrain, and it is interrupted roughly 150 km from the mouth by Moberly Lake, located between Chetwynd and Hudson’s Hope. The Moberly is unusual among the subject sites in that its distal reaches have a generally aggradational appearance (cf. Figure 3.13), with low floodplains, frequent braiding and a history of channel instability. The reason for this is unclear, but there must be substantial sediment sources between the lake and the Peace confluence. The active channel of the distal Moberly River may be over 100 m wide in braided areas, but as narrow as 20 m where the flow is concentrated into a single thread.

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Figure 3.12: Cumulative specific gauge results for the Halfway River. Results were obtained by comparing the stage of 578 m³/s (0.8 times the mean annual flood). The upper and lower stations are not comparable due to changed location and gauge datum.

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13 Medium-scale aerial photographs (not shown) indicate the Moberly River became more active between 1953 and 1967, suggesting that important sediment sources may have become active during that time. See Appendix B for photo references.
Figure 3.13: View of a typical semi-braided reach of the Moberly River, looking upstream from the left-bank bluff near transect M2. The low, light green vegetation covering most of the area next to the channel consists of annual bar grasses.

As with the other tributaries, air photos of the Moberly (Figure 3.14) show that its fan has vegetated considerably since 1970. The fan has remained more active than at the other sites, however, maintaining an active flood channel and keeping roughly half of its surface area bare of perennial vegetation. On transect M1, just west of the prominent flood channel, an old floodplain fragment was found to be 0.3 m higher than its adjacent young floodplain (17 years old). This is a topographically variable area, and a more extensive young floodplain (11 years old) east of the flood channel was surveyed as 1.3 m lower than the same old floodplain fragment (Table 3.3).

Numerous bars upstream of the fan have also become forested, but here, this mostly seems to be the result of lateral channel migration, and bars lost to floodplain succession are generally compensated for by erosion and new bar development. One possible example of localized degradation occurs at transect M2, where the river runs into a steep bedrock outcrop on its left bank. The right-bank bar has been converted to young floodplain (10 years old), and lies 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 surveyed transects, results show a mixture of apparent degradation and aggradation. For example, the old floodplain at M3 is 0.10 m lower than the young floodplain (Table 3.3). The area around M4 is highly braided. Results there suggest slight degradation, but the new
Figure 3.16: Historical aerial photographs of the Peace River. Young floodplains which have developed since the earlier photo are outlined in green. Surveyed transects are shown in yellow.
floodplain is very young (10 years) and not noticeably higher than the active bar surface. Changes at M5, in a single-thread reach, seem more straightforward, but the results are again inconclusive. The right-bank young floodplain there (21 years old) shows 0.1 m of aggradation (Table 3.3). The young floodplain on the left bank (30 years old) 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 shows 0.3 m of aggradation.

3.3.4. Pine River

The Pine River also enters the Peace from the south, around 120 km below the dam, primarily draining mountains and foothills. Its drainage area of 13,560 km$^2$ makes it the largest tributary in the British Columbia reach, with a channel width on the order of 250 m near the mouth. Like the other tributaries, the Pine is deeply entrenched, but its channel has been quite active over the past 30 years. In the most distal bend of the Pine, the right bank has undergone dramatic erosion since 1970, consuming several hundred metres of an access road and prompting the installation of groynes and riprap at the apex of the bend (visible in Figure 3.15). At present, however, this area has become congested with bar deposits and the main flow of the Pine has shifted to the left bank. Just upstream, across from transect P1, an entire segment of floodplain was removed by left bank erosion. These erosive episodes appear to have been instigated by the formation (sometime before 1967) of the large bar crossed by transect P2. Farther upstream, a new mid-channel bar has formed at above the mouth of Septimus Creek since 1970 (Figure 3.15). Over the same period, at the limit of the study reach near transect P4, two channels have filled. The most distal of these was a left backchannel behind a forested island; since 1970, it has become completely vegetated. The second infilled channel appears in the older photo to have been the main-thread, at a location where a large mid-channel bar bifurcated the flow. Since then, the bar has become vegetated, the left channel has mostly silted in, and most of the flow now occupies the right channel.

Surveying at the Pine River was limited by the size of the system, as it was impractical to investigate all morphological surfaces of interest, and difficult to extend surveys across the fast, deep current. As with the other tributaries, the Pine delta has mostly become covered with young floodplain vegetation; no surveys were done here, due to the confounding influence of Peace River water levels. The first survey transect (P1) crosses a young floodplain located where the
main-thread flowed in 1970. This surface, dated at 17 years old, lies 2.9 m below the adjacent old right-bank floodplain (Table 3.3). The comparison may be invalid, however, as the height of the older surface suggests it may have been a terrace. Comparing the local bartop to the height of buried gravel beneath the young floodplain suggests degradation of 0.8 m, but this figure may also be suspect, as it is of similar scale to the bar topography of the Pine River.

Better data are provided by transect P2. At this site the young floodplain (23 years old) is 0.8 m lower than its adjacent old floodplain, which appears as a young floodplain fragment in the 1970 photo (Figure 3.15). This figure is supported by the right active bartop, which was measured at 0.4 m below the gravel surface of the young floodplain. Degradation seems 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 has an unusual species composition, with large cottonwood, old alders, and an exceptionally dense understory. It is also quite high, lying 1.7 m above the adjacent young floodplain (12 years old). Still, it lacks the dryland species of a terrace, so comparison is assumed to be fair. Upstream, transect P4 includes two former islands which are now accreted to the left bank. Here, the young floodplain of the upstream island (shown in Figure 3.16) was surveyed to the old floodplain of the downstream island, immediately beside the channel. The results (Table 3.3) 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 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. Survey data from the infilled backchannel behind the lower island proved unreliable, as this channel seems to still be in the process of silting in, resulting in a very irregular topography.
3.3.5. Beatton River

The Beatton River enters the Peace River from the north, some 142 km below Bennett Dam. It is the first major tributary whose watershed lies almost entirely in the Alberta Plateau and, unlike most of the other sites, it carries a large suspended-sediment load, but only a small gravel load (BC Hydro, 1976). In terms of mean annual flow, the Beatton is the third-largest tributary in the British Columbia reach (Table 3.2), and its channel width is approximately 150 m near the mouth. Despite this, the river has built a relatively small fan, perhaps reflecting the under-representation of coarse material in its sediment load. The distal Beatton River flows in a narrow canyon (Figure 3.17), with floodplains and terraces infrequent and small. In fact, the first floodplain segment of any size (transect B3; see Figure 3.18) is found 4 km upstream of the river mouth.

The Beatton fan has mostly been overgrown with young floodplain vegetation. Transect B1 (Figure 3.18) crosses two such surfaces. The higher of the two (27 years old) suggests some degradation, as it was found to be 0.5 m lower than an older floodplain behind it (Table 3.3). This is a suspect comparison, however: the old floodplain was narrow and irregular, and may be no more than a slump block off the toe of the Peace River terrace behind it. Comparisons are equally poor at B2, which crosses a backchannel of the Peace River that has infilled since 1970 (Figure 3.18). This surface, which has the vegetation of a young floodplain (undated, but likely
around 15 years old or less), lies between two old Peace River floodplains or terraces whose elevations reveal nothing about Beatton River gradation.

**Figure 3.17:** View of Beatton River canyon, looking upstream from transect B2.

Upstream, at transect B3, a complex of bars and two islands has largely been vegetated since 1970 (Figure 3.18), though portions of it appear to still be active. The survey included 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 (10 years old) was found to be 0.7 m lower than the adjacent old floodplain, and 0.4 m lower than the old floodplain downstream of the backchannel mouth (Table 3.3). These results suggest the possibility of local channel degradation. On the other hand, medium-scale aerial photographs (not shown; see Appendix B for reference) show that this bend has undergone two channel switches in the past 50 years: initially from the path of the current backchannel below B3 to a course against the left bank behind the proximal island (as shown in the 1970 photo of Figure 3.18), and then to the present location. This activity suggests the young floodplains around B3 may still be accreting as the 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 (e.g. Figure 3.19) was noticed up to 3 m above the oldest surface. These clues suggest that this sharp bend may be a favoured location for ice-jam formation and backwater sedimentation, likely overwhelming any regulation-induced channel gradation.
Figure 3.18: Historical aerial photographs of the Beatton River. Young floodplains which have developed since the earlier photo are outlined in green. Surveyed transects are shown in yellow.
3.3.6. Kiskatinaw River

The Kiskatinaw River enters the Peace River from the south, approximately 156 km below the dam. Though its headwaters are in the Rocky Mountains, a large portion of its 4050-km$^2$ basin drains the Alberta Plateau. The Kiskatinaw is relatively small, with a mean annual flow of only 10 m$^3$/s (Table 3.2). 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 3.20), is flanked by a continuous series of narrow, flat surfaces. At K3 and K2, abundant old spruce suggest these are pre-regulation terraces. At K1, however, the vegetation is almost exclusively old cottonwood trees, indicating this 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 has been overgrown with young floodplain species since regulation (Figure 3.20). In addition, the air photos show several bars which became forested between 1970 and 1989. Survey data at transect K1 show that its right-bank young floodplain, dated at 13 years of age, 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 3.3). 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 as 0.6 m higher than the current bartop (Table 3.3). All of these figures point to post-regulation degradation in the study reach. Interestingly, degradation at K2 appears to have occurred in the last decade. At this site, the main-thread in 1989 ran left of the young floodplain (Figure 3.20). By the time of the 2000 field investigation, the main flow had switched to the right channel, which has downcut by roughly 1 m. The left channel, by 2000, had become secondary and overgrown with grasses (Figure 3.21). Medium scale photography shows that the main flow has alternated between sides of this island since the late 1960s.

![Figure 3.21: View of infilled left backchannel at K2, looking upstream from K1.](image)

3.3.7. *Alces River*

The Alces River is a small stream emptying into the Peace River immediately below the Clayhurst bridge, 164 km below Bennett Dam and just 4 km from the British Columbia -Alberta border. It drains an 877-km$^2$ basin which lies entirely within the Alberta Plateau, and delivers a mean annual flow of only 0.5 m$^3$/s (Table 3.2). The lower Alces frequently runs against colluvium at the foot of its steep valley-wall bluffs, and several small, low terrace fragments are also found along the lower reach. The Alces fan is negligibly small, and low enough in relief
that the regulated Peace River has been able to keep it free of encroaching floodplain vegetation (Figure 3.22). According to anecdotal evidence, 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, pers. comm.).

Although there are several bars on the Alces which have vegetated since 1970 (Figure 3.22), field results do not reveal a persistent trend of post-regulation channel gradation here. Transect A1 crosses a vegetated former backchannel on the right bank (now covered with grass and young alder) and a small former island which was dated at 19 years old, but has been forested since before 1970 (Figure 3.22). Surfaces on both ends of the transect appear to be old terraces (populated by aspen), and cannot be used to assess gradation. Based on its density and flat texture in the older photo in Figure 3.22 and 2000 field evidence (Figure 3.23), the island appears to have remained a young floodplain since at least 1970. The enduring youthfulness of this fragment suggests it may be regularly disturbed by river ice, and that the floodplain level has not changed since regulation. It is not clear why the backchannel here has so recently been overgrown, but its very clean, square outline in the 1970 photo (Figure 3.22) suggests it may have been cleared at that time by human activity, possibly as a source of gravel.

Slightly upstream, at transect A2, a large left-bank bar has become young floodplain since 1970. The elevation difference here is 0.4 m between the young floodplain (dated at 9 years of age) and the older floodplain behind it (Table 3.3). However, there has been significant right bank erosion opposite these surfaces, and the transition from older floodplain to bar on the left bank may reflect the development of a point bar sequence, rather than channel degradation. Transect A3 is located at the head of a relatively large right-bank bar which also began to vegetate between 1970 and 1987 (Figure 3.22). This transect has old terraces at either end, and no adjacent older floodplain for survey comparison. At its widest point, downstream of A3, this young floodplain grades smoothly to the active bartop, with no evidence of degradation; afforestation of this surface may due to the main channel shifting away from it. Transect A4 crosses an unnamed tributary to the Alces. Here again, there were no clear survey comparisons to be had. There is some very young floodplain with surficial gravel next to the channel, but the shrubbery may have succeeded here because of infrequent flooding in this small, dry stream. The adjacent older terraces are likely a product of the Alces River flood regime, and cannot be used for comparison.
Figure 3.22: Historical aerial photographs of the Peace River. Young floodplains which have developed since the earlier photo are outlined in green. Surveyed transects are shown in yellow.
3.3.8. *Hines Creek*

Hines Creek is another small stream entering the Peace River from the north, just upstream of the Dunvegan bridge and 299 km below Bennett Dam. Despite a relatively large watershed area of 1647 km$^2$, its mean annual flow is only 3 m$^3$/s, reflecting the dry climate of the prairie it drains. Hines Creek has quite a large fan for its size (Figure 3.24), suggesting it is a fairly prolific sediment producer. The low level air photos of this site show it to be pockmarked with excavations; it was likely a source of gravel for bridge construction in the early 1960s. By 2000, the fan had largely been refilled and overgrown by vegetation.

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 Figure 3.24. In the field, several small young floodplains were noticed, but the fact that they have not developed on 1961 bar surfaces suggests they may be kept ‘young’ by regular ice disturbance. Frequent ice-jam flooding might also help explain the unusual height (over 2 m higher than the bartop) of the floodplains on the right bank at transect HC1 and on the left bank between HC1 and HC2. Only at HC3 was a young floodplain of lower elevation found. This floodplain has surficial gravel and an unusual species mix of bar grasses, alder (the oldest dated
at 42 years) and young spruce (Figure 3.25). It is backed by an older floodplain (or terrace), populated by dense spruce and cottonwood, of roughly the same elevation (Table 3.3).

![Image of low left-bank floodplains at HC3. The rear stand of trees is composed of dense, mature spruce and cottonwood.]

**Figure 3.25:** View of low left-bank floodplains at HC3. The rear stand of trees is composed of dense, mature spruce and cottonwood.

### 3.3.9 Smoky River

The Smoky River is the largest tributary in the Peace River basin, with a drainage area of over 50,000 km². It rises in the Rocky Mountains north of Jasper, Alberta, and primarily drains the Alberta Plateau. The Smoky carries a substantial sand load and, below its confluence, the bed of the Peace River begins to grow sandy (Figure 1.3). The Smoky River was not visited during the 2000 field campaign but, due to its importance to the Peace River system, it merits investigation.

Historical aerial photographs of the Smoky River (Figure 3.26) reveal that, unlike most other sites, it has not undergone systematic vegetation of bar surfaces since regulation. The fan retains a similar proportion of bare and vegetated surface areas in 1988 as it did in 1970, suggesting it remains relatively active. For 13 km upstream of the confluence, the principal morphological activity between the photo dates was bar growth, with five bars having expanded substantially over this period (Figure 3.26). While the discharge of the Smoky was slightly lower in the 1988 photos (195-221 m³/s, versus 258-354 m³/s in 1970), the difference is small, suggesting at least
Figure 3.26: Historical aerial photographs of Smoky River. Areas of extensive bar growth are indicated with green arrows.
some of the apparent bar growth is genuine. Overall, the distal Smoky River has taken on a more braided appearance, suggesting its primary response to regulation may have been aggradation.

3.4. Discussion

The closing section of this chapter begins with a summary assessment of post-regulation channel gradation at each of the study sites. The final two sub-sections deal with spatial and temporal patterns of tributary gradation.

3.4.1. Assessment of Channel Gradation at Tributary Sites

At Lynx Creek, Farrell Creek and the 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. My detailed morphological investigation at Farrell Creek shows a consistent pattern of bars being colonized by young floodplain vegetation since regulation. The relative elevations of these surfaces compared to nearby older floodplains suggest that the site has degraded between 0.4 and 1.4 m; this agrees with the observed 1-m undercutting of the old bridge footing, and reported in the literature (Kellerhals and Gill, 1973; Kellerhals, 1982). The 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 m to 1.5 m. Specific gauge data on the Halfway (Figure 3.13) are inconclusive: they indicate 0.1 m of degradation at the lower station, a near-insignificant result which may be due to flow division around a mid-channel bar. The upstream extent of degradation at these sites in unclear. At both, 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 the Halfway River. In both rivers, gradation evidence is occasionally confounded by other morphological activity (transects F3 and F4, near a cutoff meander; the upper end of transect H2, above a sharp bend).

Below the Halfway River, the story grows more complex. In isolated locations, the Moberly River shows evidence of up to 0.8 m of degradation (transect M2, and the west part of M1). Overall, however, it looks like an aggradational system, an assessment supported by the remainder of the survey data. This aggradation, and the high degree of channel activity, appear
to be unrelated to regulation of the Peace River, as they are evident in medium-scale air photos from 1967. Most likely, this river generates enough bed material to compensate for any general degradation which might have occurred. The 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 later sedimentation. These seem to have been instigated by the pre-1967 growth of a major bar near P2, but may have been exacerbated by regulation-induced lateral instability or aggradation at the Pine delta. Farther upstream (up to 6 km) there are several more young floodplains, suggesting channel degradation on the order of 0.4 m to 1.7 m. It seems, then, that the Pine River may be degrading, but the trend is overwhelmed by sedimentation at the mouth. This may be because the Pine, like the Moberly River, is a prolific sediment producer. According to computed estimates, its specific bedload yield is approximately 1.4 times that of the Halfway River (see Appendix C, Table C.5), which clearly has degraded. Conclusions on the Pine River are tentative, however: this is a large and active river, and it is possible that the young floodplains will eventually accrete to the old floodplain level.

The Beatton River is a case where gradation evidence is too compromised by local conditions to permit any conclusion on the effects of regulation. Most of the lower Beatton is so entrenched that there are no floodplains to compare. At transect B3, the local channel morphology appears to be controlled by a sharp bend, and possibly ice jam flooding. The Alces River reportedly underwent some scour near its bridge after regulation (F. Erickstad, pers. comm.), but morphological evidence does not indicate any trend of degradation above the bridge. Ice may be an important agent in the Alces, especially at A1. At other locations, the development of young floodplains since regulation appears to be coincidental, and a function of channel migration.

Unlike these two sites, the Kiskatinaw River seems to have a consistent pattern of degradation. Survey data from the three Kiskatinaw transects suggest downcutting of between 0.6 m and 1.9 m in the river's lower 2 km. Above the field sites, the river enters a narrow canyon, so the upstream extent of channel gradation is unknown. The recent abandonment of the left channel at transect K2 suggests 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 next two tributary sites, Hines Creek and the Smoky River, are located considerably farther downstream (Table 3.2). At Hines Creek, near Dunvegan, there is no evidence of channel gradation at all. Its fan has become vegetated since regulation, but this must be credited to reduced flooding in the mainstem rather than any change in the Hines channel. Farther up Hines Creek, there are no signs of degradation or aggradation, and channel morphology suggests the strongest control here may be ice activity. Aerial photographs of the Smoky River, nearly 400 km below Bennett Dam, suggest that the distal reaches of this river have become aggradational since regulation. In this river, the most prolific sediment producer of all Peace tributaries, the dominant morphological change has been bar expansion as far as 11 km above the confluence. There are no signs of degradation: the fan seems to have remained active, and there are no examples of young floodplains taking over bar surfaces. The behaviour of these two sites implies they may lie too far below the dam to undergo channel degradation. This possibility will be explored in the final section of this chapter.

The accumulated evidence suggests that, among the proximal tributaries, channel degradation has been the most common response over the past 30 years. This reflects steepening of the lower tributary reaches as their base levels have dropped due to regulation of the mainstem. Local conditions of flow, bed material, sediment supply and channel stability seem to be important in determining whether degradation has been the dominant trend at a site, or has been partly or wholly negated by other processes. It has been suggested that post-regulation lateral channel instability in the Halfway, Moberly and Pine Rivers may be a related effect (BC Hydro, 1976; Xu and Church, 1996), with the tributaries increasing their sinuosity as a second means of reducing their slope. My analysis, however, suggests that observed planform changes may just reflect natural instability in these systems:

- The Halfway River has continued to erode banks that were under attack prior to regulation;
- The Moberly River appears to have entered a naturally aggrading and unstable phase between 1953 and 1967, before regulation; and
- Bank erosion near the mouth of the Pine River appears to have been initiated by the formation of a large bar before 1967.

While base level change may have encouraged planform instability, this mechanism is far less demonstrable than post-regulation degradation.
Aggradation due to tributary fan extension has been less obvious. It may have played a role in sediment accumulation at the mouth of the Pine River, and in the aggradational response of the Smoky River, but it was not evident at the other sites. Fan progradation may have been involved in slowing or stopping the progression of degradation, but it has not manifested itself in more obvious forms like the reoccupation of young floodplains by the river. Although there is local evidence of aggradation in the Halfway River (at the upper end of H2), this occurs above a sharp bend, and may be unrelated to fan growth. It has been predicted that aggradation will eventually predominate in the Peace tributaries (BC Hydro, 1976). There is little suggestion of this in my findings, however. It is unclear whether this will eventually occur, or whether the Peace River tributaries are near to a new equilibrium base level.

3.4.2. Gradation Timing and Rates of Change

As with the mainstem Peace River, one must attempt to determine whether recent channel gradation in the tributaries can fairly be ascribed to regulation. Data for this task are limited. At most sites, medium-scale aerial photographs from the early 1950s and late 1960s indicate that systematic overgrowth of bar surfaces (the main hallmark of degradation) only became prevalent after regulation. This method also shows that pervasive bar growth in the lower Smoky River has been a new development since 1967.

The significance of regulation can also be tested by comparing recent and historical rates of tributary incision. All of the subject rivers have been degrading over the long term, as evidenced by their deep entrenchment. If the uppermost sediments of the Alberta Plateau are assumed to be of late Wisconsinan age (cf. Mathews, 1963), then this incision took place over roughly 12,000 years (cf. Klassen, 1989). This provides the basis for calculating background degradation rates, which can be compared to post-regulation rates at the degrading subject sites. The results of this analysis (Table 3.4) suggest that post-regulation degradation has been slightly faster than historical post-glacial channel incision, though they are of the same order of magnitude. The estimated difference between rates may, in fact, be conservative. Quaternary degradation probably has slowed over time, since the rivers have cut through friable glacial and post-glacial sediments and into more resistant bedrock. Similarly, post-regulation rates of incision may be
underestimated, as they are based on the questionable assumption that degradation has been ongoing throughout the entire regulated period.

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth of Entrenchment at Mouth (m)</th>
<th>Background Degradation Rate (m/yr)</th>
<th>Mean Post-Regulation Degradation (m)</th>
<th>Post-Regulation Degradation Rate (m/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farrell Creek</td>
<td>213</td>
<td>0.018</td>
<td>0.92</td>
<td>0.031</td>
</tr>
<tr>
<td>Halfway River</td>
<td>183</td>
<td>0.015</td>
<td>0.73</td>
<td>0.024</td>
</tr>
<tr>
<td>Pine River</td>
<td>244</td>
<td>0.020</td>
<td>0.84</td>
<td>0.028</td>
</tr>
<tr>
<td>Kiskatinaw River</td>
<td>274</td>
<td>0.023</td>
<td>1.24</td>
<td>0.041</td>
</tr>
</tbody>
</table>

Table 3.4: Entrenchment depths and background degradation rates for subject tributaries. Depth was measured from the prairie surface to the valley floor at river mouths, using 1:250,000 topographic maps. Degradation rates were calculated by dividing these depths by 10,000 years, the estimated time since the rivers began to incise the Alberta Plateau. Post-regulation rates were calculated by averaging reliable measured degradation results (Table 3.3) and dividing by 30 years.

Actual rates of post-regulation change in the tributaries are difficult to assess due to the large time intervals between data sources. Most evidence suggests that there was a rapid initial response which has now slowed or stopped. At Lynx and Farrell Creeks, several feet of erosion were reported in 1972, and surveys at Farrell Creek in 1972 and 1975 reportedly showed no change in the channel form there (BC Hydro, 1976). In addition, surveyed degradation values at Farrell Creek in 2000 remained in the 1-m range. These facts suggest most of the degradation may have occurred in the first few years after regulation, 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 enough to restore an equilibrium slope. The Halfway River may have a similar history; scour around the old bridge pier was reported before the mid-1970s, when the bridge was replaced, and the degradation suggested by specific gauge analysis (Figure 3.12) occurred between 1976 and 1977.

The age of young floodplains can also provide insight into degradation timing and rates. Among the degrading sites, young floodplains ranged in age from 9 to 29 years (Table 3.3). The latter figure (taken from transect F5) 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 3.3), again suggesting that substantial degradation must have occurred within 8 years of regulation at these sites. Not all young floodplains are this mature, however. The range of their ages (Figure 3.27) suggests that degradation may have 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. This could mean that degradation is slower

![Histogram of young floodplain ages](image)

**Figure 3.27:** Histogram of young floodplain ages, according to dendrochronology of oldest trees. Results include all surfaces referred to in Table 3.3.

(and perhaps ongoing) there, or that local conditions such as channel instability or ice scour have prevented the floodplains vegetation from establishing itself so successfully. Like the Moberly River results, this emphasizes that in the Peace River tributaries, natural fluvial processes remain effective even as the channels have been modified due to regulation of the mainstem.

3.4.3. Downstream Variability of Gradation

The preceding characterization of tributary gradation suggests a downstream pattern of response. Degradation seems to be strongest near the dam, as exemplified by Lynx Creek, Farrell Creek, the Halfway River, and possibly the Pine River. Farther downstream, the degradation signal gradually becomes subsumed by other local factors such as sediment load and ice regime, as in the Moberly River, Alces River and Hines Creek. The degrading Kiskatinaw River seems to be an exceptional case, given its location quite far below the dam. The Smoky River, the most
distal subject site, seems to have begun aggrading since dam closure. Conceptually, this trend makes sense: as the Peace River flows away from Bennett Dam, its diminished floodwaters are gradually restored by flow from unregulated tributaries and, at some point, the degradation mechanism must become too weak to be perceptible within the natural river dynamics. The Pine River, as the largest British Columbia tributary, might represent a significant step in this pattern of attenuation. Another likely transition point is the junction of the Smoky River. Aggradation there may indicate that the fan-progradation mechanism does not decline downstream as rapidly as the degradation mechanism. On the other hand, the response of the Smoky River may be exaggerated due to its exceptional size and sediment load, especially if Peace River no longer removes sediment deposited on the Smoky fan surface.

The downstream pattern becomes complicated when potential degradation estimates based on mainstem-tributary stage disparity (Table 3.1; repeated below in Table 3.5) are considered. Although these estimates and survey results from degrading sites are of the same order of magnitude, they show no downstream trend. Yet the estimates do not conflict with observed gradation responses. The Halfway and Pine Rivers, with the highest potential for degradation, indeed appear to have degraded. The Kiskatinaw River has degraded despite having the lowest apparent potential for degradation. While this is initially troubling, it essentially suggests that this river should be relatively unaffected by regulation. This appears, in fact, to be the case: the Kiskatinaw was reportedly degrading before regulation (BC Hydro, 1976), and appeared to still be degrading in the summer of 2000. The Smoky River, according to Table 3.5, has moderate degradation potential. While this has apparently not been fulfilled, some incision may have been overcome by its recent sedimentation.

While the potential degradation estimates are certainly of questionable precision, they underline the fact that local conditions in individual tributaries are crucial in determining their response to regulation. Basin hydrology demands that there must be a downstream diminishment of tributarygradation at a large scale, but clearly this is mediated by strong local factors such as tributary flood timing vis-à-vis the mainstem, sediment supply, channel stability, and ice regime. The result is a highly complex picture.
<table>
<thead>
<tr>
<th>Site</th>
<th>Distance Below Dam (km)</th>
<th>Degradation (m)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Farrell</td>
<td>42.6</td>
<td>-</td>
<td>0.93</td>
</tr>
<tr>
<td>Halfway</td>
<td>64.5</td>
<td>2.5</td>
<td>0.72</td>
</tr>
<tr>
<td>Moberly</td>
<td>103.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pine</td>
<td>120.4</td>
<td>3.1</td>
<td>0.84</td>
</tr>
<tr>
<td>Beatton</td>
<td>141.9</td>
<td>1.3</td>
<td>-</td>
</tr>
<tr>
<td>Kiskatinaw</td>
<td>156.3</td>
<td>0.5</td>
<td>1.23</td>
</tr>
<tr>
<td>Alces</td>
<td>164.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hines</td>
<td>299.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Smoky</td>
<td>394.1</td>
<td>1.6</td>
<td>(aggrading)</td>
</tr>
</tbody>
</table>

**Table 3.5:** Potential and actual degradation at tributary sites. Potential figures are repeated from Table 3.1. Actual figures were calculated by averaging reliable measured degradation results (Table 3.3). No results are shown for sites with insufficient flow data or no clear gradation pattern.
4. CONCLUSION

This report represents the first thorough analysis of channel gradation in the regulated Peace River system. It has been broad in scope, covering over 1000 km of the mainstem river, most of the major tributaries in its upper regulated reach, and a time span of over 30 years. In the preceding chapters, the results of my research have been discussed in detail according to specific themes. To draw the work together into general conclusions, I will begin by revisiting the project’s hypotheses and operating questions in light of the data presented.

4.1. Hypotheses and Operating Questions Revisited

The first hypothesis, as stated at the end of Chapter 1, is:

1. Through aggradation and channel pattern change, the Peace River is steepening its course to compensate for its reduced post-regulation capacity for sediment transport.

To test this statement, the first operating question involves seeking systematic patterns of post-regulation degradation and/or aggradation in the Peace mainstem. Analyses of historical cross-sections and specific gauge records reveal a definite trend of localized aggradation below sediment sources in the regulated British Columbia reach, with only isolated instances of degradation. The pattern extends as far as Dunvegan, Alberta, where the Hines Creek delta has been prograding. Farther downstream, however, there is no apparent gradation trend. It is plausible that at some point downstream of the dam, gradation will become negligibly small due to gradual flood replenishment and fining of bed material. This may well occur some distance below the junction of the Smoky River, which contributes a large flood and sand load. In these lower reaches, however, fine sediment concentration may be higher in the reduced flow, providing another mechanism for aggradation; indeed, shoaling has been reported as far downstream as Carcajou (Church, 1995). Clearly, more information on the Alberta reaches is necessary to properly evaluate downstream gradation patterns for the whole Peace River.

The second operating question, also in support of the first hypothesis, addresses whether identified gradation trends are reinforced by post-regulation planform changes in the river channel. My results on this subject are less clear. Since regulation, in the sub-reaches containing gradation data sites, mainthread sinuosity has been remarkably stable. This is a predictable outcome, since the Peace River’s erosive power has been greatly reduced and most of
its contemporary morphological processes are passive (e.g. sedimentation and vegetative succession). Braiding index has also been quite stable according to my analysis – a conservative measure which only registers the loss of a backchannel when it is completely overgrown with floodplain vegetation. In terms of actual channel capacity, this is likely an accurate result: cross-sections with backchannels suggest that infilling has been slow over the past 30 years, despite the steady colonization of these areas by plants. Overall, planform changes seem to occur much more slowly than gradation, to the point where the two seem to have operated independently in the first three decades of regulation.

The first hypothesis, then, seems partially supported. The prevalence of aggradation in the British Columbia and Dunvegan cross-sections suggests that in the long term, the Peace River may indeed be raising its proximal bed due to reduced peak flows. This will increase the river’s slope, and may eventually help to restore some of the sediment transport capacity lost to regulation. At this time, planform changes appear not to support the pattern of channel gradation. While both are largely passive processes, the main mechanism of planform change is the abandonment of backchannels. This is controlled by vegetative succession and siltation, occurs above the normal range of regulated Peace River stages, and therefore operates on a longer time scale than channel gradation. Whether planform changes will ultimately complement channel gradation by increasing river slope is hard to predict. If backchannels close sufficiently, the river may become more dominantly single-thread, reducing braiding index and slope, and counteracting aggradation. Given the imposed flow regime, however, this should perhaps not be considered a true fluvial adjustment of the regulated river; it may be more appropriate to focus on processes occurring in the new active channel. Within this smaller area, continued aggradation may promote the formation of bars and islands around sediment sources. In the long term, therefore, complex reaches may remain complex, as predicted by Church (1995) – albeit at a smaller scale.

The second of my hypotheses concerns the tributaries:

2. Peace River tributaries downstream of Bennett Dam have systematically degraded in response to reduced mainstem water levels.

The operating question accompanying this statement seeks to identify systematic post-regulation channel degradation in the distal reaches of several downstream tributaries. A second possible scenario was also introduced: aggradation due to tributary delta growth. Air photo interpretation
and field investigation partially support the hypothesis: it appears that degradation has, in fact, been the most common response of the proximal tributaries. It is especially well-expressed in Lynx Creek, Farrell Creek and the Halfway River, all located above the Pine River confluence in British Columbia. Farther downstream, however, the post-regulation gradation response begins to be obscured by other factors such as tributary sediment supply, ice regime and the degree of flood synchronization between tributary and mainstem. Aggradation was less evident in the tributaries, though it seems to be the principal post-regulation trend in the lower Smoky River. In general, regulation appears to have played a less dominant role in the tributaries. In the mainstem Peace River, regulation has altered the primary governing variable of flow. In the tributaries, there has been only a secondary change to effective base level and, consequently, the impact of regulation is more easily lost among other active fluvial processes.

4.2. Significance Within the Literature
The morphological response of the Peace River to regulation was predicted with fair accuracy by Kellerhals and Gill (1973). Their report was quite general and observational, however. The definitive work on the subject to date is that of Church (1995), who used hydraulic geometry to quantitatively predict final post-regulation reductions in channel width, mean depth, mean flow velocity and meander wavelength (or riffle spacing). His prognoses on the subject of gradient and channel pattern change were more descriptive, however. The main gradation mechanisms identified were aggradation of cobble-gravel at tributary mouths, and sand aggradation below the Smoky confluence due to increased sand concentration in the reduced flow. It was expected that the latter process might be enhanced by increased sinuosity, and hence reduced slope, due to backchannel abandonment.

My results from the British Columbia and Dunvegan reaches confirm the prevalence of coarse deposits at tributary mouths and, further, demonstrate that the same process is occurring at other sediment sources along the river valley. However, the cobble-gravel bed of the Peace River in its upper reaches is not completely static, as most authors have suggested. Isolated cases of degradation (e.g. across from the Farrell Creek delta) and the downstream growth of a new gravel bar below the Pine River confluence suggest the Peace can still move gravel under the right conditions. This should become a more common scenario as aggradation continues to locally increase channel gradient. With respect to the sandy lower reaches of the river, my data
are too sparse to confirm or refute Church’s claims. Post-regulation channel stability at Peace River town, Fort Vermilion and Peace Point is inconclusive, as these sites are not very close to sediment sources. My planform results do call into question the notion that aggradation should be promoted by increased sinuosity due to backchannel abandonment. Mainthread sinuosity was found to be very stable since regulation, suggesting that the channel occupied by typical, below-bankfull regulated flows is not much changed. The overgrowth of backchannels is more a reflection of the new hydrological regime than a true fluvial morphological change, as demonstrated by their re-occupation during the 1996 flood.

Based on an approximation developed by de Vries (1975), Church estimated that it would take thousands of years for channel adjustments to reach completion, though the majority of the work might be done in 1% of that time (50 to 100 years). For channel width, depth and current velocity, this is doubtless true, since these respond nearly as rapidly as the imposed hydrological change. With respect to tributary channel gradation, the prediction also applies: most observed degradation seems to have occurred within a few years of regulation. In the mainstem, however, changes at some aggrading cross-sections have begun to slow (notwithstanding the effects of the 1996 flood), while at others they have just begun. If the next stage of aggradation is indeed its progression downstream from sediment sources, then the process will be a very long one. Such effects should eventually begin to appear in Peace River cross-sections farther below sediment sources.

As a last note on this topic, in his 1995 paper, Church did not emphasize the potential for downstream attenuation of the impacts of regulation. This may be because of the strength of the regulation signal even at Peace Point, where the mean annual flood has been reduced by some 40%. Yet the Peace River’s flood is gradually restored with distance downstream of the dam, and my results on the tributaries seem to reflect this, with the proximal sites showing degradation most clearly. I cannot at present make any statement on whether a downstream trend exists in the mainstem, but the possibility underscores the importance of further research on the lower reaches of the river. A key question is whether the Smoky River dampens the effects of regulation via its flow and fine sediment contributions, or sustains them by increasing the total sediment load.
Within the general literature on regulated rivers, this study fills a substantial gap. In the British Columbia reach, the cross-sectional 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 (cf. Williams and Wolman, 1984), the largely passive and aggradational character of the post-regulation Peace River provides a sharp and useful contrast. Perhaps most importantly, this project contributes to our understanding of morphological responses in regulated gravel-bed rivers. Along with the work of Kellerhals, Church and others, it helps to make of the Peace River a thorough case study which may assist in guiding the proper management of such rivers.
References


Appendix A. Annotated Mainstem Cross-Sections
This appendix contains all 39 of the surveyed Peace River cross-sections analyzed for this project. They are presented in downstream order. Annotations include distance downstream of Bennett Dam, location notes, suspected sediment sources, net gradation results, and other observations taken from the original survey notes, the report by Church and Rood (1982), and from my own analysis. In some cases, the loss of benchmarks has resulted in a significant shift of section location, with the result that some survey years are not comparable. Such sections are marked with X’s, and accompanied with a warning note. Water lines are generally drawn according to the 1991 survey, which took place during relatively high flows for the regulated period. Where no 1991 data were available, other years were used, as indicated. For the three Dunvegan sections, no water levels were available, and the line has been drawn to match a 1992 air photo. Colour versions of these plots, which are more easily legible, are available from the author.

Shorthand:
LB = left bank
RB = right bank
WL = water line
US = upstream
DS = downstream
YFP = young floodplain (colonized by floodplain species since regulation)
OFP = old floodplain (pre-regulation)
Net Gradation (m)
Pre-1996: 0.21 m  Response type = Aggradation
Post-1996: -

Notes
- Section is on bedrock.
- Both pins accurately reset between 1975 and 1981.
- RB is slide-prone.
- Sediment sources: slumping RB.
Net Gradation (m)
Pre-1996: - Response type = Stability
Post-1996: -

Notes
- Section is on bedrock.
- Probably stable.
- Apparent change due to dipping shale bed
- Sediment sources: none.
Section S4
US Farrell Creek

Net Gradation (m)
Pre-1996: -0.21  Response type = Stability
Post-1996:  0.05  Response type = Stability

Notes
- Upper end of island near RB.
- Fluctuating but stable.
- Sediment sources: unnamed creek 500 m US
**Net Gradation (m)**

Pre-1996: 0.33  Response type = Stability
Post-1996: -0.22  Response type = Stability

**Notes**
- DS end of island.
- Sediment sources: unnamed creek 1.5 km US.
Section S3
Farrell Creek Fan

Elevation (m)

1998 log jam
Farrell fan

Dist. = 42.8 km

Net Gradation (m)
Pre-1996: -0.09  Response Type = Fan Progradation
Post-1996: -0.21  Response Type = Scour / Fill

Notes
- Farrell Creek fan.
- Sediment sources: Farrell Creek.
**Section X2**
**DS Farrell Creek**

- **Dist. = 50.8 km**

**Net Gradation (m)**
- **Pre-1996: -0.03**  Response type = Stability
- **Post-1996: 0.14**  Response type = Stability

**Notes**
- Straight reach DS of Farrell Creek.
- 1968 likely in a different position; not used in net gradation calculations.
- Otherwise stable.
- Sediment sources: none.
Net Gradation (m)

Pre-1996: -0.34 Response type = Degradation
Post-1996: -

Notes
- Head of island / bar near Farrell Creek settlement.
- Bar eroded in 1986.
- LB may be slide-prone.
- 1968 survey was drafted incorrectly; not plotted.
- Sediment sources: LB slides?
**Net Gradation (m)**

Pre-1996: 3.42  Response type = Fan Progradation

Post-1996: -1.09  Response type = Degradation

**Notes**

- Halfway River fan.
- Spectacular aggradation due to Attachie landslide (1973) ~ 800 m US (on RB).
- Later aggradation due to Halfway fan growth.
- Suspicious aggradation 1986-1991 (unusual echo sounder trace), but used anyway.
- Degradation due to 1996 flood.
- Fan surface quite active (ice activity?)
- RB high bank is unstable.
- Sediment sources: Halfway River, Attachie landslide, RB talus.
**Net Gradation (m)**
Pre-1996: -0.08  
Response type = Degradation
Post-1996: 0.37  
Response type = Aggradation

**Notes**
- DS of Halfway River, mid-way along island near RB.
- RB and island pins not found in 81 survey.
- 1968 position is questionable, but was used.
- Sediment sources: unnamed creek 1 km US; possibly sediment eroded from Y after 1996.
**Net Gradation (m)**

Pre-1996: -0.11  Response type = Scour / Fill
Post-1996: 0.13  Response type = Scour / Fill

**Notes**
- DS Cache Creek, at head of a bend.
- 1968 survey questionable in vertical, but used.
- LB slightly offline prior to 1986; good after.
- Riffle shifting toward eroding RB
- Sediment sources: Cache Creek.
**Net Gradation (m)**
Pre-1996: -0.05  Response type = Scour / Fill
Post-1996: -0.08  Response type = Scour / Fill

**Notes**
- US Wilder Creek, mid-way along LB island.
- High eroding RB bluff is not a major sediment source.
- 1998: RB rebar lost, so line maybe slightly out of position (channel should be fine).
- Sediment sources: unnamed creek 4 km US; possibly distal part of eroding RB.
Net Gradation (m)
Pre-1996: 0.51  Response type = Aggradation
Post-1996: 0.02  Response type = Stability

Notes
- ~ 1 km DS Tea Creek, at head of Moberly River backwater, in a gentle bend.
- LB features slumping bluffs.
- 1968 survey likely offline, and not used.
- Sediment sources: Tea Creek, slumping LB.
Section 107
US Moberly River

**Net Gradation (m)**
Pre-1996: 0.34  Response type = Scour / Fill
Post-1996: -0.18  Response type = Stability

**Notes**
- At head of mid-channel bar, in Moberly River backwater, in a gentle bend.
- Slumping bluffs at LB.
- Sediment sources: Slumping bluffs, Tea Creek 2 km US.
Net Gradation (m)
Pre-1996: 0.60 Response type = Aggradation
Post-1996: 0.44 Response type = Aggradation

Notes
- Straight reach in Moberly River backwater.
- Slumping bluffs at LB (major slump 1975-1979).
- 1998 aggradation likely due to backwater deposition.
- Sediment sources: Slumping bluffs, Tea Creek? (3.3 km US)
**Net Gradation (m)**

- Pre-1996: 0.68  
  Response type = Stability
- Post-1996: -

**Notes**
- DS Moberly River, mid-way along mid-channel bar.
- Proposed location of Site C hydroelectric development.
- RB pin lost in 1979, this survey likely offline, but used.
- WL is an average of 1991 values for sections 108 and 112.
- Sediment sources: Moberly River, maybe slumping bluffs at C, 107 and 108.
- Section is stable according to surveys, but may be aggrading currently due to Moberly fan growth.
Eroding cliff

Cobble bar

OFP

Dist. = 105.9

Net Gradation (m)
Pre-1996: -0.04  Response type = Stability
Post-1996: 0.78  Response type = Aggradation

Notes
- DS Moberly River, in a straight reach.
- Abandoned in 1981 (lost pins); re-established in 1998 by dead reckoning.
- Eroding cliff at LB.
- 1998 RB (aggradation site) is a cobble bar; position may be wrong, results questionable.
- Sediment sources: eroding LB, Moberly River? (3 km US)
Net Gradation (m)
Pre-1996: 0.20 Response type = Aggradation / Degradation
Post-1996: -0.35 Response type = Degradation

Notes
- DS Moberly River in a straight reach.
- 1998 survey may be ~ 5 m DS of line (lost LB pin); should not be a problem.
- 1998: riffle crest may have migrated US of line (hence degradation).
- Sediment sources: Moberly River 4.5 km US, eroding LB cliff at 112.
Net Gradation (m)
Pre-1996: -0.01  Response type = Aggradation / Degradation
Post-1996: -0.78  Response type = Degradation

Notes
- Old Fort; large bar tail DS of island before tight bend.
- Eroding ammonite cliff at RB.
- 1981: LB pin lost due to road work, so backchannel not surveyed thereafter.
- Aggrading mid-channel bar not surveyed after 75.
- 1998: GPS was off; channel survey projected to fit, but degradation is realistic.
- Sediment sources: Eroding RB, Moberly River? (sand trapping in lee of island)
**Net Gradation (m)**

Pre-1996: 1.33 Response type = Aggradation
Post-1996: -0.68 Response type = Degradation

**Notes**

- Apex of tight bend at Kirchbaum's farm.
- Slumping LB.
- Sediment sources: slumping LB.
Net Gradation (m)
Pre-1996: 0.78 Response type = Aggradation
Post-1996: -0.09 Response type = Degradation

Notes
- US of BCR railway bridge, in a straight reach.
- Sediment sources: slumping LB at 117?
Net Gradation (m)
Pre-1996: 0.03  Response type = Aggradation / Degradation
Post-1996: 0.39  Response type = Degradation

Notes
- Beneath BCR railway bridge, in a straight reach.
- Possibly a Pine River backwater at high flow (there is a riffle DS).
- Fluctuating but stable.
- LB activity related to bridge maintenance.
- Sediment sources: unnamed creek ~ 700 m US, eroding sections upstream?
Net Gradation (m)
Pre-1996: 0.08  Response type = Stability
Post-1996: -0.30  Response type = Degradation

Notes
- Mid-channel bar head, Pine River backwater, in a straight reach.
- Peace River Hill landslide at LB (1974); now a source of slumps.
- 1998: GPS in left channel questionable, projected to fit; degradation is plausible, though.
- Sediment sources: LB landslide / slumping.
Net Gradation (m)
Pre-1996: 0.22 Response type = Aggradation
Post-1996: -0.25 Response type = Degradation

Notes
- Pine River backwater, in a straight reach.
- Taylor gravel pit outfall near LB.
- Slight aggradation 1975-1979; otherwise fluctuating but stable.
- Post 1996: degradation near banks, minor mid-channel bar growth.
- Sediment sources: Gravel pit outfall, landslide at 121?
**Net Gradation (m)**

Pre-1996: 0.31  Response type = Aggradation / Degradation

Post-1996: -0.15  Response type = Scour / Fill

**Notes**

- Pine River fan, just US of Taylor bridge.
- Consistent ice scour on fan surface.
- General aggradation until 1986, then stable until 1996 flood.
- LB eroding due to Pine fan growth.
- 1998: road work on LB, severe erosion on delta front.
- Sediment sources: Pine River, gravel pit outfall at 122.
**Net Gradation (m)**

Pre-1996: 1.61  Response type = Aggradation

Post-1996: 0.07  Response type = Scour / Fill

**Notes**

- Beneath Taylor bridge, at tail of Pine River fan.
- Pine River fan outlet channel near RB is unreliable.
- Not using 1979 data (unreliable; see Church and Rood, 1982).
- LB eroding due to Pine fan growth.
- 1991 survey may be ~10m US of true position; should be usable.
- Sediment sources: Pine River, gravel pit outfall at 122, eroding LB.
Net Gradation (m)
Pre-1996: 0.87  Response type = Aggradation
Post-1996: 0.34  Response type = Aggradation

Notes
- DS of Taylor Landing boat launch, in a straight reach; old bar complex at LB.
- Aggradation starting in 1986 is the DS extension of new bar at S10.
- Sediment sources: Pine River, erosion at 123, S10?
**Net Gradation (m)**

Pre-1996: 0.03  Response type = Stability
Post-1996: 0.48  Response type = Aggradation

**Notes**
- DS Taylor Landing, at end of a gentle bend; old bar complex at LB.
- 1991: RB pin lost; new LB pin placed perhaps too far US; orientation questionable.
- 1998: new LB rebar eroded, found US of line?!
- Conclude that 1991, 1998 may be rotated from early surveys, but are comparable to each other; all channel comparisons should be reliable, but not LB changes.
- Sediment sources: Pine River, erosion at 123, S10?
Net Gradation (m)
Pre-1996: -0.35  Response type = Stability
Post-1996: 0.36  Response type = Aggradation

Notes
- DS Taylor Landing, below a short bend.
- At head of old bar / island complex on RB; old backchannel at RB.
- Major logjam formed at RB in 1986.
- Aggradation on bar surface post-1996.
- Sediment sources: none identified (possibly erosion at RB of 126 after 1996 flood).
**Net Gradation (m)**

Pre-1996: 0.06  Response type = Stability
Post-1996: 0.33  Response type = Aggradation

**Notes**
- US unnamed creek, in a straight reach; old bar complex at RB.
- Young floodplain at RB subject to ice activity.
- Sediment sources: none identified (possibly erosion at RB of 126 after 1996 flood).
Section 129
Leclerc's, DS Unnamed Creek

Net Gradation (m)
Pre-1996: 0.26  Response type = Aggradation
Post-1996: -0.04  Response type = Scour / Fill

Notes
- Mid-channel bar tail, DS unnamed cr., in a straight reach.
- Old bar / island complex at LB.
- Actively aggrading bar.
- Stable landslide on RB.
- 1975 data lost; pins lost in 1981, so section abandoned.
- Re-established in 1986.
- 1991: RB a bit off, but no error found.
- Sediment sources: sand from Pine River, eroding bank at 126 being trapped in lee of bar?
Net Gradation (m)
Pre-1996: 0.98  Response type = Aggradation
Post-1996: 0.13  Response type = Aggradation

Notes
- Tail of old LB bar complex, DS unnamed creek, in a gentle bend.
- RB bank erosion.
- Sediment sources: unnamed creek 4 km US, scour at 129?
**Net Gradation (m)**

Pre-1996: 0.86  Response type = Aggradation
Post-1996: -

**Notes**
- US Beatton River, in a straight reach.
- Much confusion with benchmarks: swampy LB, disturbed RB.
- 1968, 1975 digitized from BC Hydro, 1976 report; not pins on these plots, so section was lined up with 1981 using stable LB position.
- X-coordinates set according to 1986 survey.
- 1998: unusable due to faulty GPS.
Sediment sources: Eight Mile Creek and old LB landslides ~ 5 km US.
Net Gradation (m)
Pre-1996: 0.11  Response type = Fan Progradation
Post-1996: -0.08  Response type = Degradation

Notes
- Kiskatinaw River fan, tail of mid-channel bar / island.
- Bar aggradation through 1998 (now young floodplain; no longer surveyed).
- Left channel not surveyed since 1981 (lost LB pin).
- Sediment sources: Kiskatinaw River; sand buildup on island may be from LB landslides (~ 4 km US), Galata Creek (5 km US) or Beatton River (14 km US).
Net Gradation (m)
Pre-1996: 0.14  Response type = Scour / Fill
Post-1996: -

Notes
- Beneath Clayhurst bridge (former Alces ferry landing), in a gentle bend.
- 1981: RB disturbed by bridge surveys (pin lost); not reliable.
- 1981: LB pin was bent; elevations not very precise.
- Sediment sources: eroding RB bluff 5 km US, Kiskatinaw River 8 km US.
Net Gradation (m)
Pre-1996: 0.49  Response type = Aggradation
Post-1996: -0.04  Response type = Scour / Fill

Notes
- DS Alces R. in a gentle bend; old bar complex at RB.
- 1975: LB probably too far US (pin lost); survey accepted as conservative, since it should be lower in elevation.
- Sediment sources: Alces River.
Net Gradation (m)
Pre-1996: 0.88  Response type = Fan Progradation
Post-1996: -

Notes
- Lower Hines Creek fan, US Dunvegan bridge, in a straight reach.
- LB does not line up between years; not included in calculations.
- Sediment sources: Hines Creek, Ksituan River (3 km US), landslide on LB (~ 3 km US).
Net Gradation (m)
Pre-1996: 0.76 Response type = Aggradation
Post-1996:

Notes
- Beneath Dunvegan bridge, on tail of Hines Creek fan.
- 1986 aggradation in thalweg is in lee of bridge pier.
- 1996 survey was offline and projected to fit; not reliable (apparent scour is because line passes in front of bridge pier).
- 1996 survey done after emergency release flood.
- Sediment sources: Hines Creek, Ksituan River (3 km US), landslide on LB (~ 3 km US).
Net Gradation (m)
Pre-1996: 0.00  Response type = Stability
Post-1996: -

Notes
- DS Dunvegan bridge.
- Sediment sources: Hines Creek, Ksituan River (3 km US), landslide on LB (~ 3 km US).
Appendix B. Tributary Aerial Photograph Index

The following table (Table B.1) lists the air photos I used in the tributary portion of the project. Medium-scale photos are given first, followed by low-level photos where applicable. Further coverage is likely available for the Alberta tributaries, though this was not investigated.

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Table B.1: Index of aerial photographs used to examine tributary channel gradation.
Appendix C. Tributary Sediment Transport Study

Bed material transport is the fundamental mechanism by which rivers change their channel form, and may be an important factor in explaining the variable gradation response of Peace River tributaries. This portion of the study applies bedload formulae and morphological techniques to estimate bed material transfer rates in two of the tributary sites.

The classic, semi-empirical bedload formulae predict the mass flux of bedload\textsuperscript{14} based on more readily measurable quantities, such as flow, river slope and bed material size. Problems with this approach include (Gomez and Church, 1989; Knighton, 1998):

- determining appropriate input parameters,
- coping with the spatial and temporal variability of river flow, sediment input and bedload transport;
- obtaining adequate bedload samples with which to validate the models; and
- simulating near-threshold transport, which is characteristic of gravel-bed rivers.

Morphological, or inverse, techniques use measured volumes and rates of morphological change to deduce sediment transfer rates integrated over some time period. The method used here involves the combination of erosion rates with estimated sediment travel distance, or step length (Neill, 1987; Ashmore and Church, 1998). By operating on actual channel pattern change, this approach estimates true bed material transport, and avoids the problem of extrapolating predictions to relevant morphological time scales. However, the success of inverse methods depends upon factors like the elapsed time between surveys, accurate estimation of sediment thickness and travel distance, and the assumption that no bed material movement goes unregistered in the changing channel form (notably, due to compensating scour and fill).

The Halfway and Pine Rivers were selected for this portion of the study, as they are major suppliers of bed material load (based on documented aggradation at their confluences), they have published hydrological, morphological and sedimentological data (Church, 1975b; BC Hydro, 1976), and their channels are relatively stable. Initially, the Moberly River was also included, but this frequently braided river proved too unstable to be reliably analyzed using the

\textsuperscript{14} Bedload is that portion of the total sediment load which travels with its weight primarily supported by the streambed; bed material load includes all sediment which forms the river bed and lower banks. The two are not, strictly, equivalent (Gomez and Church, 1989).
available air photos. No bedload measurements have been performed on these rivers, preventing validation of the estimated results. Still, even relative transport rates may be of value, and using consistent methodology may permit comparison between the two sites. The degree of agreement between the approaches may provide a gauge of their absolute accuracy.

C.1. Methods

C.1.1. Morphological Method
The morphological technique used here is based on the following model:

\[ Q_b = E_r \times H_g \times L_s \]

where \( Q_b \) is the volumetric bed material transport rate (\( \text{m}^3/\text{yr} \), bulk measure), \( E_r \) is the erosion rate (\( \text{m/yr} \)), \( H_g \) is the height of gravel deposits (m), and \( L_s \) is the step length of sediment displacement (m). Erosion rates and step lengths were estimated by comparing low-level aerial photographs from different dates (Table C.1). On the recent photos, channel boundaries were identified by the visible water line. In certain shallow areas (such as bar complexes and backchannels), small amounts of water were ignored and considered part of the bank. Channel boundaries were traced from the recent photos onto transparent mylar sheets, and then projected and re-traced onto the older photos. This permitted the outlining of bank areas eroded during the elapsed time between photo dates.

Erosion zones were scanned and imported into the ArcView GIS environment for digitizing and computation of their areas and lengths. These quantities, with the elapsed time between photos, were used to calculate the average bank retreat (Er) rate for each zone. The average distance of sediment movement, or step length (\( L_s \)), was determined by measuring the distance between the approximate centroids of each erosion zone and its apparent downstream deposition zone. The final digitized erosion zones and centroids are presented in Figures C.1 and C.2. For fan deposition zones, step lengths are suspect, as sediment transport near the mouth may have been bolstered by flow in the main Peace River. Transport estimates involving the fans are therefore discarded.
<table>
<thead>
<tr>
<th></th>
<th><strong>Halfway River</strong></th>
<th><strong>Pine River</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Early Photographs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Flight</strong></td>
<td>BC7279</td>
<td>BC7278</td>
</tr>
<tr>
<td><strong>Date</strong></td>
<td>Aug. 3, 1970</td>
<td>Aug. 3, 1970</td>
</tr>
<tr>
<td><strong>Scale</strong></td>
<td>1:18,488</td>
<td>1:18,488</td>
</tr>
<tr>
<td><strong>Flow (m³/s)</strong></td>
<td>50.1</td>
<td>166</td>
</tr>
<tr>
<td><strong>Late Photographs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Flight</strong></td>
<td>BC88088</td>
<td>30BCC97159</td>
</tr>
<tr>
<td><strong>Date</strong></td>
<td>Sep. 13, 1988</td>
<td>Aug. 24, 1997</td>
</tr>
<tr>
<td><strong>Scale</strong></td>
<td>1:17,982</td>
<td>1:16,990</td>
</tr>
<tr>
<td><strong>Flow (m³/s)</strong></td>
<td>31.2</td>
<td>157</td>
</tr>
</tbody>
</table>

**Table C.1:** Aerial photograph information for morphological sediment transport estimates.

To estimate the thickness of the eroded bed material, height from thalweg to bartop was measured on cross-sections surveyed across the subject sites in 1975 (BC Hydro, 1976). Finer-grained upper bar and floodplain deposits are expected to contribute only wash material when eroded (Ham and Church, 2000), and the bartop was selected as roughly the maximum height of gravel deposits. Because the bartop is not specifically identified on the cross-sections, its elevation was estimated based on breaks in slope and indicated water levels. The measured elevation differences from identified bartop to floodplain are consistent with results from field surveys conducted in August, 2000. Gravel thickness was measured on the left and right banks of all cross-sections where bar and floodplain levels could be clearly distinguished. Using these data, annual volumetric transport rates were calculated for each erosion zone, and converted to dry weight flux rates by multiplying by 1.75 tonnes/m³, a typical density for fluvial gravel deposits on the Fraser River, British Columbia (M. Church, pers. comm.). These results were averaged to
Figure C.1: Halfway River photo (1970) showing erosion areas, and erosion and deposition centroids. 1988 channel boundaries drawn in red.
Figure C.2: Pine River photo (1970) showing erosion areas, and erosion and deposition centroids. 1997 channel boundaries drawn in red. The most distal deposition centroid is positioned considering recent deposition of Pine sediment in the Peace River channel.
produce the final yield estimates for each site.

Several sources of error were identified during these procedures, including:
  - identification of recent and old bank lines;
  - re-tracing of recent bank lines on old photos;
  - planimetric distortion at edges of photos;
  - location of erosion and deposition centroids; and
  - estimation of gravel thickness.

Though no formal error analysis has been performed, some Pine River erosion areas were reproduced on adjacent photographs to assess the amount of error introduced by planimetric distortion; the results of this analysis are presented in Table C.2. In terms of percent differences, the largest errors occur on the smaller erosion sites (up to 52.6% for area at P4, up to 25.8% for length at P5), while error at the largest sites was quite small (as low as 0.6% for area at P1). To assess the overall importance of these errors, two revised sets of annual yield estimates were prepared, grouping the largest and smallest area figures. Fan deposition sites were excluded, and polygon lengths were recalculated, though this occasionally resulted in a smaller area being offset by a greater length\(^{15}\). The final difference in yields (2.84%) seems negligibly small considering the unquantified sources of error in this method.

\textit{C.1.2. Bedload Formulae}\n
The application of the classic bedload formulae to reach-averaged data is problematic, since bedload transport is dictated by local flow and bed conditions. This approach can nevertheless provide a rough idea of transport rates (Gomez and Church, 1989), sufficient for assessing relative transport rates between the study rivers. A previous application of several bedload formulae to the sites was made by Church (1975b) for BC Hydro (1976). Church used reach-averaged bed material data, hydraulic geometry and river slope to estimate transport at a range of flows, and integrated these into a yearly bedload flux rate by means of flow duration curves based on hydrometric data.

\(^{15}\) Length was calculated in ArcView as half the perimeter of the erosion polygon. Consequently, a smaller erosion area may have a greater length, depending on its particular shape.
Table C.2: Results of error analysis due to planimetric distortion in aerial photographs and operator imprecision in re-tracing bank lines. All results drawn from Pine River.

In this study, I have updated these bedload predictions using the formulae of Meyer-Peter and Müller (1948), and of Bagnold (1980). The Meyer-Peter and Müller (MPM) formula was chosen because of its common application in the literature, its tendency to predict relatively high transport rates (Church, 1975a; Gomez and Church, 1989), and the direct comparison it allows with the MPM calculations of Church (1975b). The stream-power based Bagnold formula is included because it performs relatively well in gravel-bed rivers and produces low results compared to the MPM formula (Gomez and Church, 1989), providing a range of values for comparison.

The format of the MPM formula used here is:

\[ i_b = \frac{y_s}{y_s - \gamma} \left[ \frac{(Q_B / Q)(K_B / K_G)^{3/2}YS - \theta(y_s - \gamma)/\gamma}{(0.25/\gamma)(\gamma/g)^{1/3}} \right]^{1/5} \]

where

\[ K_B = u / Y^{2/3}S^{1/2} \quad \text{and} \quad K_G = 26 / D_{90}^{1/6} \]

Here, specific mass flux of bedload \( i_b \) is computed from flow depth \( Y \), slope \( S \), dimensionless critical shear stress \( \theta \), mean particle size \( D_{MPM} \), with modifications for bed roughness \( K_B \), particle roughness \( K_G \), and several constants. The terms \( \gamma \) and \( y_s \) refer,
respectively, to the specific gravity of water and sediment. $Q_b / Q$, a term for the 'effective' discharge acting on the bed, is assumed to be 1.0, as the subject channels are relatively wide compared to the flumes within which the formula was developed. This version of the formula was taken from Gomez and Church (1989).

A simplified, rational version of the Bagnold formula (taken from Martin and Church, 2000) was employed:

$$i_b = (\omega - \omega_0)^{3/2} \left( D_{50}^{1/4} / d \right) \left( 1 / (\rho_r^{1/2} g^{1/4}) \right)$$

where $\omega$ is stream power, $D_{50}$ is the median bed material size, $d$ is flow depth, $\rho_r$ is the difference between water and sediment densities, and $g$ is the acceleration of gravity. In this formula, $\omega_0$ (threshold stream power for bedload entrainment) is calculated as

$$\omega_0 = 5.75 \left\{ \theta \left( \gamma_s - \gamma \right) \rho \right\}^{3/2} (g / \rho)^{1/2} D_{50}^{3/2} \log(12d / D_{50})$$

This estimation is necessary in the absence of field observations of bedload movement.

Reach-averaged bed material, hydraulic geometry and river slope values (Table C.3) were taken from the original work of Church (1975b). Specific bedload transport in kilograms per second was calculated for the same flows as used by Church (Table C.3). Rates were calculated at two values of $\theta$ (0.047 and 0.06), as the formulae are sensitive to this parameter. The lower value is that originally recommended by Meyer-Peter and Müller (1948), while the latter is more realistic for gravel-bed rivers with low transport rates (M. Church, pers. comm.). Total bedload transport rates were calculated by multiplying the specific rates by channel width. These results were transformed into an annual sediment yield figure by means of new flow duration curves constructed from discharge records up to 1996. These curves were based on daily mean flow data from the entire period of record (see Table 3.2). The results of Church (1975b) suggest that in the subject rivers, competent flows occur relatively infrequently. To more precisely estimate the duration of these crucial flows, all flows above an approximate threshold level\(^{16}\) were extracted and used to construct a separate 'upper range' partial duration curve for each site (e.g. Figure C.3). The actual flow duration functions were based on fitting a three-component

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\(^{16}\) Threshold flows were identified using the Einstein formula results of Church (1975b).
Table C.3: Parameters used in bedload formulae (values taken from Church, 1975b); channel width, mean depth and mean velocity varied with discharge. Flow durations indicate the percentage of total time occupied by each flow, as derived from complete and partial flow duration curves. Durations could not be calculated for some of the lowest flows, but these are all below the threshold for bedload movement.

<table>
<thead>
<tr>
<th></th>
<th>Halfway River</th>
<th>Pine River</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{MPM}$ (mm)</td>
<td>31</td>
<td>46</td>
</tr>
<tr>
<td>$D_{50}$ (mm)</td>
<td>34</td>
<td>54</td>
</tr>
<tr>
<td>$D_{90}$ (mm)</td>
<td>105</td>
<td>147</td>
</tr>
<tr>
<td>Slope</td>
<td>0.00221</td>
<td>0.00163</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Input Flows (m$^3$/s) / Duration (%)</th>
<th>Halfway River</th>
<th>Pine River</th>
</tr>
</thead>
<tbody>
<tr>
<td>1699.0</td>
<td>0.08</td>
<td>3822.8</td>
</tr>
<tr>
<td>1042.1</td>
<td>0.20</td>
<td>2194.6</td>
</tr>
<tr>
<td>722.1</td>
<td>0.22</td>
<td>1755.6</td>
</tr>
<tr>
<td>651.3</td>
<td>0.30</td>
<td>1577.2</td>
</tr>
<tr>
<td>532.4</td>
<td>0.79</td>
<td>1330.9</td>
</tr>
<tr>
<td>387.9</td>
<td>1.56</td>
<td>934.5</td>
</tr>
<tr>
<td>269.0</td>
<td>2.23</td>
<td>665.4</td>
</tr>
<tr>
<td>186.9</td>
<td>4.31</td>
<td>368.1</td>
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<tr>
<td>113.3</td>
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<td>105.6</td>
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<tr>
<td>73.6</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure C.3: Example of upper range partial flow duration curve for Pine River. The form of the curve is comparable to the full and partial curves for both sites, and is based on a six-parameter exponential decay model of the form $y = ae^{-bx} + ce^{-dx} + ge^{-hx}$. 

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exponential decay model to the plotted cumulative flow frequency data. In the final calculations, bedload transport for each level of flow was multiplied by the appropriate partial flow duration, and then by the portion of total time occupied by the upper range curve. These results were summed into estimates of annual bedload yield.

In addition to these computations, the original results of Church for the MPM formula and the Einstein bedload formula (a complex but robust model (Gomez and Church, 1989)) have been extrapolated into annual yield estimates using the new flow duration curves. As a check on these curves, the new MPM results were transformed into annual yield a second time using the original flow durations specified by Church (1975b). Finally, annual bedload yield estimates reported by BC Hydro (1976) based on their preferred results are included for comparison.

C.2. Results

C.2.1. Morphological Method
Estimated annual bed material yields based on the morphological method are presented in Table C.4. The results exclude sites where eroded material appeared to be deposited on the tributary fan. Table C.4 includes estimates based on the minimum, maximum and average gravel thicknesses (Hg) measured in the BC Hydro cross-sections of the sites. At most, the estimates approximately double from minimum to maximum Hg, and they remain of the same order of magnitude. The results all indicate that the Pine River has the higher annual bed material yield (15,063 tonnes/yr using average gravel thickness, versus 7655 tonnes/yr for the Halfway River).

C.2.2. Bedload Formulae
Predictions of annual yield from the bedload formulae are presented in the lower half of Table C.4. The first two sets of results are from my calculations using the MPM and Bagnold formulae and the new flow duration curves. It is immediately apparent that MPM predicts yields several orders of magnitude higher than Bagnold in all cases. This disparity echoes the results of a similar exercise conducted on data from the Elbow River, Alberta (Ayles, 2001; data taken from Hollingshead, 1968). Within each formula, adjustment of the Shields number (θ) also produced different results. At θ = 0.047, both formulae yield results up to an order of magnitude greater.
<table>
<thead>
<tr>
<th></th>
<th>Annual Bed Sediment Yield (tonnes/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Halfway River</strong></td>
</tr>
<tr>
<td><strong>Morphological Estimates</strong></td>
<td>Min.</td>
</tr>
<tr>
<td></td>
<td>Max.</td>
</tr>
<tr>
<td></td>
<td>Avg.</td>
</tr>
<tr>
<td><strong>Bedload Formula Estimates</strong></td>
<td></td>
</tr>
<tr>
<td>Meyer-Peter and Müller</td>
<td>$\theta = 0.047$</td>
</tr>
<tr>
<td></td>
<td>$\theta = 0.06$</td>
</tr>
<tr>
<td>Bagnold</td>
<td>$\theta = 0.047$</td>
</tr>
<tr>
<td></td>
<td>$\theta = 0.06$</td>
</tr>
<tr>
<td>Church, 1975b Results using (new flow duration curves)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MPM</td>
</tr>
<tr>
<td></td>
<td>Einstein</td>
</tr>
<tr>
<td>New MPM Results (using old flow duration curves)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\theta = 0.047$</td>
</tr>
<tr>
<td></td>
<td>$\theta = 0.06$</td>
</tr>
<tr>
<td>BC Hydro, 1976 Results</td>
<td>Einstein</td>
</tr>
</tbody>
</table>

**Table C.4:** Results of annual bed material load/bedload yield computations. Underlined results are considered most reliable. * The updated Pine River MPM result of Church, 1975b, is likely erroneous, as it was computed based on an incorrect river slope.

than at $\theta = 0.06$. This effect seems especially strong in the Bagnold results for the Pine River, where setting $\theta$ to 0.06 drives the annual bedload yield essentially down to zero. In all estimates, the Halfway and Pine Rivers produce roughly the same annual quantity of bedload; their order in terms of productivity depends on $\theta$.

The next part of Table C.4 shows the updated MPM and Einstein results of Church (1975b), extrapolated to annual yields using the new flow duration curves. In these results, the Halfway River has the highest totals; the Pine MPM result, however, is likely inaccurate as it was based on an underestimated river slope. These results generally lie between those of the new MPM and Bagnold trials. The newer MPM results were re-transformed into annual yields using the original flow duration values of Church (1975b), and the results are presented next in Table C.4.
These are the highest estimates of all, with the same relative values between sites and values of $\theta$. The final results in Table C.4 are the annual bedload yield figures reported by BC Hydro (1976), based on the Einstein results of Church (1975b). These results are similar for the Pine and Halfway Rivers, and slightly higher than those obtained by integrating the results of Church with the new flow duration curves.

C.3. Discussion

C.3.1. Morphological Method
According to the morphological estimates (excluding fan-depositing erosion zones), the Pine River is a more prolific bed material load producer than the Halfway River. Intuitively, this makes sense: the bigger river produces more sediment. The Pine River estimates are likely more accurate, as they are based on a larger number of erosion sites (10), and the Pine is a large enough river that its rates and locations of morphological change can be tracked with confidence between the air photo dates. An informal examination of medium-scale aerial photographs on the Pine (available at more frequent time intervals; see Appendix B) suggests that relatively few transient erosion and deposition events have been missed in the large-scale analysis. The Halfway River also seems suitable for this method, as it is relatively large and stable, suggesting there should be few missed morphological changes. At this site, the exclusion of the fan leaves only three erosion zones in the calculation, opening the final yield figures to bias. Nevertheless, these three zones have similar areas and step lengths (Figure C.1), suggesting they may be representative of the site.

C.3.2. Bedload Formulae
BC Hydro (1976) has speculated that the subject tributaries contain considerable ‘lag’ bed material that is immobile under modern flow conditions. This could mean that the bed material grain size distributions at the sites are biased toward the coarser fractions. On this basis, Church (1975b) performed several adjusted bedload calculations using finer grain sizes representing the apparently mobile material. In my calculations, I have not considered this effect, and have used grain sizes derived from the entire bed material composition. It is therefore possible that all new bedload results are underestimates, due to the relatively coarse grain size inputs. Some rough
calculations using the finer ‘mobile’ grain size data were performed as a check\textsuperscript{17}, however, and
the resulting differences were not appreciable within the overall variance of the results. In
addition, the highly active specific gauge history of the Halfway River undermines the claim that
it cannot move its larger bed material.

Results from the bedload formulae are highly variable (Table C.4), necessitating some culling of
the less reliable figures. To begin, it seems clear that the Bagnold results should be rejected, as
they are far lower than any of the others. The reasons for this apparent under-prediction are
unclear; an earlier test of the MPM and Bagnold formulae (Ayles, 2001) showed that the latter
tended to predict transport an order of magnitude lower than the former, but the differences here
seem more severe. The results may be narrowed further by comparing the performance of the
new flow duration curves to the flow durations of Church (1975b). The application of these
different values to the new MPM specific bedload predictions produces generally similar results,
with the new flow durations giving slightly lower annual yields. This suggests that the new
curves perform adequately, and they are likely more accurate since they are based on longer
records. Annual yields based on the old flow durations are therefore discarded.

The remaining annual yield figures include three versions of MPM (new results at $\theta = 0.047$ and
0.06, and the Church results updated with the new flow durations), and the updated Einstein
results of Church. The old MPM results may be rejected because the Pine River result is suspect.
Between the two new sets of MPM results, those obtained at $\theta = 0.06$ are likely more realistic for
gravel-bed rivers. Also, the $\theta = 0.06$ results are lower, counteracting the tendency of the MPM
formula to over-predict (BC Hydro, 1976; Gomez and Church, 1989). Thus, the new MPM
results at $\theta = 0.047$ are rejected. The updated Einstein results are considered relatively sound, as
they combine a formula well-suited to gravel-bed rivers (Church, 1975a) with the new flow
durations.

This elimination process leaves two relatively reliable sets of yield predictions (underlined in
Table C.4) based on the bedload formulae. These suggest that the Halfway River actually moves

\textsuperscript{17} In the original work of Church, bedload estimates based on the finer ‘mobile’ fraction of the bed material were
reduced to account for the smaller portion of the bed occupied by these sediments. My calculations based on the
finer inputs did not account for this, and differences would therefore have been exaggerated.
slightly more bedload than the Pine River, though both are in the range of 5000 to 20,000 tonnes per year.

C.3.3. Comparison of Methods
A comparison of the best results from the morphological and bedload formula approaches (see underlined figures in Table C.4) shows that they are remarkably close, at least within the order-of-magnitude precision allowed by the methods and input data. It is interesting that the morphological results show the Pine as the larger sediment producer, while the bedload formulae point to the Halfway River. In reality, the growth of the Pine River delta has included substantial sand deposition (M. Church, pers. comm.), suggesting an important sand component in the Pine's bed material load may have been neglected in the input bed material size distribution, which is coarser than that of the Halfway (BC Hydro, 1976). This bias may explain the relatively low transport predicted by the formulae.

In the absence of sampled bedload data, a major challenge of this study is to decide whether its results can be trusted. Based on the preceding discussion and the known deficiencies of the bedload formulae, it seems likely that the morphological estimates are better. Despite the potential for error, these estimates are based on relatively clear changes in relatively stable channels, and even the gravel thickness estimates seem reasonable in light of field reconnaissance.

C.4. Conclusion
The ultimate goal of this exercise is to estimate relative rates of sediment yield between the sites. This permits a relatively high error tolerance for the absolute transport values, provided that the methods were consistent between sites, and that the subject rivers behave similarly. It seems fair, then, to conclude that the Pine River transports nearly twice as much bed material load as the Halfway River, according to the morphological method. As a control on potential degradation, specific bedload yield may be a more relevant quantity than total yield, as it is scaled to the size of the river. Dividing the morphological results by drainage area to estimate specific annual yield diminishes the differences between sites (Table C.5). By this measure, the Pine produces roughly 1.4 times as much bed material as the Halfway, per unit area. Based on both total and specific annual yields, then, it appears that the Pine produces significantly more.
bed material than the Halfway, supporting initial observations. This system therefore has greater aggradational potential.

<table>
<thead>
<tr>
<th></th>
<th>Halfway River</th>
<th>Pine River</th>
</tr>
</thead>
<tbody>
<tr>
<td>A) Total Annual Bed Material Yield (from morphological method) (tonnes/yr)</td>
<td>7655</td>
<td>15063</td>
</tr>
<tr>
<td>B) Drainage Area (km²)</td>
<td>9400</td>
<td>13,560</td>
</tr>
<tr>
<td>Specific Annual Yield A/B (tonnes/yr/km²)</td>
<td>0.81</td>
<td>1.11</td>
</tr>
</tbody>
</table>

Table C.5: Specific annual bed material yield in subject rivers. Drainage areas correspond to the most distal gauging station; for the Pine River, where the gauge at East Pine is 80 km from the mouth, this value is an underestimate, so the final specific yield figure is conservative.