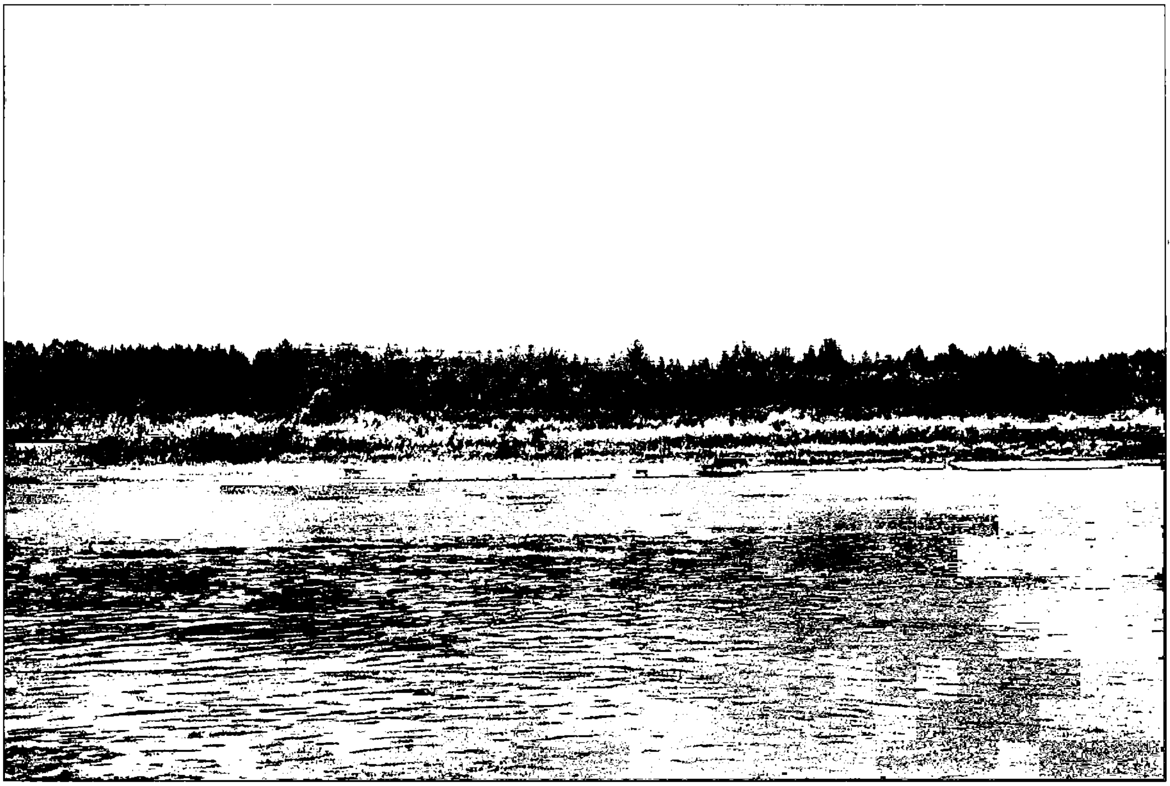
Impact of Flow Regulation on the Aquatic Ecosystem of the Peace and Slave Rivers

1

Synthesis Report



Canada Alberta Northwest Territories

Northern River Basins Study

ERRATUM No. 1 - January 16, 1997

Northern River Basins Study Synthesis Report No. 1
Impact of Flow Regulation on the Aquatic Ecosystem of the Peace and Slave Rivers

*Amendments (**shown in bold and italics**) identified by author were not incorporated into the document submitted to the publisher. The Study Office regrets any inconvenience this may create for the reader.*

I. Section - 3.2.3 Results, Page 56, INSERT:

This raises the ecological concern, as earlier expressed by the Peace-Athabasca Delta Implementation Committee (1987), that the weirs have eliminated critical, seasonal ***drawdowns*** in water levels that produce unique near-shore vegetation/habitat and waterfowl staging zones.

II. Page 114 - Figure 3.38

Replace figure with "upgraded" figure attached to this erratum.

III. Section - 4.8.1 Primary Recommendations, Page 143, DELETE & INSERT:

[1] *"Naturalized" Flow Modelling*
Evaluating the effects of regulation on the overall flow regime is hampered by the brevity of the pre-regulation period data set. One method to extend the "un-regulated" period is to model flow conditions since regulation without the effect of the dam. Such a model has been under development by Alberta Environment in conjunction with British Columbia Hydro. It was originally hoped to incorporate the results of this model into some of the NRBS studies ***but at the completion of this synthesis report, the modelling results remain in draft form and not yet available to scientists attempting to evaluate ecosystem impacts resulting from flow regulation. It is recommended, therefore, that a priority be placed by Alberta Environmental Protection and B.C. Hydro on finalizing this work, and releasing it to the public and scientific communities through official publications so that it can be used in related impact studies. Based on the normalized data set, a re-evaluation should also be made of the summary flow statistics presented in this report. Integral to this evaluation, should be an assessment of the significance of hydro-climatic variations in affecting he post-regulation flow characteristics.***

IV. Section - Literature Cited:

Page 150 - AMEND:
Andres, D.D., 1995. The effects of flow regulation on freeze-up regime of the Peace River, Taylor to the Slave River. ***Northern River Basins Study Technical Report No. 122 (in press).***

Page 153 - AMEND:
Courtney, R.F., C. Wrightson and G. Farrington, 1995. A pilot study of the use of remote sensing to analyse fish habitat on the Peace River, July to October, 1994. ***Northern River Basins Study Technical Report No. 81 (in press).***

Page 154 - AMEND:
Donald, D.B. and H.L. Craig, 1995. Mercury in the Peace, Athabasca, and Slave River Basins. Environment Canada, ***Northern River Basins Study Technical Report No. 105, 55 pp.***

English, M.C., M.A. Stone, B. Hill, P.M. Wolfe and R. Ormson, 1995. Assessment of impacts of Peace River impoundment at Hudson Hope, British Columbia on the Slave River Delta, NWT. ***Northern River Basins Study Technical Report No. 74 (in press).***

Page 160 - INSERT:
McCauley, Edward., 1996. A review and evaluation of water quality and quantity models used by the Northern River Basins Study. Northern Rivers Basins Study Report Technical Report No. 82 (in press).

Page 161 - DELETE:
Northern River Basins Study, 1996c. Technical Report no.. 47, (food chain), Fish distribution, movement and gross pathology information for the Northern Rivers in Alberta (in progress).

Page 160 - INSERT:
Mill, T., P. Sparrow-Clarke and R.S.Brown, 1996. Fish Distribution, Movement and Gross External Pathology Information for the Peace, Athabasca and Slave River Basins. ***Northern River Basins Study Technical Report No. 147 (in press).***

Page 163 - AMEND:
Prowse, T.D., Conly, M. and Lalonde, V. 1996b. Hydrometeorological conditions controlling ice-jam floods, Peace River near the Peace-Athabasca Delta. ***Northern Rivers Basins Study Technical Report No. 103, 66 pp. + Appendices.***

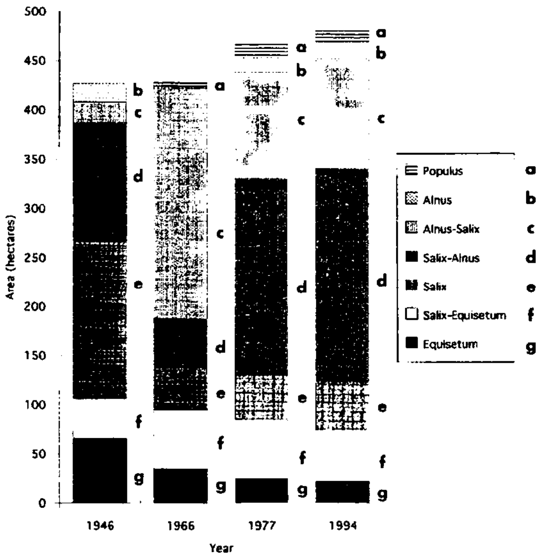
Page 166 - AMEND:
Walder, G.L., 1996. Proceedings of the Northern River Basins Study instream flow needs workshop, October 14 - 15, 1993 and January 6 - 7, 1994. ***Northern River Basins Study Technical Report No. 66 (in progress).***

Page 168 - DELETE:
Wrona, F. et al, 1996. Northern River Basins Study, draft report (in progress).

Figure 3.38 Plant assemblage changes for cleavage bar islands.
(afer English et al., 1995).

(1) Old Steamboat Channel

Fig.6.5:
Slave River Delta, Old Steamboat Channel: Cleavage Bar Island, Plant Assemblage Change



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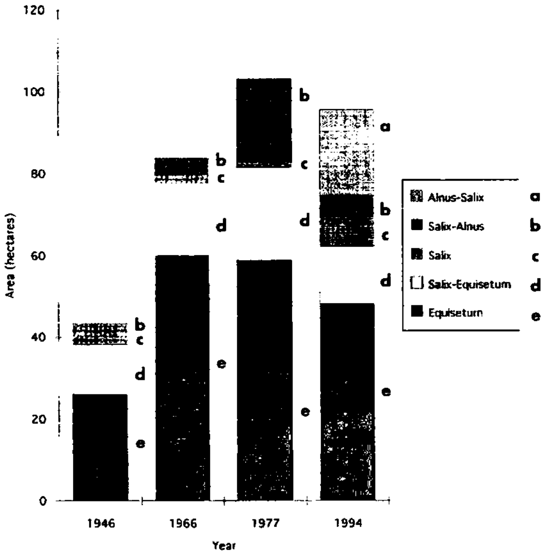
(2) Mid-Channel West

Fig.6.6:
Slave River Delta, Mid Channel West: Cleavage Bar Island, Plant Assemblage Change



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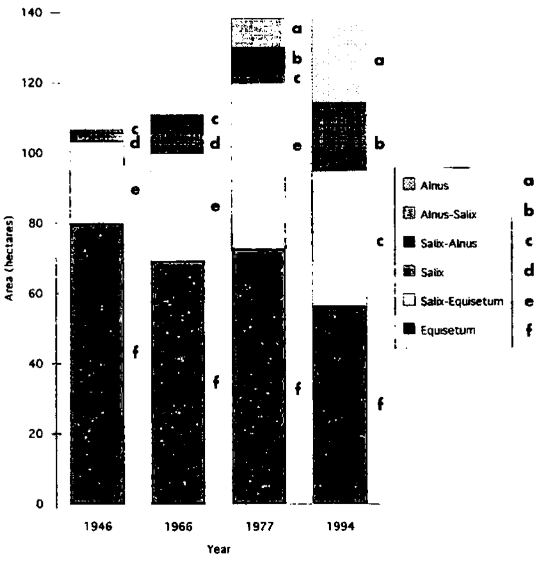
(4) East Channel

Fig.6.7:
Slave River Delta, East Channel: Cleavage Bar Island, Plant Assemblage Change



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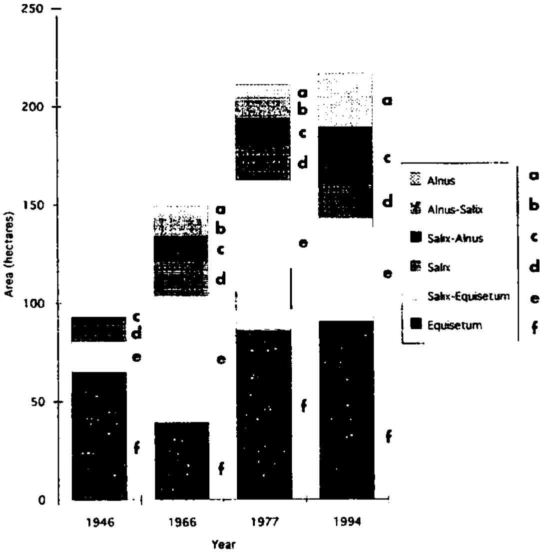
(3) ResDelta Channel

Fig.6.8:
Slave River Delta, ResDelta Channel: Cleavage Bar Island, Plant Assemblage Change



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NORTHERN RIVER BASINS STUDY
SYNTHESIS REPORT NO. 1

IMPACTS OF FLOW REGULATION ON THE AQUATIC ECOSYSTEM OF THE PEACE AND SLAVE RIVERS

by

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ACKNOWLEDGMENTS

Much of this work was completed under contract by a team of scientists and engineers. Their willingness to provide a comprehensive answer to the NRBS Question #10 is appreciated. This often involved them working outside their own field of specialization and interacting with people from other scientific disciplines. Although often difficult and challenging, it is the only way to achieve an integrated scientific response to such ecosystem oriented questions. Contributions of those who authored NRBS scientific reports are specifically referenced in this synthesis report. Many of the other contributors researched and condensed background material which was subsequently integrated into the overview sections.

The scientific and editorial reviews provided by Drs. P. Chambers, J. Culp, and L. Watson are gratefully acknowledged.

The final decision about which proposed studies were to be conducted in response to Question #10 was made by the NRBS Science Office, NRBS Science Advisory Committee, and ultimately the NRBS Study Board. Their comments, suggestions and guidance are appreciated. Thanks are also due to the NRBS office staff for their support, particulary Mr. Jim Choles, who assisted the Hydrology Component.

1.0 ECOLOGICAL EFFECTS OF FLOW REGULATION ON LARGE NORTHERN RIVERS

1.1 INTRODUCTION

The Northern Rivers Basin Study was designed in late 1991 initially around ten guiding questions with an emphasis on water quality and aquatic-ecosystem health of the Peace, Athabasca, and Slave rivers. An additional six questions were added in early 1992, one of them being Question #10 "**How does** and **how could** river flow regulation **impact** the aquatic ecosystem?". In December 1992, the newly formed "Hydrology" and "Other Rivers Uses" scientific component groups of the NRBS jointly began to formulate strategies on how best to respond to this question. Assessing the ecological effects of flow regulation is a worldwide problem that has received considerable scientific attention but much remains to be learned, particularly for large northern rivers, as is the central theme of the NRBS.

Given the limited resources that could be dedicated to Question #10, significant focussing of scientific efforts had to be undertaken. The first step was to concentrate on the major source of flow regulation in the NRBS study area, the W.A.C. Bennett dam on the Peace River. Secondly, only studies that were considered highly tractable and capable of completion within the limited time frame of the NRBS were conducted. The range of potential studies was further constrained by the lack of a comprehensive scientific understanding of the structure and function of the biotic environment of the river and delta systems. Knowledge of preferential use of fisheries habitat, for example, is very limited. In view of these constraints, field studies were dedicated primarily to assessing changes of important components of the physical environment that would directly affect the ecology of the system. Attempts were also made, however, to construct modelling tools appropriate for future ecological assessments and to define suitable monitoring schemes for evaluating long-term changes. Wherever possible, deductions were made about potential ecological impacts based on existing knowledge of the system, including valuable information provided by local indigenous peoples.

An important point to make clear about Question #10 is that it refers to the "*how does*" and "*how could*" of impacts produced by flow regulation and not to "*how could the aquatic ecosystem be managed or restored*" from the effects of flow regulation. The latter, however, was of interest to a companion study of the NRBS, the Peace-Athabasca Delta Technical Studies (PADTS). It is a three year study ending in 1996 that involves the collaboration of Alberta Environment, B.C. Hydro and Power Authority, Environment Canada, and the Cree, Chipewyan and Metis bands of Fort Chipewyan, Alberta. Unlike NRBS Question #10, the PADTS is focussed strongly on methods to restore the "role of water" to the Peace-Athabasca Delta, an ecosystem for which some information already exists about "*how does river flow regulation impact the aquatic ecosystem?*". Cross-reference is made throughout this report to scientific linkages between the NRBS and the PADTS. Unfortunately, scientific studies conducted under the PADTS were not complete at the time of writing this report. Details are provided, however, about PADTS work in progress and recommendations made for a future action plan.

This report is broken into four major sections: a) a review of the state of diversions within Canada, and ecological impacts that are known or likely to occur from regulation of large northern rivers; b) a bio-physical description of the Peace and Slave river and delta systems; c) a synthesis of the results of the various scientific reviews and field/laboratory studies; and d) a summary of the major results and a compendium of scientific recommendations for modification of existing conditions, monitoring of future trends, collaborative inter-agency work and future scientific research. Although not directly tied to NRBS Question #10, the latter section also includes the outline of a remedial action plan for "restoring the role of water" to the Peace-Athabasca Delta.

The first of the four sections, which forms the remainder of this chapter, was developed at the encouragement of the NRBS Study Board. Since only a relatively small number of field studies could be conducted with the available resources allocated to Question #10, it was decided that a prudent way to address "how ... *could* flow regulation impact the aquatic ecosystem" would be to review potential regulation-related impacts. More specifically, the review was to concentrate on aspects particularly germane to large *northern* (cold regions) rivers.

The available literature on regulation effects is quite extensive and has been rapidly growing in the past twenty years, although the amount of material dealing with large northern rivers remains quite small. The following sub-sections reviews this latter literature. Features of the of the riverine abiotic (flow, ice and sediment) system are first considered followed by a review of various biotic (water chemistry, in-channel and riparian biota) factors, including a summary of large-river ecological theory. Selected references to case studies are provided for reader reference and draw, wherever possible, from Canadian examples. For an introduction to the greater source of ecological literature dealing with flow regulation, readers are referred to, for example: general reference texts by Petts (1984) and Calow and Petts (1994); special issue publications such as *Bioscience 45*, 1995 and *Canadian Special Publication of Fisheries and Aquatic Sciences 106*, 1989; and the extensive range of papers contained with the journal *Regulated Rivers:Research and Management.*

1.2 CANADIAN DIVERSIONS AND MODIFIED FLOW REGIMES

River flow regulation primarily results from consumptive-use withdrawals (eg., irrigation, manufacturing and processing), river and lake diversions, and/or impoundment for flood control or hydroelectric production. Canada is the international leader in diversion of water, with more than 600 dams and 60 large domestic interbasin diversions. If combined, the total flow in these diversions would form Canada's third largest river, smaller only than the St. Lawrence and the Mackenzie rivers (Clark and Gamble, 1988; Prowse, 1990). A majority of these diversions have been created for hydroelectric production (Day and Quinn, 1992). Of the country's total 95,000 MW hydroelectric potential (economically-feasible; Efford, 1975), one-third to one-half has already been developed (Rosenberg *et al.*, 1987), a majority through the construction of reservoirs and/or diversions.

Two major hydraulic changes generally occur with the construction of a reservoir that can radically alter reservoir and downstream ecology. Firstly, the water storage area above the dam will change from one characterized by lotic-type (i.e., running water) hydrological processes to a system more lentic (i.e., standing water) in nature. Water entering the reservoir will undergo physical, chemical, and biological modifications as a result of storage. The quality of the water exported downstream will be further modified because of a combination of factors related to stratification dynamics, level of withdrawal, and the extent of drawdown, often resulting in significant changes to water quality and biota not normally seen in unregulated systems.

Secondly, diurnal and seasonal variations in the demand for power will cause short- and long-term variations in discharge. A hydroelectric plant generates power by running water through turbines, causing the downstream discharge to vary according to the operation of the plant. Typically, the reservoir has two purposes: to increase the head or difference in water level across the plant, and to provide storage for periods of low inflow from upstream. Hydroelectric operations are referred to as "run-of-the-river" when only the first of these is important. Such plants are common additions downstream of large reservoirs (e.g., Peace Canyon Dam below Williston Reservoir) or lakes (eg. power plants on the Nelson River system, with storage provided by Lake Winnipeg and other natural lakes), and are often used for "mini" hydroelectric operations. Such systems require only sufficient upstream storage to balance flows and to develop the necessary head across the plant.

Hydroelectric operations that include the ability to store significant amounts of water are common to larger systems. Mainly as a result of Canada's seasonal climate, demands are at a maximum during winter and at a minimum during summer, a direct contrast to the natural seasonal availability of water which is characterized by summer maxima in runoff and winter minima in low flows. To counter this imbalance between power demand and the natural hydrologic cycle, a significant portion of the flow is stored during summer and released during winter. Overall, the regulated regime results in a flattening of the annual hydrograph including a dampening of peak flows. Notably, there can also be significant diurnal fluctuations during any time of the year, depending on variations in daily power demands.

Although the above describes the most common form of seasonal redistribution of flows by regulation, other regime changes can occur depending on the interrelated design of the hydrologic and hydroelectric networks. Some rivers, for example, can experience a decrease in flows throughout the year because a portion of their flow is diverted to feed hydro-electric production in another system. This latter system then experiences an annual increase in discharge, as is the case on the Churchill and Nelson river systems in Manitoba, and the Nechako, Morice and Nanika river systems in British Columbia.

On large rivers, the physical and ecological effects of flow regulation can be experienced several hundreds of kilometres downstream, although their significance generally declines with distance and the increasing contribution of downstream tributary inflow. The nature of many of the ecological effects is outlined in later sections. Firstly, however, the following two sections delineate how flow regulation can further modify the physical template of a river system, specifically through modification of the ice and sediment regimes.

1.3 REGULATION EFFECTS ON RIVER-ICE REGIME

River ice is an integral part of most of Canada's rivers, many of which remain ice-covered for six months or more. It also governs a number of processes controlling the timing, duration, and magnitude of flow and water levels (Prowse, 1994). The related discharge and water-level hydrographs vary significantly from those of more temperate regions, although the full significance of this to winter aquatic ecology is only now gaining recognition (Prowse and Gridley, 1993). Any modification of the winter flow regime, as by reservoir regulation, for example, will have concomitant impacts on the ice regime and related winter ecology of a river. These can be highly significant, given that ice is responsible for many of the annual extremes in hydrologic events, such as floods and low flows (e.g., Prowse, 1994).

As described in section 1.5.3, one of the major regulation-related changes to downstream water quality is temperature. During early winter, the water temperature of a river will gradually cool to 0°C, ice will form, and the underlying water temperature will then remain near the freezing-point for the remainder of the winter season. Within natural lakes and impounded reservoirs, however, the underlying water temperatures remain well above freezing (typically 4∞C in deeper waters). When such water is discharged downstream, the river is warmed to levels that would not normally occur at this time of year. As a result, reaches immediately downstream may remain clear for the entire year and, further downstream, formation of the ice cover may be significantly delayed. In fact, even the ice-cover type and the nature of its hydraulic effects can be modified by other reservoir-related changes. Most river ice covers develop from the accumulation of ice generated in upstream reaches. Formation of a stable ice cover over the surface of a reservoir virtually eliminates the supply of such upstream ice to the downstream river reaches. Hence, any ice contributed to downstream ice-cover formation must be generated beginning at the downstream location of the 0∞C isotherm below the dam. This can be at a significant distance downstream considering the cooling first required of warm-water releases.

Increased discharge during the winter can lead to changes in location and number of lodgement sites for initial cover development. Moreover, enhanced flows can lead to covers of greater thickness and rougher surfaces: features that combine to elevate water levels above those occurring under unregulated conditions, and greater than those expected under high-flow events.

Once an ice cover has been established, regulated-flow conditions can further control its growth. For example, fluctuating winter discharge and associated water levels can lead to overflow and the generation of additional surface ice forms. By contrast, increased flows can also create additional heat from fluid friction that can offset downward growth of the ice cover. If fluctuations in winter water levels are large and/or rapid enough, they can promote a premature break-up of the ice cover during the main winter. The magnitude of the effect of regulation on spring break-up varies according to the ratio of the regulated flow to the total river discharge, which should decline downstream with increasing tributary inflow. Depending on this ratio, break-ups and associated ice-jam flooding could be more or less severe compared to unregulated conditions. In some cases, such as urban environments, it may be desirable to reduce such flooding activity; conversely, for some aquatic environments, flooding is critical to ecosystem health and survival (e.g., Prowse, 1994; Scrimgeour *et al.*, 1994). Aspects of the latter are discussed in subsequent introductory sections.

1.4 REGULATION EFFECTS ON SEDIMENT REGIME

River regulation can modify the sediment regime of a river through retention of material within the reservoir and through modifications of downstream erosion and deposition processes. As turbid, high-velocity water is transferred into a reservoir, the sediment load begins to deposit as water velocity is reduced. Although the level of suspended sediments is a function of discharge, glacial fed systems or catchments with heavy cultivation practices tend to have higher TDS (total dissolved solids) and turbidity. Some of the incoming material will be deposited in channels and on the valley bottom upstream as a result of backwater effects on tributary flow. Somewhat further into the reservoir, deposition often leads to the formation of sub-aerial deltas (e.g., Gardiner Dam reservoir in Southern Saskatchewan; Rasid, 1979, Galay *et al.*, 1985). Finer grained sediments tend to settle further into the reservoir, but some may remain permanently suspended (e.g., kaolin clays), thereby maintaining turbidity (Bondurant and Livesey, 1973).

Short reservoir life-expectancies are associated with small-scale dams that have impounded rivers with high levels of sediment influx. Continued reduction in storage capacity of such reservoirs through sediment accumulation results in a decreased water-retention capacity and may lead to an inability to retard the passage of floodwater downstream. Heavily forested catchments and catchments underlain by hard-rock formations usually suffer less from internal sedimentation problems (Petts, 1984). Water-quality characteristics, such as TDS, turbidity, and nutrient concentrations are affected by sedimentation rates (Walker, 1982) that in turn control the turbidity, TDS and particulate N and P levels in the water exported downstream of a reservoir. The magnitude and longitudinal extent of these levels depend largely on the nature and volume of tributary discharge downstream of a reservoir. In systems where relatively "clean" water is exported, high velocities downstream of exit ports may rapidly increase the TDS through resuspension of downstream material.

Scouring of a river channel immediately downstream of a reservoir is a common process but patterns of morphological change become more complex downstream. Changes in the flow and flood regime have implications relative to the competence of the channel to carry sediment and to the ability of the system to flush sediment deposited during low-flow events. Provided that the regulated discharge is large enough to transport bed material, the initial effect is degradation and textural coarsening of the river channel immediately downstream of the reservoir (Buma and Day, 1977; Rasid, 1979; Galay *et al.*, 1985). This results not only because of the erosive power of the flow, but also because of the lack of significant material supplied from upstream, since it is only light-fraction suspended material that is carried through the upstream reservoir. Degradation is not necessarily restricted to the main channel; nearby tributaries often become incised as a result of the degradation in the main channel (Kellerhalls, 1982; Galay, 1983; Gomez-Amaral and Day, 1987). The reduction of sediment below the point of regulation can result in a change in channel pattern from less towards more sinuous and from braided to single or split-channelled (Galay, 1983; Williams and Wolman, 1984; Church, 1995), and can lead to an overall decrease in channel width, although this is dependent on channel erodibility. Where degradation produces an armouring of the channel bed (Rasid, 1979; Galay *et al.*, 1985), adjacent unstable banks become more susceptible to erosion. On most large rivers, degradation processes are constrained to the first few or tens of km downstream of the point of regulation, and a one- to three-m depth of degradation typically occurs within a decade or two of regulation (Church, 1995).

Further downstream, where tributaries add more material to the river, aggradation begins to develop. Lower regulated flows, especially without the previous peaks, simply do not have the conveyance power to carry material produced by upstream degradation as well as that contributed by the tributary flow. Notably, however, increased flows during the winter may increase this seasonal flux of sediment, although the annual load is still likely to be smaller. Furthermore, it should be reiterated that not all cases of regulation result in lower flows or dampened flood peaks. Some diversions have resulted in rivers carrying a much larger mean flow volume and in flood events occurring at different periods of the year than under natural conditions (Kellerhals *et al.*, 1979; Day, 1985; Rosenberg *et al*, 1987; Church, 1995).

Where aggradation develops within downstream river channels, the nature of the morphologic response is influenced by the character of the alluvial deposits. Typical responses may include channel widening and a reduced mean flow depth. Progradation of vegetation down the banks onto abandoned floodplains, however, can lead to an adjustment in the overall flow pattern and, ultimately, to a narrower channel. Significant changes can occur at tributary mouths, where large deposits of material may accumulate, not unlike the formation of an alluvial fan (Kellerhals, 1982; Milhous, 1982).

One critical aspect of changes from regulation to a river-sediment regime is the time scale (Church, 1995). Although some rapid changes can be observed immediately after regulation, the time required for a system to achieve a new form of equilibrium depends on the severity of the regulation, the form and composition of the channel, and the rate at which seral vegetation communities can be established. Because of the huge volumes of sediment involved in diversions on large northern rivers and the associated slow rate of vegetation change, the time-scale for adjustments can be in the order of centuries. Significantly, however, no system has been studied systematically for more than a few decades (Church, 1995).

1.5 REGULATION EFFECTS ON DOWNSTREAM WATER CHEMISTRY

The character of the major constituents of reservoir water released to a downstream river depends upon a number of factors: geographical location (Gibbs, 1970), precipitation and altitude (Douglas, 1972), discharge (Dunst and Wirth, 1972), lithology and land-use (McLachlan, 1970; Walling and Webb, 1975), and anthropogenic effluents. After construction of a dam, the water quality may be highly variable until internal organic matter and nutrient sources are depleted or stabilized. Subsequently, in reservoirs that experience short retention times, the chemical composition of the outflows tends to reflect closely the nature of the influents. Within large reservoirs characterized by long-term storage, the water can experience numerous quality changes due to a complexity of inter-related physical, biological and chemical processes. Although many of these are important to the ecology of the reservoir, only some appear to be important to the aquatic ecosystem downstream. The most important processes are outlined in the following sub-sections.

1.5.1 Organics/Nutrients

Deposition of sediment usually includes significant quantities of seston (fine organic material). Although the overall settling processes help reduce the TDS of the inflow, high autochthonous production in the epilimnion layers of reservoirs may simply replace the trapped seston with living and dead limnoplankton, with the result that particulate organic matter levels remain approximately the same (Lind, 1971). In certain circumstances, levels may actually increase, causing turbidity to rise in downstream river reaches during periods of low discharge. In general, however, epilimnion release dams will tend to decrease the level of total dissolved solids in the discharge, while hypolimnion releases will tend to increase TDS, although the latter generally have very low levels of organic particles (Ward, 1974; 1976a,b). The concentration of suspended sediment, particulate carbon, particulate phosphorus, and particulate nitrogen in lotic systems is clearly related to discharge characteristics of the system (Brunskill *et al.*, 1975; Campbell *et al.*, 1975). Some of the highest nutrient outflows from shallow reservoirs are associated with flood events disturbing reservoir sediments and releasing large quantities of orthophosphate (e.g., Hannan and Broz, 1976; Roos and Pieterse, 1994); however, such disturbances are unlikely on large deep reservoirs. Reservoirs generally tend to act as nutrient sinks (Petts, 1984). Significant release of nutrients from bottom sediments could occur under anoxic conditions but these conditions are unlikely to develop on large, cold northern reservoirs.

The carbon/nutrient impact of reservoir outflow may dissipate within as little as 1 km below a dam (Mackie *et al.*, 1983), although it tends to extend much further downstream (tens of kilometres or more) on large river systems. The degree to which impoundment effects may be apparent downstream of the dam depends on the relative contributions of downstream tributaries to total river discharge (Reeder, 1973). Within this affected distance, tributary inflow of differing chemical signatures can produce distinct water-quality zones, especially on large broad rivers. Decreased upstream flow can exaggerate the presence of such zones because of reduced lateral mixing of water (Mackay, 1970;1972). Eventually, the river will again take on a water-quality signature of the adjacent landscape through tributary inflow and release of water soluble and exchangeable chemical constituents from inundated soils.

1.5.2 Mercury

One of the most ecologically-significant water-quality processes occurring in reservoirs is the formation of harmful levels of mercury. Numerous impounded rivers in Canada have experienced the formation of high mercury levels including, for example, Smallwood River, Labrador (Bruce and Spencer, 1979); Southern Indian Lake, Rat Lake, Notigi Lake, Manitoba (Bodaly *et al.*, 1984a; 1984b; McGregor, 1980); Cookson Resevoir, Saskatchewan (Waite *et al.*, 1980), and La Grand 2 and Opinaca reservoirs, Quebec (Boucher and Schetagne, 1983).

Methylation dynamics of mercury in the environment dictates that no forms of mercury may be considered insignificant to potential impact problems (Jones *et al.*, 1986). The methylation process is possible under oxic and anoxic conditions (Bisogni and Lawrence, 1975; Olsson *et al.*, 1979) and can occur in the water column (Furutani and Rudd, 1980; Topping and Davis, 1981) and in lake sediments (Furutani and Rudd, 1980). A number of sediment characteristics control methylation processes (Miller and Akagi, 1979): organic matter content and nutrient status, for example, being important to microbial methylation rates (e.g., Rudd *et al.*, 1983).

In the water column, the net concentration of methyl mercury is a function of both methylation and demethylation processes, mediated by microbial action (Brosset, 1981), and by pH of the water column and within bottom sediments (Ramlal *et al.*, 1985). Trophic status of the reservoir also affects the concentration of mercury. Although this is normally attributable to biomass dilution of available mercury in more productive systems (Huckabee *et al.*, 1979; Hakanson, 1980), some doubt remains because artificial enhancement of production does not always result in lower mercury contamination levels. For reviews of the pathology of mercury accumulation see Piotrowski and Inskipp (1981).

Fish accumulate mercury directly from the water (i.e., via gill respiration) or indirectly through ingestion of contaminated food sources. The relative importance of either of the vectors is probably site- and species-specific (Huckabee *et al.*, 1979). Although exposure time has been problematic in assessing accumulation rate data, evidence clearly illustrates that active feeding on contaminated food sources can lead to biomagnification of mercury in higher trophic groups (MacCrimmon *et al.*, 1980; Wren *et al.*, 1983). Several factors control its uptake from the water column: fish metabolic rate (Rodgers and Beamish, 1981), water hardness and pH (Wren and MacCrimmon, 1983).

In general, the factors controlling the rate of methylation and demethylation of mercury in reservoirs will apply equally to lotic systems. Dilution of methyl mercury downstream of a dam will be affected greatly by the degree of tributary discharge, and the hydraulic nature of lotic systems (e.g., enhanced aeration) tends to minimize additional microbial methylation. The relationship between mercury sources and bio-availability in lotic systems, however, is not fully understood.

1.5.3 Temperature

Broadly speaking, a reservoir acts as a thermal regulator of flow to the downstream river system. Significant thermal stratification can develop within the reservoir, regulated primarily by inflow characteristics (e.g., turbidity, temperature; Dunst and Wirth, 1972; Hirst, 1991) and the magnitude and temporal variability of outflow. Thus, release of water from different depths affects the thermal regime of the downstream river, hypolimnetic waters tending to be cooler in summer and warmer in winter than epilimnetic waters (Ruttner, 1973). The distance that such water-temperature effects are experienced downstream depends on prevailing climatic conditions and the magnitude of the regulated flow compared to that of downstream tributary inflow. Below the Gardiner Dam on the South Saskatchewan River, for instance, temperature changes leading to an impoverishment of the benthos have been documented for over 100 km downstream (Baxter, 1977). Repeated-pulse discharges (see section 1.6.1), common to some hydroelectric operations, can also produce highly-fluctuating, downstream water temperatures (McCart, 1982), with the degree of fluctuation generally related to the nature of electrical demand (Pfitzer, 1967).

In addition to the actual temperature of the water outflow, regulation of the magnitude of the flow can lead to important changes in downstream water temperature. Reduced summer flows on the wide Nechako River, as an example, have led to excessive warming of the flow with related impacts on salmon stocks (Fisheries and Marine Service, 1979; Kellerhals, 1987). Sudden reductions in flow can result in the stranding of faunal populations in marginal pools and backwaters where rapid solar heating can prove fatal (e.g., Hamilton and Buell, 1976). Reduced winter flows are a problem on northern rivers because they promote rapid cooling/freezing and increase the probability of habitat reduction through the anchor-ice coating of bed material (e.g., Power *et al.*, 1993).

1.5.4 Oxygen

Periodically, reservoir waters may undergo significant declines in dissolved oxygen concentrations. Hypoxia and anoxia, which are normally a direct consequence of reservoir stratification, can result in high levels of iron, manganese, and hydrogen sulphide in deeper waters (Ramsey, 1991; Hirst, 1991), particularly where the reservoir employs an hypolimnetic release. Within shallow small reservoirs, the rapid entry of flood waters can cause destratification and release of toxic compounds into the system (Arumugam and Furtado, 1980). Such flood-disturbance effects, however, are limited in large deep reservoirs.

Hyperoxic water can be discharged from a reservoir as a result of supersaturation during passage through the turbine systems (Dominy, 1973) or over-dam spillage (Holden, 1979). Turbine-induced supersaturation may compensate for problems where anoxic water is drawn from hypolimnion waters of deep outflow reservoirs (Stanford and Ward, 1979). Unintentional raising of the outflow dissolved oxygen concentration is augmented in many deep reservoirs by artificial destratification techniques, such as air injection and mechanical pumping, which help maintain isothermal conditions, continued vertical mixing, and a supply of dissolved oxygen to lower waters. Increased dissolved oxygen concentration near the reservoir sediments would increase redox potentials, thereby removing or minimizing the condition necessary for the release of, for example, carbon dioxide and hydrogen sulphide, and the release of phosphate, manganese and iron into solution.

Oxygen conditions created by a reservoir are relatively short-lived in the downstream receiving river. Rapid exchange of gases with the atmosphere induced by the turbulent flow quickly eliminates extremes in oxygen concentrations. Although an ice cover is known to eliminate such water-atmosphere gas exchanges, open-water conditions usually exist at a sufficient distance downstream of a dam, even under the coldest of winter conditions.

1.6 REGULATION EFFECTS ON DOWNSTREAM RIVER ECOLOGY

Changes in the characteristics of the physical template and/or water chemistry can produce numerous modifications and impacts to downstream aquatic communities, at a variety of spatial and temporal scales. The following sections briefly review the nature of some of the most important proximal and distal impacts. First, however, an examination is made of hydro-ecological theory that currently exists for large rivers and an attempt is made to place it in a context applicable to large *northern* rivers, the primary focus of the NRBS. This theoretical background is then used as a reference for the review of specific ecological impacts, the latter including changes to plankton, periphyton and macrophytes, macroinvertebrates, fish, and overall riparian ecosystems.

1.6.1 Hydro-ecological Theory of Large Rivers

The ecology of large rivers is a nascent science, one based on theories and experience developed largely from studies of small streams and lakes. As noted by Johnson *et al.* (1995), there is no clear theoretical basis for how large river ecosystems operate. This is especially true for large northern rivers which have received minimal study compared to rivers of more temperate and tropical areas (e.g., Sedell *et al.*, 1989).

Two major hypotheses are commonly used to describe how lotic systems function: the river-continuum concept (RCC; Vannote et al., 1980) and the flood-pulse concept Junk *et al.* (1989). Originating from studies of temperate, forested lotic systems, the RCC assumes that a gradient of physical forces and processes produce a longitudinal (streamwise) gradient in hydrologic and geomorphic features from low- to high-order streams. Moving from small enclosed streams to larger open rivers, the major energy sources for food webs changes from local inputs added by adjacent terrestrial vegetation (allocthonous), to products of primary production within the stream (autochthonous), and finally to the receipt of organic material transported from upstream reaches.

A number of problems have been identified with the RCC and to make it more applicable, two additional corollaries have been developed (Johnson *et al.*, 1995) a) Resource-Spiralling Concept (RSC; Elwood *et al.*, 1983) and b) the Serial Discontinuity Concept (SDC; Ward and Stanford, 1983). The RSC differs from the RCC in that biological resource material is considered not to move continuously downstream through the stream to large river continuum but rather, is transported in storage and release cycles, thus giving a spatial and temporal component to nutrient availability in rivers. In the case of large rivers, however, there tends to be a net export of organic material because of low biological activity and relatively small storage of material.

The SDC (Ward and Stanford, 1983a) theorized on the effects of dams on the streamwise continuum of biological and physical processes. In general, dams create a discontinuity and, for large rivers, there is an expected change in aquatic character towards that of a mid-sized river typified by a higher abundance of aquatic vegetation because of a regulation-related decrease in turbidity. Notably, however, this concept like the other RCC-related concepts does not account for the effect of downstream tributaries (e.g., Bruns *et al.*, 1984; Osborne and Wiley, 1992). In cases where significant sediment is supplied by downstream unregulated tributaries, turbidity can increase and biological productivity decrease on the mainstem river under reduced flow conditions; an opposite effect to that proposed by the SDC.

An additional important modifier of both natural and regulated systems is the disturbance (i.e., relatively discrete event that changes the local environmental conditions) created by floods. While they have been shown in numerous studies of algae, macroinvertebrates and fish to reduce overall biomass, species diversity and density, many effects are only short-term, the duration dependant on the rate at which biota return to pre-disturbance levels. The frequency of floods, however, can also affect community structure. For example, the Intermediate Disturbance Theory (Connell, 1978) applied to rivers (Ward and Stanford, 1983b) predicts that the highest species richness should be observed in rivers where floods are of an intermediate frequency and intensity. Reductions in species diversity can be expected for systems characterized by catastrophic floods or those with benign flow conditions, ones often produced by the regulatory effects of dams and reservoirs.

Related to the role of floods is the function of floodplains, a component not considered by the original RCC-based theories. Although data collected on a confined sub-arctic river by Naiman *et al.* (1987) appear to support the RCC, data from other large rivers (reviewed by Sedell *et al.*, 1989) points to the significance of floodplains to overall aquatic productivity. Moreover, most large river systems tend to be characterized by geomorphologic conditions that favour the development of floodplains which are large relative to the lotic surface area (Welcomme, 1985) and can include backwaters, marshes, floodplain lakes and even adjacent deltas [an important focus of this report]. Lateral exchanges of water, sediment and nutrients between the floodplain and main river channel are believed to have more impact on biota than that associated with resource spiralling (Junk *et al.*, 1989). More generally, more biological activity (production, decomposition, consumption) and the storage/retention of organics and nutrients occurs in the margins than within the main channel of large rivers. Furthermore, when floodplain areas are considered part of the entire channel system, biotic diversity of large rivers probably exceeds that for medium-sized rivers, as predicted by the RCC (Johnson *et al.* 1995; Statzner, 1987).

In any floodplain river, the lateral exchange of organic material, nutrients and organisms between the river and the floodplain depends on the occurrence of high stage associated with flooding events. Such exchange by annual floods is the basis for the more recent theory of the Flood Pulse (Junk *et al.*, 1989). During the rising limb of the flood hydrograph, organisms can migrate onto the floodplain and flourish by using the resources of this extended habitat. As water levels decline, nutrients and organic material are carried back into the main channel and a new layer of sediment and nutrients are deposited on the floodplain.

In general, biotic communities should exhibit a dynamic equilibrium controlled by characteristics of the flood pulse such as timing, duration, and rates of water level rise and recession (Bayley, 1995). Productivity is a function of such factors as well as their coincidence with other physical conditions, such as temperature. Five general categories of flood pulses and their associated effects can be identified (Bayley, 1995; Johnson *et al.*, 1995): a) pulses too short to permit flood-dependent organisms to complete their reproductive cycles; b) moderate duration pulses that permit aquatic and terrestrial organisms to adapt; c) flood pulses too long to permit terrestrial vegetation to develop later in the season; d) flood pulses that are poorly timed relative to temperature and radiation conditions required for optimal biological productivity, and e) regular flood pulses that enhance productivity in the floodplain and main channel.

One major deficiency of all the above theories that has special significance to large northern rivers is the role of ice cover, specifically as it controls annual flooding. For many northern rivers, ice jams associated with fall freeze-up and/or spring break-up produce the most significant hydrologic event of the year and create water levels that far surpass those possible under equivalent discharge during the open-water period (Gerard, 1990; Prowse, 1994). Unlike open-water floods, however, ice-jam flood pulses are of relatively short duration on both small and large rivers and are thus probably characterized by similar biological restrictions to floodplain productivity as identified for the short-duration floods in the general Flood Pulse theory. On many rivers, however, it has been shown that ice-jam floods attain higher flood stages at a higher frequency than those produced by open-water discharge floods (e.g., Gerard and Karpuk, 1979; Lawford *et al.*, 1995; Watt, 1989). Highest ice-jam flood levels are often near the physical upper limit imposed by the morphology of a river, in contrast to open-water floods where recorded maxima are usually far below the physical limit (Watt, 1989). Physical limit in this case is analogous to a *genetic* (influenced by geneses or origins) flood plain in the geologic sense that includes surfaces built or deposited by the present-day river in the course of lateral shifting or flooding (Kellerhals and Church, 1989). A lower-elevation definition of the floodplain is commonly used from a fisheries or aquatics viewpoint, one which focusses on the lower terrace that is more frequently inundated by open-channel floods (Welcomme, 1985).

High-elevation floods produced by ice jams are usually too brief to be of much value in creating additional fisheries habitat and, because of ice scour, may even make some margin areas inhospitable to fishes (Roy, 1989). Significant inputs to river productivity, however, can be realized by such floods through a large organic nutrient pulse to the main channel system (Scrimgeour *et al.*, 1994). Extensive amounts of allocthonous material is probably scavenged by floodwater that inundate the heavily vegetated and often forested landscape that occupies the upper terraces of large river floodplains. Moreover, since cold temperatures characteristic of such terrestrial systems slows decomposition, the contribution of high quality, decomposed detrital material to the total organic load may be greater for high latitude northern rivers than southern temperate rivers (Scrimgeour *et al.*, 1994). This is important given that the quality of such organic inputs influences the abundances of detritivores and ultimately, river productivity.

Scavenging of high floodplain material should also have a strong influence on the nutrient budget of large northern rivers which are nutrient limited, especially by phosphorus and nitrogen (Welcomme *et al.*, 1989; Bodally *et al.*, 1989; Roy, 1989) which tend to be plentiful in floodplain organic matter (Scrimgeour *et al.*, 1994). Hence, the size of the allocthonous load will be determined by the severity of break-up (see sections 1.3 and 3.3 for further discussions on river ice; Lawford *et al.*, 1995). Inter-annual variations in break-up intensity could vary the size of allocthonous organic matter inputs. Thus, for example, the amount of stored material should decrease during successive years of low intensity breakups because of in-channel consumption and downstream export of detrital carbon exceeding detrital inputs to the river. From a more general "disturbance" perspective, dynamic (high intensity) ice break-up and its associated scouring processes have a much greater potential than open-water floods to reset the biotic template in both the channel and on adjacent floodplains. Following again from the intermediate disturbance hypothesis, any conditions that favour an increase in the frequency of benign, thermal (low intensity) breakups, such as could be induced by flow regulation, should have a direct effect on overall river productivity.

As noted earlier, the following sub-sections detail some of the more significant proximal and distal impacts on various components of the aquatic system downstream of a major flow impoundment. Although no general comprehensive theory yet exists for large rivers, especially those in cold regions strongly affected by ice, many of the expected distal impacts are captured by the Flood Pulse theory and the related importance of floodplain/riparian/delta zones. Attempts are made to draw out this connection and to point out further the significance of cold regions processes.

1.6.2. Plankton

The dynamics of lentic plankton contribution to downstream reaches of an impounded system are governed by three factors: retention time, seasonal pattern of plankton development, and the character (hypolimnetic versus epilimnetic) of the outflows from the reservoir. Even with significant increases in the biomass of plankton entering a river downstream of an impoundment, however, the persistence of elevated plankton numbers in the flowing waters is relatively short lived. Sedimentation, mechanical destruction, and biotic filtering are all factors that tend to reduce plankton biomass quickly, usually within several kilometres of the dam. Although lotic systems tend to decrease the quantity and modify the type of plankton input from reservoirs, the additional modifying characteristics of an impounded river may lead to reservoir plankton communities becoming a significant additional source of inoculation for downstream reaches.

In general, the development of plankton populations endemic to lotic systems (potamoplankton) are affected by regulation, since they are controlled principally by current velocity. Although the biomass of such populations are probably small in northern rivers, wide large rivers with low flow can develop populations of potamoplankton that prefer low-velocity backwaters and areas of dense macrophyte cover providing shelter from fast current. Habitat extension can be realized through the reduction in size and/or frequency of flood events and the associated high levels of suspended inorganic matter, both of which attenuate plankton development.

1.6.3 Periphyton and Macrophytes

In northern temperate rivers, impoundment can increase the rate of autochthonous production, both periphytic and macrophytic, by maintaining elevated water levels in summer; reducing flood magnitude and frequency; reducing turbidity; stabilizing substrate; and moderating temperature fluctuations. Periphytic algae, for example, require moderate flows to stimulate aggressive growth (e.g., Welch, 1980), whereas fast-flowing water tends to move and scour substrates on which they populate. Hydrologic and chemical changes can alter the size and composition of the periphyton community but, as the proportion of tributary flow to total river discharge increases below an impoundment, the periphyton community gradually reverts back to a community typical of pre-impoundment.

Regulation-induced changes in water quantity and quality that tend to be advantageous for periphyton have similar effects on macrophyte populations. Increased deposition of fine silts from tributaries and in side-channels particularly can promote an expansion of macrophyte colonization, and the increase in abundance can, in itself, lead to increased sedimentation rates by further slowing water velocity.

1.6.4 Macroinvertebrates

As for plankton, periphyton and macrophytes, invertebrate communities just downstream of an impoundment are affected by the physical, chemical and biological characteristics of release water. Important differences relate to dissolved oxygen, organic content, and the thermal regime. Modifications to the thermal regime can have direct consequences for the timing or the actual occurrence of critical life cycle phenomena (e.g., Gore, 1980). As an illustration, depressed summer and elevated winter water temperatures may change the number of degree days available for development and phenologies, and alter emergence cues.

As per the intermediate disturbance hypothesis (section 1.6.1), stabilization of flows by regulation can greatly influence the quality of habitat and species diversity (e.g., Stanford and Ward, 1979; Armitage, 1977; Rader and Ward, 1988). Correspondingly, it can also increase the abundance of specific species. Many of the observed changes in macroinvertebrate communities, for example, are linked to increased biomass of periphyton which enhances shelter from instream current; increases the deposition of organic matter; and provides additional sources of food supply for herbivorous invertebrates (e.g., Ward and Short, 1978; Petts and Greenwood, 1981).

As suggested by the Flood Pulse theory, modifications (positive or negative) to organic fluxes from the reservoir or to flood size/frequency and inundation of riparian zones can produce concomitant changes to species diversity. Hence, decreases in terrestrial allocthonous inputs (e.g., from reduced flooding of the terrestrial floodplain) can produce reaches low in invertebrate decomposers. Conversely, where other conditions lead to an enhancement of organic deposition, decompositional invertebrates are likely to colonize.

Alterations to the sediment regime are also known to produce some important changes to invertebrate populations, although a relationship between sediment particle size and distribution of invertebrates has not been clearly established. At a coarse scale, however, particle sizes of bed material are clearly associated with species diversity and distribution.

Within the hyporheic zone, infilling of interstitial spaces by silt may lead to diversity loss as many invertebrates utilize this area as a refuge and feeding site. In cases where flow modification reduces sedimentation, the macroinvertebrate community may shift to a system dominated by species capable of utilizing the hyporheic zone.

1.6.5 Fish

In addition to physical characteristics of the flow, water-quality characteristics of reservoir outflows can affect fish in three ways: exceedance of tolerance limits; interruption of normal sequences of reproduction, development and survival; and alteration of the competitive interaction between fish species and the predation dynamics between fish and their food resources (Petts, 1984). Thermal modifications have eliminated many temperature-specific species native to impounded rivers. Although mobile adults may be able to survive thermal changes in their environment, changes in magnitude and range of temperatures can affect reproduction and survivorship of more vulnerable life-cycle stages such as eggs and fry. In general, epilimnetic waters are more suited for exploitation by coarse fish, while cooler hypolimnetic waters are more suited to sport fish (this statement may be invalid if hypolimnetic waters are hypoxic or anoxic). Hypolimnetic waters may be acutely toxic to many fish species if hydrogen sulphide gases and heavy metal concentrations are high due to low redox potentials within reservoir bottom waters. As noted earlier, the turbulent action within tailwaters may aid in reducing the impact of toxic hypolimnetic releases through re-oxygenation. Chronic effects of multiple low-level toxicant exposure cannot be assessed readily in the field; however, low-level contaminant exposure may be important to the long-term productivity and existence of fish populations in impounded rivers.

Other physio-chemical changes have been noted to have detrimental effects on the timing of critical life-cycle events (Cadwallader, 1978), such as initiation of spawning behaviour, the viability of fish eggs, and survivorship of young of the year. The delivery of organically-rich effluent, for instance, can cause unexpected redistribution of fish. Epilimnetic-drawdown reservoirs provide an abundant source of plankton as well as stimulate the growth of other sources of fish food, such as invertebrates. Suitable water temperatures and high dissolved-oxygen concentrations provide additional attractive forces for the establishment of excellent fisheries in tailwaters (Walburg *et al.*, 1971).

Supersaturation events, as discussed earlier in section 1.5.4, can have significant mortality impacts on fish populations of impounded rivers. In the Saint John River, such supersaturation was responsible for fish kills as far downstream as 2 km from the tailrace of the dam (MacDonald and Hyatt, 1973). Fish in deep water are less likely to suffer heavy mortality than species in shallower or surface waters, where the percentage saturation of gases is greater (Beiningen and Ebel, 1970).

Dams directly affect the ability of fish species to migrate either upstream or downstream. In hydroelectric power dams, turbine losses of downstream migrating fish can be significant and strong thermal stratification of reservoir waters can make passage through the reservoir lethal to migrating species. Upstream migration is no less problematic because of severe flow conditions at the dam outflow, although properly engineered fishways (ladders, terraces) can minimize this problem for smaller dams.

Besides straight obstruction to passage, the most critical regulation factor affecting fish populations of large northern rivers is the change in the flow and related velocity regime. For example, increased flow velocity can reduce the habitat quality of established spawning beds, or completely erode them. It can lead also to increased catastrophic drift of invertebrates, thereby depleting an important food source. Sudden changes in flow velocity can potentially strand juveniles or wash them downstream, while increased flow in feeding sites may lead to loss of habitat particularly suited for the rearing of juveniles. Loss of spawning habitat can also result from decreases in flow and water levels and related effects, such as infilling of gravel beds through enhanced deposition of fine-grained sediment, or formation of ice on the channel bottom that either freezes eggs or restricts flow and oxygen supply in the substrate.

Discharge is considered to be a stimulus to fish migration, with a greater tendency for fish to migrate under high-flow conditions. While high flows in unregulated systems tend to coincide with spawning times for most spring spawning species, irregular peak flows (i.e., category of poorly timed pulses described for the Flood Pulse theory; section 1.6.1) in regulated systems could lead to ill-timed runs and unsuccessful reproduction. However, the correlation between discharge and fish migration is not always clear and is not consistent at inter-river or inter-reach scales.

Changes in flow can affect habitat availability near river margins. Inundation of floodplains on an annual basis, for example, provides additional spawning sites for some species (e.g., northern pike). Such events replenish organically-rich silt beds from which fish may benefit either directly, through creation of lush growths of macrophyte communities, or indirectly through maintenance of vegetation supporting highly productive invertebrate populations upon which fish may feed. Alterations to this flooding regime would have obvious effects on the quality and availability of such floodplain-related habitat.

Regulation-induced modifications to the riparian and macrophyte habitats of lotic systems can be both beneficial and detrimental to fish species. Growth of edge vegetation can provide shade, zones of rich invertebrate communities, and stabilization of river bed substrates: all three beneficial to fish populations. Conversely, encroachment by edge vegetation into the river channel can increase organic loading and oxygen depletion due to decomposition; increase siltation and loss of gravel beds; and lead to dense stands of macrophytes that impede fish migration.

Numerous changes to habitat can result from alterations to general morphology brought about by flow regulation. Increased sedimentation can destroy valuable fish refuges by infilling of backwater channels and snyes or can lead to additional barriers at tributary mouths. Many of the expected morphological changes are discussed below.

1.6.6 Riparian Ecosystems

Clearly, as shown by the theoretical overview and the various case examples above, the margins and immediate floodplains of large rivers are important to a myriad of *in situ* and migratory riverine biota. As also demonstrated in the review of abiotic processes, flooding, river ice processes, and sedimentation are principal agents in the development, maintenance and modification of riparian communities and habitats. Aspects of their effects on the immediate riparian zone and more distant floodplain areas, including deltas, are now briefly reviewed.

A reduction in the frequency and magnitude of floods and a stabilization of low flows create the most suitable conditions for the development of riparian vegetation. On northern rivers, stabilization of discharge downstream of a reservoir leads to riparian vegetation dominated by species such as willow (*Salix* spp), poplar (*Populus* spp), and horsetails (*Equisetum* spp) (Stromberg *et al.*, 1991; Wagner, 1993). Overall, however, vegetation succession in riparian zones is complex. The intrusion of tree species into floodplains of regulated rivers, as an example, is by no means certain. Indeed, in a number of systems, the regulation of discharge has been correlated with the loss of forested floodplains (Stromberg *et al.*, 1991; Wagner, 1993). In the case of confined channels without the deposition of significant alluvial material, flooding can lead to poor habitats for the establishment of riparian vegetation. Since bank erosion is also of greater significance in confined rivers, bank stability plays a major role in the successful development of higher-elevation vegetation. Stabilization of winter flows can also lead to the loss of unique habitat formed by large air cavities beneath shore ice. Such gaps are used as migration corridors by semi-aquatic species, such as otter and muskrat (Power *et al.*, 1993). A normal winter recession in flow produces these gaps as the ice shears and drops with the declining water levels. Stabilized flow due to regulation would preclude their formation.

The relationship of regulation to deltaic communities is even more complex. The equivalent riparian community within these systems (e.g., perched basins; see later descriptions of the Peace-Athabasca and Slave deltas) is dependent on the supply of water, sediment, and nutrients provided by flooding events. Reductions in such flooding activity can lead to significant drying of these systems; alter sediment and nutrient fluxes (e.g., Marsh, 1986; Peace-Athabasca Delta Implementation Committee, 1987); and produce changes in productivity and seral vegetation communities (e.g., Jaques, 1989; Lesack *et al.*, 1991).

As noted in section 1.3, ice is often responsible for large-scale flood events on northern rivers. During such events, riparian zones along the floodplains and channel banks are exposed to intense erosion by ice action. The suspended sediment load during this period has been reported to be several times that normally measured for equivalent discharge under open-water conditions (Prowse, 1993; Beltaos *et al.* 1994; Milburn and Prowse, 1996). Scouring also reduces the encroachment of riparian vegetation and creates unique bed and bank forms, such as boulder pavements and erosion scars (see reviews by Gatto, 1993; Scrimgeour and Prowse, 1993). It has been postulated that ice action is responsible even for the overall shape of the channel margins (Smith, 1979).

As noted in Section 1.6.1, the biological productivity of a riparian zone is typically higher than surrounding lands. Excellent growing conditions for aquatic and terrestrial plants are provided by a benign microclimate, adequate water during the growing season, and a reliable supply of nutrients draining from surrounding uplands and flood-deposited sediment. On large northern rivers, these diverse plant assemblages with abundant edge habitat and high productivity provide food and cover for small mammals, including beaver and muskrat, and large mammals such as moose and deer. Ungulates often exhibit seasonal movements into and along river valleys because these areas provide critical habitat, both as winter range and during the summer calving season. Adjacent aquatic habitat provides high insect biomass, supplying food for dense populations of songbirds and the base of a food chain that supports fish-eating birds and river otters. Scarce habitat elements, such as old-growth forest, are often more common in the riparian zone because floodplains and islands are usually protected from the damages of fire. These old trees and snags provide important habitat for cavity-nesting birds, such as owls and woodpeckers. Frequently flooded lowlands, characterized by broad, flat meander floodplains and deltaic marshes, can be highly productive for waterfowl (often supporting the highest densities in a region) and other wetland-dependent wildlife.

Riparian habitats (including wetlands) are the most important and productive habitats for waterfowl in northern Canada, principally because of the annual replenishment of organic matter into these systems due to annual flooding (MRBC, 1981). Flow-regulation has been proposed as a major factor in the loss of habitat for muskrat and beaver in Canada (Kellerhals and Gill, 1973; Hawley and Aleksiuk, 1973). Such loss of habitat is directly related to the decline in food supply and cover through stabilization of flows. Since regulation of the Peace River in the late 1960s, considerable information has been gathered about near-dam impacts on riparian habitat. These are discussed in Section 3 along with other potential downstream effects.

2. BIOPHYSICAL DESCRIPTION OF THE PEACE AND SLAVE RIVERS

2.1 INTRODUCTION

The aquatic ecosystem affected by regulation of the Peace River includes the main flow system of the Peace and Slave rivers as well as the riparian zone adjacent to these rivers and in two adjacent delta ecosystems, the Peace-Athabasca Delta (PAD) and Slave River Delta (SRD). There may also be some regulation effects experienced on Great Slave Lake (e.g., modifications of sediment delivery, variations in seasonal water levels) but assessment of these was beyond the scope of this report. The following provides general biophysical descriptions of the Peace and Slave channel and delta systems. More information about the catchments in general can be found in NRBS (1996a).

2.2 BASIN LOCATIONS

The Peace River, the major tributary of the Slave River, originates within the alpine zones of the Rocky Mountains in northeastern British Columbia. Flow from these upstream headwaters, many of them of glacial origin, feeds into the downstream Williston Reservoir formed by the W.A.C. Bennett Dam (Figure 2.1). Regulated flow from this hydroelectric operation then passes downstream into northern Alberta and ultimately to the Peace-Athabasca Delta (PAD), 1200 km below the point of regulation (Figure 2.2). At this point, the river drains an area of approximately 293,000 km^2 and then joins with flow from the Athabasca and Birch river basins, via delta channels to become the northward flowing Slave River.

The Slave River drainage basin lies between 59° and 62°N, and 111° and 114°W, crossing both Alberta and the Northwest Territories (NWT). Flow contributed to the Slave River from the PAD originates primarily from Lake Athabasca, largely located within Saskatchewan, and the Athabasca River fed from southerly portions of Alberta. Ultimately, the Slave River drains via the Slave River Delta into Great Slave Lake, the major headwater body of the Mackenzie River.

Figure 2.1 Peace and Slave River Basins

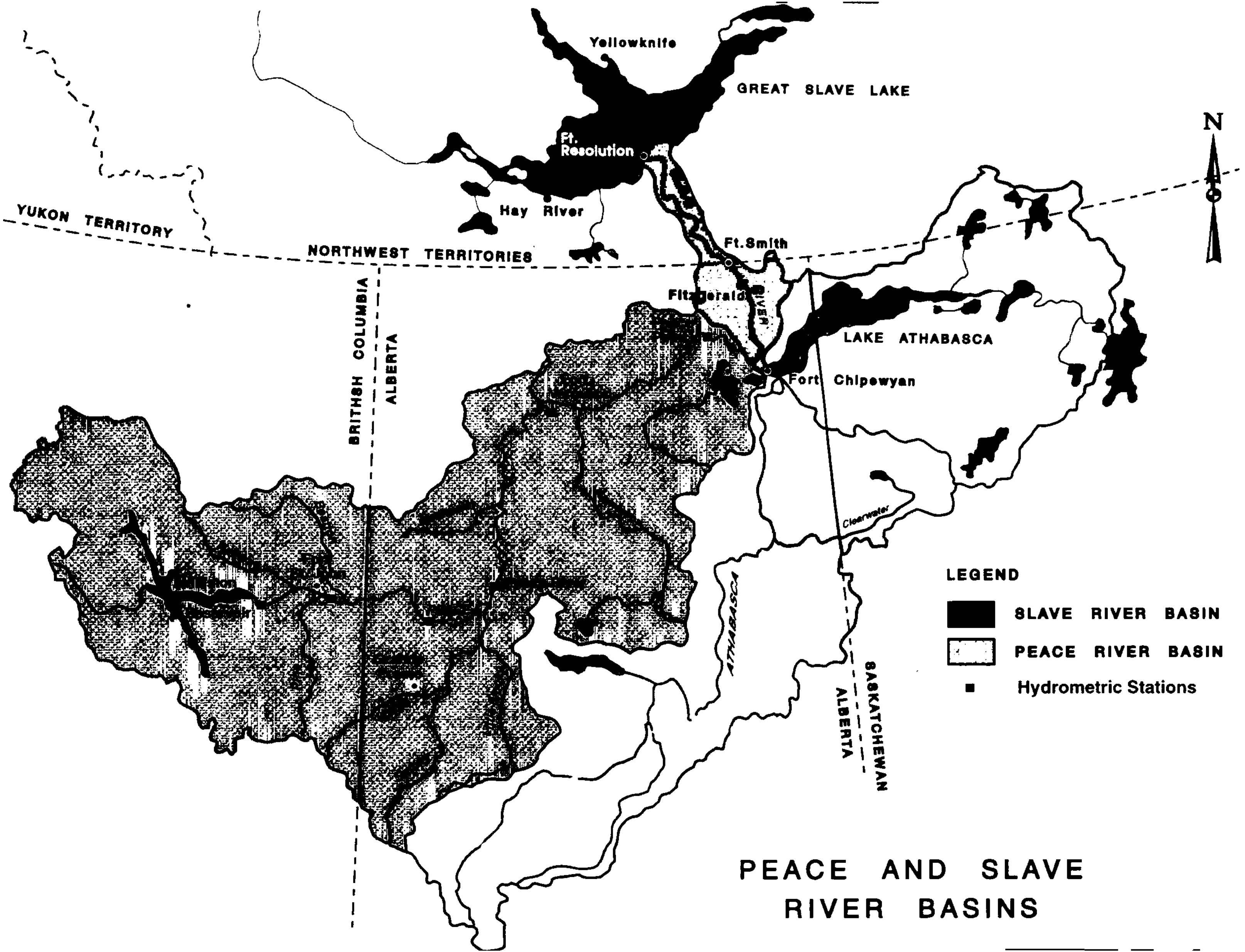
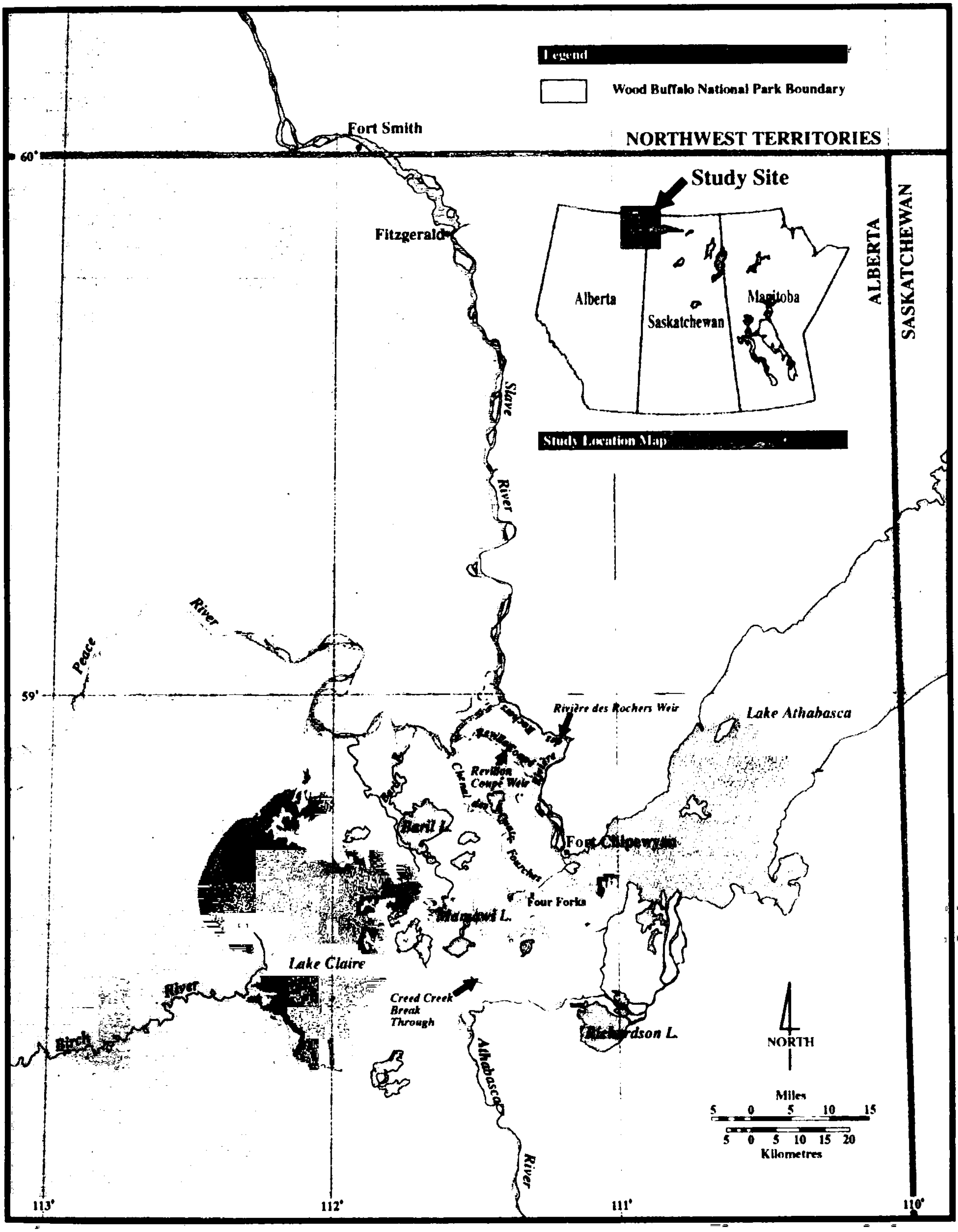


Figure 2.2 Peace-Athabasca Delta basin map (from Aitken and Sapach, 1993)



2.3 GEOLOGIC AND GEOMORPHIC CHARACTERISTICS

The Peace and Slave River Basins are comprised of three major physiographic regions: the Cordillera, Interior Plains, and Canadian Shield (Figure 2.3). The Cordillera covers much of the southwestern portions of the Basin, including the Rocky Mountains, and is composed of sedimentary rocks with deep valleys and high plateaus covered by glacial tills. The majority of the Peace River Basin is within the Interior Plains and underlain by recent metamorphic and sedimentary bedrock of Devonian and Cretaceous ages (Green, 1972). Landforms here have been modified by the effects of Pleistocene glaciation, resulting in a surficial geology consisting of glacial drift, post glacial alluvial and aeolian deposits, and recent deltaic organic deposits (Lorberg and de la Cruz, 1981). Southeastern portions of the Slave River Basin consist of Precambrian granite, gneiss and metasedimentary rocks typical of the Kazan region of the Canadian Shield. Surficial geology in the Canadian Shield portion consists of a thin veneer of predominantly unconsolidated sediments.

The elevation of the Peace River in Alberta is 375 m (a.m.s.l.) at the British Columbia-Alberta border, and 207 m (a.m.s.l.) at the confluence with the Slave River. The river drops 165 m in Alberta for an average gradient of 0.16 m/km, a major feature of the gradient profile being a drop of 9.5 m at the Vermilion Chutes (Figure 2.4a). The Slave River has a slope similar to that of the lower portions of the Peace River, but has a significant break in channel slope between Fitzgerald and Fort Smith (Figure 2.4b).

As the Peace and Slave rivers flow through three different physiographic regions, various sections of the river system display different morphologic characteristics. Changes in the underlying geologic structure, basin relief, and surficial deposits coupled with the influence of runoff from upstream and tributaries determine the overall river morphology.

2.3.1 Upper Peace River

With the exception of the Smoky River, all the major tributaries upstream of the town of Peace River originate in the Rocky Mountains. Extending downstream of the W.A.C. Bennett Dam, the river is incised more than 200 m into the Alberta Plateau as far downstream as the town of Peace River. Because the valley is cut so deeply into the plateau, the valley walls are often unstable and prone to slumping and mass movements. The Alberta Plateau is underlain by Cretaceous sedimentary strata, primarily shales and sandstones, mantled with Quaternary drift of varying types and thickness; along with the friable bedrock, they provide a major source of sediment. The Peace River Valley in the vicinity of Hudson Hope enters into the Peace River Lowlands physiographic region, which is dominated by a drainage system originating from the pre-Pleistocene.

Below the dam, the channel is primarily straight and approximately 450-500 m wide, with occasional islands and minor gravel bars. Downstream towards the town of Peace River, the channel becomes progressively more sinuous, still with occasional islands and bar features. Although channel width between the dam and the town of Peace River may exceed 500 m in some sections, it remains fairly constant. Bed and bank materials consist chiefly of gravel over easily erodible bedrock. The gradient of the channel becomes progressively shallower moving downstream, and, near the dam, has a slope of approximately 0.00049 decreasing to 0.00028 adjacent the town of Peace River (Kellerhals *et al.*, 1972).

The Smoky River, the main tributary to the Peace, enters a short distance upstream of the town of Peace River. It drains the front ranges of the Rocky Mountains and, like the Peace River, is incised into the Alberta Plateau. The Basin has an area of approximately 51,000 km^2 representing 26% of the Peace River Basin at Peace River and 16% at Peace Point. Since the construction of the W.A.C. Bennett Dam, the Smoky River represents 42% of the un-regulated basin area at the town of Peace River and 21% at Peace Point.

As with the upper Peace River, the Smoky River Basin is underlain by Cretaceous sedimentary strata. The composition of the overburden is primarily till, with some areas having a thin veneer of lacustrine material. The river is incised 100-150 m into the surrounding plains, often resulting in unstable valley walls. The channel is partly confined by the valley and occasionally constricted by valley slumps. The river is sinuous with irregular meanders, and occasional islands and bar features. Bed and bank materials are sand, gravel and till, often overlain by silt, sitting on top of soft erodible shales. Although there are several lithological and geomorphic similarities between the upper reaches of the Peace River and the Smoky River Basin, fine-grained sediment from the latter basin affects channel patterns downstream.

2.3.2 Middle Peace River

From the confluence of the Smoky River, the river trends northward toward Fort Vermilion. Primarily, this reach drains the Peace River Lowlands, although the headwaters of some tributaries extend onto the Alberta Plateau. No major tributary contributions occur between the town of Peace River and Fort Vermilion. The additional contributing area in this middle reach represents 16.5% of the total Peace River catchment upstream. This reach also is incised into the surrounding plain, but the depth decreases from 200 m in the upstream near the town of Peace River to about a 30-m incision in the vicinity of Fort Vermilion. As in the upper reaches, the area is predominately till on top of Cretaceous sedimentary bedrock. During the retreat of the Laurentide ice sheet, the last large continental glaciation, lowland areas such as this one were periodically inundated, resulting in the deposit of a thin veneer of glacial lacustrine material.

This reach can be characterized as partly entrenched and confined, with irregular meanders. Widths increase from approximately 500 m at the town of Peace River to about 650 m at Fort Vermilion. Intermittent islands and bar complexes are evident again, but the alluvial material here is finer than upstream. Bed and bank materials are primarily sand and fine gravel, with silt and erodible bedrock visible along the banks (Kellerhals *et al.*, 1972). As the river becomes less incised, the valley walls gain more stability.

2.3.3 Lower Peace River

From Fort Vermilion to Peace Point, the character of the river contrasts sharply with that of the upper reaches. The landscape of the lower Peace River valley is no more than 20-25 m deep, incised into the old lake bed of Glacial Lake McConnell (Craig, 1965). As the river cut into these lacustrine deposits, it wandered away from its preglacial course in several places and subsequently began to cut into bedrock: these locations coincide with small waterfalls and rapids (eg. Vermilion Chutes and Boyer Rapids). Kellerhals *et al.* (1972) report the channel slope between Fort Vermilion and Peace Point as 0.00008, excluding Vermilion Chutes. The Chutes, approximately 80 km downstream of Fort Vermilion, result in a 9.5 m drop in bed elevation over a few kilometres. The channel downstream of the Chutes increases dramatically in width, exceeding 1500 m at some locations. The channel pattern at this point is weakly sinuous with split channels and island complexes; farther downstream, however, the channel narrows (approximately 700 m at Peace Point) and has an irregular meandering pattern with only occasional islands and bar complexes.

The only significant tributary draining into the lower Peace is the Wabasca River, which drains the southern portions of the Birch Mountains and surrounding plains. The 35,800 km^2 catchment area of this basin represents over half of the drainage between Fort Vermilion and Peace Point. The total drainage area between Fort Vermilion and Peace Point accounts for 24% of the Peace river basin.

2.3.4 Peace-Athabasca Delta

The Peace-Athabasca Delta (PAD) is formed by the Peace, Athabasca and Birch Rivers at the western end of Lake Athabasca in the province of Alberta (Figure 2.2). Delta development began following recession of the Pleistocene ice sheet, with these rivers draining into a much larger Lake Athabasca. Initially, the Peace Delta had a rapid rate of growth, but as levees around the River attained sufficient height, most of the flow and sediment were carried directly to the Slave River; thus, the Peace River Delta can be considered inactive (Bayrock and Root, 1973). In contrast, the Athabasca and Birch River deltas are still actively depositing sediment, although the Birch River only contributes a fraction of the sediment to the total delta complex compared to the Athabasca.

As the PAD continued to grow, many water bodies became separated from Lake Athabasca. Three large shallow lakes (Claire, Mamawi and Baril; <1 to 3 m deep) currently occupy a large proportion of the 3900 km^2 delta area, and are connected to Lake Athabasca and other small basins by a myriad of active and inactive channels. Topographic relief seldom exceeds 1 m above the surface of the major PAD lakes, except for the levees and islands of bedrock from the Canadian Shield located primarily in the north-east. The PAD and Lake Athabasca are connected to the northward-flowing Peace and Slave rivers by three major channels, Rivière des Rochers, Revillon Coupé, and Chenal des Quatre Fourche. Although flow is normally northward, it can reverse when the Peace River is higher than the level of Lake Athabasca.

2.3.5 Slave River

The Slave River originates approximately 96 km downstream from where the Peace River joins the Rivière des Rochers to form the head of the Slave River. It then proceeds another 420 km before discharging into Great Slave Lake. At the SRD, an area of approximately 615,000 km^2 is drained by the combined Peace River, Athabasca River, PAD and Lake Athabasca systems. The portion of the drainage area located between the mouth of the Slave River at the PAD is only 15,100 km^2 or 2.5%.

The river flows along the western edge of the Canadian Shield, draining an area once inundated by Glacial Lake McConnell. Exposed bedrock occurs all along the river as a result of down-cutting through a thin veneer of lacustrine material. Topography of the basin is influenced by regional geology; southeastern areas of the basin have numerous lakes located in a rolling landmass with significant relief between 60 and 90 m. Low scarps of limestone and smaller lakes constitute the remaining landmass below elevations of 300 m. Although the river is dominated by regional geology, it has moved laterally, depositing alluvial material and creating floodplain areas. Island and bar complexes are common along the upper reaches. At Fort Fitzgerald, the Slave River passes over a Precambrian sill of bedrock resulting in a drop in of bed elevation of 35 m over 30 km.

2.3.6 Slave River Delta

The last 200 km of the river drain through inactive portions of the SRD. Progradation of this delta has been occurring since 8070 BP at a rate of 20.7 m per year (Vanderburgh and Smith, 1988), and has progressively filled in the south arm of glacial Great Slave Lake (Craig, 1965). As the SRD progressed into the deeper portions of the lake, progradation rates decreased so that only a small active delta is currently prograding into Great Slave Lake (English, 1984).

The entire SRD has an area of 8,300 km^2 and ranges up to 70 km wide. It is flanked by the Little Buffalo River to the west and the Taltson and Tethul rivers to the east. The slope of this portion of the Slave is only 0.000035 as it meanders through alluvial deltaic deposits. Morphology is dominated by scroll bars, abandoned distributary channels, oxbow lakes, strandlines, and flat plains. The small active portion of the SRD is an arcuate delta of approximately 400 km^2 representing only 5% of the total SRD (English, 1984; English *et al.*, 1995)

The principal depositional structures forming in the outer delta are cleavage bar islands and wave-built barrier bars. Erosional influences by Great Slave Lake are important for limiting the sediment accumulation on the subaqueous topset beds of the delta, but the effectiveness of waves or currents to alter the landform are much reduced, once the island landform is above the water level of Great Slave Lake and plants have taken root.

Figure 2.3 **Physiographic Regions of Peace and Slave River Basins**

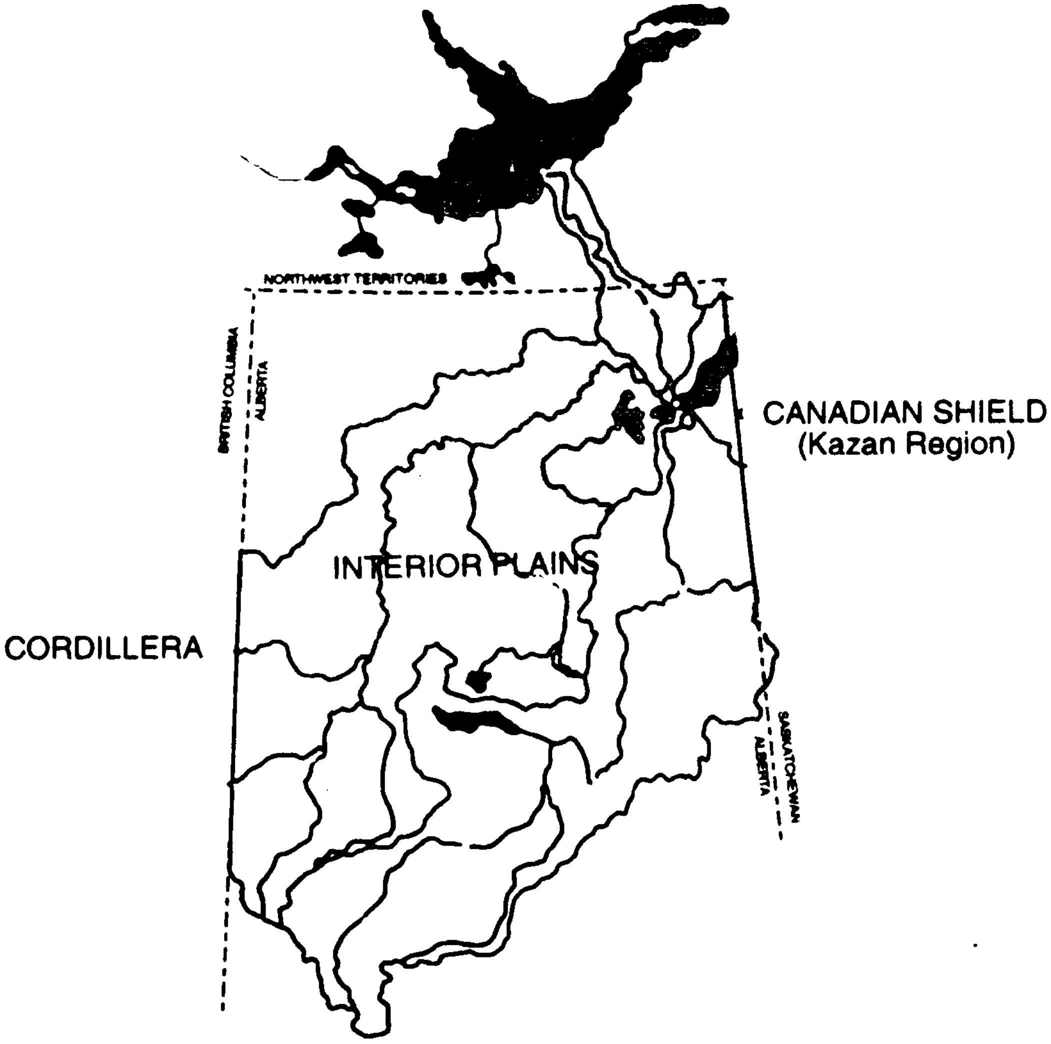
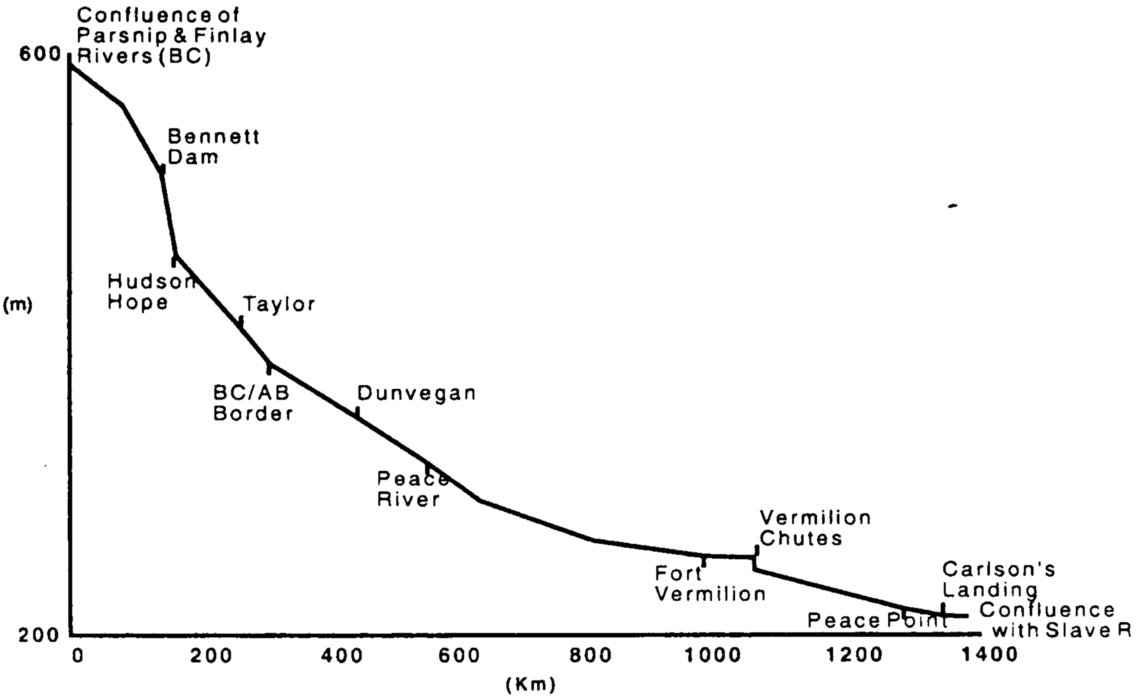
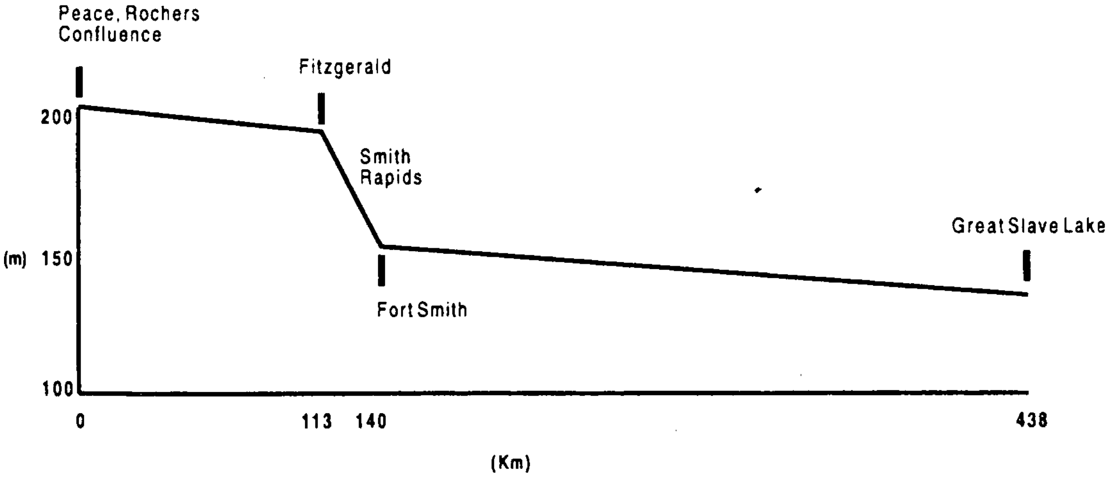


Figure 2.4 a) Longitudinal Profile of the Peace River



Source: Shaw, *et al.*, 1990

Figure 2.4 b) Longitudinal Profile of the Slave River



Source: Mackenzie River Basin Committees, (1981).

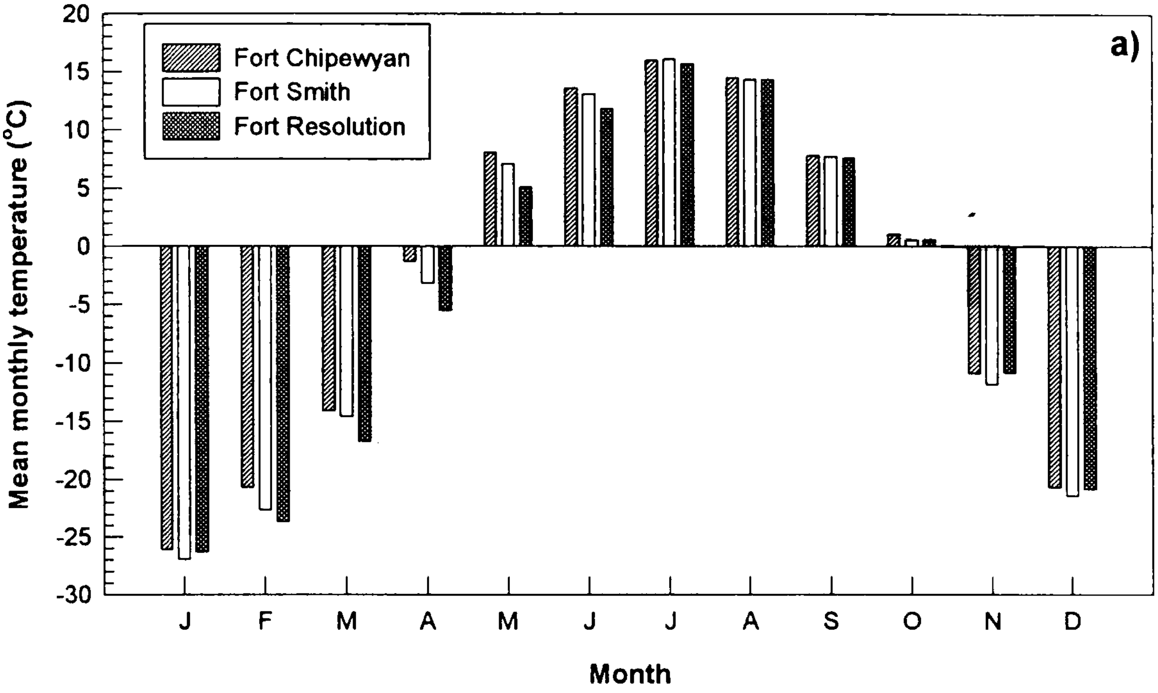
2.4 CLIMATE

The Peace River basin stretches across three broad climatic regions - Prairie, Boreal and Cordilleran - and their interaction produces a diverse set of weather conditions across the basin. The following outlines some basic differences in temperature and precipitation along the Peace-Slave system (all data from 30 year climate normals 1961-1990; Atmospheric Environment Serive, 1993). Detailed maps and descriptions of the climate over the whole basin are contained within NRBS (1996a).

Typically, the general climate is relatively dry with cool summers and cold winters. Longitudinal factors can reduce average winter temperatures by several degrees in northeastern portions of the basin (Figure 2.5a; Atmospheric Environment Service) but their effect is less pronounced for summer temperatures. The upper Peace River mainstem has higher precipitation than the middle or lower reaches. Average annual precipitation varies from 468 mm at Fort St. John (Figure 2.5b) to 388 mm in the middle reaches at the town of Peace River and 381 mm at Fort Vermilion. A more extreme version of temperate continental climate exists in the Slave River Basin, which includes two climatic regions: Boreal and Subarctic. Since the direction of the mainstem flow is principally south to north, the Slave River basin exhibits latitudinal differences in temperature, with monthly temperatures being generally cooler in the more northern river reaches (Figure 2.6a; Atmospheric Environment Service, 1993).

Precipitation along the Slave River (Figure 2.6b) also demonstrates a strong latitudinal control with the annual total declining from an average 380 mm (Fort Chipewyan), to 334 mm at Fort Smith, and finally 300 mm at Fort Resolution.

Figure 2.5 Mean monthly a) temperature and b) precipitation for Slave River at selected locations.



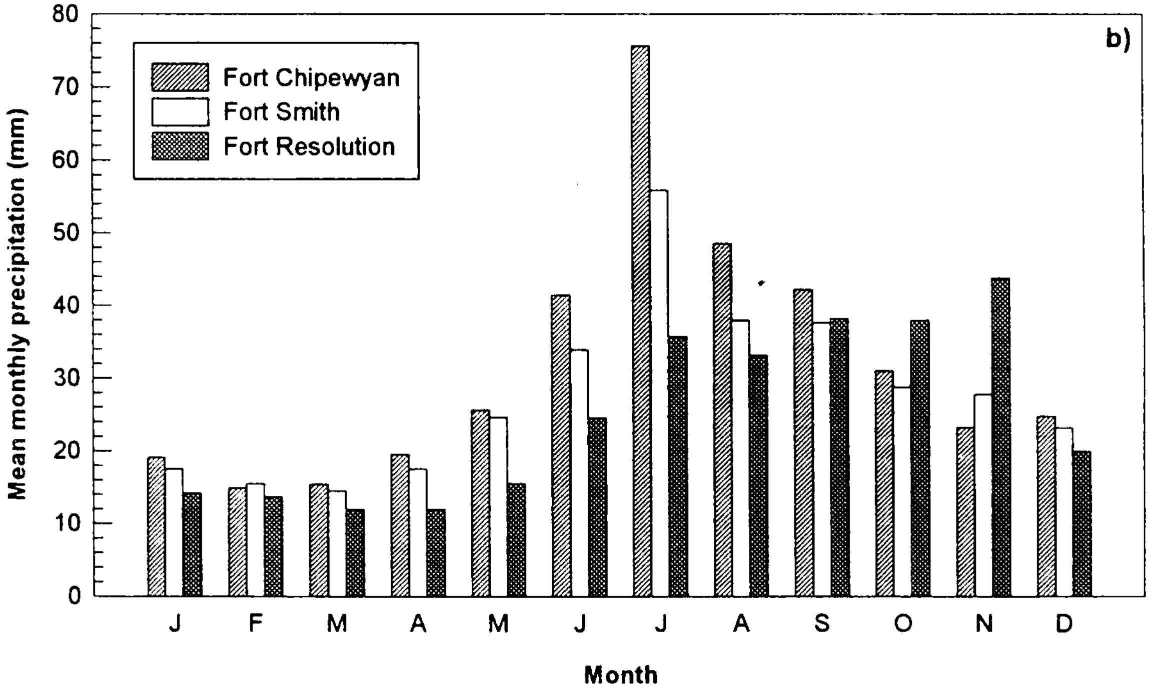
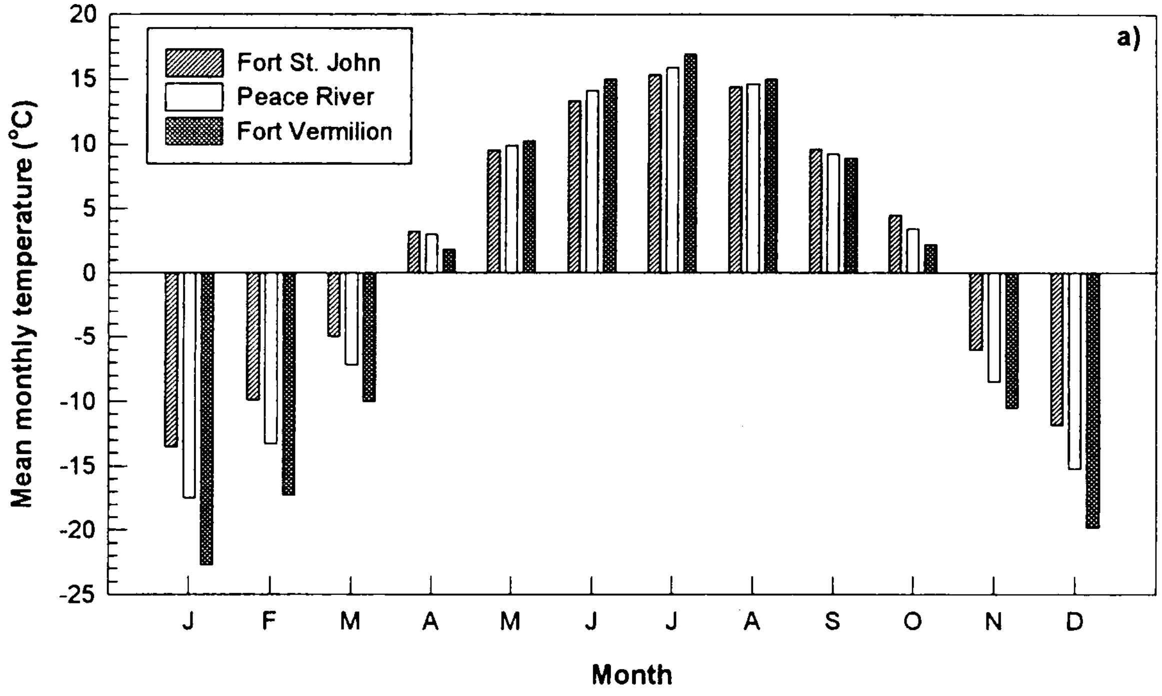
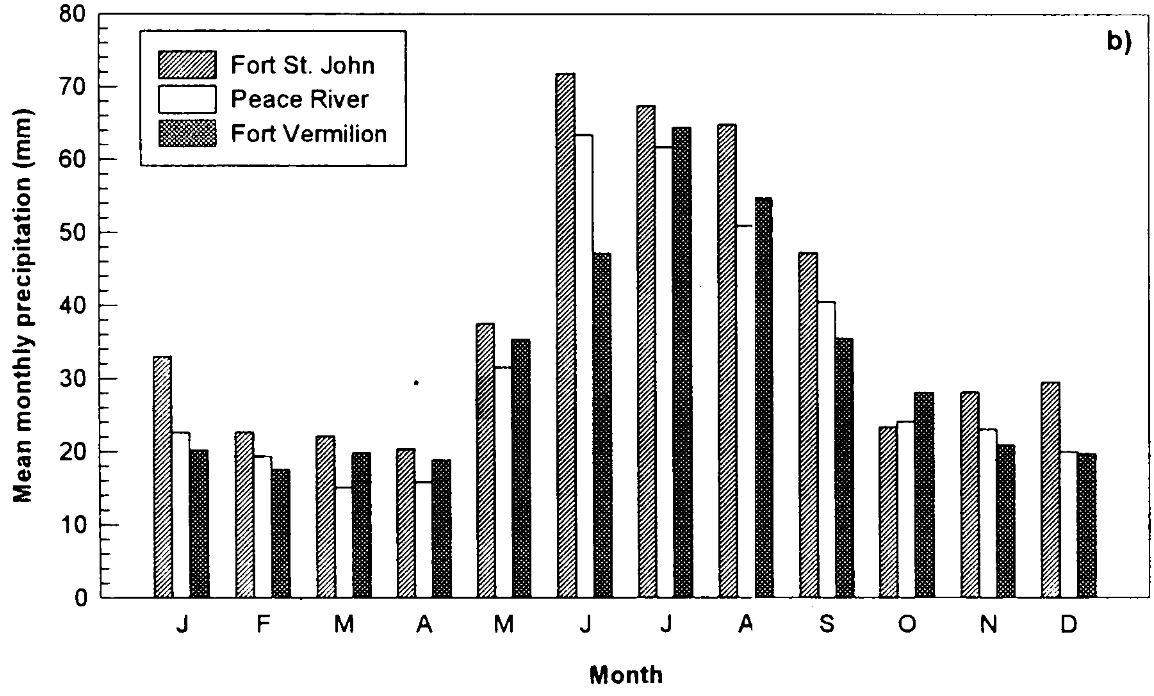


Figure 2.6 **Mean monthly a) temperature and b) precipitation for Peace River at selected locations.**





2.5 ECOZONES

The Peace and Slave River Basins consist of six ecozones (Figure 2.7): Boreal Plains, Boreal Cordillera, Montana Cordillera, Taiga Plains and Taiga Shield. Ecoregions are classified based on wide range of biological and physical characteristics such as climate, fauna and soil characteristics, range in elevation, surficial characteristics and vegetation.

Six different soil orders are found, with different soil types generally developing as functions of the underlying surficial geological deposits. Soil classification is based on the Canadian System of Soil Classification (Canadian Soil Survey Committee, 1978) and includes Chernozemic, Brunisolic, Gleysolic, Luvisolic, Organic and Cryosloic soils. Cool climates, frequent flooding, and high groundwater tables tend to impede soil horizon development.

Boreal Cordillera and Montane Cordillera are dominated by aspen, balsam poplar, spruce, and lodgepole pine. The largest ecozone in the study area is Boreal Plains, most of which is forested primarily with trembling aspen and balsam poplar, and secondarily with white spruce, black spruce, lodgepole pine, and jack pine. In drier portions of the Boreal Plains, semi-open grasslands may also be found, while extensive sections of sedge-grass meadow and shrub areas are located along river channels and in the Peace-Athabasca and Slave Deltas. Aspen and white spruce forest dominate northern portions of the Boreal Plains, while black spruce and peatland tend to dominate the Taiga regions.

In all ecozones, additional small-scale vegetation types can be found: sedge grassland, saline meadow and shrub. Characteristics of these major vegetation types and major forest types in the Basin are described in NRBS (1996a).

2.5.1 River Riparian Environments

Although the Peace and Slave rivers drain primarily through the Boreal Plains, riparian environments are not abundently reflected in the macro-scale vegetation assemblages of the ecozone. Vegetative succession along the river valley is dictated by the stability of the valley walls, flood regime, and the alluvial substrate. Riparian vegetation is usually comprised of water and sediment tolerant species and along the Peace River consists of poplar (*Populus* spp), spruce (*Picea* spp) alder, (*Alnus* spp), willow (*Salix* spp), and horsetail (*Equisetum* spp). Horsetails and grasses are located along frequently flooded riparian margins. Moving away from the channel, fewer flood and sediment-tolerant species are present, ranging from willow-alder to poplar-spruce communities in more stable and drier environments. Changes to the alluvial and flood regime of the Peace River have affected vegetation succession and are discussed in Section 3.4.

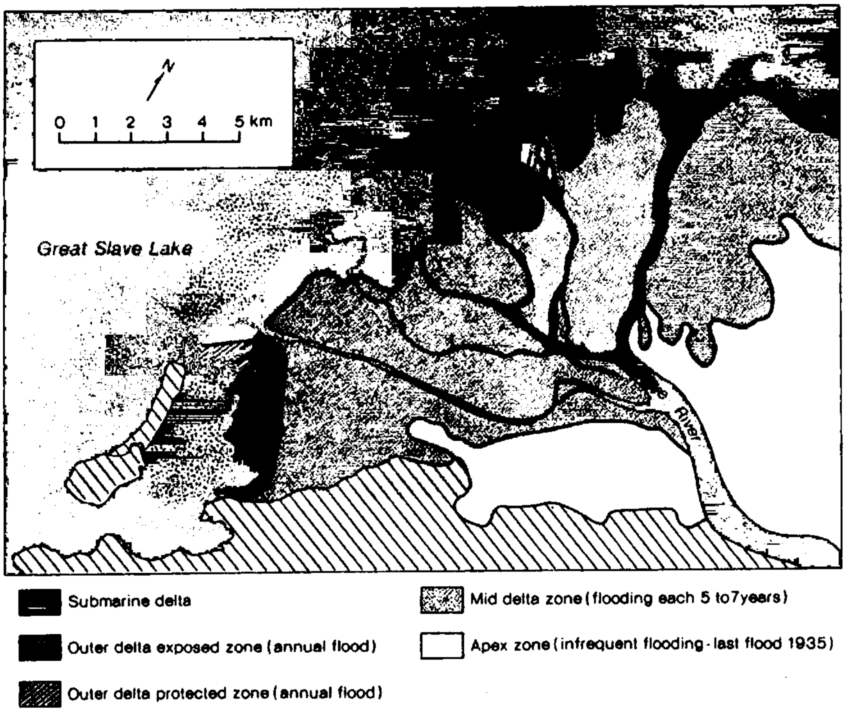
2.5.2 Peace-Athabasca Delta

As the Peace-Athabasca Delta is a dynamic, alluvial environment subject to frequent flooding and dominated by large shallow lakes and smaller wetlands and marshes, successional forms of vegetation dominate. The shallow lakes and marshes have an abundance of emergent and submergent herbaceous vegetation ranging from semi-floating aquatic plants to sedges and grasses. Large areas, in excess of 1200 km^2, are covered by sedge (*Carex atherodes*) and reed grasses (*Calamagrostis* spp), making this one of the largest undisturbed grassland areas in North America. On the slightly elevated margins of the meadows and marshes and along the distributary channels are lines of willows (*Salix* spp). Shrub and tree growth increases towards the margins of the grasslands, lakes and marshes, so that the elevated and usually older portions of the PAD are supporting populations of spruce (*Picea* spp) and poplar (*Populus* spp). In the northeastern parts of the PAD, where elevated portions of the Canadian Shield are near the surface or exposed, white spruce (*Picea glauca*), jackpine (*Pinus banksiana*) and white birch (*Betula papyrifera*) grow.

2.5.3 Slave River Delta

Based on botanical and geomorphological differences affecting flooding frequency, the SRD can be broken into three distinct areas: the outer delta, the mid-delta and the apex (Figure 2.8). Ninety-five percent of the outer subaerial delta supports aquatic and/or emergent vegetation such as horsetail (*Equisetum fluviatile*). As a consequence of annual spring flooding, nutrient-rich sediment is deposited on the large expanses of *Equisetum* plant assemblages occupying the inter-levee depressions in the outer delta. The mid-delta area is transitional between the water-dominated landscape of the outer delta and the elevated, relatively dry apex area and comprises approximately 45% percent of the active delta area. Continued sedimentation and build up of these landforms over long periods of time result in a transition in the major controls of plant succession. In the outer delta, allogenic succession dominates. Landforms in the mid-delta elevated above that of the wetter outer delta support plant species adapted to a mesic environment (e.g., poplar (*Populus* spp)), but alder-willow (*Alnus-Salix)* plant assemblages are by far the most representative of the mid-delta zone. Autogenic succession dominates in the mid-delta and apex area. A significant portion of this zone has reached the climax forest stage of white spruce (*Picea glauca*). The presence of a significant bryophyte carpet (ground mosses) over large portions of the forest floor in the apex area is indicative of low flooding frequency, as the bryophytes cannot tolerate the sediment that accompanies flooding. Only about 6% of the apex zone is classified as aquatic and most of these areas are elevated and cutoff from the Slave River flow.

Figure 2.8 Outer, mid and apex areas of the Slave River Delta (English, 1984)



2.6 HYDROLOGY

The following provides a brief overview of the hydrology of the main flow systems. Further details related to the overall hydrologic regime of the rivers are contained in NRBS (1996b). Discussion of the related ice regime and the effects of regulation on the overall hydrologic regimes is provided in Sections 3.1 and 3.4.

2.6.1 Peace River System

Mean annual runoff of the Peace River at Peace Point is approximately 66 x 10^9 m^3, of which approximately two-thirds originate outside the province of Alberta (van der Giessen, 1982). Table 2.1 provides a listing of the mean annual flows of several tributaries to the Peace River. Peak discharge generally occurs in late May to early June, coincident with the snowmelt runoff event in the headwaters. Summer rainstorm events during most years can produce additional flood peaks. Maximum daily discharges on the Peace River at town of Peace River and on the Slave River at Fitzgerald are shown in Figure 2.9 to illustrate the inter-annual variability in flow.

2.6.2 Peace-Athabasca Delta

The location of the major channels linking the PAD and Lake Athabasca with the northward flowing Peace and Slave rivers are shown in Figures 2.10. Discharge in these channels is proportional to the difference in water levels of the lake systems and the Peace River; reversing flows in the PAD are not uncommon. Water levels experience a peak on the Peace and Athabasca rivers during the spring break-up period (late April-early May) and a few weeks later (June) during a period of sustained high flow produced by runoff from the Rocky Mountain headwaters. It is during these two periods that high water levels on the Peace River can obstruct the northward flow of water. As a result, lake-water levels are typically highest in the PAD and on Lake Athabasca during the spring and summer, but then recede during fall and winter when the outflow to the Slave River is greater than inflow to the PAD. Weirs have been installed within the PAD to counter the effects of regulation and have altered dramatically the hydrologic system. The effect of these and their success in restoring water levels to pre-dam conditions are reviewed in Section 3.2. Depending on the elevation of lake and river water levels, water can also feed into the adjacent landscape, and fill the shallow perched basins. These are classified according to the degree of their connection with the lake and channel flow system as open-drainage, restricted-drainage, and isolated (Peace-Athabasca Delta Project Group, 1973). These classifications roughly correspond to the general mapping of drainage types noted on Figure 2.10: i.e., open, restricted and severely restricted drainage (Jaques, 1989; Prowse and Demuth, 1996).

In the case of isolated perched basins (severely restricted drainage), water can only enter the basin through overbank flooding, and water-level decreases are almost exclusively controlled by evapotranspiration. Average annual small-pond evaporation for this region is approximately 450 mm (Fisheries and Environment Canada, 1978) while the recorded average annual precipitation is 381 mm (Atmospheric Environment Service, 1993), thereby yielding an annual water deficit of 80 mm. Given that groundwater flow through the levees is negligible (Nielsen, 1972), periodic flooding of these perched basins is essential for their survival. When full, such basins account for over 19,000 km of shoreline within the delta (Townsend, 1984). One of the principal factors controlling the rich wildlife productivity of these basins (see below) is that early successional forms of vegetation support the largest number of wildlife. Muskrat, for example, survive best in relatively shallow marshes (e.g., ~1 m) having an abundance of emergent and submergent aquatic vegetation. Similarly, bison prefer sedge and grasses (*Calmagrostis canadensis* and *Carex atherodes*) common to these flooded marsh environments. Sustaining these types of vegetation requires either a permanent shallow depth of water or periodic flooding, as is the case for perched basins. Since the vertical range of most delta plant communities is quite small, only minor changes in water levels can lead to the advance or retreat of plant succession over large areas. Major flooding of these perched basins has not occurred since 1974 and extensive drying has ensued.

2.6.3 Slave River

The Slave River is formed at the confluence of the Peace River and Rivière des Rochers. Areas of the five major drainage basins that constitute the catchment of the Slave River are summarized in Table 2.2. Much of the flow into the Slave River comes from Lake Athabasca which is in turn fed by two main tributaries: the Athabasca River and the Fond du Lac River. The Birch River, which flows into the PAD, also contributes to the Slave River discharge.

Spring runoff of the Peace River is a major influence on the hydrology of the Slave River with highest flows in the Slave occurring in June and July. Recession of flows after these peaks is dampened, however, by flow from the PAD/Lake Athabasca system. Floods in the Slave River result primarily from flooding in the Peace River. Annual maximum daily flows for the Slave River are illustrated in Figure 2.9.

Figure 2.9 Maximum daily discharges for Peace River at Peace River and Slave River at Fitzgerald 1960-93. Post regulation period begins in 1972.

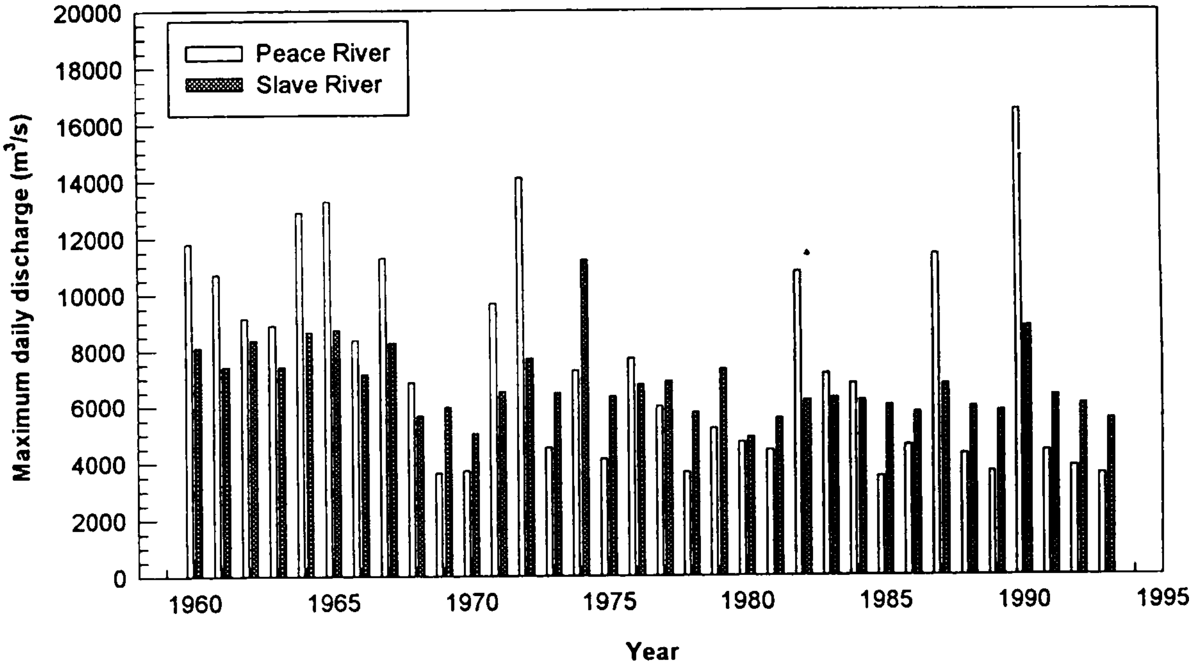


Figure 2.10 Water flow in the Peace-Athabasca Delta (after Prowse and Demuth, 1993)

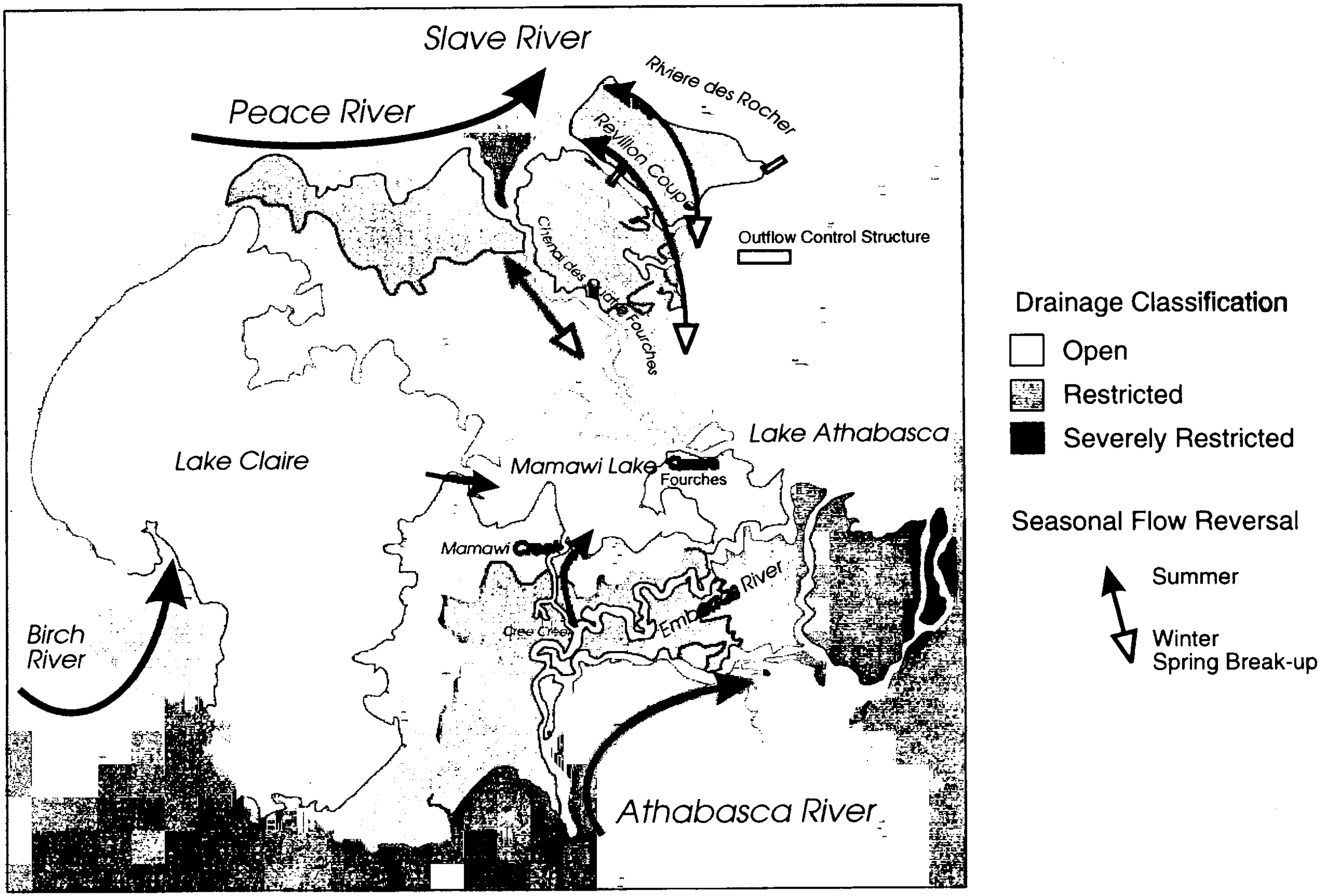


Table 2.1 **Drainage areas and flows in the Peace River mainstem and selected tributaries.**

Site	Drainage area (km$_2$)	Mean annual flow (m$_3$/s)
Mainstem		
Dunvegan	130,000	1630
Peace River	186,000	1930
Peace Point	293,000	2170
Tributaries		
Smoky River at Watino	50,300	358
Notikewin River at Manning	4,680	14.1
Boyer River near Fort Vermilion	6,660	5.18
Wabasca River at Wadin Lake Road	35,800	97.5

Sources: Environment Canada, 1989

Table 2.2 Major drainage basins of the Slave River catchment.

Watershed	Drainage Area 1000 km$_2$	Drainage Area % of Total
Peace River	295.6	48.7
Athabasca River	198.5	32.7
Fond du Lac River	78.7	13.0
Birch River	24.4	4.0
Slave River	9.6	1.6
Total (Slave River at Fitzgerald)	606.8	100.0

Source: Shawinigan-Stanley, 1982

2.7 WATER QUALITY

2.7.1 Peace River System

Three relatively homogeneous sections of the river can be identified. The upstream reach, extending from the BC-Alberta border to the Smoky River, has few tributaries, clear water, and high dissolved oxygen content (Shaw *et al.*, 1990). Organic matter content, metals, salts and nutrients are all low. Moving downstream toward Fort Vermilion, the concentration of most parameters gradually increases, most probably as a result of tributary inputs, particularly from the Smoky River (Shaw *et al.*, 1990). The lowest reach from Fort Vermilion to the mouth of the Peace River exhibits changing water quality due partly to natural tributary inflow, but more strongly due to a shift in bed and bank materials from gravel to sand and silt. Suspended solids are high and metals associated with clays are also highest in this section.

2.7.2 Slave River System

The Slave River water is relatively turbid and alkaline (Alberta Environment, 1987). Principle ions in the upper reaches are calcium and bicarbonate. However, conductivities decline as a result of significant upstream runoff routed through PAD-Lake Athabasca drainage and the dominance of the Canadian Shield drainage feeding into the river. Sodium and chlorine ions concentrations increase in the mainstem towards Fitzgerald, probably due to inflows from the surrounding Karst area (Alberta Environment, 1987).

2.8 FISHERIES

Most fish populating the Peace and Slave rivers originate from the Mississippi-Missouri refugia and Columbia refugium that were formed during the retreat of the Wisconsin ice sheets. Although species richness appears to be similar between drainages, species abundances differ (Boag, 1993; NRBS, 1996c).

The Vermilion Chutes and rapids near Fort Smith (Rapids of the Drowned; Mountain, Pelican, and Cassette Rapids) play a role in separating fish populations upstream and downstream on the mainstem rivers. Barriers to upstream movement can be total or partial, with mainstem rapids on the Slave River considered a total barrier to upstream movement, and the Vermilion Chutes considered a partial barrier (Boag, 1993).

Fish surveys indicate that deep water habitats upstream of Fort Vermilion are used for over-wintering by most of the dominant species of the Upper Peace River. In addition, goldeye and other dominant sport and coarse fish in the Lower Peace River utilize areas downstream of Peace Point for over-wintering and rearing. Reaches above the town of Peace River support abundant mountain whitefish populations. Although knowledge of fish use of tributaries is incomplete, some large tributaries including Cadotte, Notikewin, Wabasca, Mikkwa and Jackfish rivers contain spawning runs of walleye, longnose sucker and northern pike (Boag, 1993; EnviResource Consulting Ltd., 1994).

The PAD is a major spawning site for Upper Slave River fish populations. Large populations of fish migrate between the delta lakes and the major rivers. Species such as goldeye and walleye also use the delta lakes as spawning and rearing habitat. Slave River, above Fort Smith, contains relatively few fish species while a larger number of fish species occur below Fort Smith rapids. Spawning below the Fort Smith rapids is important to resident fish populations as well as migrant species from Great Slave Lake.

2.9 WILDLIFE

The habitat preferences of mammal species in both the Peace and Slave River Basins are described in Table 2.3. Detailed knowledge of wildlife habitat in the study area is generally limited to areas of pronounced ecological importance or as it relates to specific species. A number of endangered species inhabit the study area or use it as a migratory pathway.

2.9.1 Deltaic Mammals

The deltas of the Peace-Athabasca and Slave are the largest alluvial-wetland habitats in the study area and their importance is accentuated by the low availability of wetland habitat elsewhere in the basin. Muskrat has traditionally been the most important fur bearing mammal and source of trapping income for the local native people of the two delta areas (Bodden, 1981; Townsend, 1984). Although *Equisetum fluviatile* is an important source of sodium for herbivorous animals (Geddes, 1981) muskrat are highly versatile and can be opportunistic in their food preferences (Ambrock and Allison, 1973; Westworth, 1974). In general, muskrat habitat selection is based more on water depth than on vegetation type because the availability of suitable plant species is determined by seasonal water regimes. This is particularly true for northern populations where climate is an important limiting factor, and the selection of habitat type with adequate water depth and snow accumulation has important survival value (Poll, 1980). Perched basins are generally the greatest source of muskrat habitat in northern delta areas because of their more stable water regime, extensive shorelines and emergent vegetation (Poll, 1980).

Although moose do not play a major role in delta ecology, they are a valuable economic resource for many communities found in the study area. Deltaic moose habitat occurs largely in more stable areas where tall shrubs, deciduous and coniferous trees are present (Allison, 1973a). Because they are predominantly browsers, moose tend to favour areas periodically subjected to ecological disturbances (e.g., flooding, fire) where a mosaic of early seral vegetation and more mature climax stands is maintained (Rolley and Keith, 1980). In general, riparian habitats of river deltas and floodplains are expected to support greater moose densities because shifting river channels and periodic flooding provide large disturbed areas that are eventually invaded by edible shrubs (Telfer, 1984).

Bison, instead of moose, are the large mammal most significant to the ecology of the PAD which includes almost 1200 km^2 of sedge and grass meadows, forming one of the largest undisturbed grassland areas in North America. Hybrid wood bison-plains bison are found throughout the lower Peace River area; however, the highest numbers and largest herds occupy open grasslands in the delta. Meadow areas in the delta may experience significant grazing pressure due to bison (Allison, 1973b).

2.9.2 Non-Deltaic Mammals

Muskrats can also occur along river channels, but higher flow velocities appear to reduce population densities. Although beaver are better suited to river channels than muskrats, studies suggest that a shortage of food may limit the period of time a beaver colony can occupy certain sites (Hawley and Aleksiuk, 1973).

Marten, traditionally a species of pure conifers, occur along river valleys and terraces (Wooley, 1974). Lynx can be found in mixed coniferous and deciduous forests (Van Zyll de Jong, 1963). In the absence of human interference, wolves occur throughout the study area associated with populations of ungulates. Grizzly and black bears use broad areas of varied habitat throughout the year. Moose, elk, mule deer and white-tail deer occupy aspen and mixed woodland areas as well as vegetation zones along the river valleys. Bands of important habitat for ungulates, particulary wintering habitats, often follow floodplains, but much of the wildlife habitat is not within the active floodplains of the rivers and, under most conditions, is not subjected to fluvial processes (MRBC, 1981).

2.9.3 Birds

In general, river channels are not suitable for nesting waterfowl (MRBC, 1981); however, waterfowl constitute the most abundant bird group on the mainstem. Numbers of bird species on the mainstem are usually low although those species encountered tend to have very broad distribution patterns. On the Peace River, two habitat variables are known to have a significant effect on the number of species observed: average river width and proportion of agricultural land-use within a 5 km radius (Wayland and Arnold, 1993).

Deciduous forest along the Upper Peace River associated with a heavy understorey of shrubs maintains Yellow warbler and red-eyed vireo as well as the American kestrel, common goldeneye, common flicker and bufflehead. Non-migratory birds using alluvial areas along the river include ruffed grouse and willow ptarmigans.

The PAD and SRD are of national and international significance for waterfowl and other migratory species. Most of the birds using the deltas are from the Central and Mississippi Flyways, although all major migratory flyways pass through the Peace River Basin. When drought strikes the prairie regions to the south, the PAD acts as a refuge for migrating duck populations (Peace-Athabasca Delta Implementation Committee, 1987). As ice starts to break-up in spring, migratory waterfowl begin staging including Arctic-nesting tundra swans, lesser snow geese and Canada geese (Bellrose, 1976). In a single-day spring survey in 1978, Thompson *et al.* (1979) estimated that 21,000 swans, geese and ducks occupied the area comprised of the SRD and the south shore of Great Slave Lake east to the Taltson River. Estimates of the numbers of birds using the SRD at this time are as high as 432,000 duck and 145,000 geese and swans in some years (Hennan, 1973; Hennan and Ambrock, 1977). Large flocks of many different species of Arctic-nesting shorebirds also use the SRD as a stopover during their migrations, particularly during the late summer and fall when retreating water levels expose large expanses of mud flats for feeding and resting (Thompson *et al.* 1979, McCourt Management Ltd. 1982). Fall staging on the SRD begins in mid-August and the numbers of waterfowl at this time have been estimated at between 1,000,000 to 1,500,000.

The Slave River is the primary migration corridor between the staging areas of the SRD and Great Slave Lake, and the breeding areas of the PAD. Bird species inhabiting or migrating through the Slave River Basin include rare water birds, such as white pelicans and whooping cranes. Seventeen species of ducks and geese are known to regularly breed in the basin, and a number of rare raptors and commercially valuable upland game bird species utilize the available habitats.

Table 2.3 Wildlife habitat regions and their significance in the Peace and Slave River basins (MRBC, 1981; McCourt Management Ltd., 1982; Alberta Environment, 1987).

Habitat region	Brief description of biophysical region	Significance to wildlife populations
1. Peace-Athabasca and Slave Deltas	Alluvial deposits, numerous islands, silt bars, meadows, open and closed marshes. Abundant aquatic vegetation, some aspen, balsam poplar and spruces.	Muskrat, beaver, moose, waterfowl breeding, migration and staging areas, raptors. P-A Delta has significant bison habitat.
2. Lowland forests	Typically high water tables and numerous channels. White and black spruce, aspen and willow. Meadows with some marsh habitat.	Moose and other ungulates, aquatic and upland furbearers.
3. Savannah lowlands	Relatively low relief, large areas of grass-sedge meadows, scattered willow and aspen forest. Drainage channels provide wet regions in spring.	Slave River savannah main range of bison herds. Wolves, ptarmigan winter habitat, sharp-tailed grouse and sandhill cranes.
4. Open forest lowlands	As (3) but with more extensive regions of forest which also includes spruce.	Slave River bison herd winter range during severe winters.
5. Upland forests (Peace basin)	Upland and foothill regions with extensive forest cover of aspen, balsam poplar, spruce and pine. Dry and wet channels with some riparian and marsh habitats.	Muskrat, beaver, ungulates, wolves, wolverine and bear. Also numerous song birds and raptors.
6. Upland forest-wetland complex (Slave basin)	Transition zone between the Canadian Shield and lowland areas of the Slave River. Variable relief, sparse upland cover of aspen and pine. Areas of wetlands include lakes, streams, marshes and meadows.	Beaver, muskrat, waterfowl breeding, fall migration and staging areas, raptors.
7. Murdock meadows and lowlands (Slave basin)	Vegetation includes willow, balsam poplar and white spruce. Murdock Creek, side channels and sinkhole lakes provide riparian and meadow habitat.	Winter range of bison population, waterfowl and muskrat. Possibly also moose.
8. Upland forest on karst (Slave basin)	Extensive forests of pine, aspen, spruce and willow. Areas of sinkholes, sand dunes, beach ridges, underground caverns and evaporite flats provide a unique diversity of habitat features.	Bison summer range, bat hibernacula (possibly snake) and forest species; marten, fisher, wolves, et cetera.
9. Salt plains (Slave basin)	Saline/sedge meadows and grasslands interspersed by aspen and willow.	Summer/winter ranges of bison, wolves, garter snake hibernacula, spring waterfowl, pelican foraging area, sharp-tailed grouse.
10. Peace and Slave River mainstems and floodplains	River habitats include islands, silt bars, floodplains and side channels; vegetation highly variable from sedge meadow in channels to riparian vegetation consisting of Equisetum, willow and balsam poplar, white spruce and floodplain forest. Perched channels and backwaters along certain reaches.	Probably ungulates, beaver in side channels, some bison use in Slave River basin, some limited waterfowl migration, staging areas.

3.0 AQUATIC IMPACTS OF FLOW REGULATION ON THE PEACE-SLAVE RIVER SYSTEM: SCIENTIFIC REVIEWS AND STUDY RESULTS

As described in the Introduction (Section 1.1), producing a response to NRBS Question #10 required the NRBS science components to review and summarize existing hydro-ecological material from a regulation-impact perspective, conduct a limited number of field studies to evaluate some of the changes to the bio-physical regime, and develop appropriate tools for use in future impact assessments. The following summarizes and integrates the results of all three of these tasks.

3.1 FLOW REGULATION OF THE RIVER MAIN STEM

The major regulation structure on the Peace is the W.A.C. Bennett dam in northeastern British Columbia. Primary filling of the Williston reservoir occurred between 1968 and early 1972 resulting in the storage of $41X10^9$ m^3 of water (Muzik, 1985) and a significant reduction in downstream flow. A run-of-the-river structure, the Peace Canyon Dam, was subsequently constructed 21 km downstream of the Bennett Dam; however, it has had negligible impact on the flow because of its limited storage.

Numerous methods can be used to reveal regulation-induced changes in the flow regime. The following sections use summary statistics, considered to be most illustrative from an ecological perspective, to provide relevant background for subsequent discussion. The periods of summary are limited, however, by the availability of hydrometric records. In the early years of operation, records are often intermittent or seasonal, e.g., open-water only. Hence, records at a specific station might be quite extensive for particular months but much shorter for other months and for complete annual records. The problem is exacerbated when attempting to make inter-station comparisons. A complete inter-station comparison of annual flows for all major stations is possible only for 1960 to 1967, an eight-year period. The limiting stations are Peace Point and Fitzgerald, which did not record complete years until 1960. Thus, two time periods have been employed to characterize pre-regulation conditions: a) the total record length that varies significantly from station to station [denoted in the text by ^{b}], and b) an eight year period beginning in 1960 [denoted in the text by ^{a}]. The post-regulation record covers a twenty-two year period from 1972 to 1993. All data have been extracted from Water Survey of Canada (1993).

Another indication of the impacts of regulation on the overall flow regime can be derived by modelling the flow since regulation without the effect of the dam. Alberta Environment, in conjunction with the British Columbia Hydro and Power Authority, have developed such an approach using a hydrologic routing model (SSARR, Streamflow Synthesis and Reservoir Regulation Model). Originally, it was hoped to incorporate the results from this modelling effort into some of the NRBS studies. Unfortunately, at the time of this report, the modelled results for downstream stations remain in draft form and are still under review. However, draft results contrasting "natural" and regulated flows over the period 1960 to 1991 generally confirm the conclusions derived from an analysis of the pre- and post-regulation data sets noted above.

Four stations on the Peace and Slave rivers were examined: Hudson Hope, British Columbia, located a short distance below the Bennett dam and representing 69,600 km^2 of the Peace basin; town of Peace River, Alberta (187,000 km^2); Peace Point above the Peace-Athabasca Delta (293,000 km^2); and Fitzgerald, Alberta (606,000 km^2) which records flow from the Peace River, Athabasca River, Lake Athabasca, and internal Peace-Athabasca Delta catchments. Major tributaries along the Peace River were also evaluated. A separate discussion on regulation effects in the Peace-Athabasca Delta is contained in following Section 3.2.

3.1.1 Mean-Annual Flows

The mean-annual flow record for all four stations is shown in Figure 3.1. The pronounced effects of reservoir filling are evident for all sites from 1968 to 1971 but become less significant further downstream because of the compensating effect of tributary inflow. After 1971, with the reservoir full, mean annual flows returned to near pre-dam values, but with seasonal shifts due to the demands of hydroelectric production on release times and rates. Average mean-annual flows appear in Figure 3.2. The average percentage contribution of the mean annual flow at Hudson Hope to the three downstream stations for pre-[a] and post-regulation periods are: Peace River, 57 and 60%; Peace Point, 52 and 54%; and Fitzgerald, 32 and 34%. Although a significant proportion, the contributing flow from above the point of regulation becomes less significant to the mean annual flow with distance downstream. In general, long-term pre- and post-regulation mean annual flows should vary only because of long-term climatic factors (including the role of enhanced evaporation from the reservoir) since no significant amounts of water are withdrawn from the reservoir for consumptive use. Just at the point of regulation (Hudson Hope), the long-term pre-regulation and post-regulation mean annual flows are virtually identical. Even the shorter record for 1960-1967 differs by < 5%. The longest period of pre-regulation annual records (1916-1930 and 1958-present) exist for the station at the town of Peace River. Notably, comparing the brief 1960-1967 pre-regulation period[a] to that for the post-regulation period, reveals a slight decline; however, this becomes a slight increase when the entire pre-regulation record[b] is employed. It appears that there has been a slight shift in mean annual flows between the immediate pre-regulation period 1960-1967 and the longer post-dam record, most evident by Fitzgerald. The possibility of this being related to climatic variations is explored in some of the subsequent discussions, particulary Section 3.3.4 dealing with spring break-up and snowmelt runoff from tributaries.

3.1.2 Annual Peak Flows

Figure 3.3 illustrates the historical record of annual peak flows derived from all available flow data (including years of missing winter records since flow peaks are expected during the spring to summer seasons) and Figure 3.1, the related mean values (also noted are the absolute maximum and minimum values for the respective periods of record). In general, the mean annual peak flows have been reduced, the magnitude of the decrease diminishing with distance downstream. At Hudson Hope, the post-regulation mean flood peak is only one-third the average that occurred in the record prior to regulation. Furthermore, the peaks are relatively consistent and show minimal inter-annual variation. Further downstream, average peak flows are reduced to a lesser degree because of the compensating effect of unregulated tributary inflow which also ensures significant inter-annual variability. Ratios of post- to pre-regulation peaks are approximately 0.71 for the town of Peace River; 0.63 for Peace Point; and 0.85 for Fitzgerald on the Slave River. The Smoky River is a particulary important tributary but downstream attenuation often means that flood peaks are lower at downstream stations like Peace Point than they are at the town of Peace River.

Although all station records exhibit reductions in mean-annual peak flows, the maximum peak flow for all stations, except Hudson Hope, has occurred since regulation (Figure 3.3). The occurrence of such peaks downstream reflects the strong influence of tributary inflow although it could be argued that peaks may have been even greater if not for the effects of regulation. Notably, some of the studies presented below (Section 3.4) show that peak flows do not necessarily produce peak water levels. This is due to the complicating effects of river ice, a regime that can also be significantly altered by regulation.

3.1.3 Seasonal Contrasts in Flows

Seasonal demands for hydro-electric power production have significantly changed the nature of the monthly hydrographs throughout the Peace and Slave river system and altered the seasonal significance of tributary flow. Mean monthly flows are presented in Figure 3.4 for the two pre-regulation intervals[a,b] and the post-regulation period. The typical reversal in the annual hydrograph is apparent for the Hudson Hope station where the previously high summer flows become lower than those for the regulated winter period. The annual hydrograph also exhibits a reduction in the range of winter to summer flows. For discussion purposes, the "summer" season is herein defined as May 01 to October 31, and "winter" as November 01 to April 30. Ice effects, however, do not cease on the lower portions of the system until mid- to late-May.

In the pre-regulation period[b], both the mean- summer and winter flow approximately doubled between Hudson Hope and the downstream end of the Peace River. With regulation, the mean summer flow at Hudson Hope (2013 m^3/s) declined by approximately one-half (1007 m^3/m) but the winter flow approximately quadrupled (383 to 1304 m^3/s), exceeding the new mean summer flow. Overall, this effect diminishes downstream so that at Peace Point, the post-regulation mean summer flow (2635 m^3/s) is 2/3 that prior to regulation, and the winter flow (1650 m^3/s) is increased by approximately 2.5 times.

There has also been a shift in the timing and magnitude of minimum monthly flows and in seasonal ranges in flows. Again the most pronounced changes occur immediately downstream of the reservoir. Here the average seasonal low flow occurred in March but now occurs in June and at approximately 4 times the volume. Similarly, the average seasonal high flow occurred in June but now occurs in winter, in December. Moreover, the post-regulation range in flows is only 14% of that prior to regulation[b]. Further downstream (town of Peace River to Fitzgerald), the average seasonal low and high flows still occur in winter and summer respectively, but the range in flows has appreciably declined [b]: Peace River, 29%; Peace Point, 31%; Fitzgerald, 56%.

3.1.4 Flow Duration

A further illustration of changes in the flow regime is obtained by comparing example flow duration curves for pre-[a] and post-regulation periods at an upstream and downstream location, i.e., Hudson Hope and Peace Point (Figure 3.5). It should be understood, however, that the post-regulation data result from a non-stochastic process: i.e., one in which the flow can no longer be treated as a random independent variable. Significant variations in future flows can result from extremes in reservoir operation produced by fluctuating demands for electricity or emergency repairs: factors which cannot be considered random events. Hence, the post-regulation curves should be viewed only as a summary characterization of the recorded flows and not be used for predictive purposes.

The magnitude of the regulation effect is reflected in the degree to which the flow duration curves have been "flattened" by regulation: average flows are now much more consistent throughout the year; higher flows are reduced; lower flows are increased; and the overall range in flows is reduced. At Hudson Hope, for example, the pre-impoundment[b] flow could be expected 10% of the time to exceed 3130 m^3/s but after regulation, only one-half this value (1680 m^3/s). Notably, this latter figure would be even smaller if the apparently anomalous, post-regulation peak flow of 5130 m^3/s was not included in the analysis. This flow occurred in 1972, immediately after reservoir filling, and is probably more associated with early test trials than normal reservoir operations. The reverse has occurred at the 90% recurrence level where flows have approximately doubled with the effect of regulation.

Much further downstream at Peace Point similar effects are evident. Before impoundment[b], flow could be expected to exceed 6250 m^3/s 10% of the time but only 3590 m^3/s after impoundment. At the other end of the duration scale, the pre-[b] and post-regulation flows at the 90% exceedance level are 399 and 1220 m^3/s, respectively.

A parameter closely tied to the above duration curves and commonly used in water-quality assessments is the "7Q10", referring to the annual minimum 7-day flow expected to occur once in ten years (i.e., 10% of the years). With the elevation of minimum flow values throughout the Peace-Slave system due to regulation, concomitant increases will occur in the magnitude of the 7Q10. Notably, however, the timing of the 7Q10 may also change, most probably close to the reservoir where the effects of regulation have produced an average shifting in the time of minimum flow from summer to winter (see previous discussion). Importantly, like many other flow parameters, the downstream extent to which this seasonal shifting occurs depends on the operational scenario employed at the Bennett Dam.

3.1.5 Significance of Tributary Flow

As noted throughout the above discussion, downstream changes in the flow regime are influenced greatly by tributary inflow. Examination of Figure 3.4 shows that inflow from tributaries below Hudson Hope are important in the post-regulation period for retaining the original pre-regulation seasonal pattern of flows, if not the original relative summer volumes of flow. It is worth noting, however, flow of the tributaries has been down on average since regulation (see later recommendation).

The overall seasonality of the influence of tributary inflow has been altered by regulation. Figure 3.6, for example, depicts the mean monthly ratio between a) the difference in flow between the point of regulation (Hudson Hope) and Peace Point (i.e., effectively the contribution from tributaries between the two stations) and b) the flow at Peace Point. In the pre-regulation period, downstream tributary inflow was approximately equal to that produced above the point of regulation (ratio ~ 1.0; range 0.6 to 1.3). In other words, it used to cause an approximate doubling of the flow between Hudson Hope and Peace Point. Since regulation, it only represents approximately 20% of the flow recorded during the winter (November 01 to May 01; at Peace Point) but causes a doubling to tripling of the flow during the main summer months. In the case of the Smoky River (17% of the Peace basin area as measured at Peace Point), its average summer contribution to Peace Point flow increased from approximately 15 to 23%, while its winter contribution decreased from 16 to 7%. Similar percentage changes apply to the other tributary basins.

Figure 3.1 Mean annual flows for selected hydrometric stations on the Peace and Slave Rivers. No records are available between 1931 and 1951, therefore time scale has been removed. Pre- and post-regulation means are illustrated by solid line.

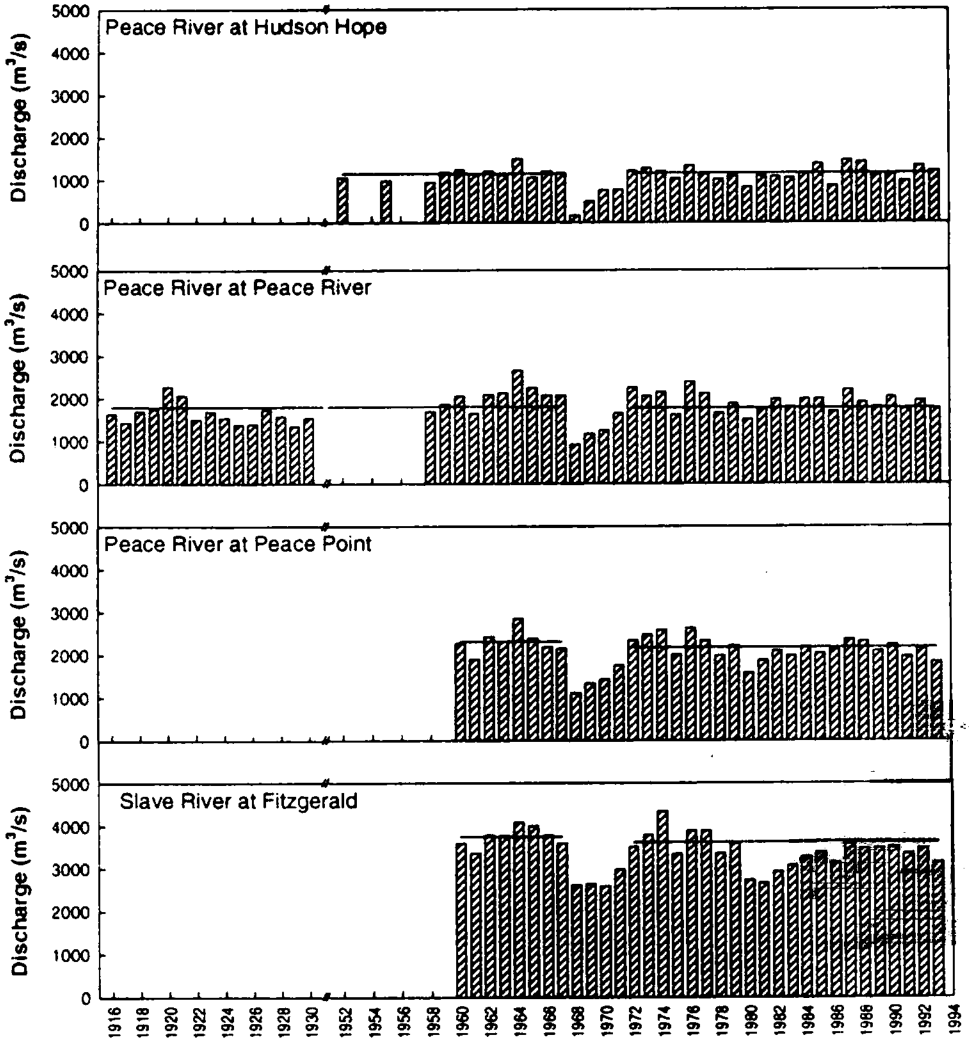


Figure 3.2 **Comparison of mean and annual peak flows for selected hydrometric stations on the Peace and Slave Rivers. Pre-regulation data based on the largest continuous record occurring from 1960-1967**

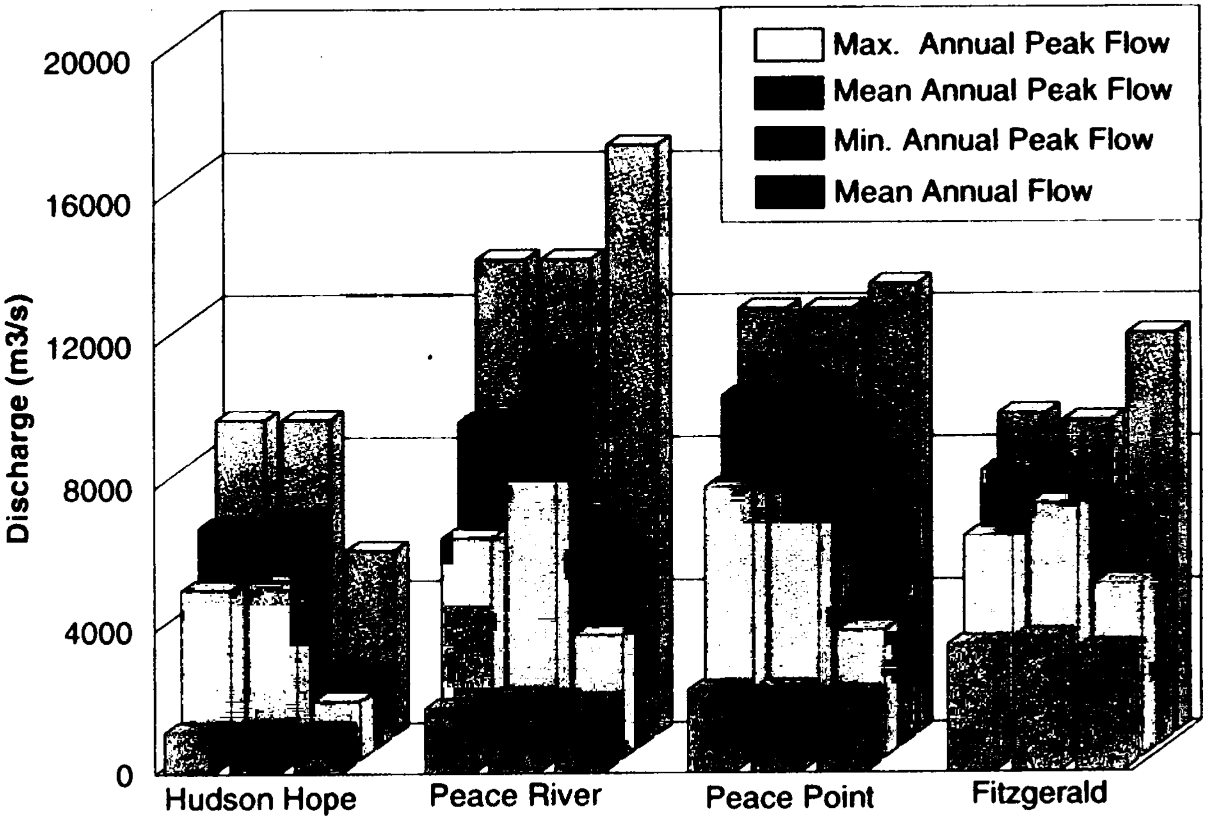


Figure 3.3 Annual peak flows for selected hydrometric stations on the Peace and Slave Rivers. No records are available between 1932 and 1949, therefore timescale has been removed. Pre- and post-regulation means are illustrated by solid line.

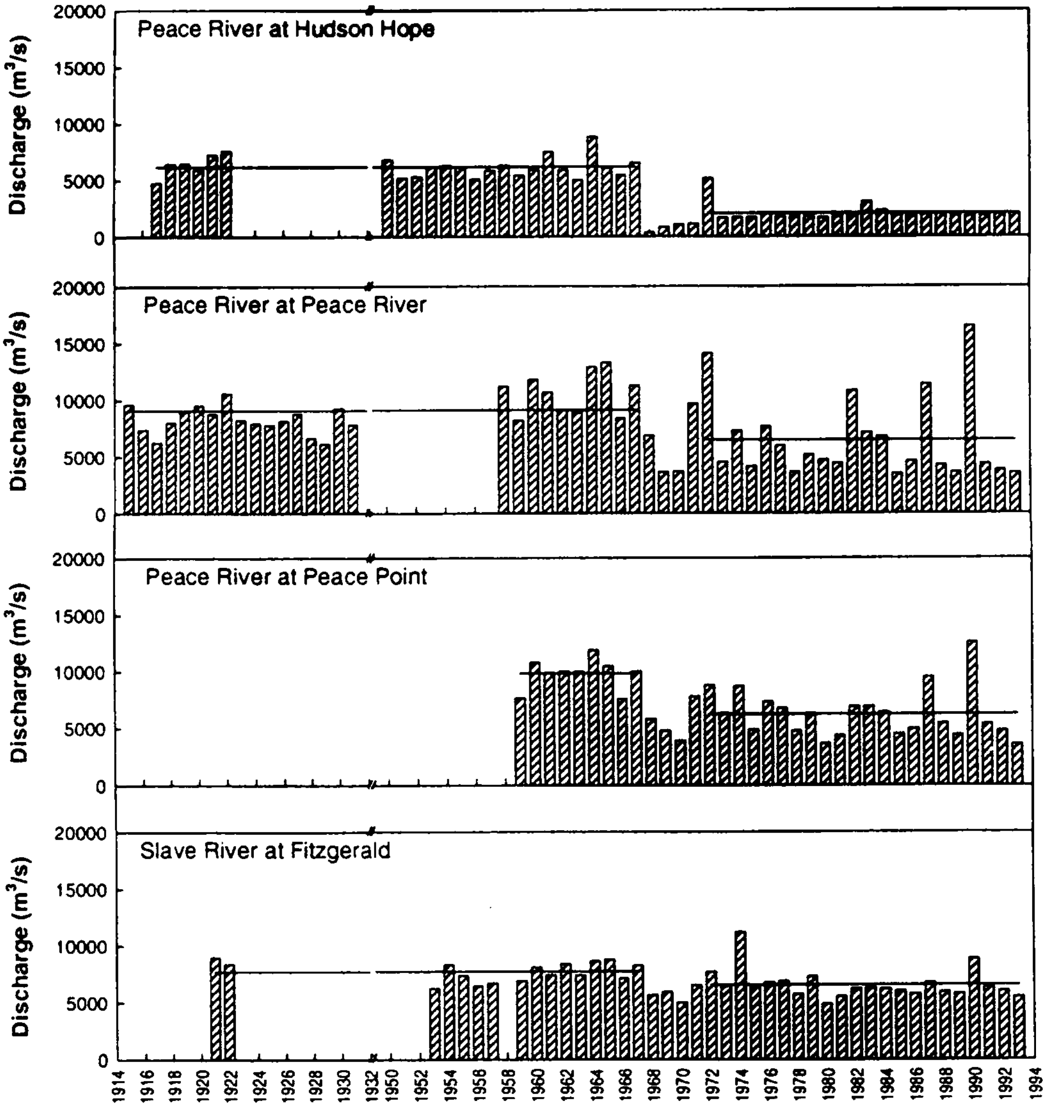


Figure 3.5 Pre- and post-regulation flow duration curves for the Peace River at Hudson Hope and Peace Point. Values at 0 and 100% represent the minimum and maximum flows for the periods, respectively.

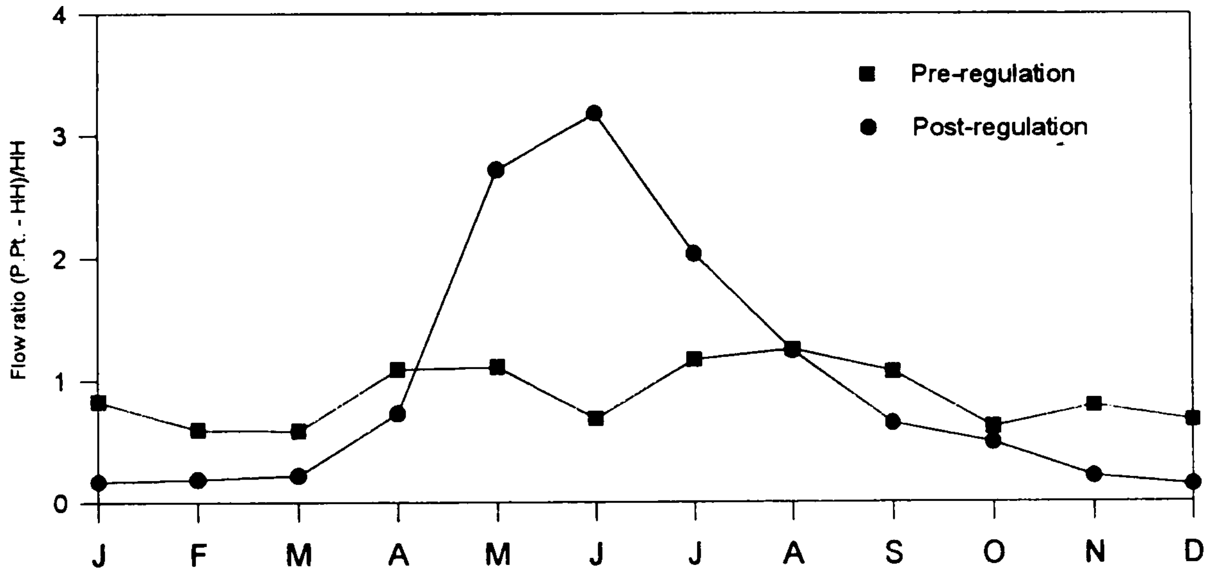


Figure 3.6 Pre- and post-regulation tributary flow ratios relative to flows at Hudson Hope.

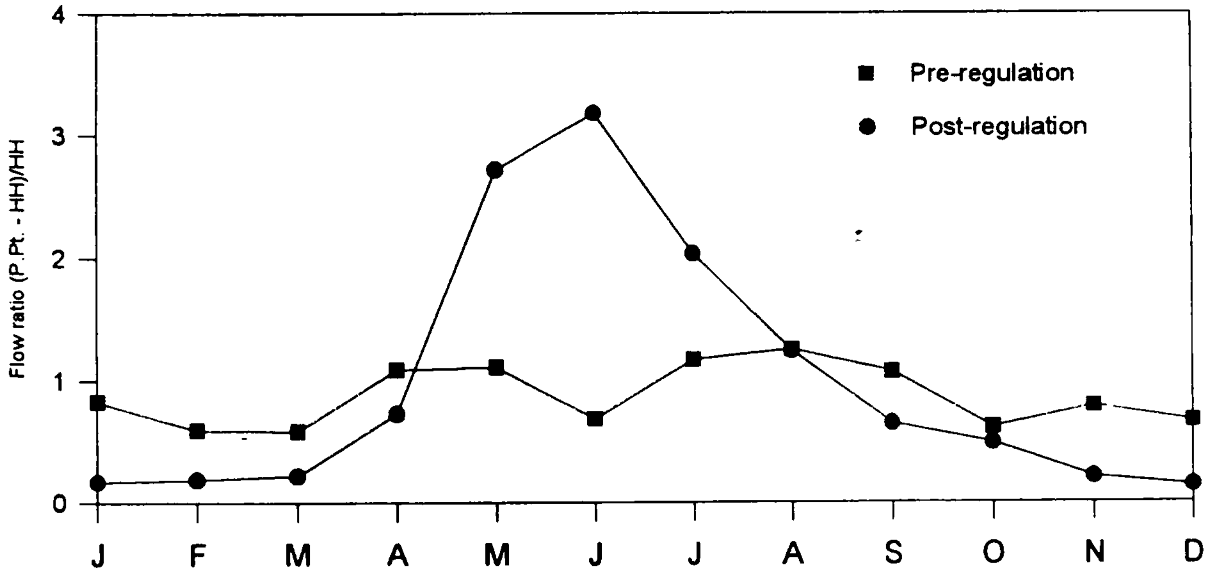


Figure 3.4 **Pre- and post-regulation mean monthly flows for selected hydrometric stations on the Peace and Slave rivers.**

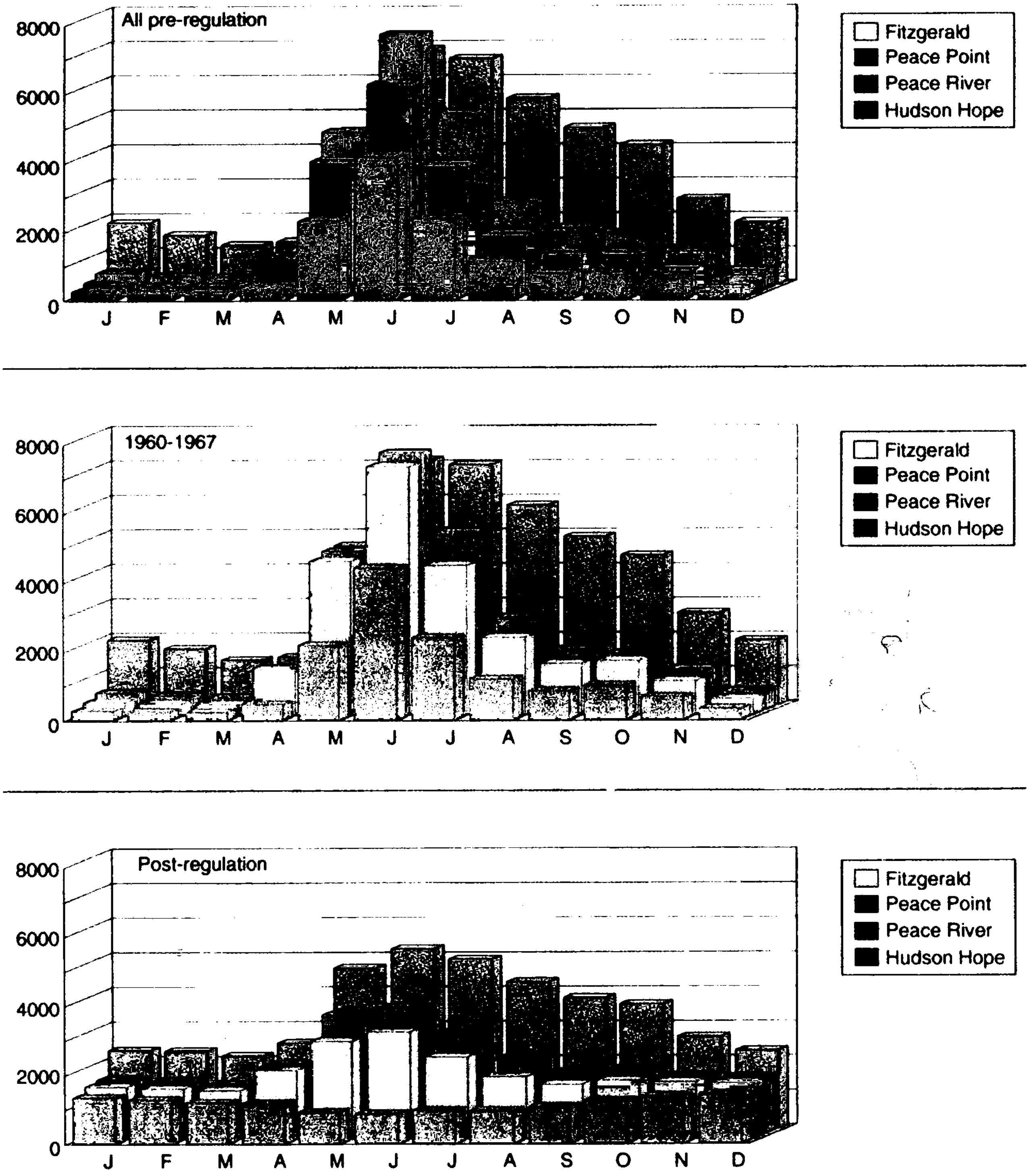
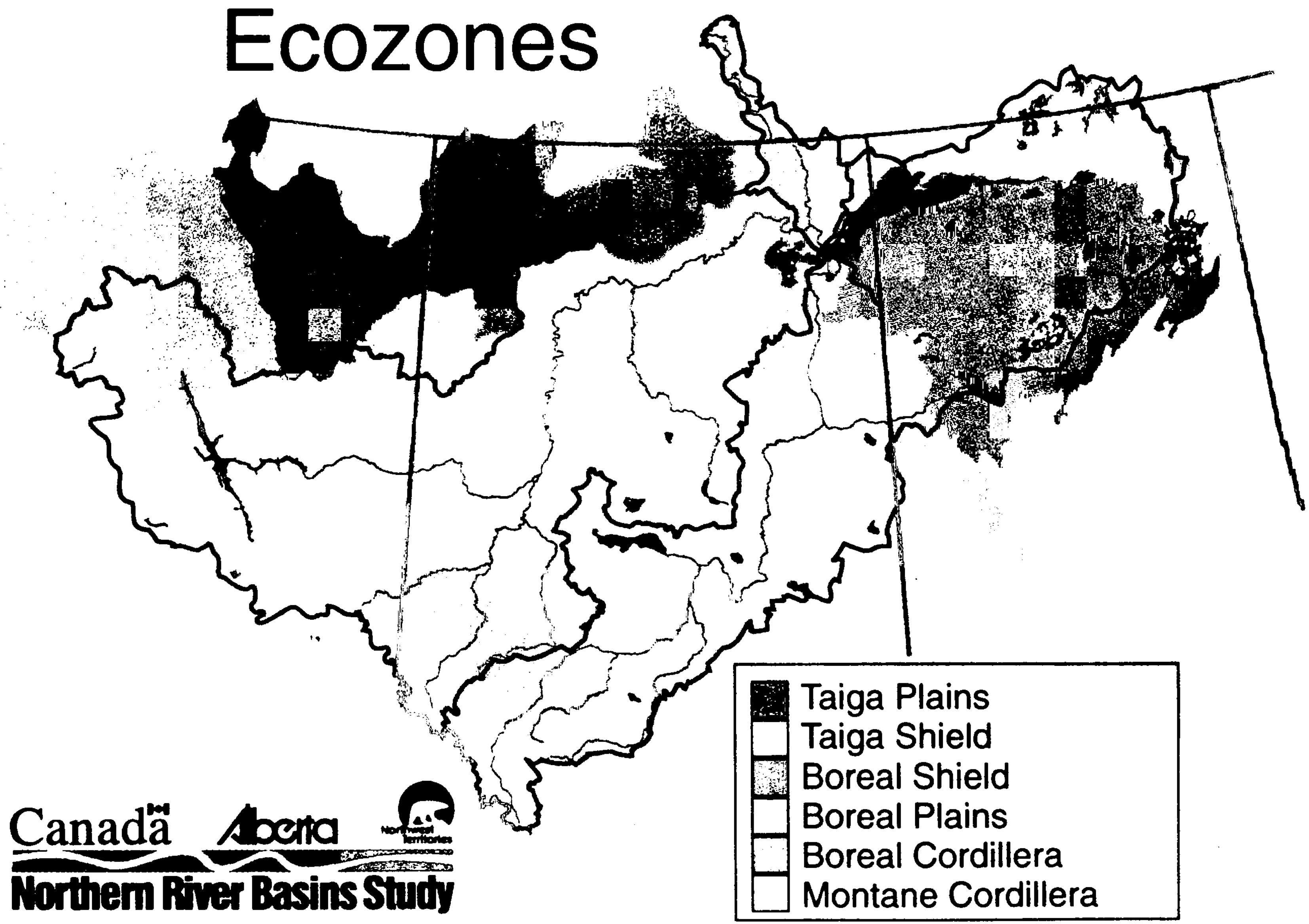


Figure 2.7 Ecozones of the Peace-Athabasca-Slave river basins.



3.2 FLOW REGULATION OF THE PEACE-ATHABASCA DELTA

During the period of dramatic flow reductions associated with the filling period of the Williston Reservoir, the perched-basin shoreline of the Peace-Athabasca Delta was reduced by approximately 36% and the water-surface area by 38%, exposing some 500 km^2 of mudflats. A number of ecological impacts accompanied such dramatic changes to the hydrologic regime including, for example, replacement of productive sedge meadow vegetation by more invasive woody forms such as willow and poplar, and a rapid decline in the muskrat population (e.g., Townsend, 1975).

As previously illustrated in various figures contained in Section 3.1, impacts of regulation on the seasonal flows near the PAD (as exemplified by the nearby Peace Point hydrometric station) were dramatic even after the filling ceased. In general, summer peaks were lowered and winter flows increased. Although dampened to some degree by inflow from the Athabasca River system, similar effects were experienced throughout the main flow channels of the PAD (see hydrologic description in Section 2.6.2). The ecological effects of these changes prompted the construction of weirs in the early 1970's. The history and an evaluation of their effectiveness are reviewed next.

3.2.1 Regulation of Water Levels by Rockfill Weirs

In the fall of 1971, a temporary dam was constructed on the west arm of the Quatre Fourches with the objective of raising water levels on Lakes Claire and Mamawi and any adjacent perched basins. Unfortunately, by restricting the exchange of water with Lake Athabasca and the channel network, this structure hampered fish migration and reduced the flushing action necessary to maintain water quality and a detritus source for zooplankton (Peace-Athabasca Delta Implementation Committee, 1987). The dam was subsequently removed and two rockfill weirs were constructed on the Rivière des Rochers (including an ancillary fish bypass channel) and Revillon Coupé by March, 1976 (Figure 2.10), thus controlling two of the three main channel systems from the PAD to the Peace River.

3.2.2 Modelling of Regulation Effect of Weirs

An early assessment of the performance of the weirs was made by the Peace-Athabasca Delta Implementation Committee (1987). An NRBS study was commissioned to extending the period of assessment up to 1990 (Aitken and Sapach, 1993). Performance evaluations of the rockfill weirs were conducted by comparing observed water-level data with two other modelled scenarios: a natural state in which the river is completely unregulated (natural), and a dam-regulated state without the weirs. Background to the one-dimensional (1-D) hydraulic flow model can be found in (Sydor *et al.*, 1979; Farley and Cheng, 1986; Environment Canada, 1988). The model is defined by an extensive series of reaches and nodes connecting the major lakes and flow channels (Figure 3.7). Unregulated (natural) flow was generated by determining flow at the hydrometric station just downstream of the dam (Hudson Hope), adjusting for the change in storage of the Williston Lake reservoir, and then routing it downstream with the use of a hydrologic routing model and the addition of other tributary inflow. Evaporation is also accounted for on the large lakes. Output is verified at six locations across the PAD. In the worst case, model accuracy at some verification points during these periods can be off by +/- 1 m or more but it is normally within +/- 0.1 to 0.3 m (Aitken and Sapach, 1993).

3.2.3 Results

Figure 3.7 depicts the modelled results for the effect of the weirs, Bennett dam, and a combination of the two on annual water levels at the various lakes and channel nodes. Monthly maps of these three conditions are contained with the original NRBS report (Aitken and Sapach, 1993). As was found by the earlier modelling assessment (Peace-Athabasca Delta Implementation Committee, 1987), it appears that the effects of the Bennett dam are greatest along the Peace River and reduce in magnitude with distance into the PAD. As is the case on the river system, regulation increased winter water levels and decreased summer levels. The modelled results also found that the weirs have their greatest effect on winter and spring water levels, particularly immediately upstream. They restored peak-annual water levels on the large delta lakes to near pre-regulation conditions but also raised the mean and minimum water levels. This raises the ecological concern, as earlier expressed by the Peace-Athabasca Delta Implementation Committee (1987), that the weirs have eliminated critical, seasonal drawdowns in water levels that produce unique near-shore vegetation/habitat and waterfowl staging zones.

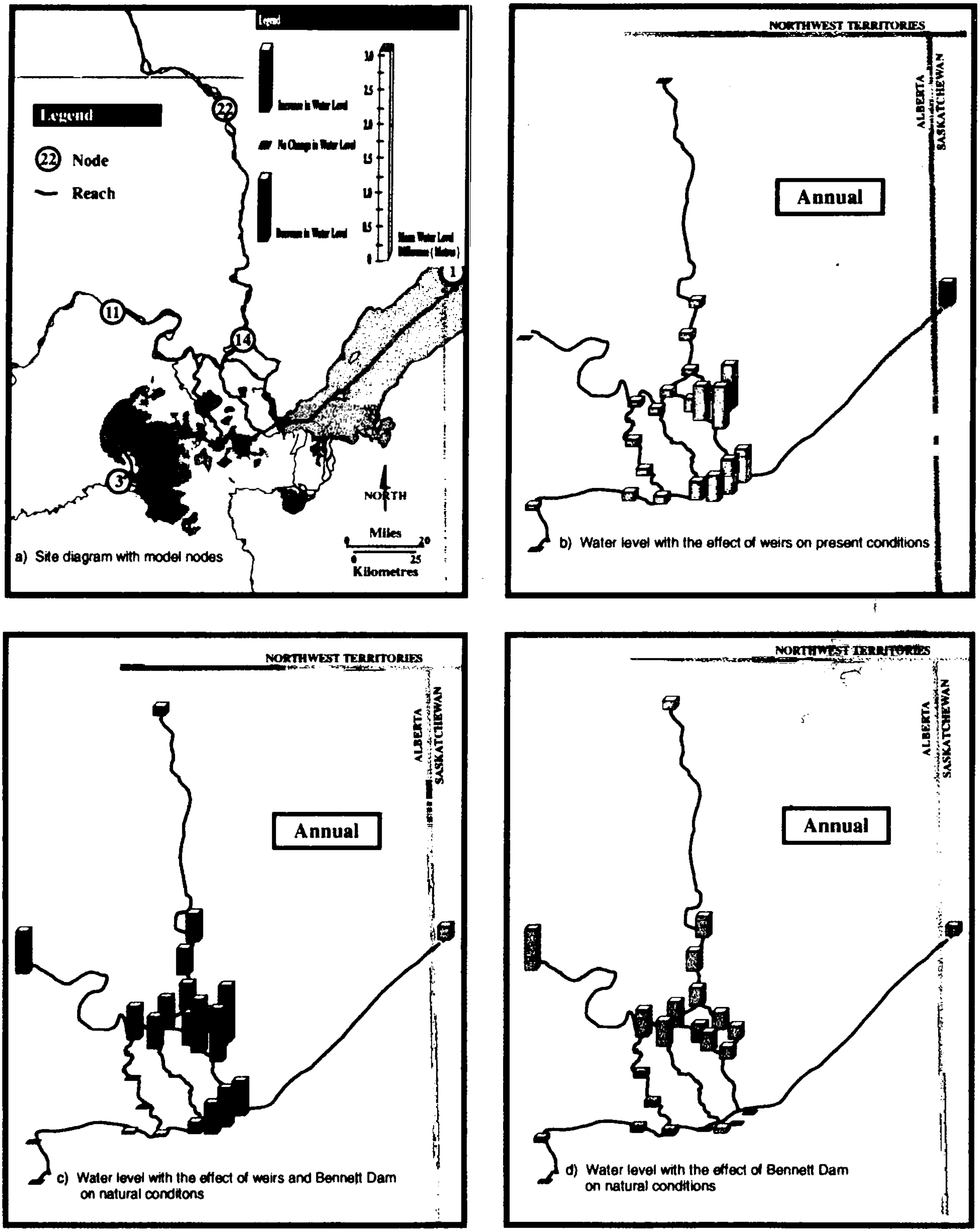
Recognizing that previous assessments only compared modelled data, Prowse *et al.* (1996a; Figure 3.8) completed an additional study using hydrometric data collected on the large lakes (Claire, Mamawi, and Athabasca) since the weirs were installed (vertical line labelled weir) and comparing them to the modelled data (natural and regulated) for the same period. The horizontal bars on the weir record (recorded data) refer to the modelled results as reviewed in Aitken and Sapach (1993).

The effect of regulation and the restoration effect of the weirs are evident for all lakes and most pronounced for Lake Athabasca. All mean-maximum lake levels were raised by the weirs from as little as 0.08 m on Lake Mamawi to as much as 0.75 m for Lake Athabasca. Notably, in this analysis, the mean-annual amplitude in water levels is approximately equal to that under a natural regime for Lakes Athabasca and Claire. In the case of Lake Mamawi, the observed mean amplitude in water levels is much greater than that under regulation or natural conditions. One explanation for this may rest with the overprediction of minimum values for all Lake Mamawi scenarios as evident in some earlier calibrations of the model (Peace-Athabasca Delta Implementation Committee, 1987, p.23).

3.2.4 Summary Discussion

Since their construction, the weirs appear to have been quite effective in restoring maximum lake levels, although there appears to be some question about the seasonal range in water levels. Unfortunately, the hydraulic model developed for evaluation of drying conditions in the PAD does not explicitly define the perched basins and it is this environment that has extensively dried since 1974, the time of the last major flood. Moreover, Jaques (1990) found water levels produced by the weirs to be largely ineffective in halting the invasion of persistent shrub communities, such as willow and poplar, into the sedge-meadow zones. Over a 13-year period, 1976 to 1989, Jaques (1990) measured (by satellite image

Figure 3.7 Modelled flow scenarios for the Peace-Athabasca Delta (from Aitken and Sapach, 1993)



a) Site diagram with model nodes

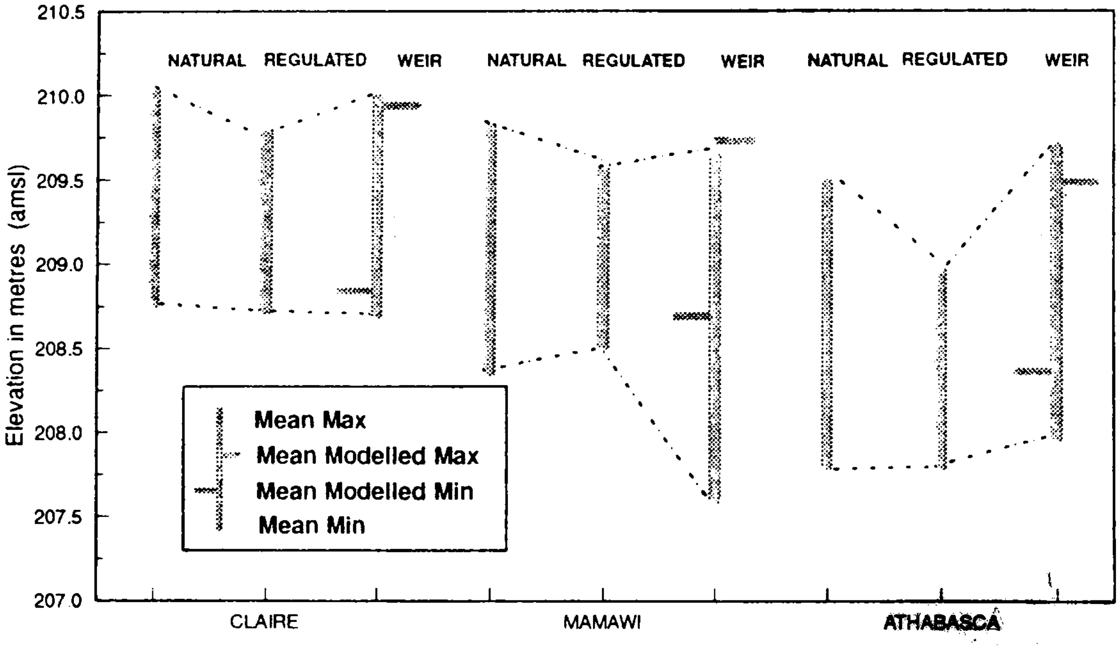
b) Water level with the effect of weirs on present conditions

c) Water level with the effect of weirs and Bennett Dam on natural conditons

d) Water level with the effect of Bennett Dam on natural conditions comparisons) a 47% reduction in the aquatically-productive vegetation community, a significant proportion of which is located at elevations above those influenced by the weirs.

Although high lake and channel levels provide flow to many of the open and restricted drainage basins, it became apparent during the historically-high flow event in 1990 that flooding of the high-elevation and/or isolated perched basins has not been achieved during the period of recent record under open-water flow conditions. Although there is a lack of instrument-record data on water levels in the PAD prior to regulation, historical accounts from local inhabitants gathered by Thorpe (1986) and Peterson (1992) suggest that backwater flooding created by spring ice jamming is probably important to the PAD. The significance of this was explored as a joint NRBS-PADTS study and is discussed in Section 3.4.

Figure 3.8 Mean maximum and minimum open water levels for three Peace Athabasca Delta Lakes for the period of 1976-1990. Natural and regulated (dam) data are completely modelled
(see Aitken and Sapach, 1993).
Weir data consist of observed values with some modelled values (Prowse et al., 1996a).



3.3 HYDRAULIC FLOOD ROUTING MODEL

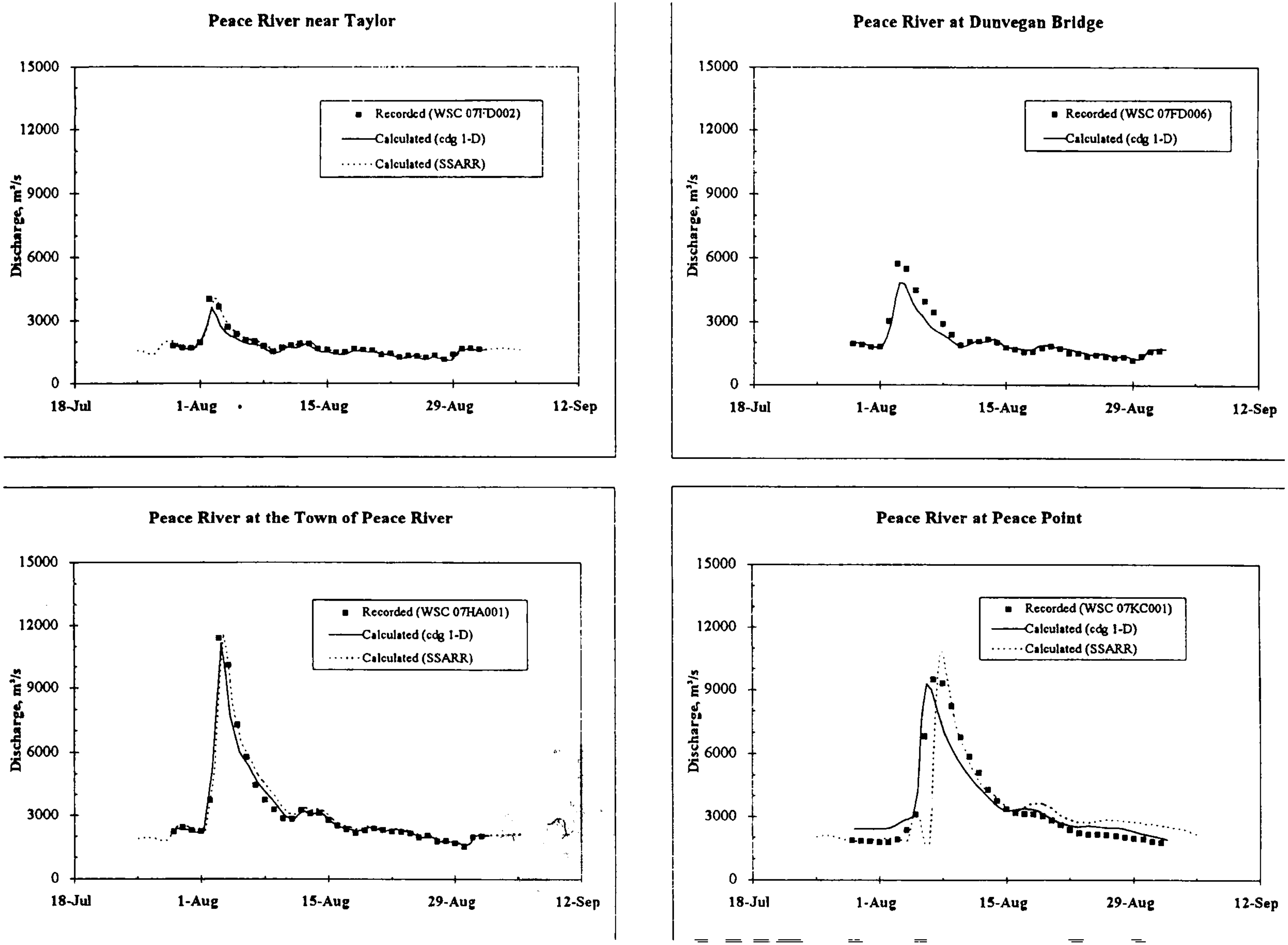
As described in Section 3.1, an assessment of the effects of regulation is being conducted by Alberta Environment using an hydrologic flood routing model (SSARR) that provides discharge information at the major hydrometric stations on the Peace River. Recognizing, however, that many of the hydro-ecological assessments (see discussion in later sections) of flow regulation require estimates of flow parameters not available from hydrologic models, such as stage and velocity, as well as discharge hydrographs at intermediates sites, it was decided to develop an unsteady, hydraulic flow model for the Peace River. Recognizing that such a model could also permit the eventual coupling of modelled flow from the Peace-Athabasca system (1-D hydraulic model; Section 3.2), the model was extended into the Slave River. Notably, regular hydrometric data is only available from one station on the Slave River. Application of the hydraulic model permits the modelling of flows right to the Slave River Delta, the site of another NRBS study (Section 3.5.2).

The developed model employs a Petrov-Galerkin finite element method known as the Characteristic-Dissipative-Galerkin (CDG) scheme. Comparisons of this numerical scheme to more conventional, commercially available code have been conducted, confirming the superiority of the CDG scheme in terms of both solution accuracy and numerical stability. This is important if rapidly varying flood flows are to be modelled, such as those produced by the ice jams surges that often characterize spring flow conditions on the Peace River and are important to the formation of ice-jam floods near the Peace-Athabasca Delta (see Section 3.4.3).

Because of the apparent significance of river-ice to the morphology and ecology of the Peace and Slave rivers (Sections 3.4, 3.5 and 3.7), a long term objective in assessing overall impacts of flow regulation will be to model changes in the river-ice regime. Notably, an earlier version of the hydraulic model has already been used for a related purpose on the Hay River, NWT. Specifically, it has proven useful in modelling the potential impact of ice jam release surges, a process found to be important to flooding near the Peace-Athabasca Delta (Section 3.4.3) and possibly the Slave River Delta (Section 3.5.2). More generally, development of such a hydraulic model will provide the essential foundation for the eventual incorporation of a comprehensive river-ice model (RIVICE) currently being developed through Environment Canada, and for state of the art IFN (Instream Flow Needs) two-dimensional hydraulic flow models (Section 3.7).

A major component of this project involved the development of a geometric model of the river system using available cross-section surveys supplemented with N.T.S. map data. The final geometric model consisted of more than 1100 computational nodes describing channel width, effective bed elevation and channel roughness, the latter being the only calibration parameter. Figure 3.9 illustrates example output of the model compared to measured hydrometric data and modelled SSARR results. It has been further refined with the incorporation of additional field surveys in some of the lesser known reaches of the Peace and Slave Rivers. Complete details about the model are contained in Hicks *et al.* (1994; 1995). A number of recommendations for the use of the model are made in subsequent sections.

Figure 3.9 Comparisons of measured and computed discharge hydrographs.



3.4 REGULATION EFFECTS ON THE ICE REGIME

River ice is known to control numerous physical, biological and chemical processes in a river system (Section 1; and reviews: e.g., Prowse and Gridley, 1993; Prowse, 1994; Scrimgeour *et al.*, 1994). For example, it produces hydrologic events (low flows and floods) the magnitude of which exceeds that possible under open-water conditions; determines unique types and availability of aquatic habitat; and regulates major atmospheric exchanges, such as the flux of oxygen, to the water column. Regulation of the flow in a river can affect its ice regime significantly. On a river, such as the Peace, normally ice covered for almost half the year, modifications to the ice regime could have numerous ecological impacts.

As the first step to understanding the changes that have occurred to the ice regime on the Peace River resulting from regulation, two NRBS studies were undertaken. The first dealt primarily with changes to the freeze-up regime along the Peace River (Andres, 1995) and the second focussed on the break-up regime, specifically within the lower portions of the Peace River (Prowse *et al.*, 1996b). This latter study directly interfaced with the Peace-Athabasca Delta Technical Studies (PADTS) designed to understand the change in the frequency of flooding, inundation proven to be essential to the health of the PAD ecosystem. Completion of these two studies also produced an understanding of changes that have occurred in the timing and duration of the overall ice cover season.

3.4.1 Changes to Freeze-up Conditions

The nature of freeze-up processes on northern rivers depends primarily on their meteorologic conditions and hydraulic characteristics. Most large rivers can be considered to be steep rivers: i.e., rivers in which the velocity is high enough to prevent a surface cover forming as on lakes. Instead, covers develop from the growth, downstream transport, and eventual accumulation of frazil-ice forms. As such, cover formation processes are sensitive to changes in flow and velocity. To evaluate the ice changes that result from regulation of winter flows, a freeze-up model, comprised of both thermodynamic and hydraulic algorithms, was applied to six distinct reaches along the Peace River between Taylor, British Columbia and the Slave River. Details of the model are provided in Andres (1995). The modelling work was augmented by exhaustive dissection of records and field notes collected at the main hydrometric stations along the Peace River (Andres, 1995; Prowse *et al.*, 1996b).

Prior to regulation, at flows generally less than 1,000 m^3/s, the river cooled from a maximum annual water temperature of approximately 22∞C to the freezing point at approximately the same rate as the declining air temperature (Figure 3.10a; also shown in this figure are modelled temperatures used in the modelling of ice conditions). In general, there was little streamwise gradient in temperature along the river except that due to natural variations in climate and weather. Discharge in the fall tended to be on a gradual decline and, because of the near-simultaneous cooling, ice could develop at a variety of locations at almost the same time.

In most years prior to regulation, ice began to form in early November, and was soon followed by the formation of a stable ice cover in the downstream reaches near Peace Point. Subsequent progression of the cover upstream resulted in an ice cover at the town of Peace River in late November to early December, and at Hudson Hope by early to mid-December

(Figure 3.11a). Under regulated conditions, winter discharge has been on average two to three-fold greater, tributary flow has become relatively less important, and a fall recession in flow is no longer typical (see Section 3.1). Given that warm hypolimnetic water (warm water from deep of the reservoir) is discharged from the reservoir, such increased flows have created a significant hydrothermal heat flux to the downstream river system. Figure 3.10b illustrates the extension of warm-water flows into the winter period as measured near the Bennett dam. A minimum is reached by January but even this remains above freezing (i.e., approximately 1.5∞∞C) throughout the winter period.

The high discharge of relatively warm water has delayed the time of freeze-up and shortened significantly the ice-covered season in upstream reaches (Figure 3.12a to e; dates refer to periods of "ice effects") but the timing of freeze-up appears not to have been significantly affected downstream of Vermilion Chutes, suggesting that this area is too far downstream to be affected by the additional warm-water outflow. Between approximately the town of Peace River and Fort Vermilion, the freeze-up date has been delayed by as much as one to two months. At Taylor and upstream of the British Columbia/Alberta border, formation of a complete ice cover has become the exception rather than the rule.

Regulation has also led to changes in the nature of the freeze-up process. Two types of cover normally form on a river: a juxtaposed cover and a consolidated cover. The former is created by the simple surface accumulation of ice floes (Figure 3.13) and is common to all but the steepest reaches. The latter develops from the collapse and downward telescoping (thickening) of an accumulating cover (Figure 3.14). This results when the internal strength of the cover is unable to resist the forces applied by its own downstream gravitational weight and the under-ice drag produced by the flow. Such forces are greatest in steeper reaches of a river and can be augmented by increased flow velocity, such as produced by regulation. A consolidated cover tends to be thicker and produce higher water levels (a result of backwater effects due to the thickness and roughness of the ice cover) than simple juxtaposed covers. Cover formation processes were modelled for the Peace River and the resulting ice thicknesses and stage increases expected at varying discharge for each of the four upper reaches are presented in Figure 3.15a,b.

Mild hydraulic gradients in the lower portions of the Peace River (i.e., below approximately the confluence of the Notikewin River, see Figures 2.1 and 2.4a) means that the ice cover will form by a juxtaposition process under even high winter discharge. Further upstream, steeper slopes mean that a consolidated ice cover can develop. Between the Notikewin confluence and Dunvegan, the steepening river slope can lead to the formation of either a juxtaposed or consolidated cover, the final result being dependent on a combination of temperature and flow. For typical post-regulation discharge, the air temperature must be at least -30∞∞C for a juxtaposed cover to form. To ensure that a juxtaposed ice cover develops and stage increases are minimized, the flow should be less than approximately 800 to 1,000 m^3/s for the normal range of expected air temperatures (see sample flow duration curves Figure 3.5). The increase produced by a juxtaposed cover is less than 2 m, but as great as 5 m for a consolidated cover with a corresponding ice thickness of about 4 m.

Further upstream, between Dunvegan and Hudson Hope, steep river slopes prevent the formation of a juxtaposed cover for any combination of discharge or air temperature.

Although the development of an ice cover in this area is now infrequent and short-lived, these temporary covers can approach 5 m in thickness and produce stage increases of up to 6 m.

In locations where consolidated ice covers develop and remain throughout the winter period, so do the elevated stages. In the reach upstream of the Notikewin River to approximately Dunvegan, increased water levels can exist for relatively long periods of time (two to three months): a duration that far exceeds that produced by an open-water flood of comparable stage increase. This can result in a supercharging of the groundwater conditions along the margins of the river, such as experienced at West Peace in the town of Peace River where high groundwater levels can lead to flooding of the basements of some residences.

3.4.2 Changes to the Winter Ice Season

Since regulation considerable information has accumulated about changes to the timing and duration of the ice season along the Peace River. As part of this study, an attempt was made to consolidate and standardize the available information. The main sources of information are the observer notes that form part of the standard hydrometric measurement procedure conducted by Environment Canada personnel and the recorder charts that continuously record water levels at the various hydrometric stations. Ancillary information was obtained from local sources such as newspapers and records from municipal "break-up date" lotteries.

Table 3.1 lists the hydrometric stations along the Peace River and the dates of available record. Locations of the stations are noted in Figure 2.1. Unfortunately, not all stations have the same period of available record and only one site (*Peace River at Hudson Hope*) has a lengthy pre-regulation record. Fortunately, however, the stations with the longest periods of record (*Hudson Hope, town of Peace River, and Peace Point*) are dispersed well along the full length of the Peace River, thus permitting an evaluation of temporal and spatial trends in the ice regime data. Table 3.2 provides the summary statistics regarding the mean and standard deviation of freeze-up and break-up dates, and duration of the seasonal ice regime, for the pre-regulation and post-regulation periods. Note that the years 1968 to 1972 have been excluded from this data summary because they are representative of a highly anomalous flow regime that prevailed only during the filling of the reservoir. As evident in Figure 3.12, however, they do appear to have cause major disruptions to the ice regime. Also provided in Table 3.3 are the results of statistical tests to evaluate for significance differences between the mean dates or season duration. This could not be assessed for some stations simply because the general winter conditions changed from ice-covered to open-water or intermittent ice cover, with the introduction of the regulated regime, most prevalently in the upper reaches of the Peace River closest to the point of regulation.

The ice-regime record for the Peace River at Hudson Hope (uppermost station) includes an interval from 1917 to 1922 but the most recent continuous record did not begin until 1949. Prior to regulation, the main freeze-up cover was in place by mid to late November. Records indicate that the winter ice cover was often intermittent with the latest indications of ice occurring by late April to early May. Following regulation, this station has not reported any significant ice effects.

As described in the previous section, it is the supply of warm hypolimnetic water from the Williston reservoir that produces the significant retarding of freeze-up dates to as far downstream as approximately the town of Peace River. The data in Table 3.3 and Figures 3.11a and 3.12 confirm this. Overall, there has been a significant decrease in the average length of the ice-covered period at the town of Peace River, decreasing from 124 days in the pre-regulation period (averaged from 1958 to 1967) to approximately 97 days following regulation. The modifier "approximately" is used in this case simply because of the problems in identifying a true freeze-over (establishment of complete ice cover) date in many of the years following regulation. It appears that this site can experience a number of short-duration ice covers before establishing a complete cover that will remain intact until the spring break-up. The advancing front of a freeze-up cover is often characterized by a cycling between freeze-up and break-up conditions (see paragraph below). The recording of such conditions near the town of Peace River may simply indicate this station now occupies a position in the post-regulation ice regime near the uppermost point of complete freeze-up conditions. It may also be due in part to a greater emphasis being placed on the observation of ice conditions since regulation of the river. In either case, there has been a significant change in the occurrence of freeze-up conditions near the town of Peace River and this, more than the change in the date of spring break-up, accounts for a shortening in the overall ice season. The mean date of spring break-up at the town of Peace River has not significantly changed but the data shown in Figure 3.12c suggest that it might be more variable since regulation. A significance test on the coefficient of variation does not confirm this, although the lack of significance could be more a function of the small sample size.

An added point to be stressed about the break-up dates for the town of Peace River shown in Figure 3.11b is that they refer to the spring break-up. Significant mid-winter break-ups, have also occurred at the town of Peace River, the most notable being in February, 1992 (Fonstad, 1992). In such a break-up, there is limited temporal distinction between the times of freeze-up and break-up. Historically (pre-regulation), this site experienced a fall freeze-up but, with regulation, the arrival of the freeze-up has been delayed much later in the fall or into the main winter period. With an intense period of warming in the winter, such as occurred in 1992, a break-up event can be precipitated almost concurrently with the initial establishment of the freeze-up cover. The potential hazards, responsibilities and design of safe operating procedures associated with such events are currently the focus of internal-agency reviews and a joint British Columbia-Alberta Task Force (British Columbia-Alberta Task Force, 1992).

Further downstream, some records exist for Fort Vermilion but they are of insufficient length or quality to permit any valid assessment of temporal or spatial data trends. Thus the only remaining data are available for the site of interest, Peace Point, near the Peace-Athabasca Delta. While this is a remote site, it has an excellent record of ice conditions. As the data in Figures 3.11/ 3.12e and Table 3.2 indicate, this site has not experienced any significant change in the timing of freeze-up or break-up, and thus the overall ice season.

In summary, regulation appears to have significantly altered the timing and duration of the ice regime upstream of the town of Peace River. Closest to the dam, the ice season has been virtually eliminated. Further downstream only an intermittent ice cover develops and, at the town of Peace River, there has been a significant delay in the initiation of freeze-up and the overall ice season. At the downstream extremity of the Peace River, regulation does not appear to have affected the timing or duration of the main ice season. As outlined in the subsequent section, however, there have been significant changes to the temporal severity of break-up conditions in the downstream reaches. The role of various factors controlling this variability is outlined next.

3.4.3 Changes to Flooding of the Lower Peace River

At the outset of the NRBS study, it was recognized that the Peace-Athabasca Delta (PAD) had been experiencing a severe drying trend since the mid-1970's. This was most apparent in the perched-basin environment of the PAD, especially near the Peace River. The last time these basins were flooded was 1974. Although there had been extensive attempts to restore water levels within the Delta through the construction of rock-filled weirs (Section 3.2) this has only been successful for the large lake and channel systems directly connected with the main flow system of the Athabasca, Peace and Slave rivers. Drying has continued in the higher perched basins because of the lack of large overbank floods and apparently led to changes in vegetation succession (Section 3.7).

A common perception has been that lower flows on the Peace River have precluded flooding of the perched-basins. In addition, there were numerous anecdotal references within the Delta literature and opinions expressed by local inhabitants that ice jams also played a role in some flood events. No analysis had been completed, however, to determine whether such events were more or less important to flooding than open-water floods. This became the objective of one of the NRBS studies.

3.4.3.1 *Open Water Flood Peaks*

Because of the remoteness of the Peace River near the Delta, hydrometric data are relatively scarce except those collected at Peace Point (Figure 2.1). This is the location of the closest (approximately 70 km upstream of the main Delta area) hydrometric station to the Peace-Athabasca with a pre- and post-regulation flow and water-level record. The effect of regulation on the monthly flows at this site is evident in Figure 3.4. The pre-regulation peak-monthly flows typically occurred in June ranging from a low of 5,950 $m^3 s^{-1}$ to a maximum of 9,790 $m^3 s^{-1}$ and averaged 7,482 $m^3 s^{-1}$. With the seasonal adjustment to flow, these figures all decreased by some 3,500 $m^3 s^{-1}$, translating into a decrease of open-water levels ranging from approximately 1.75 m, at the higher maximum mean-monthly flows, to 3.25 m for the minimum mean-monthly flows (-2.56 m for the change in mean-monthly flows). More specifically, Figure 3.3 shows the peak-annual water levels achieved under open-water flow conditions before and after regulation. For the eight-year pre-regulation period, peaks averaged 217.5 m. whereas the post-regulation period averaged 215.4 m. This 2.1 m decline in instantaneous peaks is comparable to that for the mean-monthly values.

Notably, the post-regulation data include the largest flow event on record for the Peace River. In 1990, the Peace River discharge reached 12,600 $m^3 s^{-1}$, 700 $m^3 s^{-1}$ greater than the previous high recorded in 1964 prior to regulation. Significantly, however, even this historically-high open-water flood failed to recharge the high-elevation perched basins. It is estimated that an open-water flow in the order of 14,000 $m^3 s^{-1}$ is required to overtop the Peace River banks near the Delta (i.e., at Sweetgrass Landing near the mouth of the Claire River). The major conclusion of this analysis is that open-water floods have not been responsible for the overbank flooding of the high-elevation perched-basin regime. The next step was to evaluate the effectiveness of ice jams.

3.4.3.2 *Ice-induced Backwater Peaks*

Again, because of the lack of any other suitable data, hydrometric records from Peace Point were used to provide the index of ice-related flooding near the Delta. Peak-instantaneous, water level data during the spring break-up were extracted directly from original hydrometric chart recordings for the period 1962-1992 (although chart records of break-up are only available beginning 1962, published flow records exist from 1959). Figure 3.16 shows these data and the open-water rating curve for the Peace Point station. Notably, peak break-up water levels for seven break-up years exceed that produced by the 1990 open-water event - some by as much as 2 m. Furthermore, these levels were produced by Peace River spring flows of a 1/3 to a 1/2 that which produced the 1990 open-water event. Three of the large break-up events occurred biennially during the 6-year record preceding regulation and four within the subsequent 25-year period. All the large-order events were corroborated by the results of published surveys of local/traditional knowledge and/or ancillary data contained within historical archives.

3.4.3.3 *Summary of Flood Peaks*

In summary, the hydrometric analysis of the Peace Point hydrometric record in conjunction with various historical and local-knowledge data confirms that open-water floods have been ineffective in producing high-elevation floods along the Peace River adjacent to the Delta. Even the historically high flow event of 12,600 $m^3 s^{-1}$ did not produce a flood of sufficient magnitude to flood the Delta. Over the period of hydrometric record, backwater produced during river-ice break-up has contributed to water levels that often exceed the water level produced by the 1990 historically-high open-water event. Based on data from the Peace Point hydrometric station, this occurred on a biennial basis in the 1960's prior to regulation but only three times since.

3.4.3.4 *Break-up Flooding-Hydrometeorological Characteristics*

In view of the apparent decrease in the frequency of large ice-jam floods, a second objective was to explain the hydrometeorological conditions, including the effects of flow regulation, that could have lead to a decrease in ice-jam flooding. In general, the severity of river-ice break-up is a function of the hydrometeorological conditions that precede the period when the cover is finally dislodged from its "overwintering" position. Break-up activity is usually classified into two types: thermal or overmature, and dynamic or pre-mature (the latter also often referred to as mechanical). Mature break-ups are similar to those which occur on a lake where the forces exerted by water flow are at a minimum. The hydrometeorological conditions that produce this on a river include low spring runoff, usually the result of a small winter snowpack or protracted melt, and extensive decay of ice thickness and strength. Ultimately, the remnant ice cover is so thermally weakened that it can be dislodged by discharge comparable to the low-flow winter period. Although the remnant ice may jam downstream, it rarely remains long enough or develops sufficient thickness that it creates significant backwater.

Quite an opposite set of hydrometeorological conditions characterize dynamic break-up events. This usually includes the generation of a large spring flood-wave produced by the rapid melt of a large winter snowpack. Such conditions offer little possibility for the thermal decay of the river ice cover. Thus the advancing flood-wave must push into a reasonably competent ice sheet, one that can only be dislodged by large upstream forces such as created by large ice-jam surges. As the strong, thick ice passes downstream it can jam and create significant backwater flooding.

Overall break-up and the associated ice jamming are governed by a balancing of upstream forces and downstream resistance. Components of these were evaluated to determine whether they exhibited any temporal trend and whether their variation was correlated with break-up flood levels. Three factors affecting the downstream resistance were evaluated: winter ice growth, spring ablation (melt) and pre-break-up changes in ice strength. Evaluation of all three components required development and calibration of various heat flux models for application in the lower Peace River. A major obstacle to this aspect of the study was the quality (low level of detail) or simple lack of meteorological data.

3.4.3.5 *Resistance to Break-up; Temporal Trends in Pre-Break-up Ice Thickness*

The first step in the analysis of ice thickness was to calculate the expected difference in ice growth that would result from additional fluid friction produced by the increased winter flow (due to regulation). Assuming all such heat is transferred to the overlying ice cover, it was determined that on average the additional winter flow would result into a melt-equivalent of approximately 56 mm for the four-month winter period. The only regular measurements of ice thickness on the lower Peace River are those conducted by the Water Survey of Canada (WSC) near Peace Point. A detailed inspection and analysis of the WSC hydrometric survey revealed that prior to regulation (records beginning in 1959), the pre-break-up peak ice thickness averaged 0.86 m ($s = 0.08$; $n = 9$) while that for the post-regulation period was actually 3 cm greater ($s = 0.13$; $n = 15$), although the difference is not statistically significant ($a = 0.5$). Recognizing that there are a number of errors associated with the WSC data, a degree-day model was also employed to calculate peak-ice thicknesses as shown in Figure 3.17. Unfortunately, relevant meteorological data were only available beginning in 1963. Overall the data suggest that there may be some form of decreasing trend with time, but this would appear to occur in the mid-1970's and not at the point of regulation. The step-like decrease of modelled thicknesses in approximately the mid-1970's suggests that the "coldness" of the main ice growing season (date of freeze-up to date of first significant spring melt) may have changed. The modelled, average peak thicknesses were 0.96 m (s = 0.033; n = 5) for the period 1963 to 1967 (pre-regulation) and 0.94 m (s = 0.061; n = 18) for the longer post-regulation period (1972 to 1992). Again, these two mean values are not statistically different.

3.4.3.6. ***Resistance Factors: Temporal Trends in Pre-break-up Ice Melt and Strength***

The final resistance of ice to break-up and ice jamming also depends on the degree of melt and decay it experiences in the spring period. Two approaches were used to model the magnitude of the spring melt periods; the type of approach being again dependent on available meteorologic data. It was possible to employ a detailed energy-balance approach from 1963 to 1979 but only a simplified degree-day model for 1963 to 1992.

Results of the energy-balance modelling revealed that most spring melt periods were dominated by radiative melt (Figure 3.18), thus also indicating that significant changes probably also occurred in the ice strength (changes in the strength of 0∞C-ice being primarily determined by absorption of short-wave radiation). In modelling changes in ice strength, however, no clear temporal pattern emerged nor was there a significant relationship between years of severe break-up (high ice-related backwater) and break-up ice strength or the overall pre-break-up heat flux (Figure 3.19). Such analysis was only possible for a relatively small number of years, possibly precluding the identification of any significant trends or relationships.

The lack of suitable meteorological records prior to 1963 also made it difficult to compare the pre- and post-regulation periods using the degree-day analysis model. Although there is no significant difference for the melting degree-day values (accumulated during a defined pre-break-up melt period) associated with the pre- and post-regulation periods, nor a strong relationship with break-up backwater levels, there does appear to be a tendency to more intense melt conditions after the mid-1970's as shown in Figure 3.18. In an attempt to identify any potential temporal trend in the data more readily, they were analyzed by means of residual mass curves, a method commonly used in the analysis of hydrometeorological data Figure 3.20. Again, as indicated by the inflection point on this curve, there appears to have been a shift to years of generally greater pre-break-up melt after 1979. Such enhanced heating would lead to increased thinning of the ice cover and, all other factors being equal, an ice cover less suitable to the production of severe ice-jam flooding.

3.4.3.7 *Resistance Factors; Summary*

In summary, the available data do not support the hypothesis that there has been a significant change in the three factors that control ice-cover resistance (i.e., winter thickness, pre-break-up melt, and mechanical strength) as a result of regulation. Although some minor reduction in thickness associated with additional fluid friction may occur, it is no greater than that expected from inter-annual variations in meteorological conditions. Moreover, there is some evidence to suggest that there have been temporal shifts in the winter and, more significantly, the pre-break-up melt period. Given the potential significance of such shifts to the probability of ice-jam flooding, it is recommended that more detailed climatic studies be undertaken of these shifts to determine their magnitude, origin and other hydrometeorlogical significance. Further discussion is provided later in this report about other temporal trends in hydrometeorological factors important to spring flooding of this area.

3.4.3.8 *Driving Forces to Break-up: Flow Contributions at Break-up*

In the case of ice jams, the magnitude of the jam is very much a function of the flow at the time of formation. In response to a commonly-held hypothesis that reduced flows have been responsible for reduced ice-jam activity, an analysis was completed of spring flows that have contributed to break-up events on the Peace River near the PAD.

An analysis of data from main-stem hydrometric stations revealed that on average more flow is carried by the Peace River at the time of break-up at Peace Point under regulated conditions than under pre-regulation conditions. This is apparent in the mean flow values shown in Figure 3.21. For example, the mean pre- and post-regulation flows for April 15 more than doubles from approximately 800 m^3/s to 1800 m^3/s. This difference steadily declines until May, after which the pre-regulation values become greater. Notably, a majority of all break-ups and the recordings of peak break-up water levels have occurred at the Peace Point site before May 05.

Recognizing that average conditions might obscure specific processes, and that the pre-regulation record for Peace Point is very short, specific flow conditions were also analyzed for large flood years. Figure 3.21 shows the hydrographs for the 3 major Peace River stations for the spring break-ups of 1965 and 1974 - major events before and after regulation with reliable hydrometric records. More importantly, these are also two years known to be years of very large ice-jam flooding of the Peace-Athabasca Delta (see Section 3.4.3.2).

In both example years, it was found that the Peace River at Peace River Town was experiencing a major spring-flow event at the time of break-up near the Peace-Athabasca Delta (flows were lagged based on the hydraulic flood-routing model described in Section 3.3). By contrast, flow from upstream of Hudson Hope (point of regulation) was much less significant (Figure 3.21). An analysis of the all the major tributary flow along the Peace River revealed that many of the downstream tributaries were experiencing abnormally-high spring runoff that would significantly contribute to the Peace Point break-up. This was particularly true for the Smoky River, which drains almost one quarter (23%) of the total Peace River catchment between Hudson Hope and Peace Point, an area equivalent to 72% of that above the point of regulation (above Hudson Hope). The Smoky was found to be the dominant source of spring runoff whereas the flow contributions from above Hudson Hope were relatively small. Similar conclusions emerged when all years of break-up were analyzed. Between the two periods, 1962-67 (pre-regulation) and 1972-1992 (post-regulation), there has been a significant change in the average contribution provided by headwater and downstream flows. From 1962-1967, the upstream flow contributed an average 17% of the flow producing peak break-up levels near the Peace-Athabasca Delta, whereas the Smoky River alone contributed almost twice as much (average of 28%). The larger importance of flow contributed from the downstream portion of the basin (below the point of regulation) compared to that from the upstream becomes more apparent if all the downstream tributary flow is combined, (see Figures 3.22a,b) , although the Smoky River still dominates.

Since 1972, the percentage of the flow upstream of Hudson Hope has on average become relatively more important to Peace Point break-up conditions, rising from an average 17% to 33%. As the hydrographs of Figure 3.4 suggest, this reflects the change to sustained higher flows throughout the winter period. By contrast, the mean flow of the Smoky River between the two periods has declined: its average contribution decreasing from 28 to 15%. Decreases in the relative importance of the downstream flow are related to the increasing regulated flows but further analysis also revealed there has been a decrease in the size of the spring snowpacks driving spring runoff from the tributaries. Figure 3.23 shows residual mass curves for total winter precipitation and size of the spring snowpack for Grande Prairie sites on the Smoky River. It appears that smaller snowpacks developed in the mid-1970's, possibly related to changes in climatic circulation patterns as found in British Columbia (Moore and McKendry, 1996).

Figure 3.12 a) Ice conditions for mainstem Peace River stations:
Hudson Hope 1917-93

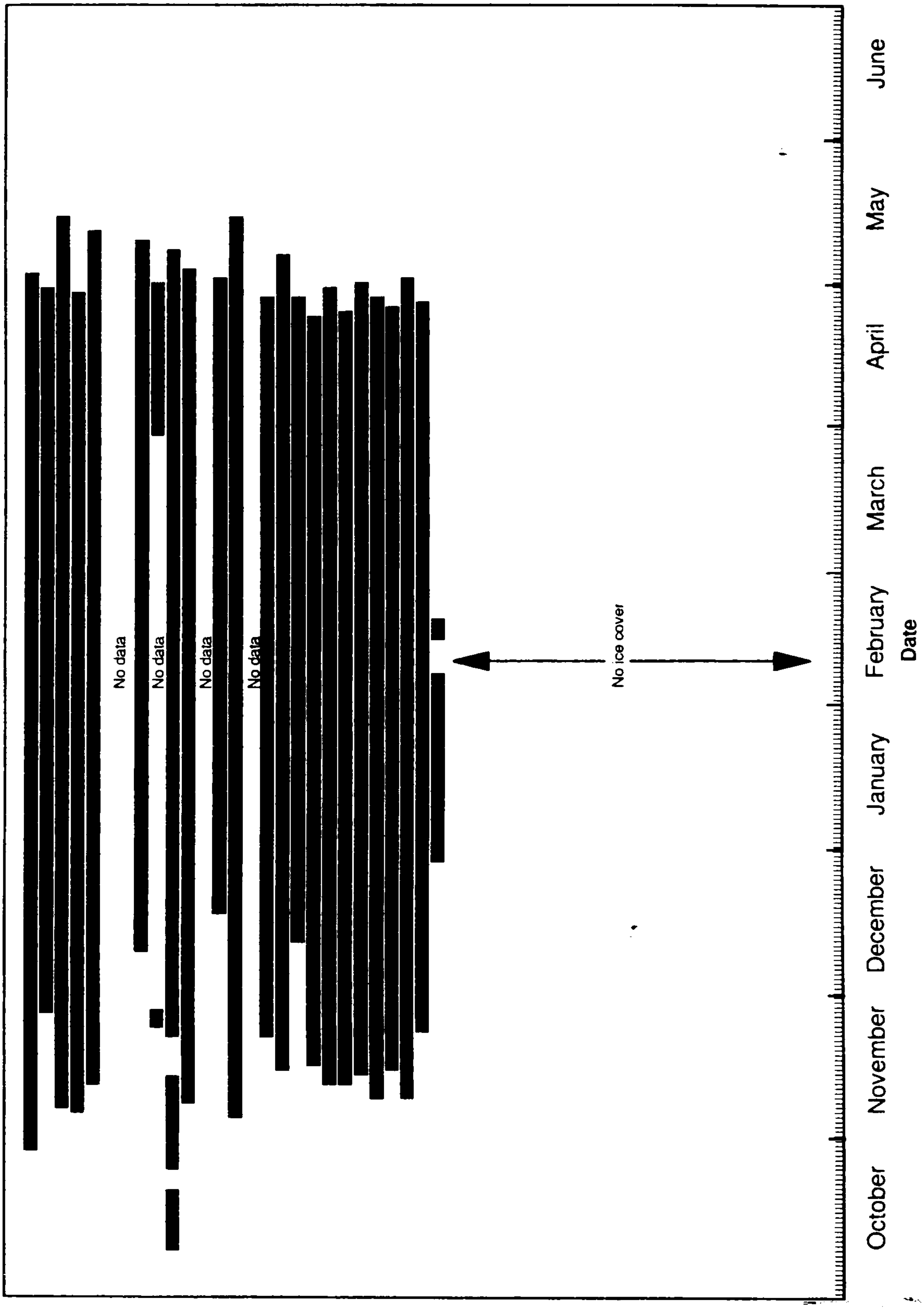


Figure 3.12 b) Ice conditions for mainstem Peace River stations:
Taylor 1917-93

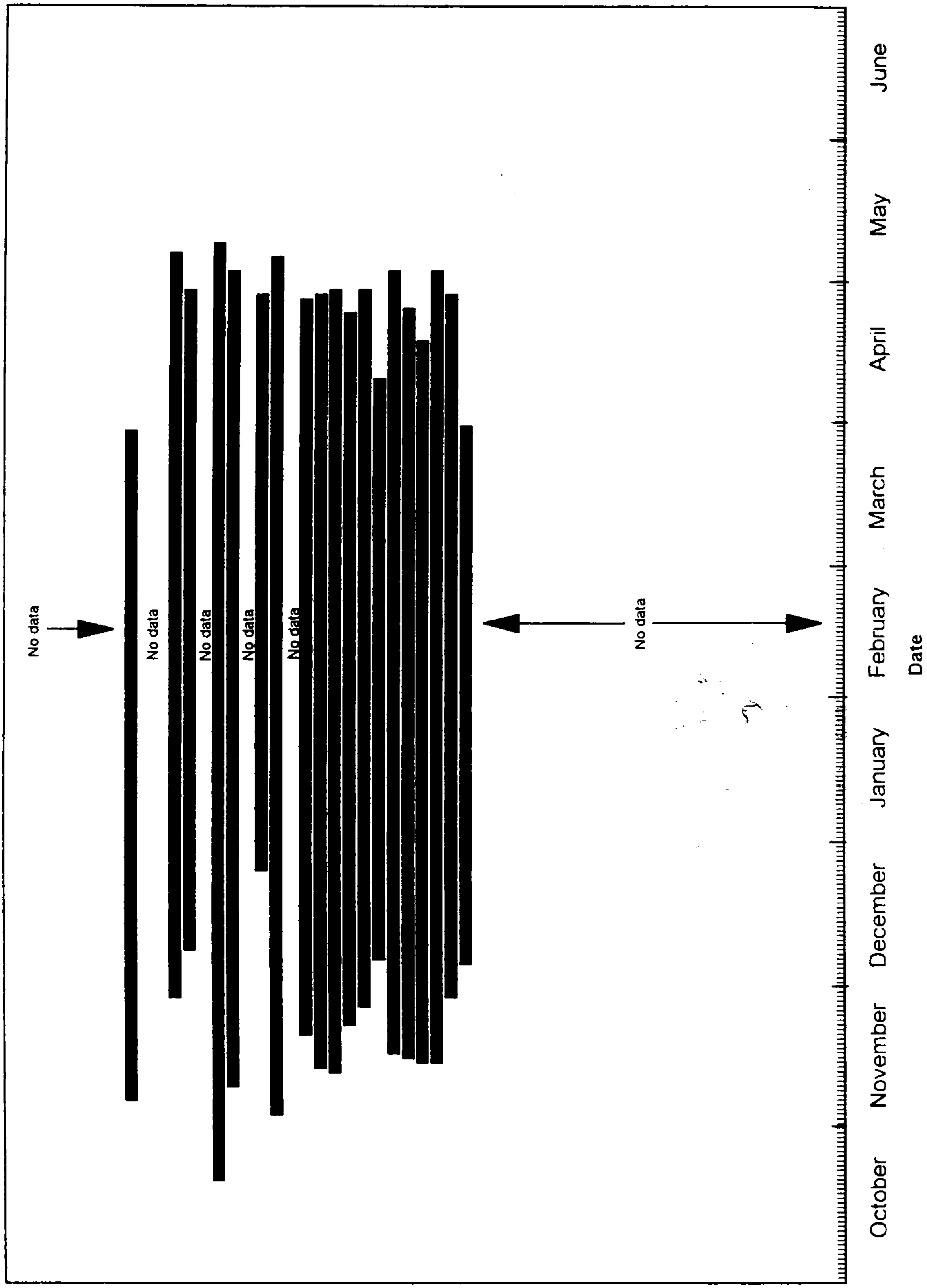


Figure 3.12 c) **Ice conditions for mainstem Peace River stations: Peace River 1917-93**

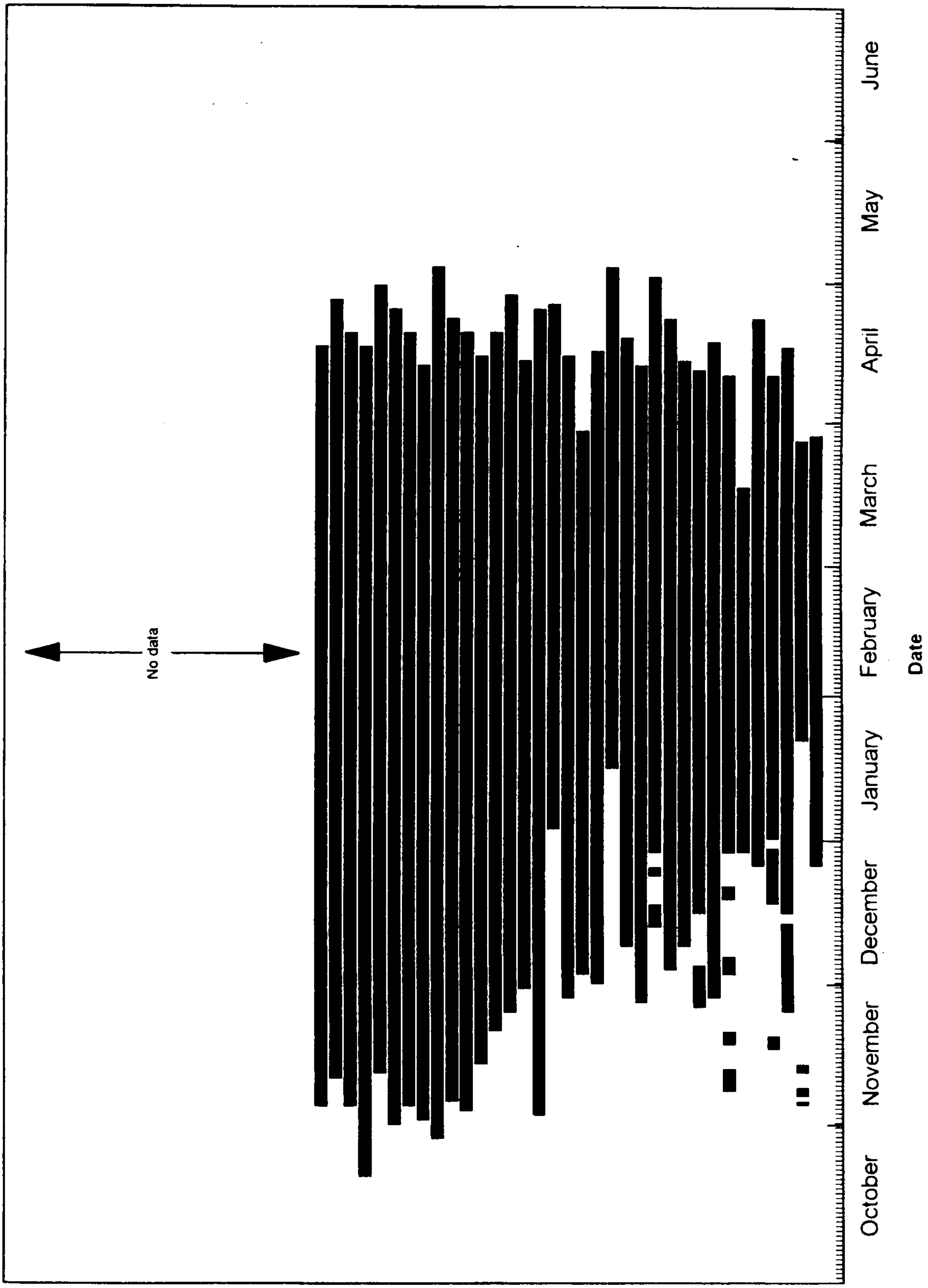


Figure 3.10 a) Comparison of measured and calculated water temperatures at Peace River prior to regulation (Andres, 1995)

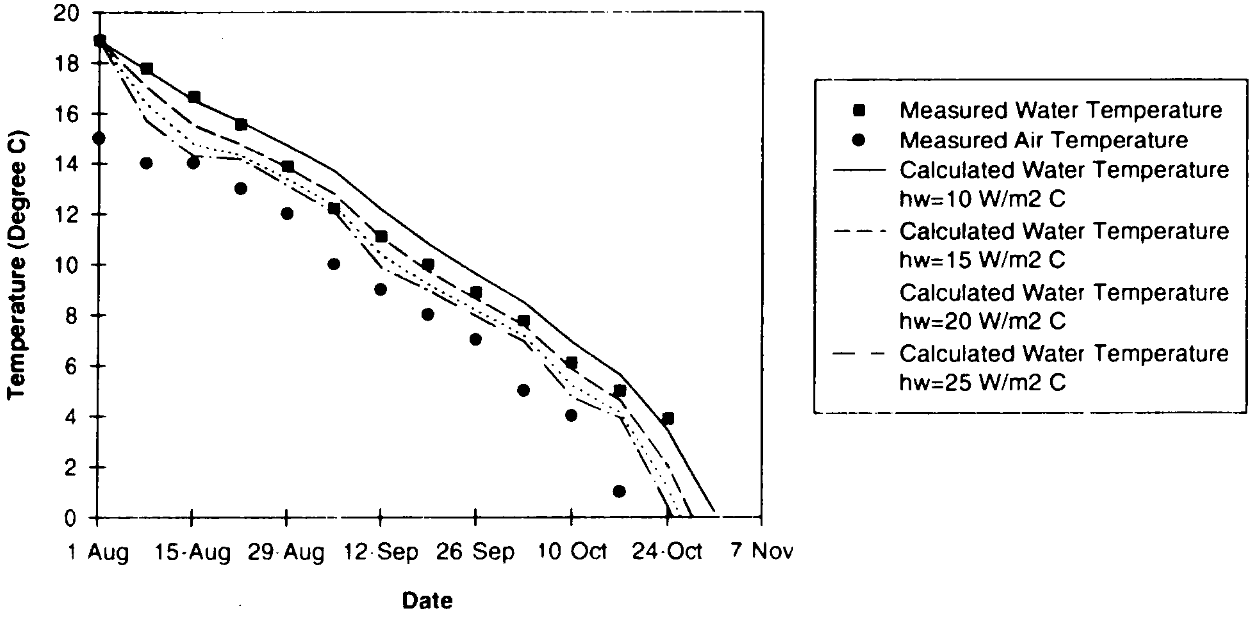


Figure 3.10 b) Monthly water temperature downstream of the Bennett Dam (Andres, 1995)

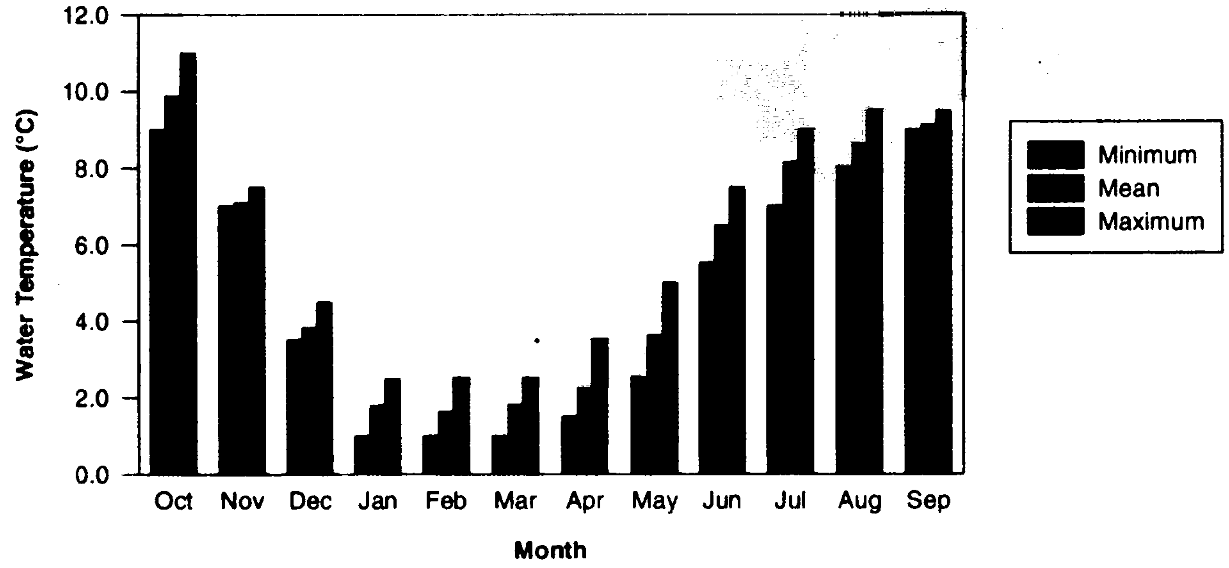


Figure 3.11 Comparison of pre- and post-regulation freeze-up and break-up dates (modified from Andres, 1995 and Prowse et al., 1996)

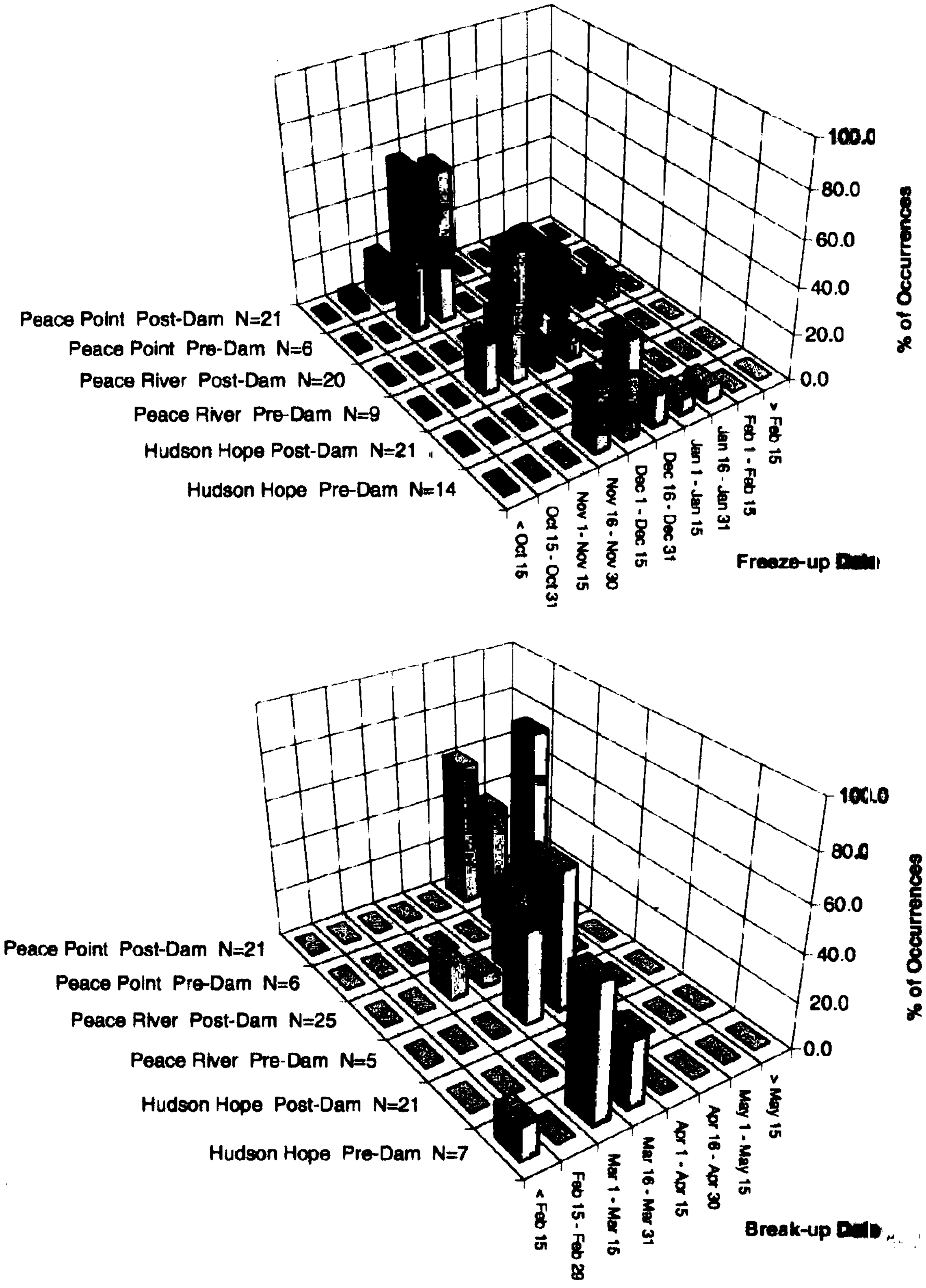


Figure 3.12 d) Ice conditions for mainstem Peace River stations: Fort Vermilion 1917-93

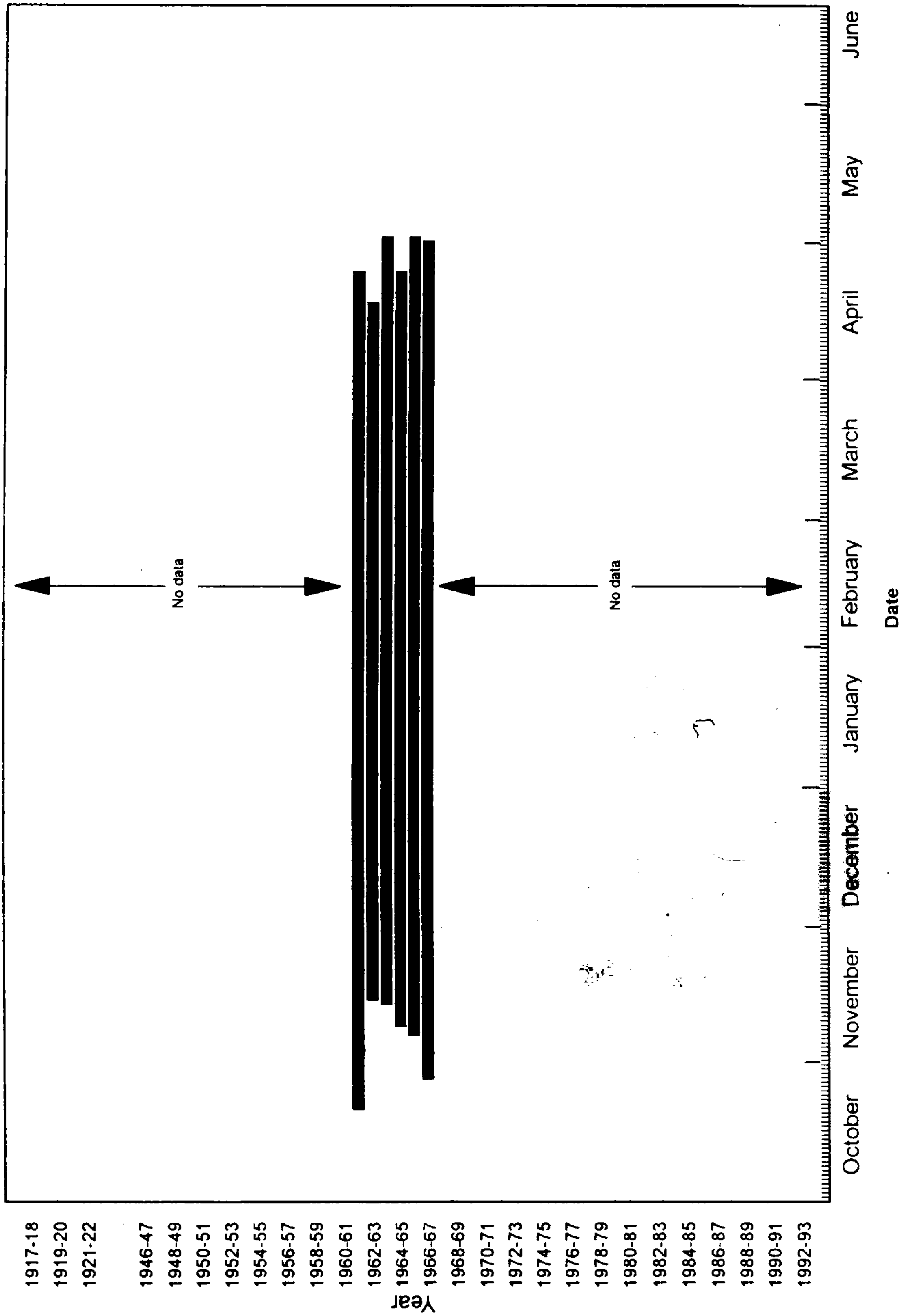


Figure 3.12 e) Ice conditions for mainstem Peace River stations:
Peace Point 1917-93

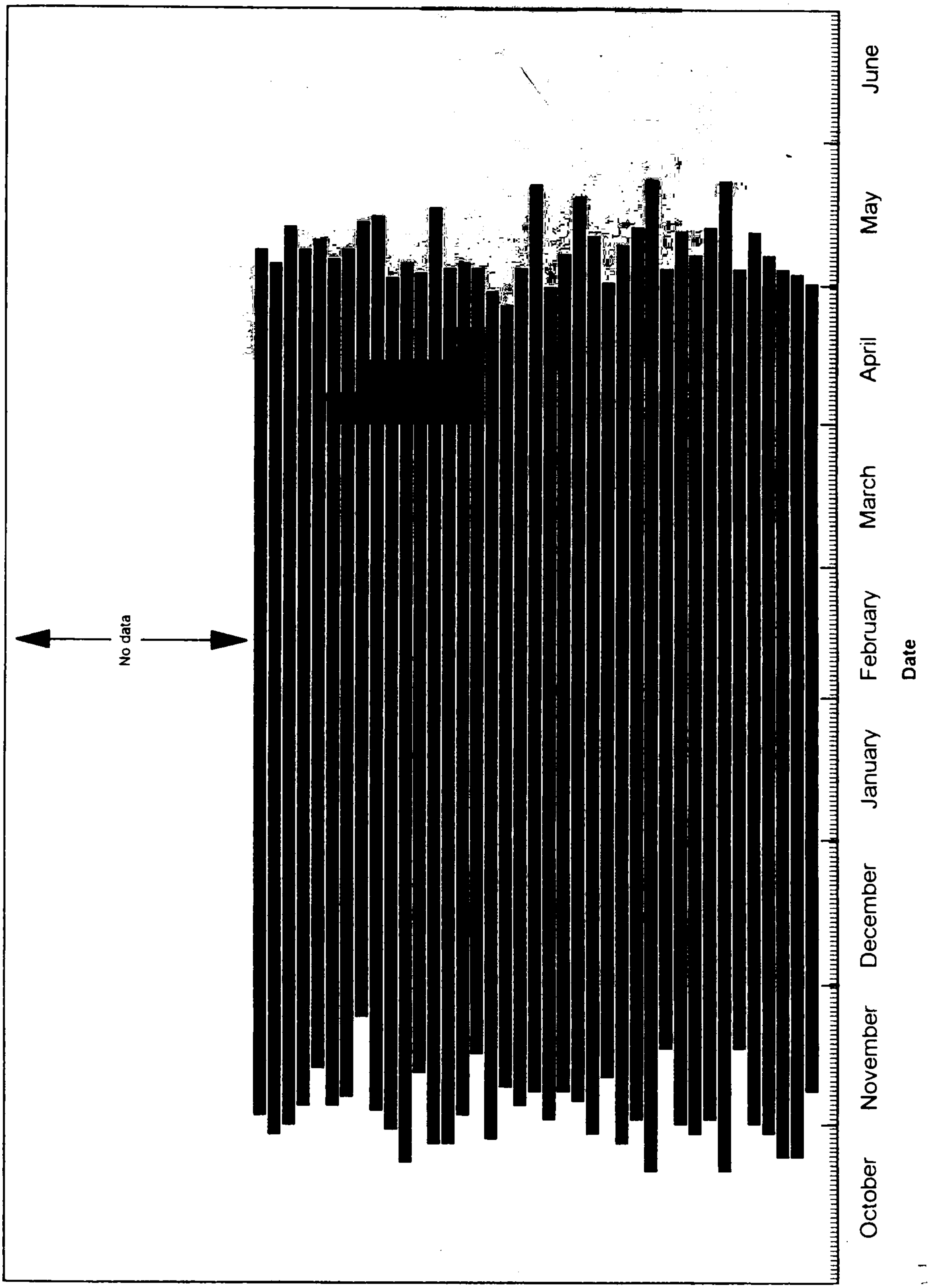


Figure 3.13 Example of juxtaposed ice cover.

Figure 3.14 Example of consolidated ice cover.

Figure 3.15 a) Ice cover thickness in a consolidated ice cover (Andres, 1995).

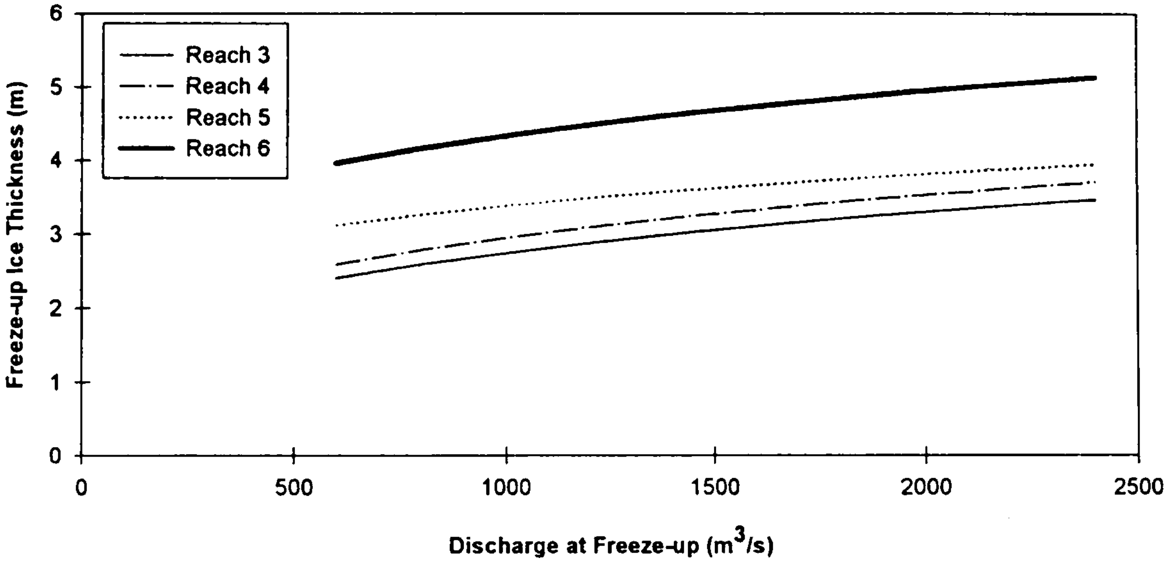


Figure 3.15 b) Freeze-up stage increase in a consolidated ice cover (Andres, 1995).

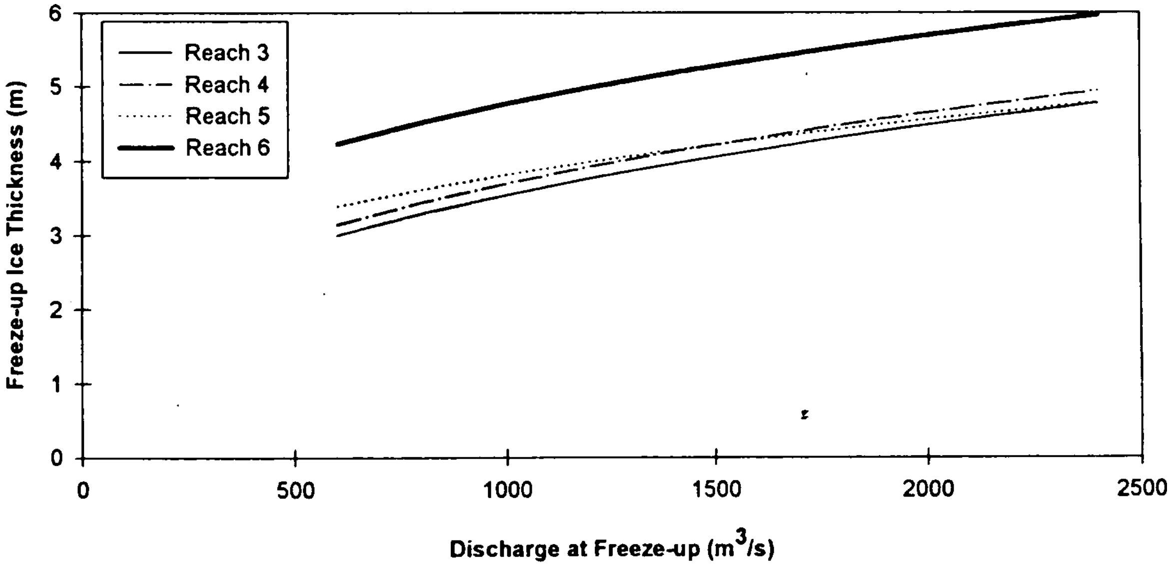


Figure 3.16 Annual peak water level versus discharge under break-up conditions (Prowse and Lalonde, 1996)

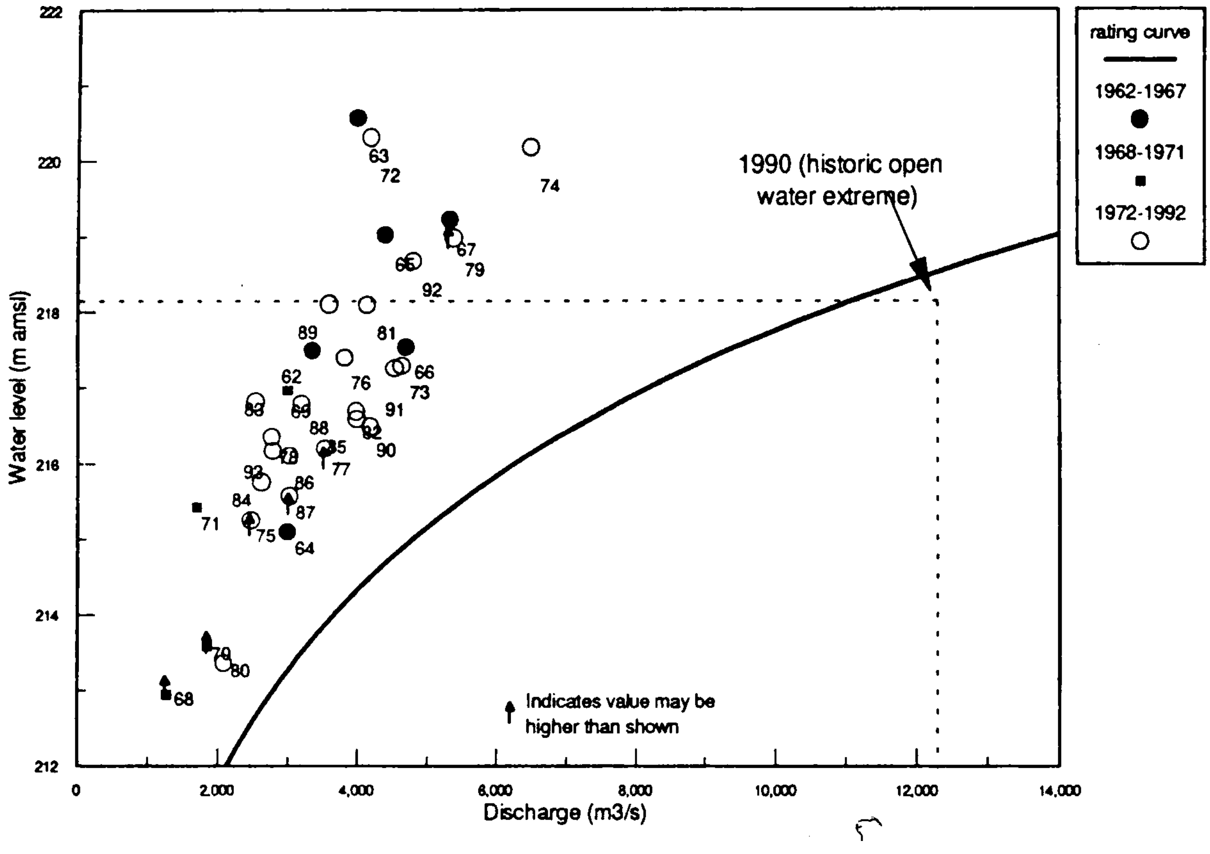


Figure 3.17 Modelled ice thickness based on freezing degree day index (Prowse et al., 1996b).

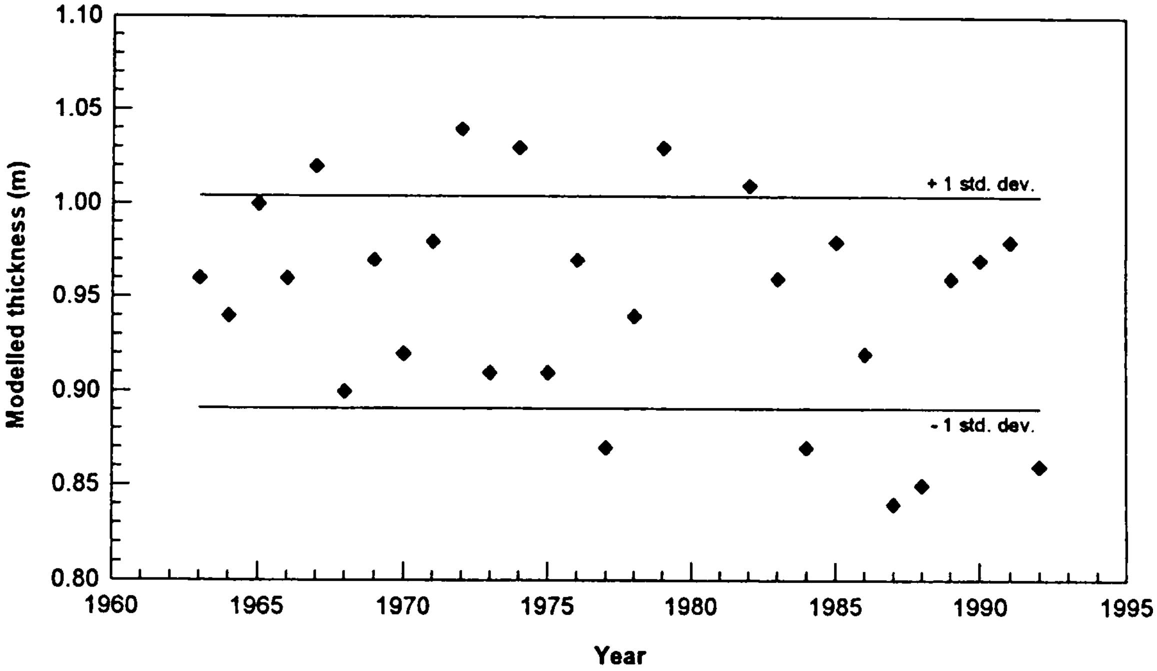
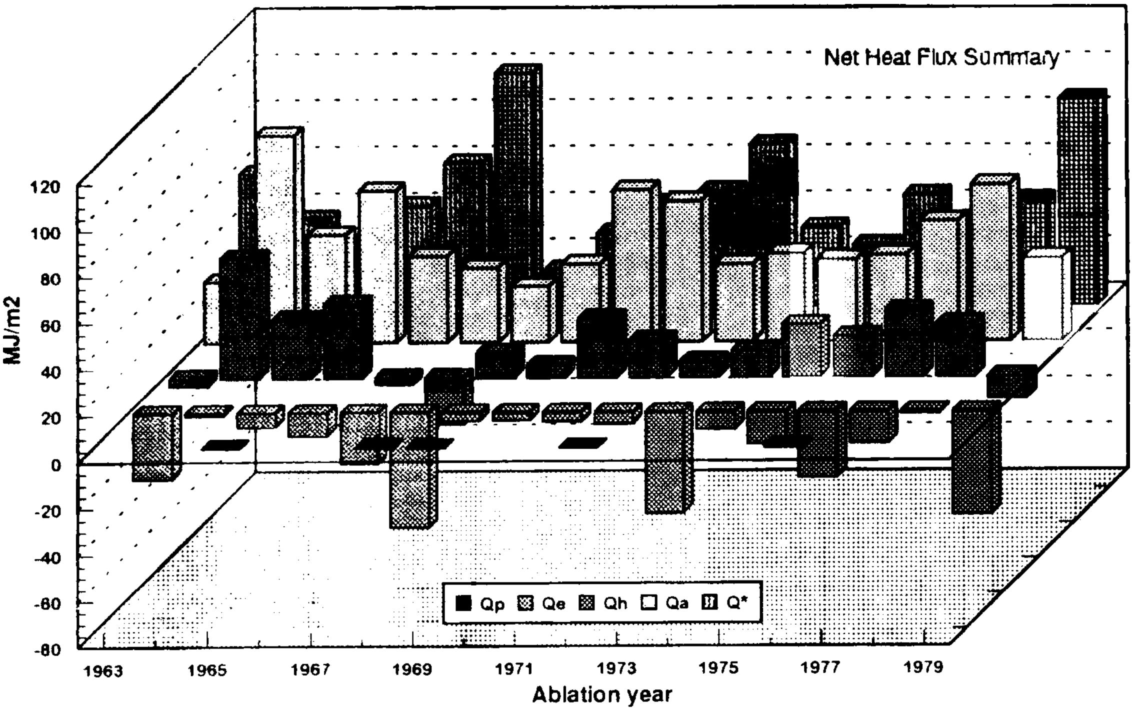


Figure 3.18 Neat heat flux and radiative flux for the Peace River 1963-79 (Prowse et al., 1996b).



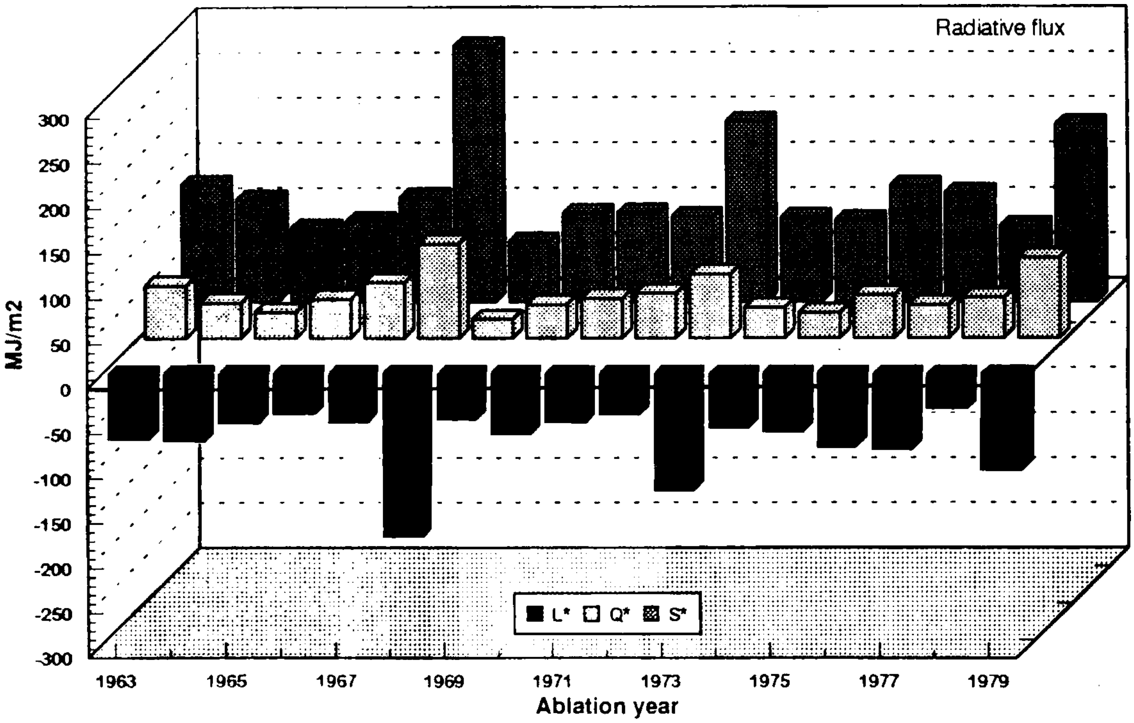


Figure 3.19 Net heat flux vs. stage increase for Peace Point 1963-79 Prowse et al., 1996b).

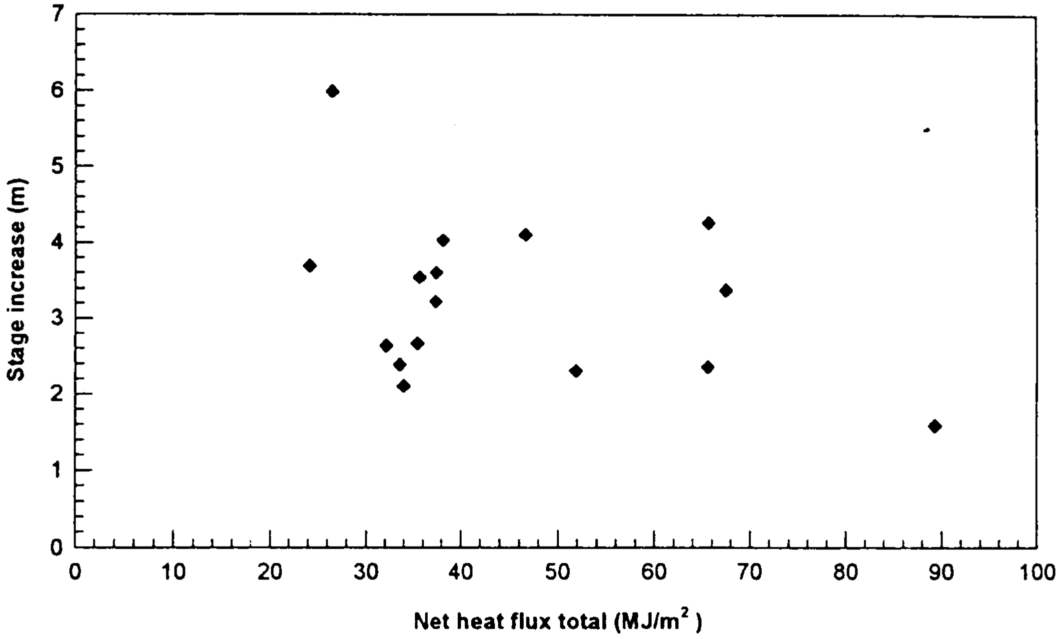


Figure 3.20 Residual mass curve - melting degree days from first day of melt to break-up for Fort Chipewyan 1963-92 (Prowse et al., 1996b).

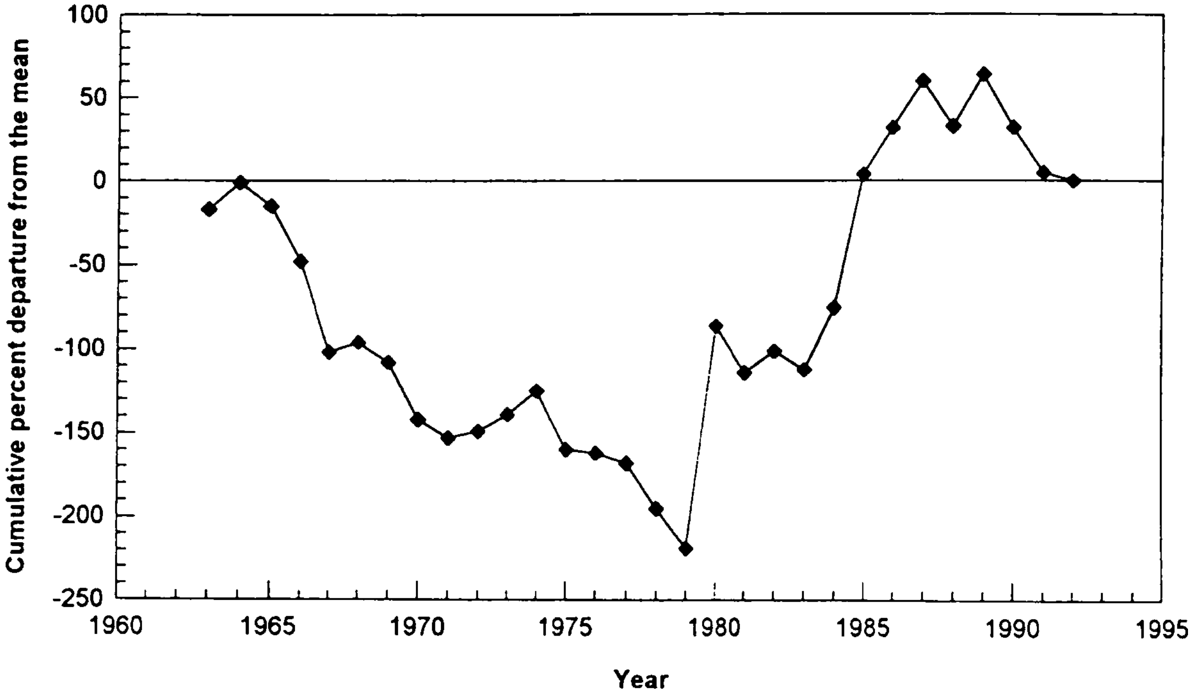


Figure 3.21 Spring hydrographs for large pre-regulation flood year - 1965, and a large post-regulation flood year - 1974 for three Peace River mainstem sites (Prowse et al., 1996b).

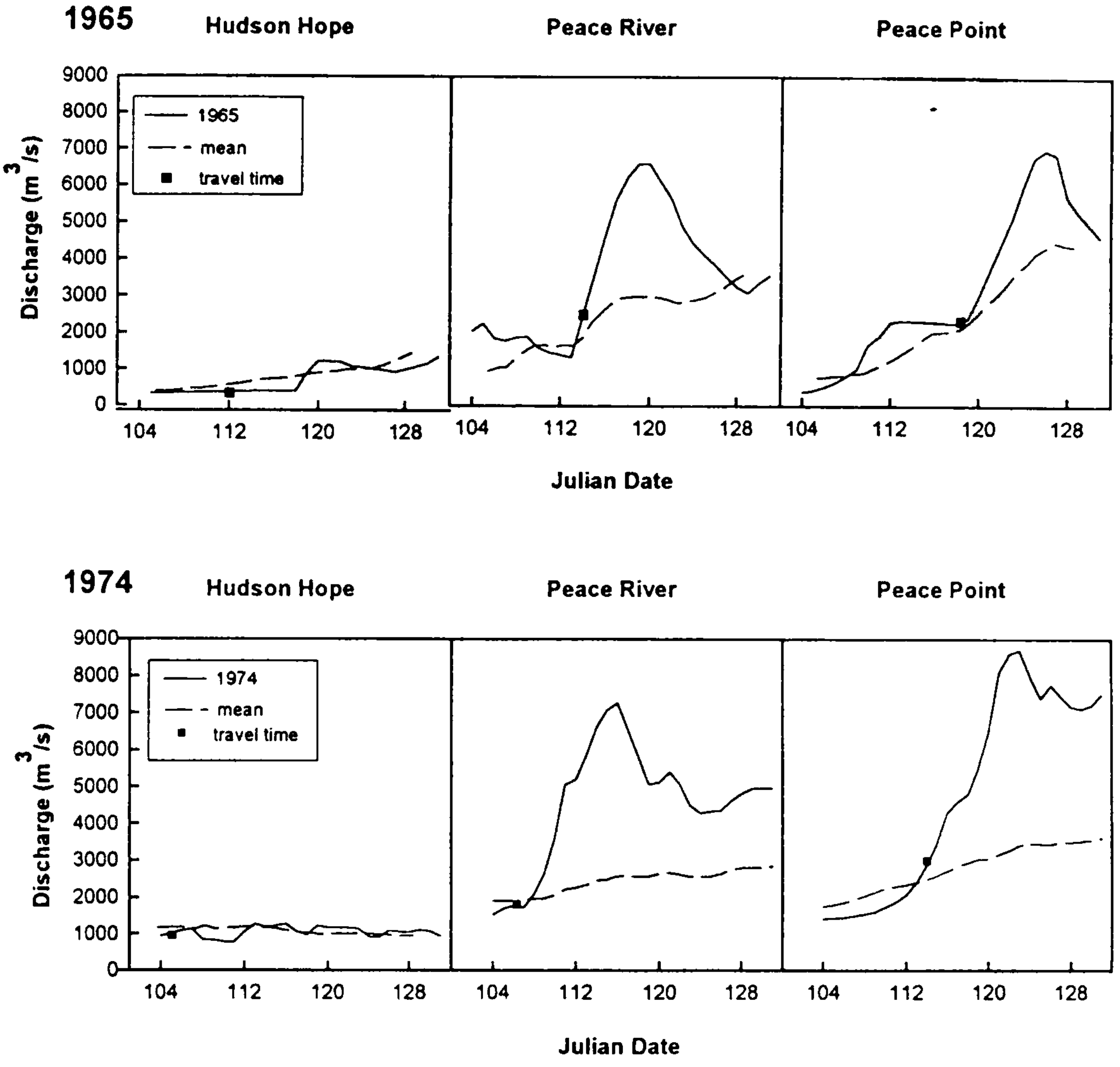
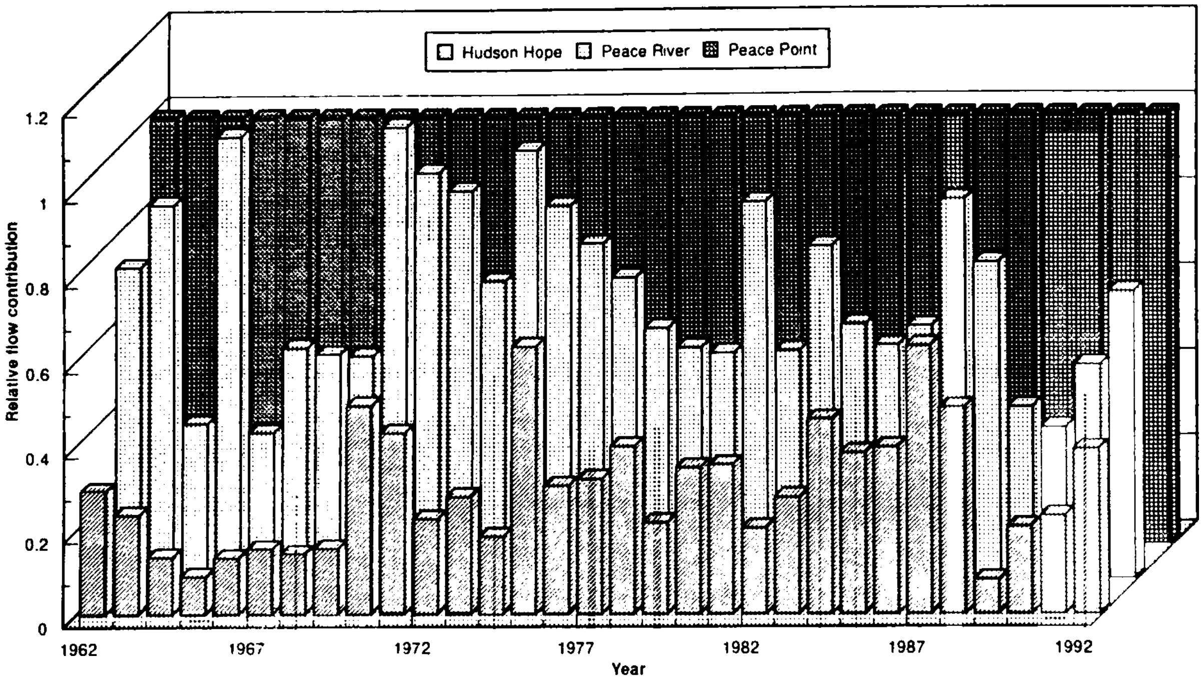


Figure 3.22 Flow contributions relative to Peace Point at time of break-up peak stage (Prowse et al., 1996b).

a) Peace River mainstem stations



b) Tributaries to the Peace River.

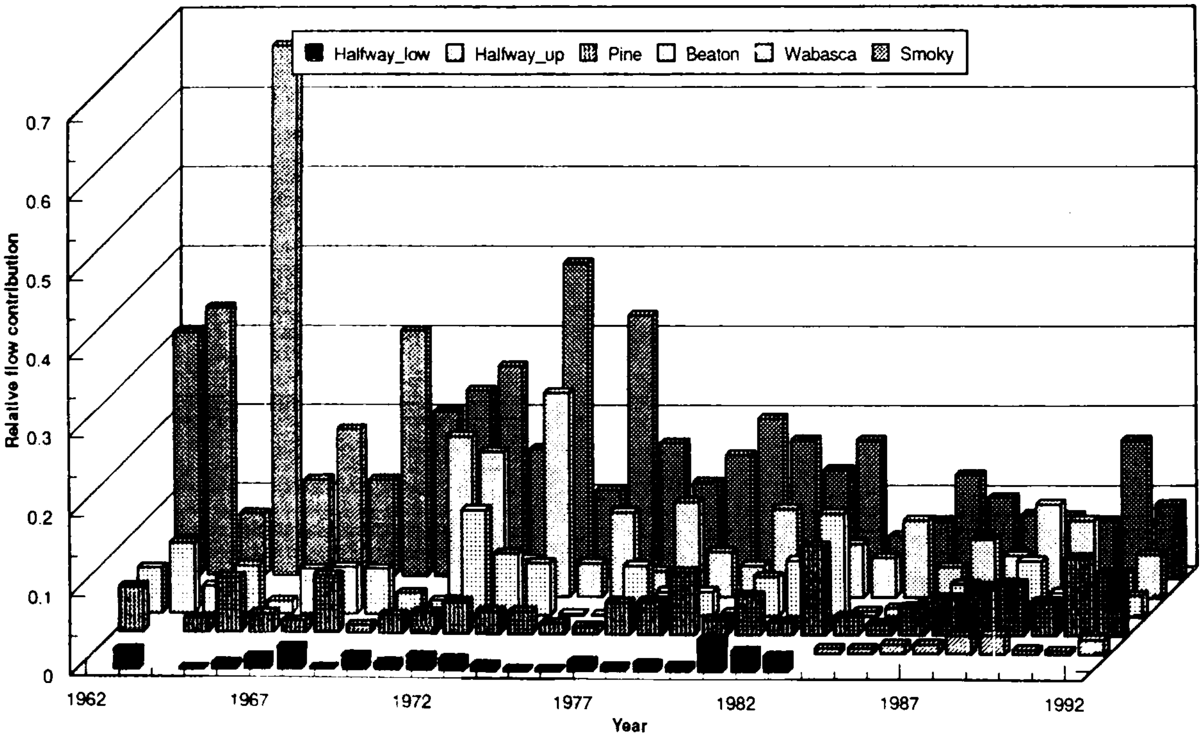


Figure 3.23 Residual mass curve of spring snowpacks and snow water equivalent, for Grande Prarie (Prowse et al., 1996b)

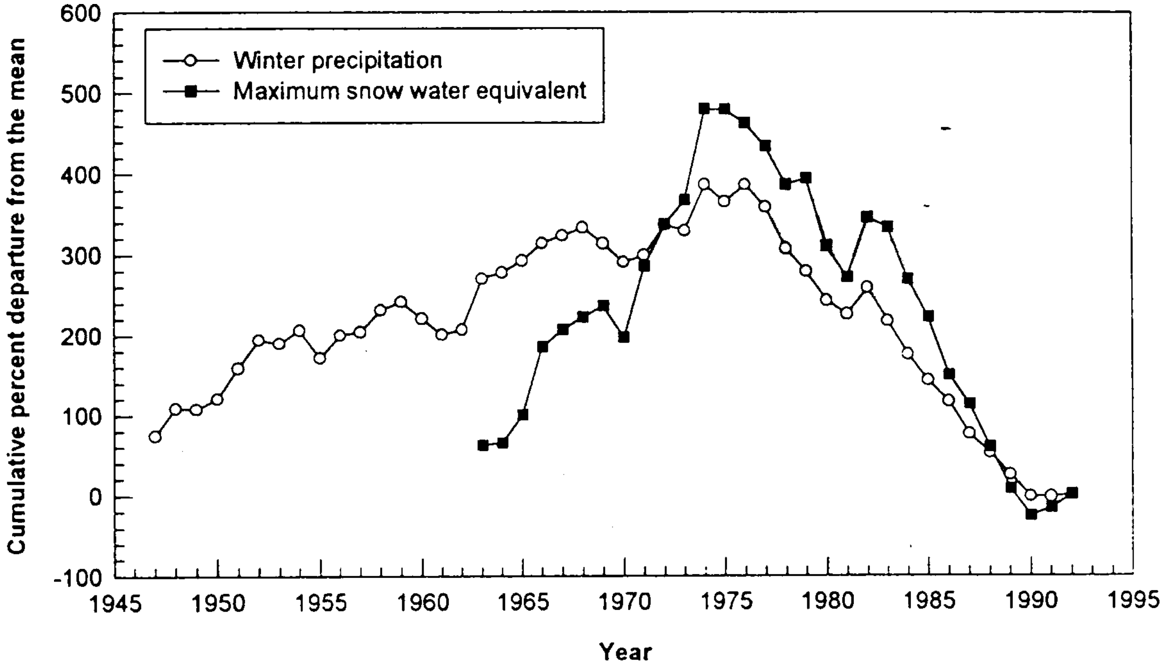


Table 3.1 **List of Water Survey Canada stations along the Peace River for which some river ice related data is available.**

Name and Location	Record Count	Years of Record
Peace River at Hudson Hope	50	1917-22; 1949-92
Peace River at Taylor	49	1944-92
Peace River at Dunvegan	29	1960-69; 1974-92
Peace River at Peace River	54	1915-32; 1957-93
Peace River at Fort Vermillion	25 + 14	1915-22; 1961-78 1979-92 (Level)
Peace River at Peace Point	34	1959-92

Table 3.2 **Pre- and post-regulation mean dates for freeze-up and break-up for mainstem Peace River stations. Bolded values indicate significant differences occur between pre- and post-regulation dates (a = 0.05) (after Prowse et al., 1996b).**

Station	Mean date Pre-regulation Freeze-up F_{avg}	Mean date Pre-regulation Break-up B_{avg}	Mean date Post-regulation Freeze-up F_{avg}'	Mean date Post-regulation Break-up B_{avg}'
Hudson Hope[1] 07EF001	N/A	N/A	N/F	No Ice
Taylor 07FD002	N/A	N/A	N/F	No Ice
Dunvegan[2] 07FD003	N/A	Apr 27	N/A	N/A
Peace River 07HA001	**Dec 13**	May 2	**Jan 01**	Apr 10
Fort Vermilion 07HF001	Nov 15	**Apr 29**	N/A	**Apr 24**
Peace Point 07KC001	Nov 16	May 2	Nov 21	Apr 28

3.5 FLUVIAL GEOMORPHIC AND VEGETATION REGIME ANALYSIS

As outlined in the introductory sections (Section 1.4), flow regulation can significantly alter the ability of a river to transport sediment and can modify the overall alluvial and riparian regimes. To evaluate what changes have occurred on the Peace and Slave river systems, the Hydrology Component of the NRBS undertook two separate studies. Using field survey and remote-sensing techniques, the first of these focussed on predicting and measuring morphological and riparian vegetation changes along representative reaches of the Peace River (Church and North, 1995). Many of the study results presented here (Section 3.5.1) have already been published in Church (1995). The second was an exploratory study of similar changes that might be occurring in the Slave River Delta (English *et al.*, 1995). It should be noted that a companion study of vegetation succession resulting from hydrologic changes in the Peace-Athabasca Delta has been undertaken by the Peace-Athabasca Delta Technical Studies, and it is expected that results will be available near the completion of the NRBS.

3.5.1 Peace River

A major hydrologic parameter controlling the ability of a river to transport sediment is peak flow. As demonstrated in Section 3.1, although there has not been a significant change in mean annual flow, regulation has decreased the average size and frequency of peak flows - the effect diminishing downstream from the point of regulation. One expects that the reduction in peak flows will reduce the sediment transporting capacity of the river. Unfortunately, the lack of suspended sediment data for the Peace River prior to construction of the Bennett Dam precludes a pre- to post-regulation comparison. A number of logical deductions, however, can be made about expected changes using basic principles of sediment transport and recent studies of the sediment delivery system operating in the Peace River. The validity of these deductions is tested by subsequent examination of the morphological changes that have occurred on the Peace River.

3.5.1.1 *Sediment Regime of the Peace River*

An important feature of this particular regime is that the headwater streams above the point of regulation are not a major source of sediment (Church *et al.*, 1989), unlike many other regulated systems where interruption of upstream sediment transport by reservoir retention significantly affects downstream morphological changes (see Section 1.4). In essence, such changes on the Peace River can be considered independent of sediment interruption by the Williston Reservoir. Most sediment entering the Peace River system is supplied by downstream tributaries, the Smoky River being of major significance.

A recent sediment budget analysis of the Peace River indicates that the mean annual suspended-sediment load of the Peace River at the town of Peace River (just downstream of the Smoky River) is 33.7 Mt (Carson, 1992). Over one half of the mean annual load at this station is derived from the Smoky River, and one third from the Beatton River. Progressing downstream to Peace Point, the load increases by only 2.7 Mt, despite a 36% increase in contributing area; however, the inter-annual variability of sediment loads at Peace Point is high. Carson (1992) suggests that increases between Peace River and Peace Point occur in conjunction with high flows on the Wabasca River and losses occur when peak flows at Peace Point are less than at Peace River. The Wabasca tributary appears, then, to be a major sediment supplier during years of high runoff. No measurements have been made of the transport of gravel over the bed in the upstream parts of the river. It is evident, however, from its buildup at tributary junctions, however, that the transport of gravel in the Peace River has greatly diminished since regulation.

3.5.1.2 *Predicted Changes in Mean Channel Geometry*

Given that a majority of Peace River sediment is derived from unregulated tributaries, reductions in summer flow in the mainstem by regulation should translate into increases in suspended-sediment concentrations. However, the same reduction in peak flows should reduce the capacity of the river to convey the sediment delivered by these downstream tributaries. The river should, then, begin to aggrade. Although pre-regulation data about sediment composition are unavailable, it is reasonable to expect the suspended component would experience a relative increase in fine sands and silts since coarser material should remain on the bed under the reduced flows.

Increases in winter flow, on the other hand, should tend to reduce the concentration of suspended sediment, particularly since little material is supplied by unregulated tributaries during this time of the year. It is possible, however, that enhanced winter scour may result in higher post-regulation sediment concentrations due to seasonal in-channel scour. This is discussed further in Section 3.5.2

Although specific questions remain about precise sediment composition and the role of enhanced winter transport, reductions in peak flows of the main stem and a continued supply of tributary sediment load should cause reaches downstream of the dam to aggrade. Estimates of how such aggradation can affect reach-average characteristics of channel morphology were made based on descriptive equations of channel "hydraulic geometry" (see Leopold and Maddock, 1953) and varied to account for the nature of bed and bank material and channel shape (Church, 1995; Church and North, 1996). A scale equation describing the relationship between flow and meander/riffle spacing was also used (cf. Dury, 1976). Based on these, a ratio was developed between regulated and unregulated flow conditions to determine the channel geometry adjustments. The mean annual flood was used as the "channel forming flow", and values for the coefficients were adopted from a previous analysis of Alberta rivers in a similar hydroclimatic zone.

Results of the analysis are presented in Table 3.3. Widths and depths are predicted to decline to 60 and 75% of their current respective values in the gravel reach upstream of the town of Peace River (i.e., above the major Smoky River tributary). Further downstream, slightly lower reductions in these two parameters are expected (to 75 and 83% respectively). Predicted percentage reductions in meander wavelength or riffle spacing are similar to those for width. Flow velocity should decline by no more than 10% in either reach.

What will happen to the gradient and planform pattern of the river is a more complex question. These two characteristics are intrinsically related because the easiest way for a gradient adjustment to occur - in the sense that the least sediment transport needs to be completed - is for the river to become more or less sinuous. The necessity for adjustment is mediated by changes in form resistance to flow along the channel and by the concentration of mobile sediment in the river - the greater the sediment load, the higher must be the gradient to maintain the ability of the flow to move it downstream. Superficially, then, one may expect the river to become less sinuous. However, the simple prediction is complicated by the possibility that the river will eliminate islands -formerly frequent in some reaches - as a means to achieve a "more efficient" sediment transferring channel.

3.5.1.3 *Time Scales for Adjustment*

Although the transition to a regulated flow regime is fairly rapid, the time-scales for an alluvial river to adjust to the new regime can be extremely long. An estimate of when 50% of the bed adjustment will be complete was obtained from (de Vries, 1975):

$$T_{50}=\frac{L^2}{Y}$$

$$Y=\frac{b\overline{Q_b}}{3w_sS}$$

where $L > 3d_*/S$ is the distance from the origin of disturbance; d_* is the hydraulic mean depth of the channel; S is the channel gradient; b is a bed sediment transport coefficient; Q_b is the mean annual bulk volume of bed material transported; and w_s is channel width.

Although the issues associated with the transport of bed material are not yet well understood (see Gomez and Church, 1989), even if the de Vries model is in error by an order of magnitude, morphologic adjustments will be measured by centuries (Church, 1995). Any estimate of time-scale adjustments must also include the influence of riparian vegetation (see following Sections 3.5.1.5 and 3.5.2.4). Specifically, progradation of vegetation down the banks helps to re-define the new channel edge on the lower floodplain. Exposure of bar surfaces and post-regulation sub-aerial deposition of sediment also provides new substrates for allogenic succession. Once new plants colonize these zones, they promote further trapping of sediments, especially during flood events, and once they stabilize, seral plant assemblages can develop. Time-scales for ecological changes in riparian ecosystems are estimated to be in the order of centuries, simply because of the long succession time for the establishment of new forest communities.

3.5.1.4 *Observed Changes in Channel Geometry and Pattern*

As part of this study, efforts were made to document morphological changes that have already occurred. A series of inter-decadel aerial photographs of four 60-100 km reaches along the Peace River has been assembled, but time and resources permitted only a partial analysis of all data. An emphasis was placed on three reaches (Figure 3.24) and two time periods. A photographic set, taken between 1966 and 1969, represents conditions just prior to regulation (although regulation was underway in 1969 only minor changes would have occurred by that time). A post-regulation 1993 set, specifically obtained by the NRBS for this study, ensures the inclusion of the changes produced by large flow event of 1990 (see Section 3.1). The three selected reaches were to include contrasting regimes: a) upstream: cobble-gravel; b) mid-stream: gravel-sand; and c) downstream: sand bed. Field verification surveys were conducted in the summers of 1994 and 1995. Table 3.4 summarizes the 'reach-wide' changes in the major morphologic and vegetation features (bar, island, river and fan) and the length-width dimensions of the reaches.

Everywhere along the river, the old floodplain has become a low terrace. Former bar surfaces have become the sites of new floodplain development. In the upper reaches, where the reduction in flood flows is most pronounced, the newly active floodplain level is approximately 2 m lower than the former floodplain surface. Further downstream, it appears to be 1-2m lower, but the long-term effect of ice-jam water levels may eventually reduce the difference to a smaller value.

As shown in Table 3.4, channel narrowing is also occurring along the river: a conservative measure of average width was derived by dividing the sum of open-water plus bare (non-vegetated) bar areas by reach length. All reaches exhibit a percentage decline in width, ranging from -4% to -16%. This forms a significant percentage of the predicted long-term changes in width noted in Table 3.3. Width adjustment is occurring because of abandonment of formerly seasonally-inundated channel bar surfaces; abandonment of secondary channels in split reaches; and accretion of sand and silt to channel edges.

Comparative mapping of specific changes (at-a-point) in the major morphologic and vegetation regime types was also conducted, the results noted under 'Morphology Changes' and 'Vegetation Changes' in Table 3.4 and discussed below. Net deposition exceeds that due to net erosion in the upper two reaches, although the difference is more extreme in Reach 2, i.e., below the Smoky River confluence. In Reach 3, net deposition is less than net erosion but this reach records the greatest net deposition and, therefore, the largest overall change per river kilometre.

As previously described, the upper section of the Peace River is a cobble-gravel wandering channel, frequently split about channel islands but maintaining an identifiable main thread along its course (cf. Desloges and Church, 1989). Kellerhalls and Gill (1973) suggested that the Peace River would not degrade downstream from the dam because it would no longer be competent to move the cobble bed under a regulated flow regime. Their predictions have been confirmed and subsequent investigations indicate there has been no systematic change in channel cross-sections (Church and Rood, 1982), probably due to the static nature of the cobble-gravel bed. Because of the static nature of the cobble bed, the upper section of the river is, in effect, no longer an alluvial channel (Church, 1995).

With a reduced ability to transport large material, cobbles and gravel delivered by major tributaries are being deposited in the upper reaches of the Peace River as 'in-channel alluvial fans'. Such fans reduce channel width and push the river towards the opposite valley wall and, once large enough, can act as low submerged weirs creating significant backwater upstream and a steepened gradient downstream (Figure 3.25). Over many decades, the Peace River will develop a 'stepped profile' between successive fans not unlike those that occur naturally in rivers in many mountain valleys (e.g., Church, 1983). Reduction in cobble-gravel also means that sand will contribute an increased proportion of the sediment load. Most of the sand can still be conveyed downstream because of the relatively high gradient of the river ($>10^{-4}$) in the upstream reach.

In areas where island complexes exist, for example at the Many Islands (Figure 3.26), there have been few changes to the islands themselves but sediment accretion and/or bar extensions have occurred around them, often resulting in the filling or cut-off of secondary channels. These processes result in a narrowing of the channel and a reduction in its total length.

Although the same mechanisms contribute to channel narrowing in the mid-reaches as in the upstream (and in the same order of significance), channel edge accretion is relatively more prominent because of the increased load of sand and silt from the downstream tributaries. With a decrease in conveyance power of the Peace River, the 'fan' of the Smoky River has prograded into the main channel, creating a substantial additional bar area (Figure 3.27). In addition, the former secondary channel along the downstream edge of the confluence fan has been virtually abandoned and substantial bar accretion around the islands downstream from the confluence has occurred.

Along much of its course to Carcajou, the Peace River is confined. As a result, long-term aggradation will be required to adjust the gradient to permit the downstream transfer of sediment. These are long-term changes but a number of important points can be made about expected morphological changes. Secondary channel abandonment in some reaches due to the decreased flows will increase the general sinuosity of the river locally, decrease the average channel gradient, and thus promote aggradation. Secondary channel abandonment may also reduce channel form resistance by concentrating the flow in a single, relatively deep channel. In the long term, aggradation will cause increased shoaling in order to increase the channel's gradient to a point where where the river is again competent to transport material downstream. In aggrading reaches, where the river is not confined, irregular lateral instability and renewed island formations may occur. The predicted reduction in riffle spacing (Table 3.3) will be accomplished as part of this process.

The full predicted reduction in overall channel width may, therefore, not develop if channel division increases again so that the total channel width conveys water less efficiently. Shoaling and renewed island formation imply that a change to a low-order braided channel may indeed be occurring in this reach. This would invalidate the morphological changes predicted in Table 3.3 for the sand reach near Fort Vermilion. Specifically, the river width in Reach 3 averaged 776 m before regulation and the eventual width is predicted to be 582 m. If, instead, the river takes up a low-order braided habit (i.e., division about a single central bar), the width may conform, more closely, with an equation for braided channels (Ashmore, 1991) that predicts an eventual channel width of 632 m (Q - 5800 $m^3 s^{-1}$). The equation for braided channels is not well established, but is the only available predictive equation for braided channels and performed reasonably in a test conducted by Desloges and Church (1992) following an outburst flood. Velocity would likely not decline, but the channel would be somewhat more shallow. Such an effect is already becoming evident downstream from Carcajou, where channel shoaling has made small boat navigation locally and seasonally difficult (NRBS, 1996d). This channel aggradation offers an explanation for the small difference measured in the sediment loadings between the town of Peace River and Peace Point, as discussed in Section 3.5.1.1.

3.5.1.5 *Related Riparian Vegetation Changes*

Clearly evident in Table 3.4, is a significant expansion of vegetation in all reaches. Details of the types of riparian vegetation are discussed in Section 3.7. Rates of overall vegetation advance are similar in the upper two reaches (60 and 57 x 10^3 m^2 per km of river length) but are almost three times as great in Reach 3. Those sub-reaches with very high advance rates (>85 x 10 m^3 per km) are characterized by numerous islands: i.e., Reach 1: Many Islands, Montagneuse Islands; Reach 2: Smoky River confluence, and Reach 3: almost the entire reach from Moose Island to near Fort Vermilion.

In the gravel reach, upstream of the Smoky River confluence, the initial stages of vegetation establishment on gravel bars are marked by invasion of balsam poplar (*Populus balsamifera*) and a variety of annual plants. On sites with finer soils, river alder (*Alnus icana*) establishes near the new high water line and willows (*Salix* spp.) become established at lower levels (Church, 1995). Farther downstream, in the sandy gravel and sand reaches, there is more channel edge accretion and bar surfaces are quickly covered by fine material. Early vegetation succession in these reaches consists of establishment of willows and grasses, while balsam poplar invades later (Church, 1995). Similarly, initial colonization of side channels that have become filled is characterized by invasion of willows. After the new flood surface stabilizes, seral succession commences towards the establishment of a boreal coniferous forest. Figure 3.28 shows typical colonization by allogenic vegetation on to a modified substrate and Figure 3.29, the seral vegetation communities that ultimately establish. Examples of the silting and subsequent growth of riparian vegetation in inlets and outlets of secondary flow channels are depicted in Figures 3.30 and 3.31 .

Overall, the rate of vegetation expansion has been greater than that due to the supply of new depositional areas (Table 3.4; ratios of vegetation recovery to net deposition are all >1). This is partly related to the reductions in large flood peaks after regulation. Reductions in high-bank scouring permits vegetation to prograde down the banks as demonstrated in Figure 3.32. It is likely that changes in the severity of the break-up ice regime and reductions in the height and frequency of ice scour may also play a role.

3.5.2 Slave River Delta

Deltaic deposits of the Slave River Delta (SRD) have been prograding into Great Slave Lake since 8070 BP and now cover an area of approximately 8300 km^2 (Vanderburgh and Smith 1988). Only about 5% of this area, primarily in the outer delta (see Section 2.3.6) is classified as active and most directly affected by changes deriving from flow regulation. This zone, a critical deltaic habitat, was the focus of the NRBS.

It should be remembered that the SRD is more than 1500 km downstream of the point of regulation. Many of the flow impacts observed further upstream are appreciably dampened or altered by tributary inflow at such a great downstream distance, especially with the complicating effect of flow and sediment fed to the Slave River by the unregulated Athabasca River via the Peace-Athabasca Delta and Lake Athabasca. Such effects are apparent in some of the flow statistics presented in Section 3.1. Moreover, the SRD is also known to be experiencing a number of natural morphological adjustments as it migrates into Great Slave Lake and responds to isostatic rebound from the last glaciation period.

Despite the obvious problems associated with attempting to identify flow-regulation impacts on the SRD, an exploratory study was initiated by the NRBS to examine potential impacts (English *et al.*, 1995). This study was to build on a previous examination of SRD changes completed as part of an environmental assessment of potential damming of the Slave River (English, 1984). This earlier study provided an excellent set of high-resolution colour photography of SRD morpholgy and vegetation to compare with historical aerial photographic records. To support this comparative analysis, the NRBS obtained a second set of colour aerial photography of the SRD in 1994. Quantification of changes was supported by detailed field verification surveys conducted over the 1995 summer. To establish a context for interpeting morphological change, an assessment of regulation-induced changes to the suspended-sediment regime was conducted. Unfortunately, as on the Peace River, a suitable sediment record does not exist for the Slave River in the pre-regulation period. Methods to obviate this problem are described later.

3.5.2.1 *Sediment Regime of the Slave River*

Sporadic measurements of sediment within the active portion of the SRD have been made, but only since regulation. Similarly, recording of suspended sediment did not begin until 1971 at Fitzgerald, the only such station on the Slave River, located approximately 200 km upstream of the active SRD. Unfortunately, these data were collected only during the summer months, May to October.

In a recent assessment of sediment transport data for the Peace and Slave rivers, Carson (1992) found that the post-regulation, mean-annual suspended-sediment loads for the Peace Point (36.4 Mt ± 20.0) and Fitzgerald (33.6 Mt ± 16.4) stations differ by less than 3 Mt. The sediment load at Fitzgerald, however, is not derived entirely from the Peace River but also from the Athabasca River and Peace Athabasca Delta. Considering that the Athabasca system is estimated to contribute approximately 6 Mt (Carson, 1992) to the Slave River, there is a net loss or deposition of approximately 9 Mt between Peace Point and Fitzgerald. The mechanisms involved in this sediment loss are not clear. Flow reversal to Lake Athabasca during years of high flow on the Peace River may account for some of the loss, yet there are individual years where significant losses occurred without evidence of flow reversal (Carson, 1992). Overbank deposition is another possible explanation but, as shown in Section 3.4.3 (Prowse and Lalonde, 1996), even the historic open water flood peak of 1990 generated minimal overbank flooding. The only other explanation would be in-channel deposition, for example, on point bars and in secondary channels. Overbank sedimentation and flow reversals into Lake Athabasca were probably more important during pre-regulation, but since then flows are largely contained in the channel, suggesting in-channel sedimentation has increased.

Although there are some interesting geomorphologic processes occurring, Peace River still has a strong influence on the sediment transport regime of the Slave River (Carson, 1992), and it is assumed this holds true for the pre-impoundment period. Furthermore, with virtually no additional tributary input between Fitzgerald and Great Slave Lake, data from the Fitzgerald station can be considered a good indicator of the sediment load expected to enter the active portion of the SRD. Existing data from 1980 indicate that the total sediment load recorded at Fitzgerald and the SRD for the same periods are essentially identical.

3.5.2.2 *Predicted Changes in Suspended Sediment Regime*

To permit comparison of pre- and post-regulation sediment conditions, a sediment rating curve was developed (English *et al.*, 1995) using monthly mean flows from Peace River at Peace Point and mean monthly sediment loads for the Slave River at Fitzgerald. This follows from previous work by Carson (1992) who showed that Peace Point flow data provide a superior sediment-rating curve for the Slave River to flow recorded at Fitzgerald. Post-regulation monthly sediment data were generated and compared to pre-regulation[a] recorded data on a monthly basis (Figure 3.33). The results suggest that the sediment load at Fitzgerald has decreased by almost one-half after regulation for the open-water period, with the most pronounced changes being during the main flow months of June and July. This is primarily due to the reduction in peak flows during this period as detailed in Section 3.1.

An attempt was made to calculate changes in sediment load for under-ice conditions. Difficulties with this are the same as those outlined in Section 3.5.1. In estimating monthly winter loads, equivalent open-water values were reduced by a % value based on winter data reported for a similar northern river (Liard River, Milburn and Prowse, 1995). The final results indicate that increased winter flows would approximately triple the suspended sediment load as shown in Figure 3.33. If the system is more supply-limited by ice conditions than the Liard River, these values could be an overestimate. However, they are small compared to reductions that occur during the open-water period. Overall, the data in Figure 3.33 indicate that the annual sediment load at Fitzgerald has decreased by almost one-third (even greater if the winter values are overestimates).

Although lack of data precludes an assessment of changes in grain-size composition, it can be argued logically (as in the Peace River case) that decreases in the sediment load and flow competence should result in a decrease in the size fraction capable of being carried within the system and an increase in the relative composition of fine-grained sediment. This has some implications for the type of morphological development occurring at the SRD.

3.5.2.3 *Observed Changes to Delta Morphology*

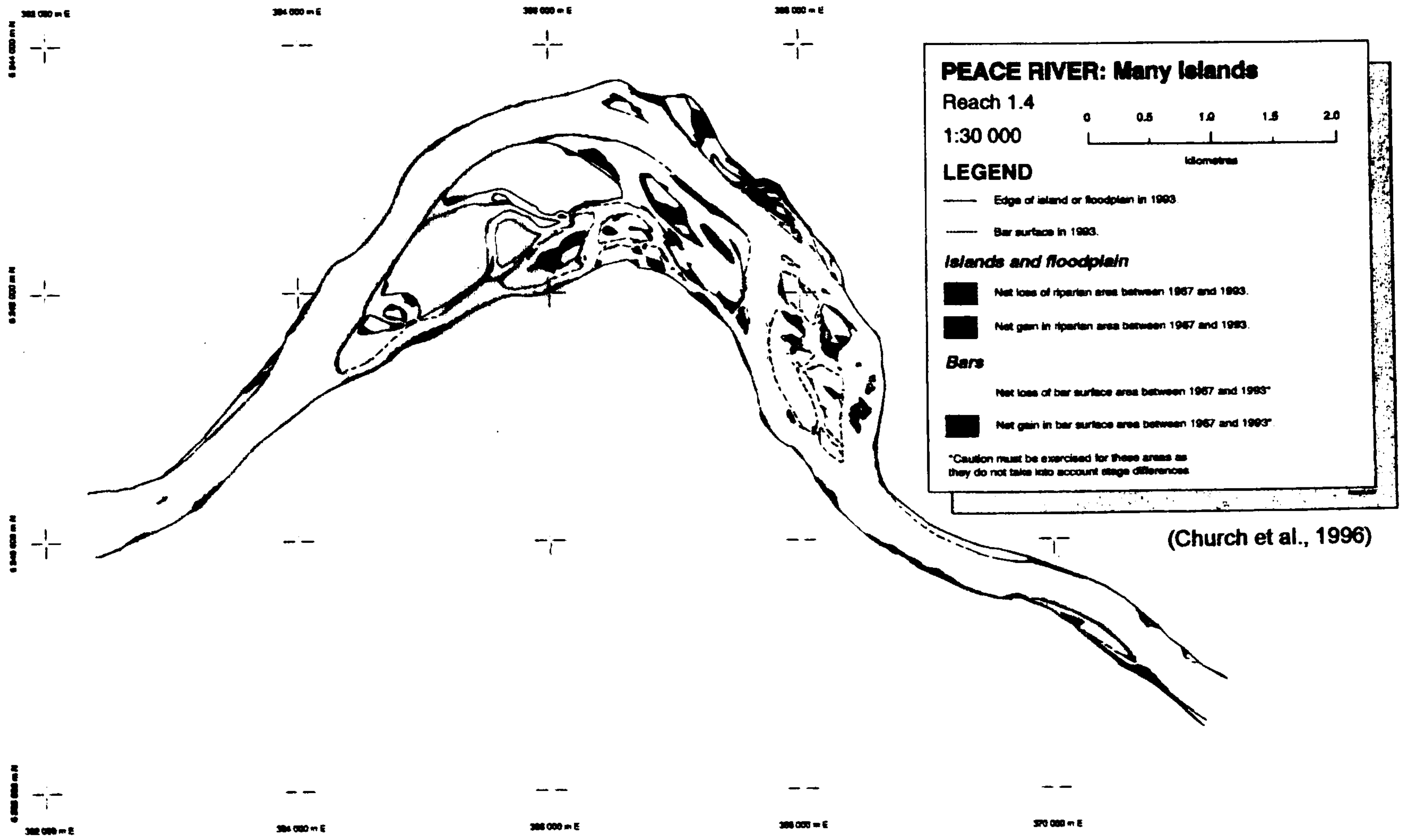
In evaluating changes to the morphology of the SRD, aerial photography was compared for the years 1946, 1966, 1977, and 1994. As expected for a deltaic environment, the outer portion of the sub-aerial delta has generally increased, but there has been a lateral shift in the active depositional zones and in their rate of formation. It is difficult to determine how much change or whether rates of change can be associated with upstream regulation effects, but interpretation of process changes relative to the morphologic changes provides some insight.

One of the most apparent long-term changes in the Slave River is redistribution of flow among the major distributary channels. In particular, ResDelta Channel has become the dominant distributary, increasing in channel width by approximately 50% between 1946 and 1994 (Figure 3.34a) while, over the same period, the widths of East Channel and Old Steamboat Channel have decreased by a similar percentage. Based on a standard relationship between channel width and discharge (Leopold and Maddock, 1953), and available discharge measurements, it was calculated that the flow of the ResDelta had also doubled while flow in the other two channels declined as shown in Figure 3.34b. An earlier field survey by Water Survey of Canada (May and August, 1980), indicated that ResDelta was the major flow carrying >88% of the distributary flow and >86% of the suspended-sediment load.

Delivery of sediment to the productive portions of the outer SRD (see Section 2.3.6) depends on the conveyance properties of the distributary channels. Although time-series sediment records for individual channels do not exist, some idea of sediment delivery can be obtained by analyzing the rate of growth in the cleavage bars that develop at the mouths of these channels (Figure 3.35). Importantly, although ResDelta Channel is the primary conveyer of water and sediment, and the site of most pronounced aggradation (Vanderburgh and Smith, 1988), there has been a steady reduction in the rate of subaerial growth of the cleavage bar island at its mouth (Figure 3.34c). Two other cleavage bars have also shown a decline (Old Steamboat Channel) or complete cessation (East Channel) in their rate of growth since 1977. The one at the mouth of Mid Channel West has actually recorded a small negative growth rate indicating some erosion has taken place. This suggests that some offshore activity may be affecting this bar, since the channel that feeds it has not experienced an increase in flow (Figure 3.34b). Unfortunately, linking rate changes to regulation impacts is difficult because of the overall complexity of the deposition and erosion processes.

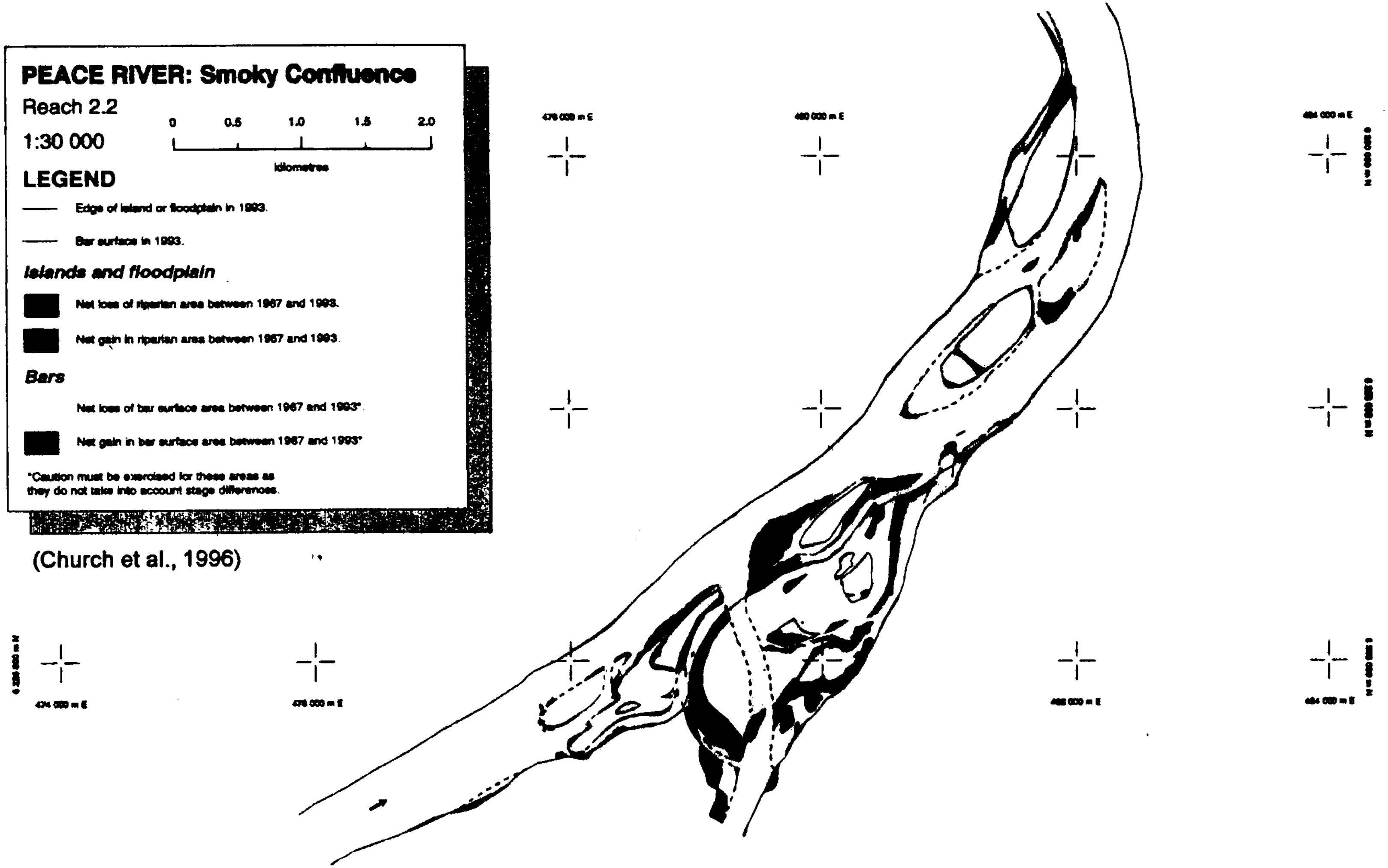
A number of inter-related processes can possibly explain the reduction in growth of the ecologically important cleavage bars. Firstly, the simple reduction in suspended sediment to the SRD offers one explanation. Reduced peak flows could mean that the larger clast size deposits required for building cleavage bars have also been reduced. Moreover, if the composition of suspended sediment has shifted towards finer particles, such material may not be deposited in cleavage bar locations but transported further offshore into the deeper portions of Great Slave Lake. Where narrowing of distributary width has occurred (e.g., East Channel and Old Steamboat Channel), the conveyance power of the channel may have been diminished because of a build up of bars at the entrance to these distributaries: Figure 3.36 is an example of a bar formed at the entry point of Old Steamboat Channel. Although the build up of such bars is a natural process in a deltaic environment, a decrease in the seasonal

Figure 3.26 Map of morphologic and vegetative changes:



(Church et al., 1996)

Figure 3.27 Map of morphologic and vegetative changes:



(Church et al., 1996)

flushing of distributary mouths by large flows probably accelerates their formation (English *et al.*, 1995).

Two other factors that might also control the rate of development of the outer delta are the offshore slope and the wave action of Great Slave Lake. As material continues to prograde into deeper portions of Great Slave Lake, more sediment probably goes into the formation of bottom-set (near-shore lake bottom) and forset (near-shore slope) deposits (i.e., sub-aqueous "marine" deposits as compared to the topset or sub-aerial formations). Such "losses" of material would naturally tend to slow the growth rate of outer delta formations, such as cleavage bars. Increased exposure to wave action as the delta advances into the lake may also cause an erosion of such formations. As it is probable that all the above factors play some role in the rate of delta progradation, more detailed field investigations, beyond this initial exploratory study, are required to assess the relative importance of natural processes and those affected by flow regulation.

3.5.2.4 *Related Delta Vegetation Changes*

The natural sequence of allogenic succession of plant assemblages in the highly productive outer delta area includes *Equisetum*, *Salix-Equisetum*, *Salix*, *Salix-Alnus*, *Alnus-Salix*, and *Alnus*. Of key importance to the maintenance of high biological productivity in this area is the continued development of sub-aerial cleavage bar islands that provide a suitable environment for highly productive stands of *Equisetum* fluviatile. Over a period of years, the levee and inter-levee depressions of these features become elevated to a point where *Equisetum* spp are succeeded by *Salix* spp and eventually *Alnus* spp. Since there appears to be an apparent slowing of cleavage bar development, this could cause changes to the composition of the plant communities. To validate this, the spatial extent of the major plant assemblages at the four major cleavage bar islands were digitized and mapped from the four aerial photographic surveys. Unfortunately, this was especially difficult for the early surveys (1946 and 1966) because of their poor resolution and colour. Figure 3.37 illustrates a sampling of the 1977 and 1994 mapping of the ResDelta cleavage bar. The relative compositions of the various plant assemblages are contained in Figure 3.38. In general, there has been a shift toward an increased areal coverage of *Salix, Salix-Alnus, Alnus-Salix* and *Alnus* assemblages. The areal proportion of *Equisetum* forms has either declined or not kept pace with the change in area of the cleavage bars. Such trends are indicative of a general drying of this normally wet environment: an observation held by many local people living in the area NRBS (1996d). However, the degree to which this drying is related to decreased flooding remains unknown because of the poor hydrometric records in the area. As demonstrated for the Peace-Athabasca Delta in Section 3.4.3, and is known to occur in many other river and delta environments, changes in river ice break-up processes might be responsible for some of the deceased flooding in the area. Again, insufficient historical records are available to assess this.

Although not evaluated in this NRBS study, changes in flooding frequency could also have an impact for the mid-delta areas, characterized by plant assemblages that are transitional between hydrophillic and hydrophobic species, and the delta apex, with its significant portion of climax forest of *Picea glauca*. Diminished post-regulation flood peaks and associated flooding could potentially affect the pattern of plant succession in these two delta zones. Reductions in overbank flooding and sedimentation could lead to an extension of bryophytes from the apex into the mid-delta areas, eventually leading to a change in the microclimate of the soil and subsequent invasion of *Picea glauca*, although the timing of this is highly speculative.

An additional factor, not specifically examined in this exploratory study, is the modification of sediment/flow pathways for phosphorus (P), a limiting nutrient in many aquatic ecosystems. The distribution of P is linked to sediment transfer and conveyance processes between the land and receiving waters (Miller *et al.*, 1982). The forms and amounts of P in aquatic ecosystems are a function of the input, output and interchange between sediment and water compartments. Although the relative mobility of P in these systems is a highly complex phenomenon, it is likely that reduced flood frequency (open-water and break-up related) and associated sediment loading will affect the delivery of sediment-bound P to the lower and middle sections of the delta. Also, as a result of the potential shift in texture of suspended sediment to finer grained materials, P (bound to the fine-grained materials) may be increasingly transported through the distributary network and into Great Slave Lake. The effects of this potential decline in nutrient loading to the delta environment is unknown but probably has implications for overall biological productivity.

Figure 3.28 Downstream view from the right bank, upstream of Montagneuse Islands, showing characteristic silt accumulation of accreting shores and growth of shoreline vegetation. (Photograph courtesy of L. Uunila).

Figure 3.29 View from the river downstream of Tompkins Landing, showing shrub vegetation communities prograding across the bar. Forest communities will follow where bar surface is sufficiently high and ice incidence sufficiently rare. River flow is left to right. (Photograph courtesy of L. Uunila).

Figure 3.30 Downstream end of secondary channel, which has been abandoned. The channel floor is occupied by willow with equisetum occupying the lowest areas along the centre of the channel. (Photograph courtesy of L. Uunila).

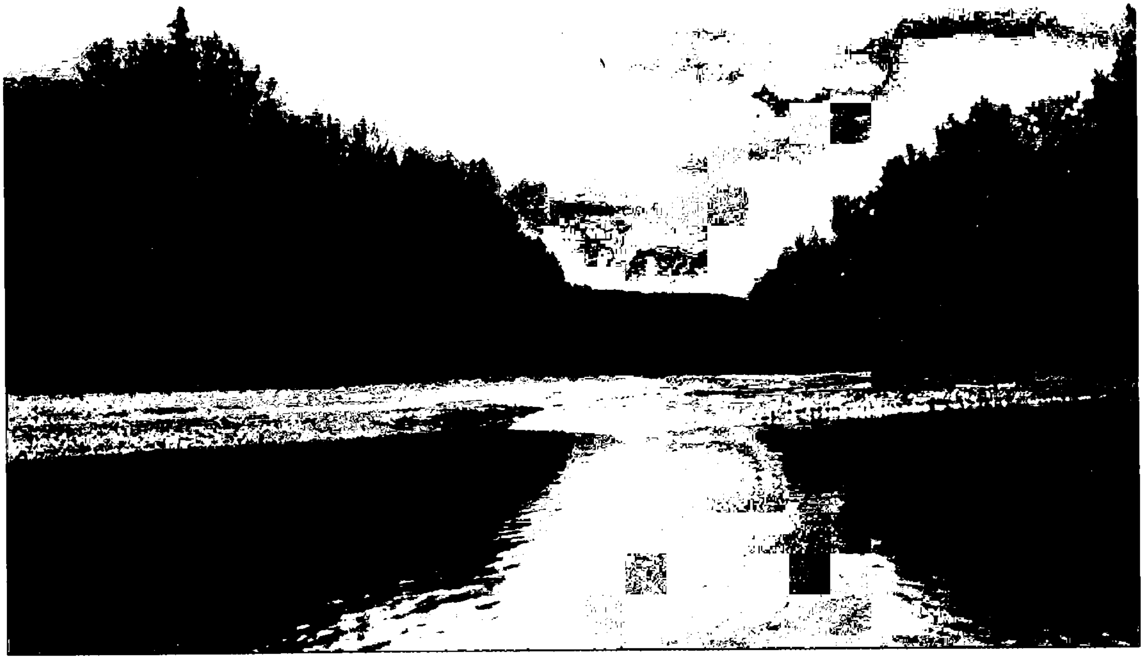


Figure 3.31 Downstream view along a former secondary channel on the main island of the Montagneuse Island Complex. Vegetation primarily consists of grasses and hrbs, but shrubs and trees are prograding into the area. (Photograph courtesy of L. Uunila).

Figure 3.24 Geormorphic study reaches on the Peace River

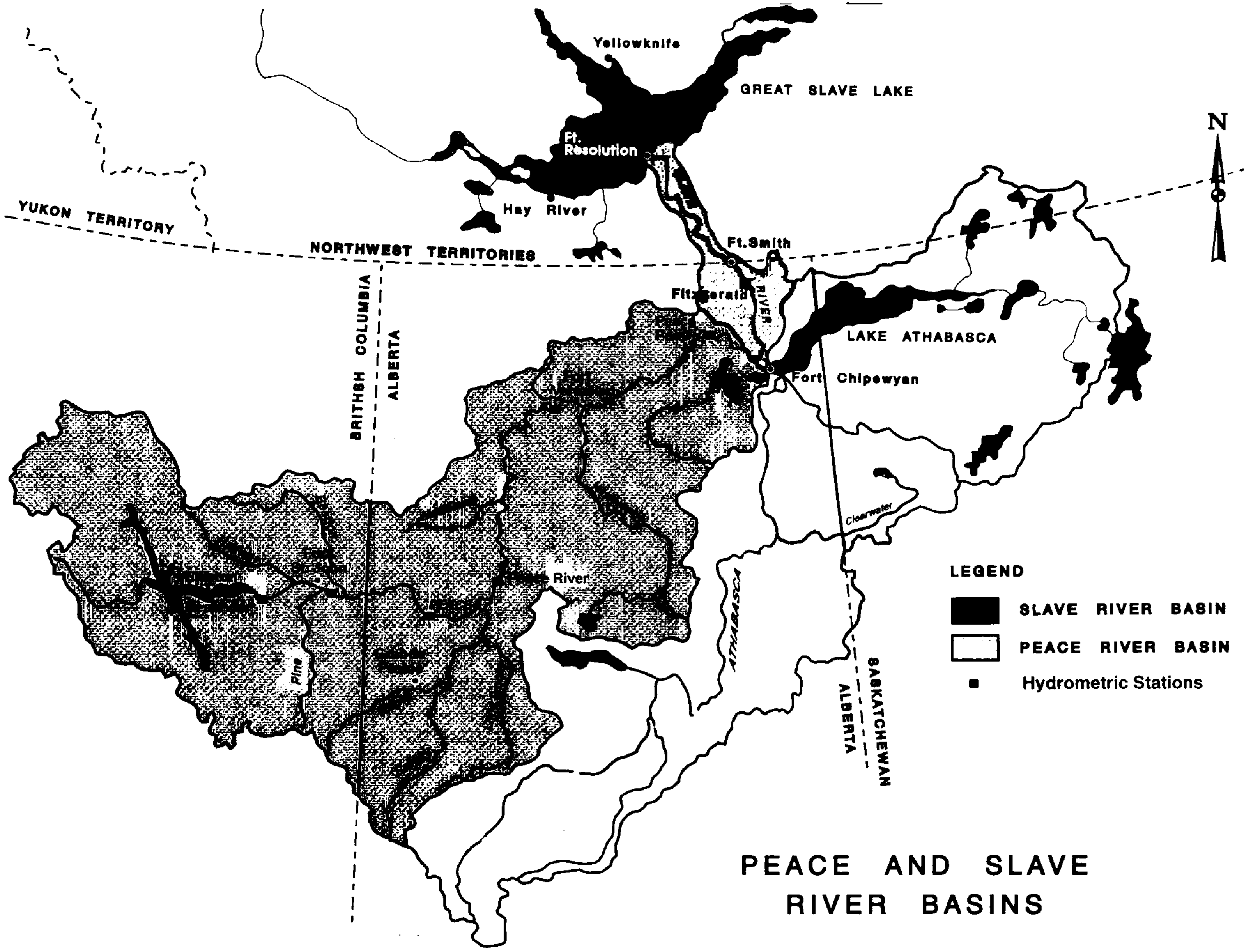


Figure 3.25 Morphologic changes following flow regulation on the Peace River. a) Sketch of typical changes in channel cross-section. b) Sketch to indicate the effect on the gradient of the Peace River due to ‘alluvial fan’ gravel accumulation at tributary mouths since regulation (from Church, 1995).

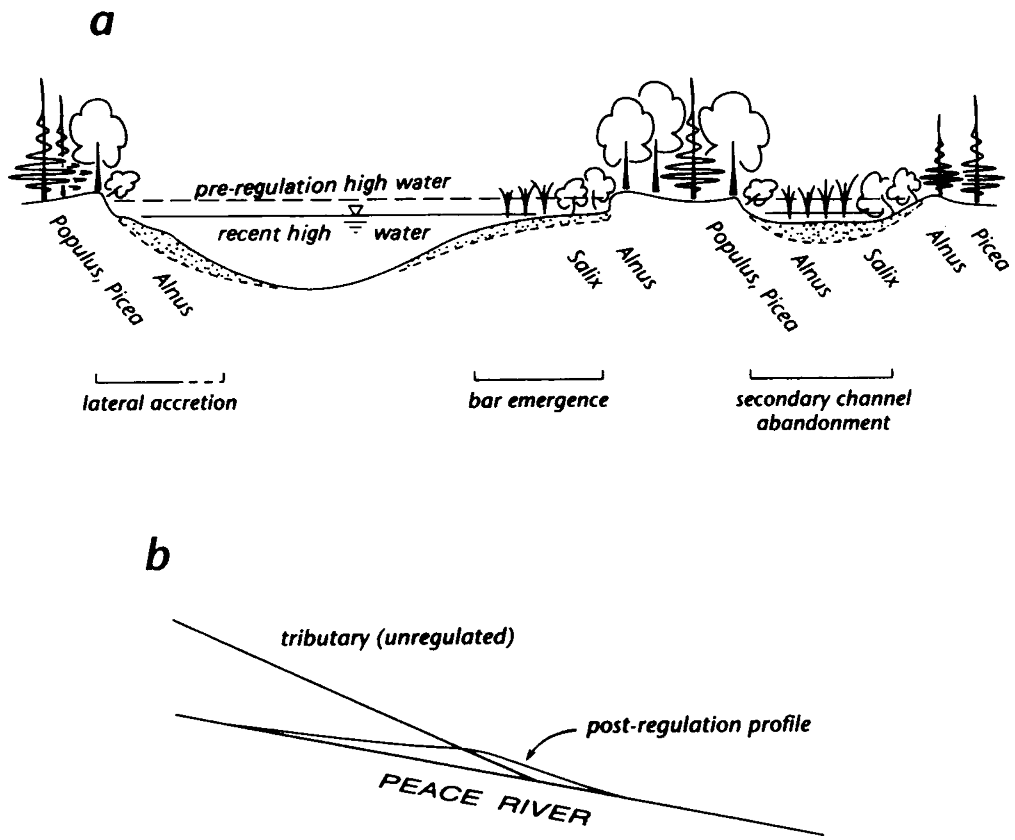


Figure 3.32 Downstream view from right bank, downstream of Tompkins Landing, showing three vegetation communities: scattered willow is established on the cobble paved shore; the lower bank is occupied by 1m high willows and sweet clover; the person is standing in front of 5-8 m high willow and alder on the upper bank. Lower communities are still affected by ice. (Photograph courtesy of L. Uunila).

Figure 3.33 Mean monthly pre- and post-regulation suspended sediment load, Slave River at Fitzgerald (English et al., 1995)

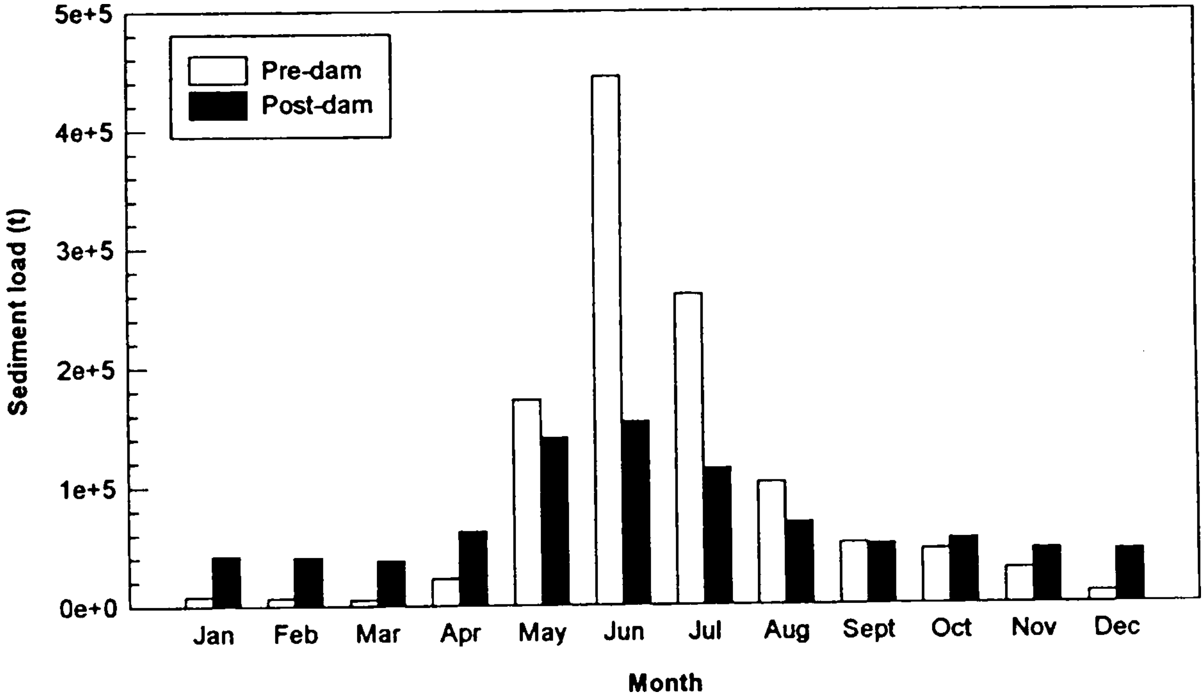


Figure 3.34 a) Changes in distributary channel widths: Slave River Delta
b) Predicted changes in distributary channel flows: Slave River Delta.
c) Change in subaerial surface area of cleavage bar islands: Slave River Delta.

(Source: English et al., 1995)

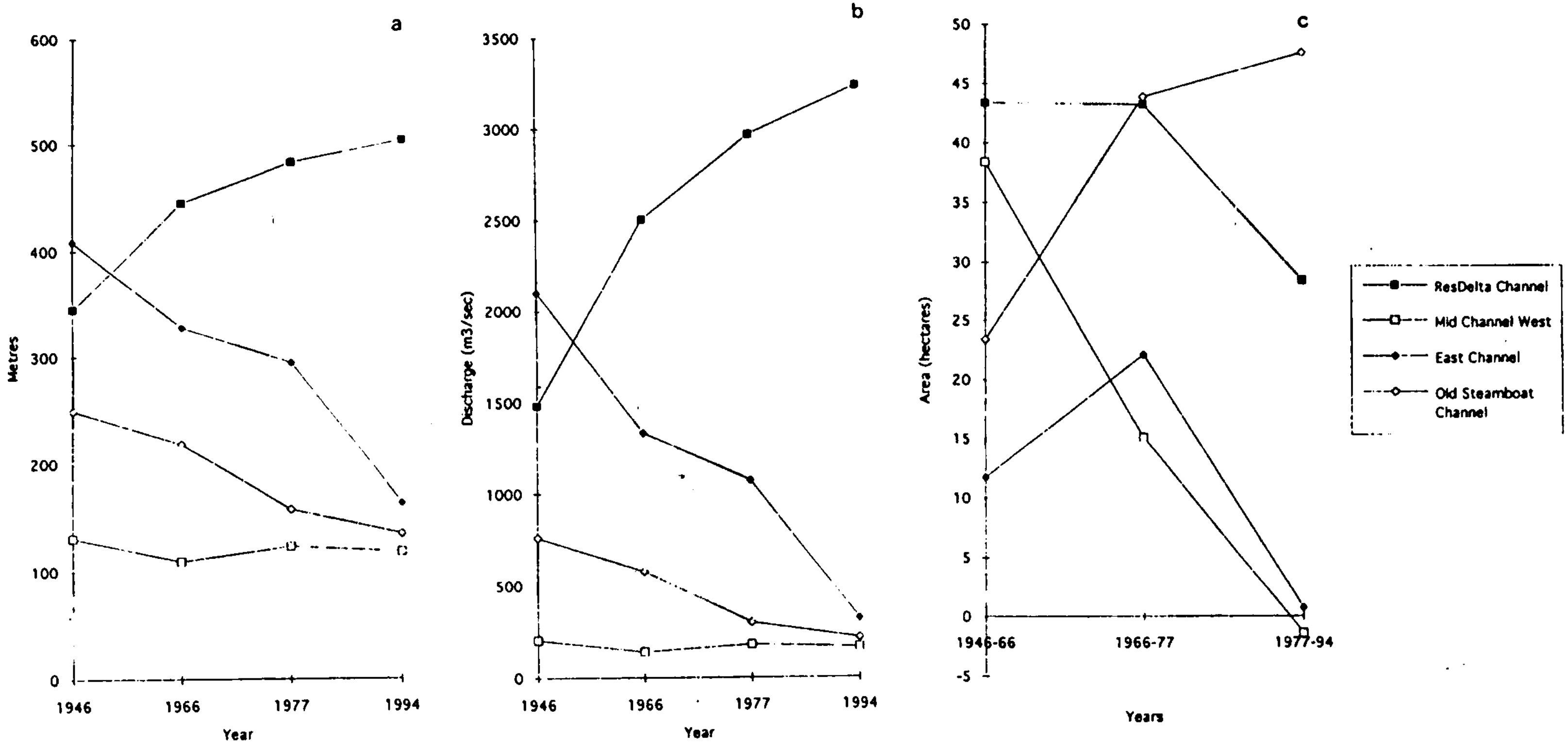


Figure 3.35 Maps of Slave River Delta illustrating changes over time. Map from 1994 shows locations of cleavage bar study sites.
(English et al., 1995)

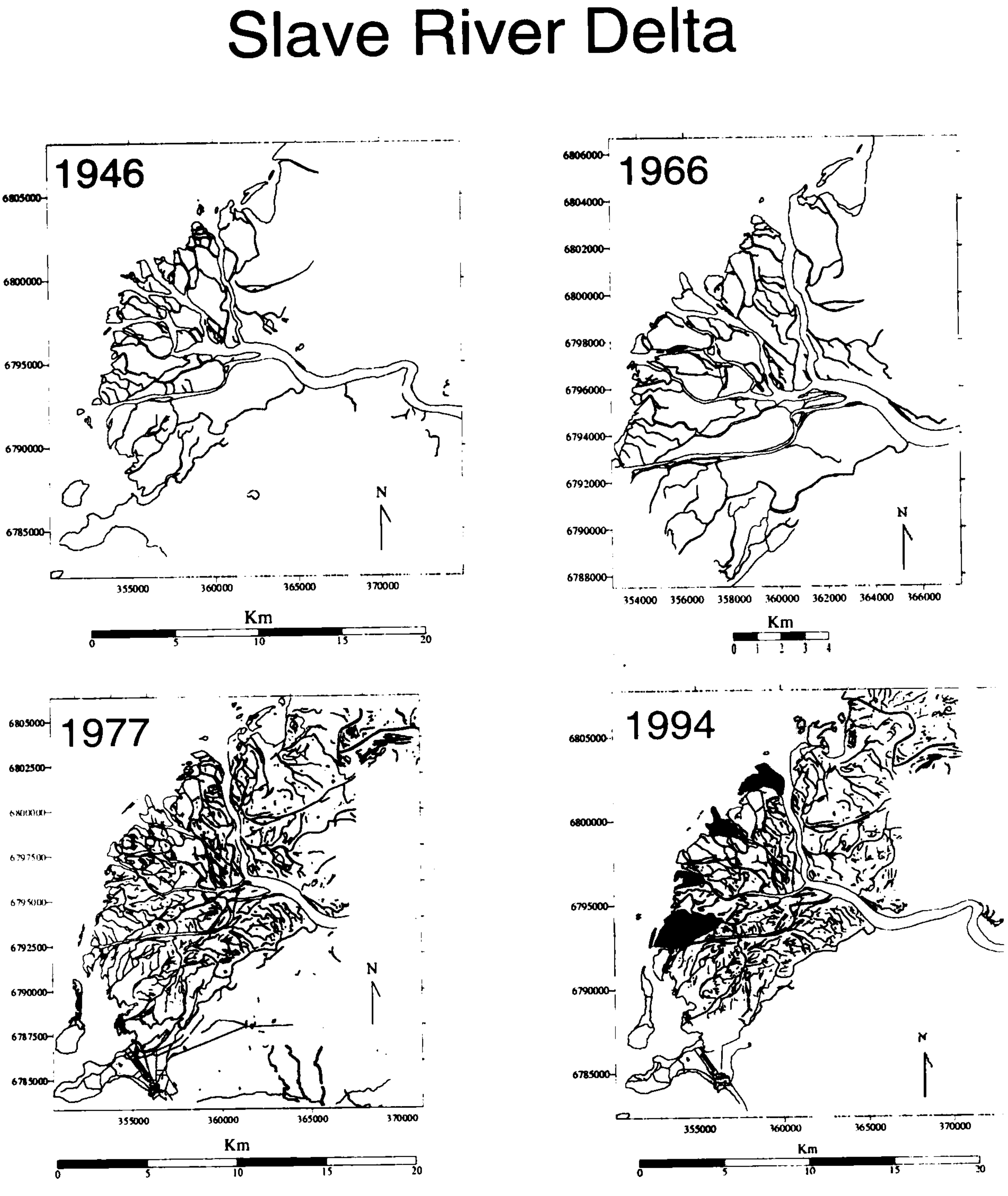


Figure 3.39 Pre- and post regulation water temperatures for Peace River mainstem locations. Open triangles and solid line represent temperatures during the pre-regulation period (up to 1968). Shaded squares and dashed line represent water temperatures during the post regulation period (after 1971).

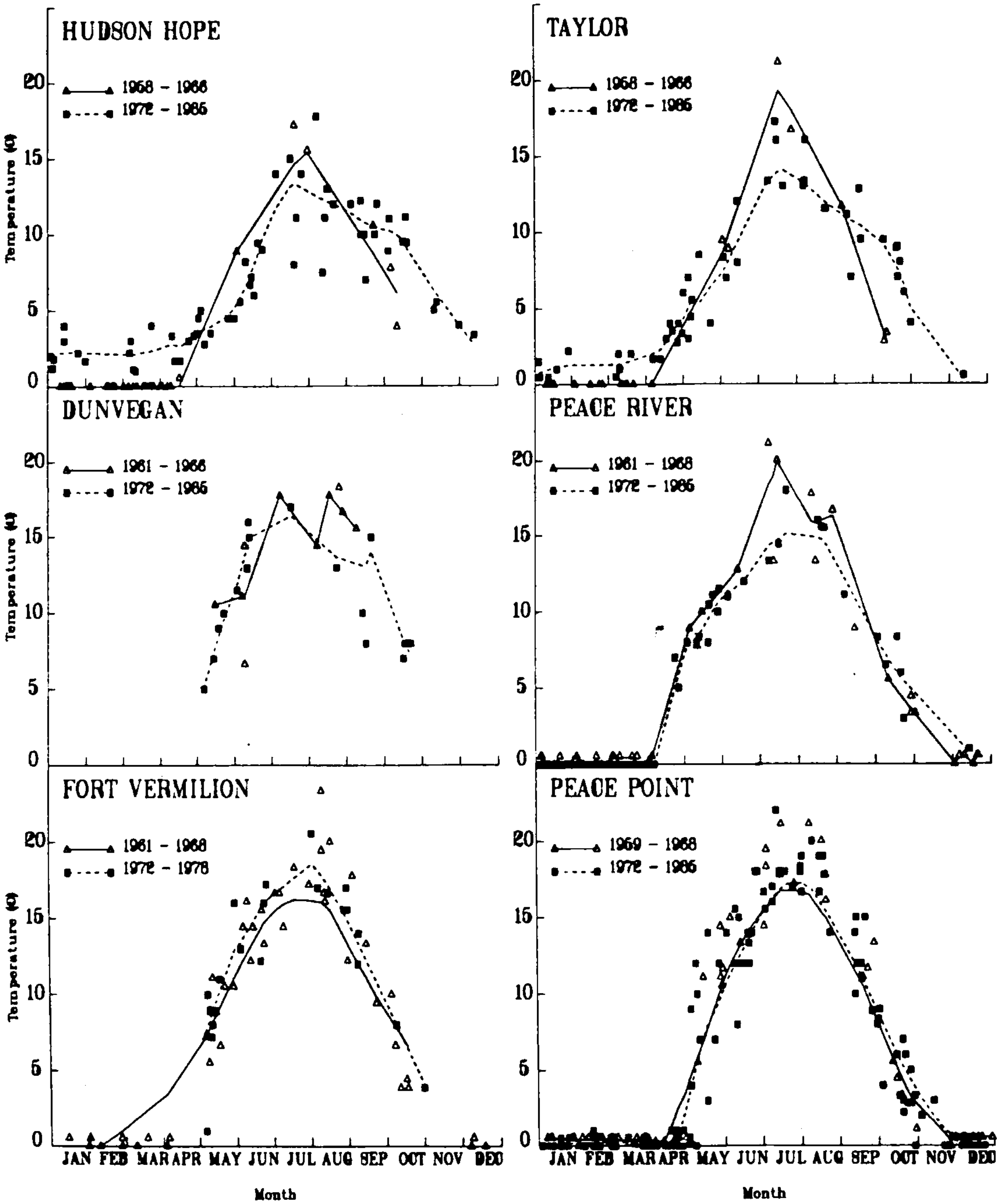


Figure 3.37 Vegetation maps of ResDelta cleavage bar from 1977 and 1994. (English et al., 1995).

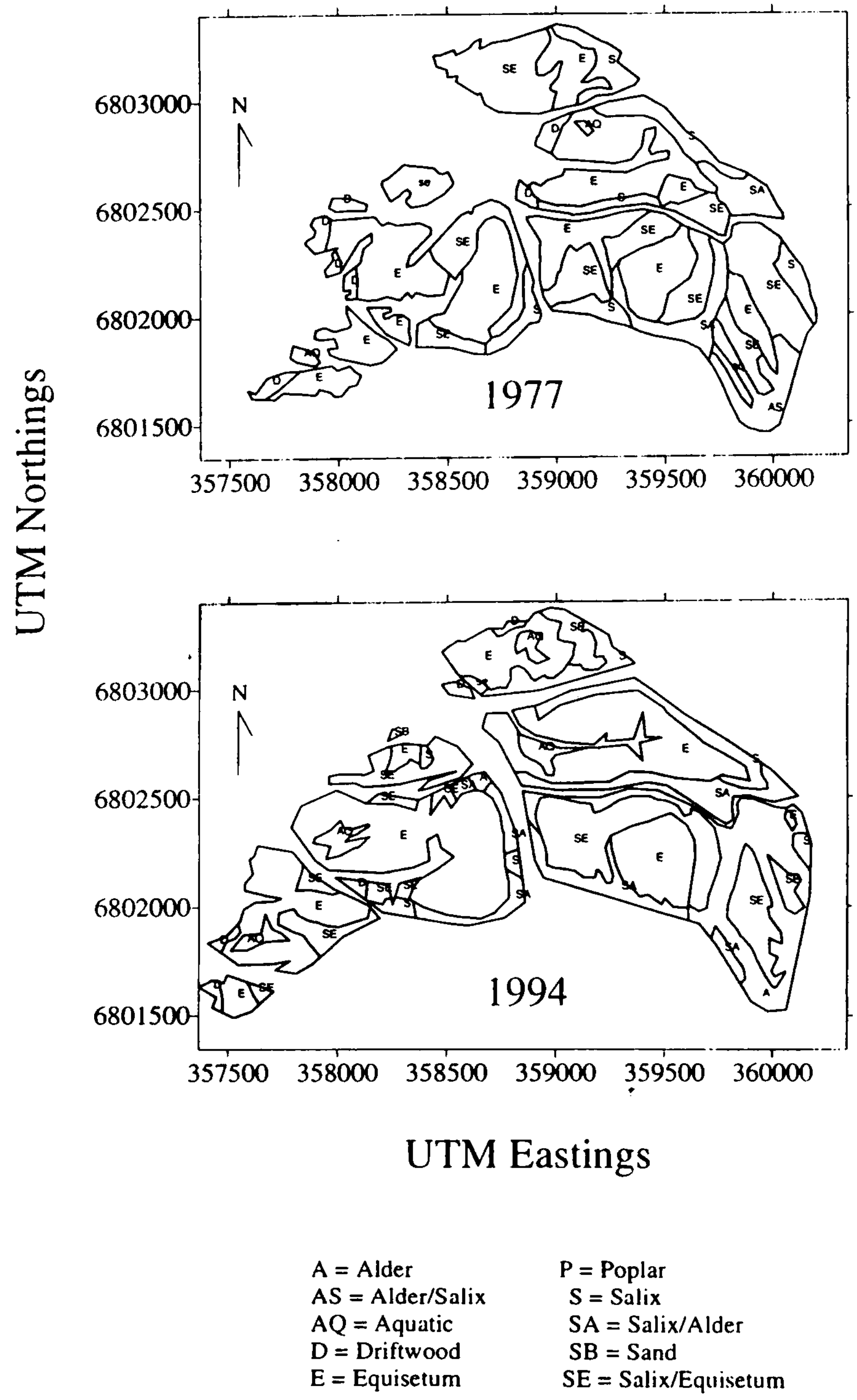


Figure 3.38 Plant assemblage changes for cleavage bar islands. (after English et al., 1995).

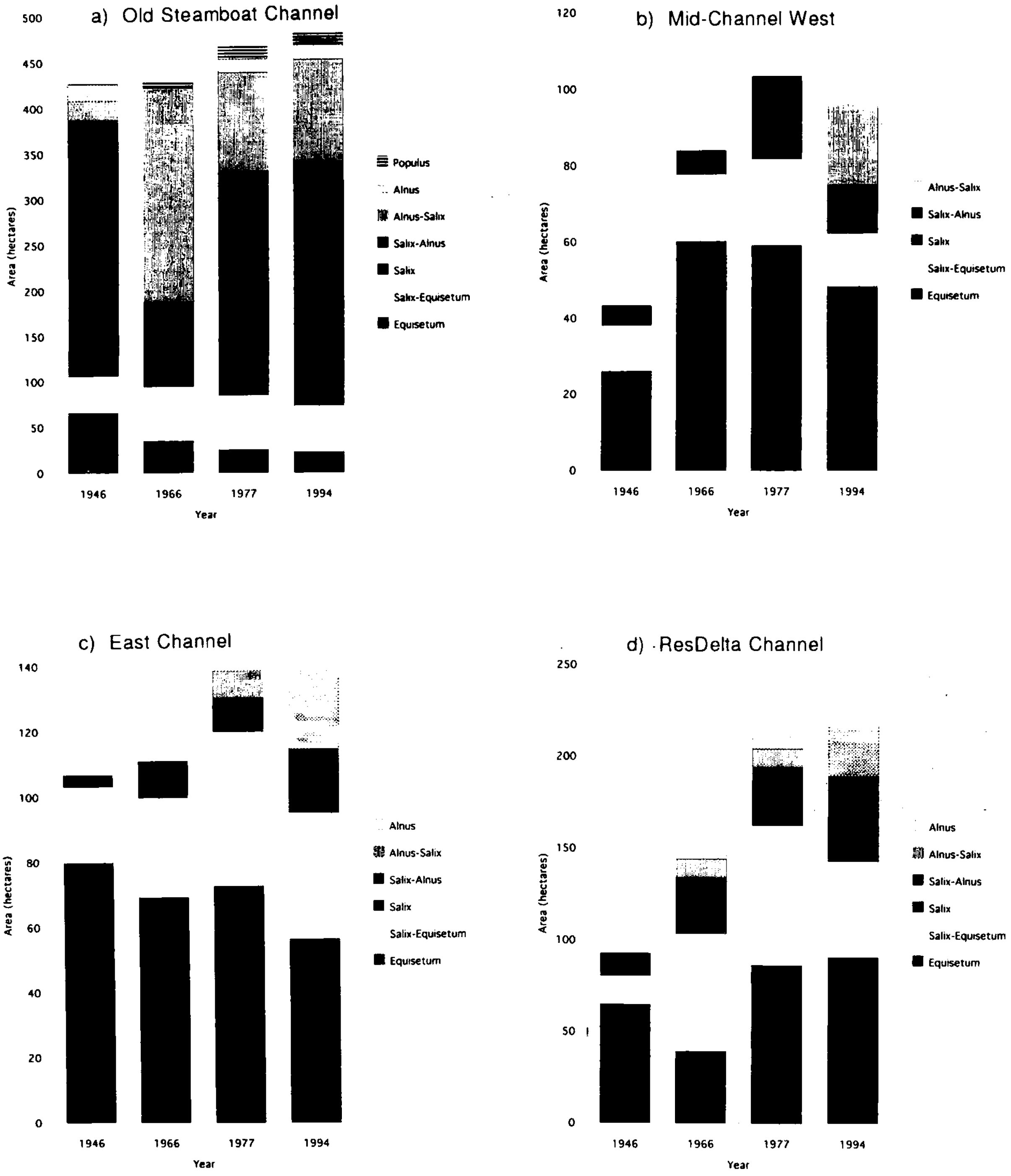


Table 3.3 **Predicted changes in mean channel dimensions: Peace River (Church, 1995).**

Station	Q_r/Q_u	w_{sr}/w_{su}	d_{*r}/d_{*u}	v_r/v_u	L_r/L_u
Exponent		0.540	0.333	0.125	0.500
Gravel reach	0.39	0.60	0.75	0.90	0.65
Taylor B.C.					
Dunvegan Bridge	0.43	0.63	0.75	0.90	0.65
Transition reach	0.58	0.74	0.83	0.93	0.76
Peace River					
Sand reach	0.59	0.75	0.84	0.94	0.76
Fort Vermilion					
Peace Point	0.58	0.75	0.83	0.93	0.76

Q is stream discharge ($m^3 s^{-1}$); w_s is channel width (m); d_* is hydraulic mean depth (m); v is mean flow velocity ($m s^{-1}$);
L is meander wavelength or riffle spacing (m); subscript u indicates unregulated value; and subscript r indicates regulated value.
Estimates for Fort Vermilion based on Q_r for the period 1970-1979, for which there are eight years of record. Gauging discontinued.

Table 3.4 Summary of morphologic and vegetative changes for the Peace River study reaches (after Church et al., 1996).

Changes 1966-69 to 1993	Reach 1	Reach 2	Reach 3
Physical Characteristics			
reach length (km)	134	145	158
change in width (m)	-46	-20	-123
% change in width	-10	-4	-16
Morphology Changes			
net erosion (sq. m. x 1000)	2149	2465	13768
net deposition (sq. m. x 1000)	4465	8187	10602
stable (sq. m. x 1000)	62267	83878	138969
net deposition (sq. m/km length)	33321	56462	67101
Vegetation Changes			
removal (sq. m. x 1000)	2059	3968	2621
advance (sq. m. x 1000)	8013	8198	22978
stable (sq. m. x 1000)	6187	13414	36208
advance (sq. m/km length)	59799	56538	145430
Feature Changes			
bar (bare; sq. m. x 1000)	-3057	3678	-21798
bar (vegetated; sq. m. x 1000)	6181	2002	18417
island (sq. m. x 1000)	570	1056	829
river (sq. m. x 1000)	-3116	-6574	2322
fan (sq. m. x 1000)	320	-1	-19
bar (bare; %)	-45	62	-58
bar (vegetated; %)	194	18	252
island (%)	13	17	3
river (%)	-6	-10	3
fan (%)	98	-0.3	-100

3.6 WATER CHEMISTRY

Although studies of regulation effects on water chemistry of the Peace-Slave River system were not initiated by the NRBS (Section 1.1), brief syntheses of existing data and reports have been made, especially on the topics of water temperature, mercury and general water quality. More detailed information is available in NRBS (1996a) and in the reports associated with the NRBS contaminant, oxygen and nutrient studies.

3.6.1 Water Temperature

As noted in Section 1.5.3, reservoirs act as a thermal regulator of flow to the downstream river system, the distance water-temperature effects are experienced downstream depending on prevailing climatic conditions and the magnitude of the regulated flow compared to that of downstream tributary inflow. No specific NRBS studies investigate regulation-induced changes in water temperature; however, existing data were reviewed to provide a general assessment of changes within the NRBS study area. Figure 3.39 displays pre- and post-regulation, summer water temperatures recorded by Water Survey of Canada for five stations on the Peace River including Hudson's Hope, Dunvegan, town of Peace River, Fort Vermilion, and Peace Point. The role of regulation on late-fall to freeze-up temperatures has already been discussed with respect to the delay of ice-cover formation (Section 3.4.1). Mid-winter water temperatures will not vary in the presence of an ice cover.

Apparent within both sets of temperature data is a slight downstream warming of peak temperatures. The effect of regulated summer flows on peak water temperature is evident for the station at Hudson's Hope but has all but disappeared by Dunvegan. At most, there may be a slight shift to cooler, early summer water temperatures for this site, but even this effect seems to disappear further downstream. A complete assessment of water temperature changes requires a modelling approach that considers variations in discharge and atmospheric heat fluxes. Groundwater heat flux can also be significant in affecting the temperature of low-flow conditions, but its importance has probably diminished with the increase in minimum flows (Section 3.1). In general, the data of Figure 3.39 suggest that the major effect of regulation on summer water temperatures is greatly diminished by the time flow reaches the British Columbia-Alberta border. As earlier noted, the greatest seasonal effect on water temperatures is in the delay of freeze-up.

3.6.2 Mercury

Processes affecting mercury in lentic and lotic systems have been elaborated in Section 1.5.2. As described, the level of direct mercury contamination downstream will be related principally to reservoir mercury levels because the hydraulic nature of lotic systems tends to minimize microbial methylation processes. Moreover, dilution of methyl mercury downstream of a reservoir is a function of the magnitude of tributary inflow. The NRBS conducted a study to summarize existing levels and distribution patterns of mercury the Peace, Athabasca and Slave river basins (Donald and Craig, 1995). A similar study has recently been completed by the Department of Indian Affairs and Northern Development focussing on sources of mercury to the Slave River (Grey *et al.*, 1995). In both cases, the lack of pre-regulation data precluded a pre/post comparison. This section briefly reviews the data for the reservoir and the main stem portions of the Peace and Slave Rivers, reaches that could be affected by the downstream transport of mercury from the reservoir.

One of the conclusions of the Donald and Craig (1995) report was that many historical measurements of mercury within the water column are suspect because of problems and variations in field-sampling protocols, especially at very low detection levels. Hence, discussion focusses only on levels found in sediment and fish. Within the Williston Reservoir, available post-regulation data suggest that mercury levels are at low levels (i.e., n =5; mean = 27.2 mg/kg; Watson, 1992), below the average mercury content found in Canadian soils (81 mg/kg, McKeague and Kloosterman, 1974). Quite high levels of mercury, however, were found within some fish sampled within the reservoir. Specifically, mercury levels in bull trout (a predator species) were found to average 804 mg/kg but with a maximum level for one individual of 4870 mg/kg. Moreover, 35% of the bull trout sampled exceed the Health Canada limit of 500 mg/kg.

Downstream of the reservoir, a three-point sampling between the reach upstream of the Smoky River confluence to the lower reach below Vermilion Chutes found river-sediment mercury levels (68 to 75 mg/kg) to be higher than those found in reservoir sediment. The reverse, however, was found for levels in fish. Mercury levels in burbot, lake whitefish, bull trout, rainbow trout and kokanee were lower in the Peace River downstream of the reservoir (Donald and Craig, 1995).

A review of data (1988-1990) for walleye, pike and whitefish (Grey *et al.*, 1995) further downstream found that the first two predator species had comparable average mercury concentrations of 340 mg/kg (maximums of 800 and 600 mg/kg, n = 99 and 63, respectively) while those for whitefish were much lower (80 mg/kg; maximum of 130 mg/kg; n = 30), indicative of its trophic level. Noting little difference was evident in mercury concentrations (for the same species) with the nearby Hay River, Grey *et al.* (1995) suggested that fish in the Slave River were not being affected by upstream mercury sources. Furthermore, an analysis of larger-scale regional patterns (e.g., using data from remote lakes) indicated that sources were not of anthropogenic origin but that local lithology was important.

Both reports tend to the conclusion that the reservoir is not playing a significant role in affecting downstream mercury levels. The specific concentration of mercury within the water column and the overall downstream transport of mercury will remain unknown, however, until more data are collected using improved sampling protocols.

3.6.3 General Water Quality

Water chemistry in reservoirs and the effects to downstream riverine environments are reviewed briefly in Section 1.5. Because storage of water in reservoirs results in chemical and biological changes, water released from large reservoirs, like the Williston on the Peace River, often has a different chemical composition than natural river water. Different seasonal patterns of water quality may also be observed as a result of impoundment, with water quality fluctuations moderated downstream of impoundments, annual variability reduced, and short-term extremes possibly much less pronounced.

Although the NRBS did not carry out a specific study of regulation effects on water chemistry of the Peace-Slave Rivers, a review was recently conducted by Alberta Environment (Shaw *et al.*, 1990) of the general water quality in the Peace River, based primarily on data recorded at Dunvegan (1969-1989). A number of observations in this report were made on potential effects of impoundment, the most significant of which are reviewed briefly below. Unfortunately, this review relied primarily on post-regulation data. The most extensive set of pre-regulation data (1960-1974) exists for the town of Peace River but only contains two years of post-regulation data and is unsuitable for a time series evaluation of regulation effects.

In general, Shaw *et al.* (1990) found the water quality of the Peace River to be different, in many respects, from that of other major rivers in Alberta. Concentrations of dissolved materials in the Peace River tend to be lower and less variable, while concentrations of suspended material (silt and organic matter) tend to be higher. The regulated volume of flow in the Peace River is large relative to tributary inflows and effluent discharges have relatively little effect on water quality in the Peace River mainstem. Details of specific reaches and parameters are outlined next.

3.6.3.1 *Major Reaches*

Three distinct reaches of the Peace River were recognized by Shaw *et al.* (1990). The upstream reach, extending from the B.C.-Alberta border to the Smoky river, has few tributaries and no effluent discharges. Relative to other portions of the Peace River, this reach has clearer water and higher dissolved oxygen. Concentrations of metals, nutrients, organic matter, and salts are low.

The second reach extends from the confluence with the Smoky river downstream to near Fort Vermilion. Concentrations of both dissolved and suspended materials are higher due to large tributary inflow, particularly from the Smoky River. Increases in sodium and chloride in this reach have also been partly attributed to discharges from the Weyerhaeuser pulp mill at Grande Prairie and the abandoned Peace River Oils flowing well.

Water quality in the downstream reach, extending from Fort Vermilion to the mouth of the Peace River, is influenced somewhat by tributary inflows. A more important influence, however, is the change from gravel to sand and silt within the river channel, as well as along the bank. Concentrations of suspended particles are high in this reach and those constituents associated with clay particles (e.g., metals) are most pronounced.

3.6.3.2 *Flow Dependency of Water Quality Variables*

Concentrations of some water quality constituents are often related to river discharge (Harned *et al.*, 1981; Hirsch *et al.*, 1982). Concentrations of total dissolved solids, major ions, and dissolved metals tend to decrease with increased discharge resulting from precipitation, snow melt, or releases from a reservoir. Concentrations of suspended particulate material tend to increase with increased discharge, as do concentrations of constituents associated with silt and particulate organic material (e.g., nutrients).

Based on the set of water quality data from the Peace River at Highway 2, near Dunvegan, Shaw *et al.* (1990) examined the flow dependency of 30 water quality variables.

Lists of flow-dependent and flow-independent variables, as determined in that study, are given in Table 3.5. Fifteen were found to be flow dependent and although the flow-dependencies were statistically significant, the correlation coefficients between concentration and discharge were low ($r^2 = 0.10$ to 0.21). In addition, some variables, usually inversely related to discharge (e.g., total dissolved solids and major ions), showed no significant flow dependency.

These results were considered by Shaw *et al.* (1990) to be due to a moderating influence produced by the relatively large volumes of water released from the Williston Reservoir. The water quality of such water is probably more constant than that occurring in the river under natural flow conditions. Similar poor correlations between discharge and the concentrations of water quality constituents have also been reported downstream of other reservoirs (Smith *et al.*, 1982; Weagle, 1987).

3.6.3.3 *Seasonal Trends*

Seasonal trends in water quality of measurements from the Dunvegan site were also investigated by Shaw *et al.* (1990). Significant seasonal differences were found in seven flow-independent variables and 12 flow-dependent variables (Table 3.5). Although fluctuations in discharge may account for seasonal changes in some of the water quality constituents, they may also be due to other factors such as seasonal changes in temperature (indirect relationship to flow regulation), photoperiod, and human activities such as agriculture or other land use practices.

Colour, dissolved and particulate organic carbon, suspended solids, turbidity, iron, and manganese all showed similar seasonal patterns of change, with levels being highest during the summer months (period of reduced flows) and lowest during winter (period of elevated flows). Because these variables are positively correlated with discharge, the seasonal changes can be explained in part by higher flows in summer than winter, although the seasonal difference has been reduced by regulation. However, a number of other factors play an important role including overland runoff and erosion, and inputs from tributary streams. As noted in Section 3.1.5, regulation has modified the seasonal importance of tributary inflow, becoming on average less important in winter but more important in summer. In general, the importance of tributary inflow to water quality of the main stem will become more evident downstream of Dunvegan as tributaries contribute an increasing proportion of the total flow.

Dissolved oxygen concentrations were highest in winter and lowest in summer, due to the greater solubility of oxygen at colder water temperatures. Dissolved oxygen concentrations in the Peace River mainstem are at or near saturation levels for the entire year. Overall, winter depletion of oxygen in the Peace River is low because BOD concentrations are low, reaeration occurs at the Vermilion Chutes, and the reach upstream from the town of Peace River remains ice-free for much of the winter as a result of regulation by the Bennett Dam.

Nutrients in the Peace River near Dunvegan also exhibited seasonal changes attributable to the seasonality of discharge and runoff events. Both total phosphorus and total nitrogen in the Peace River are largely particulate and strongly correlated with suspended solids. Total and particulate nitrogen exhibited peak concentrations from April to June and minimum levels in January and February. Total phosphorus was highest in late spring and lowest during fall and winter. The concentration of a number of major ions (sodium, potassium, magnesium and sulphate) partly regulated by desorption from suspended particles exhibited comparable monthly contrasts. As noted in Section 3.5, reductions in conveyance power of the river may increase the relative concentration of finer particles in the suspended sediment load. If this is the case, similar effects would be expected in phosphorus, nitrogen and the above ions that are particulate dependent. All this provides additional rationale for improving the sediment-composition measurement program.

3.6.3.4 *Long-Term Trends*

The Dunvegan data were also tested for long-term trends (1977-1988) in 35 water quality variables by Shaw *et al.* (1990). There were significant long-term increases in two variables, decreases in 11, and no significant change in 21. Water quality variables exhibiting significant long-term trends are noted in Table 3.5. Major long-term trends associated with regulation are related to reservoir aging processes and changes in the downstream physical template (e.g., sediment composition).

Dissolved oxygen concentrations increased significantly over the period of record, but at a gradual rate (0.07 mg/L/yr). One possible explanation for this trend is the decrease, due to erosion, in the amount of oxygen-demanding sediment material in the upper cobble-gravel reaches (see Section 3.5).

A significant, but slight, long-term decrease in colour was also noted. The reason for this change is not clear and there has been no similar change in some of the constituents that contribute to colour (e.g., iron and dissolved organic carbon). It is possible that the decrease may be due to long-term changes in the colour of Williston Reservoir water as it aged.

The long-term decreases observed for all nitrogen fractions, while statistically significant, were relatively small. Shaw *et al.* (1990) suggested three possible reasons for these long term trends: a decrease in nitrogen loadings from sewage effluents, a reduction in surface runoff of agricultural fertilizers, and reduced concentrations in the Williston Reservoir due to reservoir aging.

3.6.3.5 *Discussion*

It should be stressed that the above assessments by Shaw *et al.* (1990) focussed on one station close to the British Columbia-Alberta border. To evaluate changes to water quality from regulation more fully, data should be collected from sites further upstream and compared to those from downstream stations. Moreover, this should be done for a range of flow conditions. Unfortunately, the dearth of water quality data collected prior to regulation will make assessments of the effects of regulation on water quality very difficult. Hindcasting using water quality models and boundary condition data measured near the reservoir may be the only way to assess regulation effects quantitatively.

Figure 3.36 Aerial photographs at inlet to Old Steamboat Channel for 1946 and 1994. (English et al., 1995)

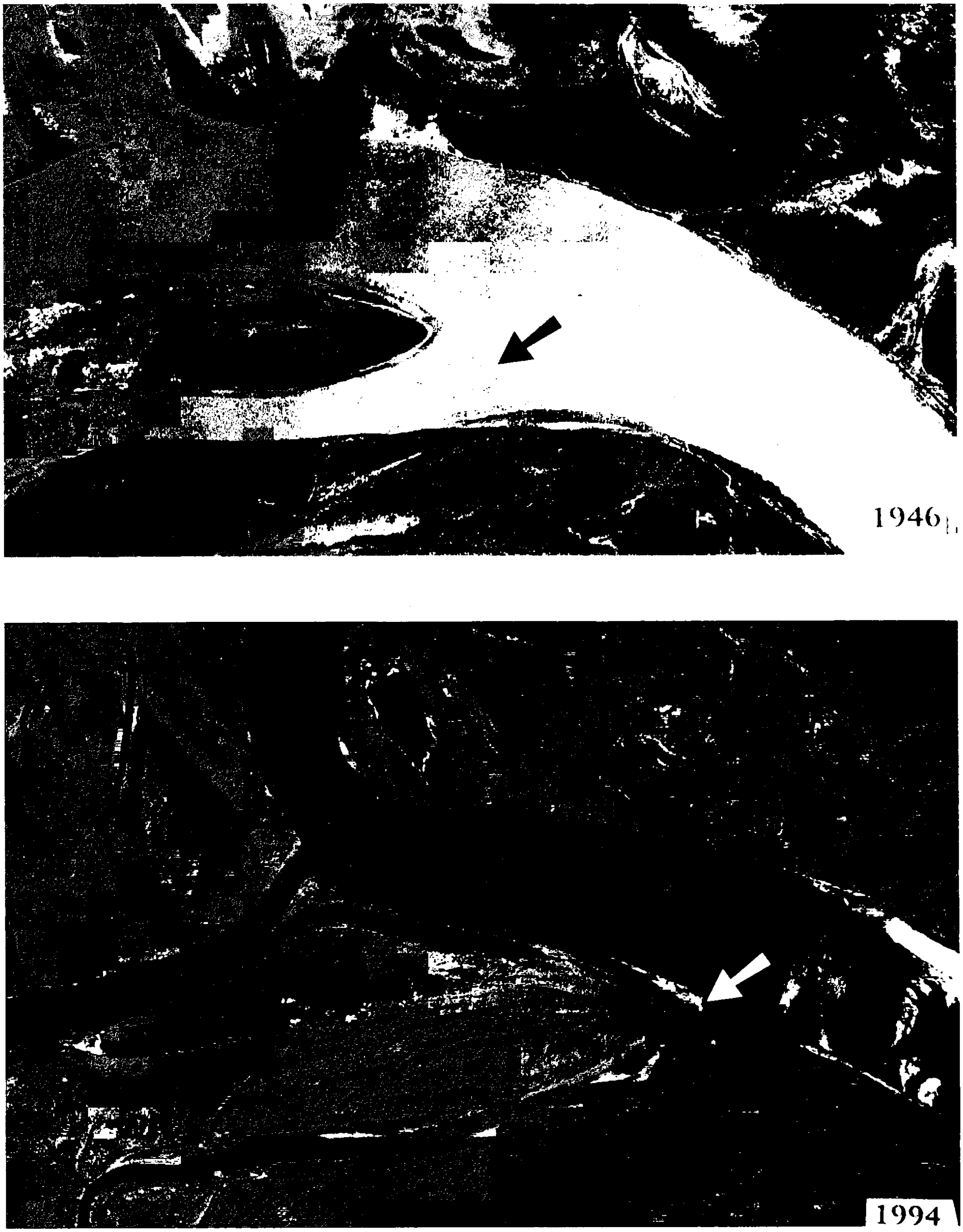


Table 3.5 **Flow-dependency and temporal characteristics of water quality variables, Peace River.**

FLOW-INDEPENDENT VARIABLES

Alkalinity
Boron (dissolved)
Chloride
Dissolved Oxygen*↑
pH ↓
Silica (reactive)*↓
Sulphate*
Total Dissolved Phosphorus
Arsenic (dissolved)
Calcium ↓
Coliforms (total)* {Fecal streptococci ↑}
Organic Carbon (dissolved)*
Potassium*
Sodium*
Total Dissolved Solids

FLOW-DEPENDENT VARIABLES

Bicarbonate
Magnesium*↓
Specific Conductance
Total Hardness ↓
Colour (true)*↓
Iron (extractable)*
Organic Carbon (particulate)*
Manganese (extractable)*
Nitrogen (dissolved)*↓
Nitrogen (particulate)*↓
Nitrogen (total)*↓
$(NO_2 + NO_3)$ - Nitrogen*↓
Phosphorus (total)*
Suspended Solids*
Turbidity*

Table adapted from Shaw *et al.*, 1990.
* indicate variables that exhibit seasonal changes in the Peace River.
↑ indicate an increasing trend through time
↓ indicate a decreasing trend through time {presence of a-BHC, an impurity in lindane also decreased}

3.7 EFFECTS ON AQUATIC ECOSYSTEMS

No systematic measuring/monitoring of the biological components of the aquatic ecosystem of the Peace-Slave system has been conducted, rendering it impossible to compare pre-regulation aquatic communities with those existing after regulation by the Bennett Dam. Effects of flow regulation on aquatic biota must be inferred, therefore, from interpretation of documented physical and chemical modifications in the system. These modifications include the changes previously noted in hydrology, water chemistry, water temperature, ice regime, sediment regime, river morphology and riparian vegetation.

3.7.1 Effects of Flow Variations

Variations in flow as a result of regulation are known to affect aquatic habitat availability and quality significantly (Section 1). Assessment of such effects requires detailed knowledge of how availability and quality change over time under differing flow conditions, natural and regulated. Although there is a dearth of such data for the Peace and Slave rivers, the following summarizes some of the most important impacts that are likely to result from flow regulation, especially those associated with variations in short to medium (daily to seasonal) flows.

The most obvious impact of flow variations on the aquatic system is on habitats located along the river margin, particularly on side channels, snyes, backwaters, and shoals. These habitats are most vulnerable to changing flows and are first to be affected. They are also the most important from a fish habitat perspective. Snyes, backwaters and side channels are preferred habitat types for many fish species in the Peace River (Hildebrand, 1990); moreover, any relatively shallow, low velocity areas along channel edges are potentially important rearing areas for young juveniles of many fish species.

The seasonal availability of these important habitat types may be affected by flow regulation on the Peace River because of reduced spring and summer peak flows and increasing winter flows. Seasonal differences between natural and regulated flow regimes may also affect access to spawning areas by some species. Northern Pike, for example, spawn in the spring during high water levels, usually in marshes or flooded vegetation. If reduced peak flows during this period limit access to suitable areas, spawning success and recruitment will be reduced.

Reductions in the magnitude of peak flows may reduce the frequency of occurrence of conditions that allow fish passage in specific locations. The Vermilion Chutes, for example, is a significant obstacle to fish movements in the Peace River, but it may not be a complete barrier at all discharges (Hildebrand, 1990). The area appears impassable to upstream migrants at most flows that commonly occur in the Peace River, but it might be passable at significantly higher flows. Such a barrier could be eliminated with reduced peak flows.

Large flow fluctuations over short periods of time (e.g., daily) can have significant adverse effects on aquatic habitats and biota such as: increased stress to fish due to rapidly changing conditions; reduced utilization of the affected area by fish; and reduction in benthic invertebrate abundance due to repeated scouring and increased catastrophic drift. If flows are reduced extremely rapidly, fish can also become stranded in isolated pools. Such pools are subject to intense solar heating and can produce lethal water temperatures. Large daily flow fluctuation is an issue in the upper reach of the Peace River, above the confluence with the Smoky River (Hildebrand, 1990; Courtney *et al.*, 1995).

Assessment of all of the effects of an altered flow regime on short-term habitat availability and quality requires an examination of how availability and quality change over time under both the natural flow regime and the regulated flow regime. Unfortunately, this has not been done for the Peace River and the data currently available are not sufficient to undertake such an assessment.

3.7.2 Modelling of Habitat Availability/Quality

In consideration of the dearth of information about habitat use and availability on the Peace and Slave rivers, the NRBS held an experts workshop on methods for determining flow-habitat relationships and for assessing effects of flow alteration on habitat quality and availability. The specific objective was to determine the most suitable method for measuring habitat changes on large northern rivers like the Peace and Slave. Results of the workshop are contained in an NRBS report by Walder (1996). The most frequently used approach is the Instream Flow Incremental Methodology (IFIM), reviewed in more detail in a summary report by the NRBS Synthesis and Modelling Component (Wrona *et al.*, 1996). The method employs simulation modelling to predict depth and velocity conditions within a stream segment, in two dimensions, over whatever range of discharges is of interest. The predicted micro-habitat conditions, as described by depths and velocities are then compared to known depth and velocity preferences of the fish species of interest. This method is difficult and expensive to use on large rivers due to the amount of data required to calibrate the hydraulic model and the difficulty of obtaining reliable micro-habitat preference data. New generation two-dimensional (2-D) hydraulic models, however, can greatly reduce field data requirements about flow conditions. On large rivers, it is only practical to apply such models at small reaches of specific ecological significance. The only field requirements are an initial set of detailed cross-sections for the reach of interest. The model is then capable of calculating depth and velocity throughout the reach for a full range of flows that may occur. The recently developed hydraulic model of the Peace River creates the possibility to initialize (provide input flow) to such 2-D models at any reach along the Peace and Slave rivers.

Considering that the current 2-D hydraulic-habitat models are now only being validated for small rivers, a pilot NRBS study was initiated to investigate other methods for describing discharge-habitat relationships on large rivers, like the Peace and Slave. The selected study (Courtney *et al.*, 1995) involved the mapping of important habitat types using airborne remote sensing equipment (CASI multispectral scanning imager and multispectral videography) as well as conventional aerial film photography. Capabilities of the system to map and measure changes in meso-scale aquatic habitat features at different discharge was evaluated. Habitat types included: primary and secondary main channels, side channels, riffles, snyes, sloughs, shoals, and backwaters. Courtney *et al.* (1995) concluded that conventional film photography was as suitable as multispectral remote sensing techniques for discriminating the major habitat types on the Peace River, although colour-infrared film was superior to standard colour film. Figure 3.40 shows sample colour and colour- infrared aerial photographs of part of the Many Islands area (Figure 3.26) reproduced from a scanned image with a ground resolution of 2.5 m pixels. In general, infrared wavelengths are best for determining waters margins because water strongly absorbs this portion of the spectrum. Colour infrared was also found to be superior choice in terms of: ability to reveal depth variations (water penetration), ease of georeferencing, and level of accuracy for mapping aquatic habitat. Its major limitation is a poor ability to discriminate features with very specific spectral signatures, such as different substrate categories.

Because this was a pilot study, mapping was limited to two reaches (an upstream reach in the Many Islands area, and a downstream reach near Fort Vermilion) and three discharges. Although the preliminary habitat-discharge relationships are of limited use for analyzing the effects of flow variations on habitat availability, their utility could be increased with additional sampling over a wider range of discharge.

3.7.3 Effects of Changes in Ice Regime

Changes in the hydrological and thermal regime due to flow regulation have altered the ice regime of the Peace River. The effect of reduced duration and extent of ice cover on dissolved oxygen in the Peace River has been discussed in Section 3.6.3 and implications for fish and other aquatic biota are discussed in Section 3.7.3.

The absence of an ice cover in the upper reaches of the Peace River can interrupt the normal movement patterns of larger mobile mammal species with large home ranges (Simpson, 1991). By contrast, however, open water during the winter can increase the productivity of other species, such as beaver. Lack of an ice cover and enhanced growth of desirable riparian vegetation (see Section 3.8) has meant that some beaver do not build food caches in the upper Peace River but rather forage all winter (Blood, 1979).

Where an ice cover does form, the large increase in deposits of frazil ice are probably the most significant aspect of the altered ice regime affecting aquatic habitats and biota in the Peace River. As noted in Section 3.4.1, frazil ice is deposited in low-velocity areas and may reduce or eliminate flow in shallows around islands and along banks. Many areas of low velocity are particularly important as fish habitat because they provide a refuge from current velocity and serve as holding areas (e.g., Power *et al.,* 1993). In addition, the shallow areas along stream margins are typically utilized by fry and juvenile fish, although there is generally a tendency for these life stages to occupy somewhat deeper areas in late fall and winter than during the rest of the year. Because frazil-ice deposits are dramatically thicker in reaches of the Peace River upstream of Vermilion Chutes (e.g., Figure 3.41), it appears likely that the amount of suitable winter habitat for fish has been reduced as a result of flow regulation. It is uncertain, however, what effect this might have on fish populations because it is not known if winter habitat availability is a limiting factor in any reaches of the river. Spawning areas utilized by fall spawning species would also be adversely affected if frazil-ice deposits cause dewatering or freezing of incubating eggs.

As earlier noted, the Vermilion Chutes can also be a major obstacle to fish movements except under high flow. Enhanced staging of the ice cover (and associated water levels) due to flow regulation could also reduce the severity of this barrier to fish movements. Even if this situation allows fish passage through the area, however, it probably has not dramatically affected distribution or movements of fish in the river. The major fish migrations in the Peace River occur either in spring, after break-up, or in fall, prior to freeze-up.

River ice break-up is a disturbance factor with important implications for aquatic community structure and function. During dynamic break-up events (see Section 3.4.3.4 for descriptions of break-up types), bed scouring, erosion, and high sediment concentrations can reduce, for example, benthic invertebrate density, biomass, and diversity (Scrimgeour *et al.*, 1994). There may also be mortality to fish eggs, juveniles and adults. In general, ice break-up is a major biological set-point for lotic systems. Its level of aquatic disturbance varies depending on its physical severity which can be modified by flow regulation. In the upper reaches of the Peace River, the effects of break-up have been greatly reduced after regulation simply because of the reduced frequency of ice-cover formation (Section 3.4.2). One expected result would be the establishment of a more stable benthic community, with higher invertebrate abundance. Inter-annual adjustments in the aquatic community would also be expected to occur in downstream reaches if the intensity of break-up has been modified, as suggested in Section 3.4.3.

3.7.4 Effects of Geomorphological Changes

Results of the geomorphology studies of the Peace River (Section 3.5) indicate that the gravel reach upstream of the Smoky River confluence is being affected largely by island growth and expansion of vegetated areas. This reach contains two island groups of significant physical complexity that are particularly important for providing a diversity of fish habitat. The presence of side channels, snyes, backwaters, and shoals provides a range of habitat conditions suitable for several different fish species and life stages. Since regulation, there has been some loss of complexity in the most upstream island group. This has not been extensive, however, and the area still provides high quality fish habitat. In the most downstream island group, there has been some increased development of fish habitat, consisting of smaller channels with more stable, vegetated banks. The presence of bank vegetation and more woody debris along these small channels provides improved cover for fish. In addition, there is likely increased input of terrestrial allochthonous organic material that may increase benthic invertebrate production. Such improvements in fish-habitat quality may be temporary, however, as the river morphology continues to adjust to the new regulated regime (Section 3.5.1.3).

In the gravel-sand reach, downstream from the town of Peace River, there has been some growth of islands and bars due to sediment deposition but relatively little development of new bars. Dominant morphological changes in this reach are the stabilization of bar features by the marked encroachment of vegetation. In some areas, the quality of fish habitat, particularly for rearing juveniles, has probably improved due to development of smaller side channels with vegetated banks, better cover features, and potentially increased benthic invertebrate production. However, some side channel sites may have become less suitable for spawning because of the accumulation of fine sediments. Within this reach, sediment plugs are forming in some side channels and there has been some isolation and abandonment of side channels. Loss of side channels and associated snyes is significant because these habitats typically are utilized extensively by fish in large rivers and have been shown to be the preferred habitats for several species and life stages of fish in the Peace River (Hildebrand, 1990). Where significant amounts of sand and silt have accumulated in areas that once were primarily gravel, the benthic invertebrate community will have been dramatically altered.

Within the sandy reach just upstream of Fort Vermilion, major morphological changes have included bar and island accretion, mid-channel shoaling, transverse bar formation, and vegetation encroachment. Channel narrowing is occurring as side channels become abandoned; this process is expected to continue for some time. Again, the loss of side channel habitats is the most significant impact to fish resources of this reach because of the variety of habitat features that they normally provide to a range of fish species and life stages (Hildebrand, 1990).

3.7.5 Effects of Changes in Water Chemistry

Given the relatively small changes in water chemistry, it is unlikely that aquatic biota in the Peace River within the NRBS study area have been affected in any substantial way. Impacts would be most pronounced in the upstream reach of the Peace River, above the confluence with the Smoky River, and would diminish with distance downstream due to the increasing influence of tributary inflows.

While it is possible that some species of invertebrates or periphytic algae particulary sensitive to certain aspects of water chemistry might have been affected, any changes in benthic community structure should be subtle. None of the fish species are likely to be significantly affected by the type and magnitude of the observed water chemistry changes. It should be noted, however, that the potential for adverse water quality conditions to develop during the extreme low flow periods that can be created by flow regulation (e.g., by very low releases during reservoir filling) has not been evaluated. Similarly, although the altered temperature regime may have had some effect on aquatic communities in the upper reaches of the Peace River, the extent of such impacts cannot be readily estimated from existing data.

Dissolved oxygen concentrations in the Peace River currently remain at or near saturation levels throughout the year (Shaw *et al.*, 1990). However, pre-regulation data are not available to make comparisons. If flow regulation has significantly affected dissolved oxygen in the Peace River, it has resulted in increased winter concentrations, at least in the upper reaches. Fish and other aquatic biota would not be adversely affected by this effect.

Analysis of measured water temperatures in the Peace River, discussed in Section 3.5, did not provide conclusive evidence of flow regulation effects within the NRBS study area (i.e., downstream of the B.C.-Alberta border), except during the fall freeze-up period. Because hypolimnetic water is released from the Williston Reservoir, river temperatures downstream from the reservoir should be lower than natural conditions during summer and warmer than natural conditions during winter months. Although this effect may persist for quite some distance downstream, its extent in the Peace River within Alberta is unclear. The limited data available suggest that while summer water temperatures downstream of the Alberta-B.C. border might be influenced by flow regulation, they have not been dramatically affected.

As reviewed in Section 1.6.3, the occurrence and timing of important life cycle events

Figure 3.40 Colour and colour infrared aerial photography for part of Many Islands area of the Peace River (from Courtney et al., 1995)

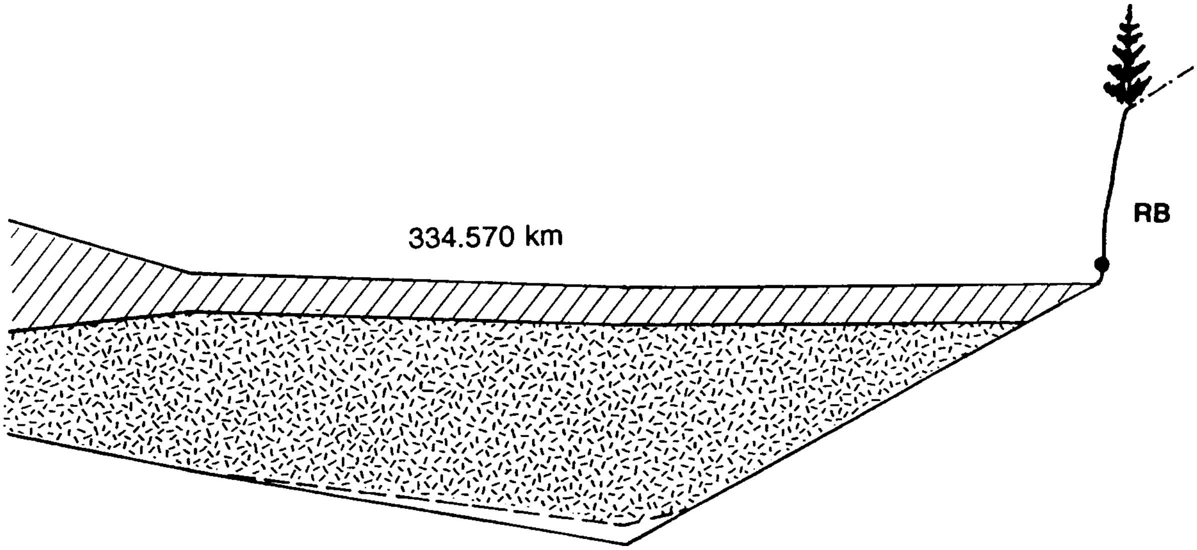
Color

Infrared

of benthic macroinvertebrates (hatching, growth, emergence) are temperature dependent (Gore, 1980). In general, therefore, the expected effects of reduced summer temperatures include changes in benthic community structure, productivity and species diversity. Reduced summer temperatures may also affect the longitudinal distribution of fish, due to the different temperature tolerances and preferences of different fish species. The range of cold-water species, such as mountain whitefish, could be extended farther downstream. If, as suggested, summer water temperatures in the Peace River within Alberta have not been dramatically affected, impacts on the benthic communities and fish populations probably have been minor. However, as noted by McCart (1982), rapidly fluctuating discharges from hydroelectric reservoirs can result in similarly fluctuating downstream temperatures. The extent to which this might occur in the Peace River within the NRBS study area is unknown. If the magnitude of summer temperature fluctuations is large, it would be expected to affect benthic community structure and productivity significantly, and adversely affect the relative suitability of fish habitat in upstream reaches.

Delays in fall freeze-up (Section 3.4.1) and the related higher water temperatures in the upstream portions of the Peace River could also influence the aquatic system. Increased water temperatures at this time of year, in conjunction with reduced summer temperatures, would be expected to affect benthic invertebrate community structure, diversity, and productivity; moreover, elevated winter temperatures can significantly affect development and hatching of eggs of fall spawning fish species (e.g., mountain whitefish). Graybill *et al.* (1979) reported that developmental rates were accelerated and time to hatching reduced as a result of increased temperatures during egg incubation. Elevated winter temperatures could potentially result, therefore, in fish fry emerging at a time not appropriate for optimum survival. Due to a lack of detailed data on post-regulation winter temperature changes, it is impossible to estimate how significant any effects on fish populations or macroinvertebrate communities might be. It is improbable, however, that communities downstream of the confluence with the Smoky River have been significantly affected.

Figure 3.41 Ice thickness and frazil ice accumulation in the vicinity of Vermillion Chutes (from Andres, 1995).



3.8 EFFECTS ON RIPARIAN ECOSYSTEMS

3.8.1 River Main Stem

Riparian succession is playing a dominant part in the development of the new river floodplain. As detailed in Section 3.5, observed changes consist of progradation of riparian vegetation down the banks, expansion of the vegetated area on islands, colonization of bar surfaces that were formerly inundated on a seasonal basis, and establishment of vegetation at sites of accretion along channel margins.

At present, the forest component of the riparian ecosystem is not negatively affected by flow regulation, and in fact will be allowed to expand within the floodplain over time. These observed and predicted future successional changes in the riparian community will likely benefit a wide variety of wildlife species that use edge habitats and mature forest. Economically important large mammals such as moose and deer often make extensive use of these riparian habitats along the Peace River during both summer and winter (N. Lizotte, pers. comm.; B. Johnson, Alberta Fish and Wildlife, pers. comm.). Moose should benefit from the temporary increased biomass of available browse, specifically the young shoots of alder and balsam poplar. Moose and deer sign was recorded frequently on the majority of the islands visited during reconnaissance level site visits conducted in June, 1995, between Many Islands and Vermilion Chutes. The security of islands is attractive to moose and deer as calving sites, although many of the same islands exhibited signs of predator species such as wolf, coyote and bear.

Other wildlife benefitting from the increase in edge, tall shrub and forest habitats includes many species of mammals and birds. The colonization of exposed gravel bar surfaces by willow, alder and other tall shrub species provides more habitat for shrubland birds such as yellow warbler, common yellowthroat, Linclon's sparrow and song sparrow. An increase in the areal coverage of alder will produce more biomass for beaver and hare, both of which eat the bark of this species, and ruffed grouse which use alder for food (young leaves) and cover. The eventual increase in coverage of balsam poplar and white spruce forest will be beneficial to many forest-dwelling birds. Large mature trees are essential for cavity-nesting species such as American kestrel, tree swallow, nuthatches, owls and woodpeckers, including the pileated woodpecker. This large woodpecker prefers to excavate its nesting cavities in large deciduous trees not less than 50 cm in diameter (Semenchuk, 1992). Islands and floodplains often possess these old growth stands because the locations are somewhat protected from fire and other catastrophic disturbances, such as logging. A wide variety of forest-dwelling birds will also likely benefit from increases in treed area, including neotropical migrant warblers, vireos, thrushes, western tanager, grosbeaks and others.

The negative effects of flow regulation were apparent during NRBS site visits in 1995. The most noticeable impacts occurred in the wetland habitats found in abandoned channels and cutoff meanders that are only periodically connected to the river during high water events. The decreased frequency of high water events, resulting from peak flows and ice jamming, has reduced the probability of recharging water levels and nutrient inputs to these wetland habitats. It is apparent that less rejuvenation by flood waters has, in many cases, allowed the advancement of vegetation succession from emergent plants and sedges, to willow, alder, grasses and annual plants. This drying trend and the successional change are particularly noticeable in many of the smaller side channels between islands along the length of the river. Wetland wildlife such as waterfowl (mallard, teal, American wigeon and lesser scaup), shorebirds (lesser yellowlegs and solitary sandpiper) great blue heron, amphibians (primarily wood frog) and other semi-aquatic species will be affected by these changes. Typical of the habitat provided within the mainstem of a large northern river, these wildlife species were not particularly numerous along any of the reaches surveyed in 1995.

The section of the Peace River most likely to be affected by lower water levels is the reach found within Wood Buffalo National Park, between Garden Creek and Sweetgrass Landing. The broad meandering floodplain with its numerous side channels and oxbow lakes represents some of the most productive wetland habitats along the Peace River. Although the reach was not surveyed during this study, an abundance of productive wetlands probably support much higher densities of waterfowl and other wetland-dependent wildlife species than any of the sections upstream. It is recommended that this portion of the Peace River should be included in future studies, similar to those in the Peace-Athabasca Delta, that address the effects of flow regulation on riparian ecosystems of a large northern river.

3.8.2 Peace-Athabasca Delta

Lack of flooding in the Peace-Athabasca Delta has killed sedge meadows and allowed the invasion of more persistent shrub communities such as willow and poplar. As previously described Jaques (1990) found from analysis of satellite imagery that there had been an estimated 47% reduction in the aquatically-productive vegetation community between 1976 and 1989. This primarily (78%) existed above the elevation-zone influenced by the rockfill weirs and the mean-peak, summer water level (post-regulation period) (Section 3.2). Specific changes noted between 1976 and 1989 by Jaques (1990) included no major change in forest tall shrub; an increase from 10 to 25% in the area of low willow shrublands with primary encroachment into meadow and wetland habitats; and a decrease from 51 to 27% of meadows, fens, and mudflats.

As earlier noted by Fuller and La Roi (1971), a remarkable feature of the Delta is its important bearing on the distribution and abundance of large mammals. The extent of contiguous wetland meadows and marsh serves as both summer and winter range for bison. It was forecasted that if plant succession proceeded in these areas forming willow scrub, or even a forest zone, the carrying capacity for bison would be much reduced. By contrast, an increasing abundance of willow should provide improved conditions for moose.

In the case of muskrat, a review of trapping records by Thorpe (1986) reveals that there is a strong correlation between high water levels and high trapping success, especially when perched basins are flooded by ice jams. Water level is the key factor in determining the extent of suitable emergent habitat and thus the year to year abundance of muskrats. Poll (1980) suggested that periodic floods and drawdowns, on a three to five year basis, are required to maintain optimum muskrat habitat conditions. This has not occurred in many of the perched basins, especially those located near the Peace River and dependent on ice-jam flooding for inundation. Local residents have indicated that some of these larger perched basins (e.g., Jerry's Lake, Push-up Lake and Egg Lake) were once so highly productive that one basin alone could support 15 muskrat trappers (Thorpe, 1986).

The companion study of the NRBS, the Peace-Athabasca Delta Technical Studies (PADTS), is currently completing a three year detailed study of this delta. As noted in Section 1.1, the PADTS is focussed strongly on methods to restore the "role of water" to the Peace-Athabasca Delta, an ecosystem for which some information already exists about "*how does river flow regulation impact the aquatic ecosystem?*". Although drying effects are believed to be impacting vegetation succession, additional PADTS studies have been undertaken to gain a better understanding of the spatial extent of such impacts (Timoney *et al.*, 1995) and to produce a model that relates vegetation succession with drying and wetting. Historical reviews have also been conducted of flood events (Peterson, 1994) and of the hydrometeorological conditions controlling ice-jam flooding (Prowse and Lalonde, 1996; Prowse *et al.*, 1996b). Recognizing that the major floods to the perched basins were produced by ice jams, the PADTS evaluated methods to create artificial ice jams on major channels within the Delta (see Peterson, 1993; Wilson, 1995; Prowse and Demuth, 1996; Prowse *et al.*, 1996a). To identify how frequent such artificial events should be created, detailed water balance models are being developed for the perched basins. Evaluations are also being made of long-term climatic trends in precipitation, evaporation and lake levels; factors that could also be significant to determining water levels in the perched basins. In anticipation of large flood events, the PADTS re-opened a channel (Claire River; buried by sawmill debris) that historically provided a major flow pathway at high stage between the Peace River and the northern delta lakes. The hydraulic 1-D flow model of the PAD (Section 3.2) is currently being upgraded to include some of these more ephemeral channels and to account for a new flow pathway (Embarras breakthrough) that links the Athabasca River to the southern portions of Lake Mamawi. Summary reports of the PADTS work should be completed in early 1996 and will provide major updates on how this ecosystem has been altered by extensive drying. Included in this NRBS report, however, is an action plan that builds on preliminary results of the PADTS studies. This is provided following the NRBS recommendations in Section 4.

3.8.3 Slave River Delta

Two physical processes related to flow regulation have the potential to affect the ecology of the SRD: changes in the timing, frequency and magnitude of open-water and ice-effected floods, and alterations to sediment supply and delta progradation. Both interact to affect the nature and quality of riparian habitat.

Northern delta environments are extremely important to waterfowl during spring migration and it is the break-up and spring flood of the Slave River that are influential in providing early open water when the surrounding ponds and lakes remain ice-covered (Smith *et al.*, 1964). It is also this type of overbank flooding that supplies water to the perched basins and abandoned channels of the middle and upper delta (Section 3.5.2). By contrast, during the late-summer to fall, recessions in the flow are required to supply the large expanses of mud flats used by fall migrations for feeding and resting (Thompson *et al.*, 1979, McCourt Management Ltd., 1982). Decreases in the size or seasonal timing of flooding would therefore affect the type and availability of spring and fall waterfowl habitat.

Periodic overbank flooding in the outer and middle delta zone is required to sustain the dominance of hydrophillic species such as horsetail, carex, cattail, reed grass and bulrush. Primary productivity is higher in these plant assemblages than it is in the more terrestrial assemblages of grasses and willow-alder (English 1984). In addition to resting, many staging waterfowl feed on the abundant vegetation in these *Equisetum* marshes. English (1984) predicted that the lowering of water levels and reduction of sediment deposition in the interlevee depressions of the SRD would allow vegetation of later successional stages to invade and displace the highly productive emergent plant assemblages, similar to what is believed to be occurring in the Peace-Athabasca Delta (Peace-Athabasca Delta Implementation Committee, 1987). Although some degree of overbank flooding and sediment deposition has occurred in the middle delta since 1977 (English *et al.*, 1995), an apparent reduction in the normal frequency has contributed to advanced vegetation succession and drying of these wetlands. Temporal evaluation of vegetation assemblages in this study has revealed that the coverage of willow and alder has increased in the outer delta, displacing the shade-intolerant *Equisetum fluviatile*. Although the areal coverage of *Equisetum* marsh was reduced by only 8% (20 ha) between 1946 and 1994 (Figures 3.38), the degree of change was found to be quite dynamic between sampling periods and a pronounced general decline has occurred since 1977. Interestingly, this fits the same temporal trend (i.e., after the mid-1970's) observed for drying trends further upstream in the PAD and for decreases in major spring floods on the Peace River main stem.

A 1978 survey of the SRD for breeding ducks revealed an estimated duck population of +10,400 (33.6/km^2) with highest brood densities recorded on the more permanent ponds and channels having heavily vegetated shorelines and relatively stable water levels (Thompson *et al.*, 1979). Although more recent surveys have not been conducted in the SRD directly, breeding waterfowl populations in the Slave Lake survey stratum have declined from a high of 1,514,000 in 1972 to a low of 252,000 in 1993 (USFWS, 1972-1993). Similar waterfowl declines have been described by many of the local people living in the Fort Resolution area, and have contributed to the recent drying trends in the SRD (NRBS, 1996d).

Other wildlife most likely to suffer negative impacts from these drier conditions are those species dependent on these wetlands, such as semi-aquatic furbearers. Muskrats have traditionally been the most important fur bearing mammal and source of trapping income for the local native people of the SRD area. Similar to the Peace-Athabsca Delta, perched basins are generally the greatest source of muskrat habitat because of their more stable water regime, extensive shorelines and emergent vegetation (Poll, 1980). However, distributary channels in the SRD, supporting bands of emergent horsetails and bordered by moderately sloping levees, also provide suitable habitat for muskrats if winter water level fluctuations are not extreme (Geddes, 1981). Despite limited information on muskrat populations in the SRD, fur trapping records indicate that the area has long been very productive for muskrats (Bodden, 1981), providing the most productive habitat along the entire Slave River corridor (EMA, 1984). Although more recent population estimates are not available for the SRD, interviews with local people of the area indicated that trapping returns for muskrats have been very low for the last few years (NRBS, 1996d).

A continued drying trend in the SRD would allow an increase of more terrestrial plant assemblages of grasses, willows, alders and poplars. Although not favourable for muskrats, such changes would likely increase the habitat base for moose, deer, hare, beaver, and many other furbearing animals and forest-dwelling birds. Although the *Equisetum fluviatile* of the outer SRD is a valuable food source for moose, they tend to favour areas with a mosaic of early seral vegetation, as noted in Section 2.9.1. Population surveys in the SRD, however, indicate that moose numbers are consistently below the habitat carrying capacity, possibly the result of continuous hunting pressure (Eccles *et al.*, 1986).

An increase in woody vegetation would tend to improve the supply of food and building materials for beaver. Although water depth in more permanent waterbodies may have decreased, there is apparently an increased use of distributary channels by beaver. In 1995, field crews reported an abundance of beaver sign, with numbers far higher than in the 1970's (M. English, pers. comm.). Other animals that may benefit from these reported successional changes include snowshoe hare, mice and voles, and carnivores (lynx, fox, coyote, fisher) and raptors (hawks and owls) that depend upon this small mammal food supply. Forest-dwelling terrestrial birds will also benefit from an increase in shrub-tree assemblages.

The impact of the ecological changes discussed in this section has been the source of concern for the local human population, many of whom still obtain a living from fishing, hunting and trapping. Local people have also stated that low water levels, reduced overbank flooding, and the increase of willow and alder has made it more difficult to travel by boat in the delta to areas that were previously accessible, thereby affecting their traditional way of life (NRBS, 1996d).

4.0 SUMMARY CONCLUSIONS AND RECOMMENDATIONS

Responding to the NRBS Question #10: "How does and how could river flow regulation impact the aquatic environment?" required a three-prong approach: a) reviewing and summarizing existing hydro-ecological material relevant to the regulation of northern rivers; b) conducting a selected number of new scientific studies to evaluate some of the major changes that have occurred to the aquatic environment of the Peace and Slave system, and c) developing appropriate tools for use in future environmental impact assessments. In the course of this study, a number of scientific needs and recommendations began to emerge. These are summarized below in conjunction with summary conclusions regarding the major study sub-components. Included are recommendations for modification of existing conditions, monitoring of future trends, collaborative inter-agency work, and further scientific research. The end of the section includes potential actions for restoring water to the Peace-Athabasca Delta.

4.1 EFFECTS ON THE FLOW REGIME

Regulation of flow has produced a change to the seasonal hydrograph of the Peace and Slave Rivers with diminishing effects downstream as tributary flow becomes more important to the total discharge. In comparing the pre-dam record to that following regulation, a number of important changes appear to have occurred.

4.1.1 Peak Flows

Mean annual peak flows have been reduced, the magnitude of the decrease diminishing with distance downstream. At Hudson Hope, immediately downstream of the reservoir, the post-regulation mean flood peak is only one-third the average that occurred in the decade prior to regulation. Further downstream, average peak flow is also reduced but to a lesser degree because of major tributary inflow.

Maximum peak flows are smaller immediately downstream of the reservoir (Hudson Hope) after regulation but are greater at stations further downstream. This again reflects the additional flow from tributaries. Notably, such peaks may have been even greater if not for the effects of regulation.

It has been shown that peak flows do not necessarily produce peak water levels. This is the case for freeze-up within some steep reaches and for break-up, especially near the Peace-Athabasca Delta.

4.1.2 Summer - Winter Contrasts in Flow

As a result of winter power demands, winter flows from the reservoir have been accentuated and summer flows diminished as water is placed into storage. In the pre-regulation period, the mean summer flow and winter flow approximately doubled between Hudson Hope and the downstream end of the Peace River.

The post-regulation mean summer flow at Hudson Hope is approximately 1/2 that which occurred prior to regulation. The winter flow, however, is approximately 4 times as great. Again, this effect diminishes downstream so that at Peace Point, the post-regulation mean summer flow is 2/3 that which occurred prior to regulation and the winter flow is approximately 2.5 times as great.

4.1.3 Significance of Tributary Flow

The significance of tributary flow in the winter regime has greatly diminished. Whereas it used to cause an average doubling of the flow between Hudson Hope and Peace Point, the same flow volume now represents only <20% of the flow recorded during the winter at Peace Point.

Because of reduced summer flows due to regulation, the tributaries have become more important during this part of the year. Notably, the flow of the tributaries appears to be down, on average, since regulation.

4.1.4 Seasonal Ranges in Flow and Low Flows

Again, the most pronounced changes in flow ranges occur immediately downstream of the reservoir. Here the average seasonal low flow used to occur in March but now occurs in June and at approximately 4 times the volume. Similarly, the average seasonal high flow occurred in June but now occurs during the winter in December. Moreover, the post-regulation range in flows is only approximately 14% that which occurred on average in the ten years prior to regulation.

Further downstream (Peace River to Fitzgerald), the average seasonal low and high flows still occur in winter and summer respectively, but the range in flows occurring in the post-regulation period are much below those that occurred prior to regulation.

4.2 EFFECTS ON AQUATIC HABITAT OF THE RIVER MAIN STEM

Knowledge of the preferential use of aquatic habitat on the Peace and Slave Rivers is meagre. Even with such information, traditional methods of assessing changes to habitat (e.g., Instream Flow Incremental Methodology, IFIM) are hampered by the scale of northern rivers, like the Peace and Slave Rivers, and the significant additional complexities posed by winter ice cover. Establishing habitat preference for ranges in flow conditions for fish life stages and other aquatic organisms will prove to be difficult and very expensive for the high flow conditions of these large rivers. A more appropriate method identified by NRBS is to employ remote-sensing methodologies. The advantages of these are that they can classify habitat of much larger reaches and are oriented toward preserving a heterogeneous mix of habitat features than more traditional methods. They are not, however, suitable for evaluating the suitability of micro-habitat features.

4.3 EFFECTS ON FORMATION AND TIMING OF THE ICE REGIME

Increased magnitude and temperature of winter flow from the reservoir has altered the timing and duration of the downstream ice regime. This is most apparent upstream of the town of Peace River. Closest to the dam, the ice season has been virtually eliminated. Further downstream, only an intermittent ice cover develops and at the town of Peace River, there has been a significant delay in the initiation of freeze-up and the overall ice season. At the downstream extremity of the Peace River, regulation does not appear to have affected the timing or duration of the main ice season.

Enhanced winter flows can, in a combination with specific climatic conditions, lead to a change in the nature of the freeze-up: i.e., from a relatively thin juxtaposed-cover to a thicker, rougher consolidated-cover. This is especially true in the steeper reaches of the upper and middle portions of the Peace River. In locations where consolidated ice covers develop and remain throughout the winter, so do elevated stages. In the reach upstream of the Notikewin River to approximately Dunvegan, increased water levels can exist for relatively long periods of time (two to three months), a duration far exceeding that produced by an open-water flood of comparable stage increase. This can result in a supercharging of groundwater along the river margins, such as experienced at West Peace in the town of Peace River where high groundwater levels can lead to flooding of the basements of some residences. Elevated winter stage may also have a direct impact on the succession of particular forms of riparian vegetation.

Increased flow velocities produced by elevated winter discharge leads to enhanced under-cover deposition of frazil ice especially within margins and shallows, areas often touted as valuable shore habitat.

Investigation of the Vermilion Chutes area suggests that enhanced staging of the winter ice cover may occur as a result of greater winter discharge. Open-water zones, especially those associated with reaches of rapids, are important feeding and over-wintering zones. Vermilion Chutes has also been identified as a partial barrier to fish migration. More complete ice coverage of such rapids zones may reduce/eliminate critical winter aquatic habitat, and/or reduce their effectiveness as a migration barrier.

4.4 EFFECTS ON SEDIMENT TRANSPORT AND RIVER MORPHOLOGY

Evaluation of the Peace River sediment regime indicates that the Williston Reservoir poses a minor hinderance to the downstream transport of sediment. Relatively minor amounts of sediment are carried into the system by tributaries upstream of the reservoir as compared to those downstream. Reductions of peak flows as a result of regulation, however, have decreased the capability of the river to convey the sediment delivered by these downstream tributaries. As a result, the river is aggrading, which will eventually lead to channel narrowing, abandonment of secondary channels, and some in-channel shoaling. Specific changes depend on existing channel structure and material texture. Everywhere along the river, however, reduced peak flows are transforming the old floodplain into a new low terrace. Sand and silt accretion along channel edges and in former back-channels is providing sites for the progradation of semi-aquatic and shoreline vegetation. Progradation of vegetation down the banks is important to the long-term width and pattern adjustment, ultimately leading to a substantially narrower channel because a smaller conveyance area is required.

Time scales for morphological adjustments to the river channel geometry is estimated to range upwards of several decades. Channel pattern and gradient adjustments will take longer because of the cumulative volumes of sediment to be transported. Time scales for ecological changes in riparian ecosystems are estimated to be in the order of centuries, simply because of the long succession time for the establishment of new forest communities.

4.5 EFFECTS ON THE LAKE-CHANNEL SYSTEM OF THE PEACE-ATHABASCA DELTA

It has been long established that reduced summer flow peaks caused drying of the main delta channels and lakes. Remedial measures using rockfill weirs have proven to be effective in restoring water levels to many of the Delta lakes and channels to near pre-dam levels although there are some inaccuracies associated with modelling of water-levels, particulary during the winter period and especially under break-up ice conditions (see below). Questions remain, however, about the decrease in the seasonal range of water-level fluctuations as a result of the weirs and upstream flow regulation.

4.6 EFFECTS ON FLOOD PEAKS AFFECTING THE PERCHED-BASINS OF THE PEACE-ATHABASCA DELTA

Hydrometric analysis in conjunction with various historical and local-knowledge data confirm that open-water floods have been ineffective in producing high-elevation floods along the Peace River adjacent to the Peace-Athabasca Delta. Even the historically high flow event of 1990 did not produce a flood of sufficient magnitude to flood high-elevation portions of the delta. Over the period of hydrometric record, backwater produced during river-ice breakup has exceeded that of the 1990 open-water event. Based on data from the Peace Point hydrometric station, such events occurred on a biennial basis in the 1960's prior to regulation but only three times since. It is break-up backwater, therefore, that historically inundated the hydraulically-isolated perched basins, especially those nearest the Peace River that have not experienced a major flood since 1974.

Flow regulation has produced only minor changes in factors such as ice thickness and strength in the lower portions of the Peace River that could control the severity of break-up and related ice-jam flooding. A commonly held perception was that reduced flows due to regulation were responsible for the decline in severe ice jams. Results show, however, that flow contributed from above the dam is higher at the time of break-up near the Peace-Athabasca Delta in the post-regulation period than it was prior to regulation.

The major ice-jam floods that occurred in the 1960's prior to regulation and in the early 1970's after regulation have been associated with large runoff events from downstream tributaries, especially the Smoky River. The flow contributed by tributaries at the time of break-up far exceeds that contributed by headwaters above the point of regulation. These large tributary flow events also appear to be correlated with large spring snowpacks and associated snowmelt runoff. A preliminary evaluation of temporal trends in the size of the snowpack on the Smoky River suggests that there has been a shift in the mid-1970's to values lower than the long-term average. A similar trend has been identified in British Columbia and appears to be responsible for decreased spring runoff on some rivers.

The major effect of regulation on the occurrence of break-up ice jamming near the Peace-Athabasca Delta is related to the higher winter flows and freeze-up elevations. In general, the higher a freeze-up cover is stabilized, the greater the flows it can pass without breaking. The amount that the spring flows exceed a freeze-up level depends on two contributing sources: the upstream flow from above the point of regulation and the downstream tributary flow. Under regulated conditions, a major increase in upstream flows (above the point of regulation) is unlikely at the time of break-up near the Peace River Delta under the standard operational strategy of the W.A.C. Bennett dam: i.e., at the time of transition to lower summer releases. Furthermore, if the amount of regulated flow at the time of break-up is also declining, additions from tributary flow will also have to account for this "loss" to the main-stem discharge. Thus under the current regulated regime, production of severe break-ups has become more dependent on tributary inflow, particularly from the Smoky River. Large spring runoff from the tributaries have been effective since regulation in producing large break-up floods (e.g., 1972 and 1974) but the apparent decline in spring snowpacks has reduced their subsequent effectiveness.

4.7 EFFECTS ON THE SLAVE RIVER DELTA

Recognizing the biological and cultural importance of the Slave River Delta, an exploratory study was conducted on the impact of flow regulation on the morphology and riparian vegetation regime of the Slave River Delta. Flow regulation effects on this system are expected to be heavily dampened by distance and the intervening influence created by major tributaries and the Peace-Athabasca Delta. Reduced summer peak flows are also experienced at this distant location. As a result, there is a reduction in the annual supply of suspended sediment to the Slave River Delta, although the winter flux has been enhanced because of higher winter flows. Unlike the Peace River, however, little sediment is added by tributaries along the Slave River. Most suspended sediment carried into the system originates from the Peace River and Peace-Athabasca Delta.

While it was impossible to separate the relative importance of various processes affecting changes to delta morphology in this exploratory study, comparisons of aerial photography indicate that progradation of the aquatic-productive outer zone of the delta has slowed. Reduced sediment supply is one possible reason for this but depositional processes are complicated because of wave-action from, and the steep transition into Great Slave Lake. These outer delta zones provide an initial substrate for plant colonization, particulary hydrophillic species that enhance the habitat quality of this marsh environment. With time, however, such species are naturally replaced through allogenic succession by less hydrophillic plants, ones less preferred by important local mammals, such as muskrat and moose. In the long term, sustaining marshland habitat in the outer delta requires continued progradation.

The extent of marsh plant species could also be reduced by drying, e.g., from reduced open-water or ice-jam flood peaks. As observed from aerial photography, the areal extent of *Equisetum* marsh has fluctuated between 1946 and 1994. There has, however, been a pronounced decline since 1977. Unfortunately, insufficient hydrometric knowledge exists to conclude whether changes in flow or ice-jam floods have produced a drying of the Slave River Delta. Traditional knowledge in the area, however, indicates that such a drying trend has occurred in the recent past.

4.8 RECOMMENDATIONS

4.8.1 Primary Recommendations

[1] *"Naturalized" Flow Modelling*

Evaluating the effects of regulation on the overall flow regime is hampered by the brevity of the pre-regulation period data set. One method to extend the "un-regulated" period is to model flow conditions since regulation without the effect of the dam. Such a model has been under development by Alberta Environment in conjunction with British Columbia Hydro. It was originally hoped to incorporate the results of this model into some of the NRBS studies but at the completion of this synthesis report, the modelling results remain in draft form and not yet available to scientists attempting to evaluate ecosystem impacts resulting from flow regulation. It is recommended, therefore, that a priority be placed by Alberta Environmental Protection and B.C. Hydro on finalizing this work, and releasing it to the public and scientific communities through official publications so that it can be used in related impact studies. Based on the normalized data set, a re-evaluation should also be made of the summary flow statistics presented in this report. Integral to this evaluation, should be an assessment of the significance of hydro-climatic variations in affecting he post-regulation flow characteristics.

[2] *Hydro-climatic Studies of Tributary Flow*

Given the importance of tributary flow in producing downstream peaks on the Peace and Slave River systems, a hydro-climatic study needs to be conducted of inter-annual variations in tributary flow. Special attention should be placed on spring snowmelt events that are known to enhance sediment contributions and be a driving force in producing break-up floods. A companion study should also be undertaken of the apparent climatic signal in the snowpack record. Temporal anomalies needs to be evaluated relative to atmospheric circulation and synoptic climatic variations. The network of snow survey stations must also be improved/expanded to permit more accurate snowmelt modelling of critical tributary basins. No data, for example, is currently collected within the Wabasca catchment, a tributary known to be important to break-up conditions near the Peace-Athabasca Delta.

[3] *Linking of Hydraulic Models*

The current one-dimension hydraulic model of the Peace-Athabasca Delta needs to be coupled with the new hydraulic flood-routing model of the Peace and Slave Rivers. The focus of the Peace-Athabasca Delta model should be expanded beyond water levels within the Peace-Athabasca Delta to include explicitly full-season modelling of discharge to the Slave River, including the dynamic freshet period. Obtaining reliable modelled discharge from the Peace-Athabasca Delta is the only way by which flow can be modelled accurately through to Great Slave Lake and by which pre-regulation and "naturalized" flows can be calculated for the Slave River. The one-dimensional flow model of the Peace-Athabasca Delta should also be integrated with ice-jam models currently being developed in the PADTS for the reach of the Peace River that controls spring flooding of the Peace-Athabasca Delta.

[4] *Ice Break-up Modelling*

The importance of ice-jam floods on the Peace River (negative impacts to settlements and positive to riparian ecosystems) presents an excellent reason for developing and testing a river-ice break-up model. The Peace River hydraulic flood routing program, developed for the NRBS, offers the ideal building block for the development of such a break-up model. Testing and validation of the model will require more extensive monitoring of break-up conditions in the lower portions of the Peace River. This could be accomplished by extending downstream the current ice observation program conducted near the town of Peace River.

[5] *Ice Jam Enhancement*

Although break-up modelling and forecasting is still in a state of early development, it is recommended that the current regulation scheme be modified to increase the chances of creating a break-up jam near the Peace-Athabasca Delta. Relying solely on the reservoir to produce a major break-up near the Peace-Athabasca Delta would require an enormous release of water from the Williston reservoir. Notably, this could also lead to unpredictable ice-related backwater flooding at other upstream and downstream locations. Some success could be achieved, however, if minor adjustments are made to the regulation strategy in years where tributary inflow is forecast to be large. In some years, the only modification might be a delay in the retarding of spring flows. Current ice jam modelling by the PADTS should provide an idea of the size of combined flow needed to initiate flooding of the Peace-Athabasca Delta. Furthermore, PADTS water-balance modelling will provide guidance on how frequently such intervention might be required. A single agency is needed to co-ordinate these scientific activities.

[6] *Changes to Morphology and Riparian Habitat*

Evaluation of morphologic/vegetative changes to the Peace River involved comparison of two sets of aerial photography: just prior to regulation in the mid-1960's and a recent set obtained by the NRBS in 1993. Additional sets of photography covering other decades before and after regulation were also assembled but insufficient time precluded their analysis. It is recommended that this additional photography be analyzed to provide a better long-term record of morphological and vegetative change, one that permits validation of predicted rates of change likely to result from flow regulation.

Although morphologic studies of the Peace River included four representative reaches, the lack of aerial photography precluded an analysis of the lowest reaches, characterized by broad floodplains and numerous large islands. This zone represents a significant and productive riparian habitat consisting of a multitude of wetlands interspersed among old-growth boreal forest. Furthermore, it has been observed that the large number of split and side-channels located in this area (downstream of Peace Point) may contain backwater areas bedded with silt and clay sediment - the fine fractions known to be associated with industrial pollutants. It is therefore recommended that this reach be selected for long-term monitoring and that monumented cross-sections specifically include backwater areas that can be assessed for changes in bed sediment quality. Monumenting of sites should be conducted in collaboration with Parks Canada who have already established some permanent study plots to monitor vegetation succession within the floodplain.

[7] *Riparian Habitat Assessment*

Some of the most significant ecological impacts produced by altered flow and water level regimes are experienced along the flow margins. To evaluate the nature and spatial extent of habitat impacts within this zone, it is recommended that further quantification (following from experienced gained from the test trials of multi-spectral imaging) be made of habitat availability, over the full range of flow conditions. This will provide the basis for establishing requisite seasonal sets of regulated flow conditions, specifically in terms of timing, duration and magnitude.

There is also a need to more fully understand how vegetation changes on the river mainstem and particularly in the two deltas affect wildlife habitat and related species populations and diversity. It is recommended that wildlife habitat changes be assessed through such methods as Habitat Evaluation Procedures (HEP) and associated wildlife surveys. Because it is not practical to assess the habitat suitability for all affected wildlife species, representative species such as muskrat, moose and buffalo should be used. A recommendation should be made to the upcoming "Bison Research and Containment Program" for the Peace-Athabasca Delta to include a science component that focuses on developing linked hydrologic, vegetation-succession and wildlife-habitat models.

[8] *Peace-Athabasca Delta Lake Stabilization Effects*

Further investigations of the aquatic impact of stabilized water levels should be conducted for some of the large delta lakes, especially regarding changes in the nature and availability of waterfowl habitat. A special focus should be placed on fall and winter water levels that do not experience the natural seasonal drawdown as a result of both forms of regulation (weirs and upstream reservoir).

[9] *Slave River Delta*

To obtain a better understanding of the temporal and spatial effects of flow regulation in the Slave River Delta, further studies related to the changing dynamics of the Delta are recommended possibly similar those of the PADTS. Integral elements of this ecological monitoring program should include assessments of: a) flood frequency, including open-water and ice-jam flooding, and the role of Great Slave Lake fluctuations; b) water-balance studies to determine the relative importance of flooding recharge; c) sediment regime changes including under-ice investigations; and d) vegetation succession, aided by remote-sensing assessments and the establishment of permanent transects through representative cover.

4.8.2 Secondary Recommendations

The following recommendations stem from the results of studies conducted in response to NRBS Question #10 but are considered secondary to completing a first-order assessment of flow-regulation impacts. Aspects of some, however, relate directly to the primary recommendations.

[i] A water temperature model should be applied to the Peace River so that the relative effects of variations in climatic conditions and regulated flow can be discerned. Ideally, the model should be integrated with the new hydraulic flood-routing model developed for the NRBS.

[ii] A detailed ice-hydraulic study should be conducted of flow conditions leading to reductions in open-water zones associated with rapids such as the Vermilion Chutes. Such an evaluation should include other turbulent reaches that historically remained open under lower pre-regulation flow conditions and be coupled with hydro-ecological studies of the importance of open-water zones to aquatic life, especially fisheries.

[iii] Studies should be conducted of the long-term effect of freeze-up staging on regional groundwater levels and of its more local effect on riparian zone habitats, such as in the recharging of backwater snyes or in the succession of seral vegetation.

[iv] Studies should be conducted on the role of frazil deposition in modifying/eliminating winter aquatic habitat.

[v] The ultimate adjustment time of a large river is extremely long but no system has been studied systematically for more than a few decades. The Peace River data set provides an excellent opportunity to evaluate fully the long-term effects of flow regulation. As part of a long-term study, it is recommended that monumented cross-sections for monitoring changes in channel morphology and riparian vegetation be established within the representative reaches used in the current NRBS studies.

[vi] More detailed studies of sedimentation processes in the outer delta are required. These are essential to separate the effects of flow regulation from natural processes, such as isostatic rebound and the role of wave action from Great Slave Lake. Such work first requires completion of the hydraulic flood-routing model of the Peace-Slave Rivers, preferably with a delta-channel network component similar to that developed for the Peace-Athabasca and Mackenzie deltas.

[vii] An attempt is being made by the PADTS to improve the understanding of how changes in the hydrologic regime of the perched basin environments control changes in the vegetation regime. It is recommended that further efforts be expended on such model development and that the model be applied and validated for conditions on the Slave River Delta.

4.9 PEACE-ATHABASCA DELTA ACTION PLAN

The following was produced in response to a request from the NRBS for an experimental action plan for the Peace-Athabasca Delta. It presupposes, based on groundwork conducted by the PADTS, that flooding of the PAD is the key to restoring the ecosystem health of the perched-basin environments. Many of the proposed actions also stem from the results of PADTS discussions about potential methods and, in some cases, actions that have already been field tested in the PAD. Prior to describing these, it is useful to review the PAD hydrology so that the recommendations can be placed in context.

4.9.1 Background Review

As earlier described in Sections 2.6.2; 3.2; and 3.8.2, the PAD is composed of two different hydrologic regimes. The first includes the large shallow lakes and the major deep channels which link them to Lake Athabasca and the Peace, Athabasca and Slave rivers. It is this flow system that has been affected by the construction of rockfill weirs. In general, the weirs have restored the summer mean-maximum water levels to near pre-regulation values but they have also reduced the seasonal amplitude in water levels. Although the decrease in amplitude should create an ecological impact on lake margins, research in this area has been meagre (see Section 4.8.1: Recommendation [8]).

The second major regime is that of the "perched basins" which are to varying degrees disconnected from the main flow system. It is these basins that have experienced the most extensive drying and are not affected directly by water levels produced by the rockfill weirs. Notably, however, this perched-basin regime can be further subdivided according to source and frequency of flooding. For example, since the time of the last major flood of 1974, the Athabasca River has inundated some of the perched basins in the southern portions of the PAD. Similarly, some of the low-lying southern basins have been flooded by high lake levels. Perched basins that have experienced the most extensive drying exist in the northern portions of the PAD and are dependent on macro-scale flooding of the Peace River for filling.

4.9.2 Proposed Experimental Actions

Given the above differences in hydrologic regime, it is useful to consider experimental actions that differ by scale and location.

4.9.2.1 *Small-Scale Basin Specific*

The basic experimental approach here is to capture water in single basins during high flow events with the use of simple control structures. The structure is constructed within the levee of the basins and operated to permit the entry of water during periods of high stage and prohibit its exit when flow in the main channels and lakes decline. Since this method relies on the main flow network, it can only be conducted in basins with suitable levee/elevation characteristics. The results of such an approach (e.g., on vegetation succession or small mammal populations) are limited to the experimental basin. Results could provide, however, invaluable data for developing the requisite models for predicting vegetative response to large-scale wetting of the PAD.

An alternative to the expensive construction of variable-height weirs is the use of pumps to recharge specific basins. Pumps offer the additional opportunity of flooding basins perched above the main flow network.

4.9.2.2 *Meso-Scale Basins Adjacent to Large Lakes and Channels*

Meso-scale flooding of the PAD requires the redirection of water flowing through the Delta onto the adjacent landscape. The best method to achieve this is to present an obstruction to the flow at a critical hydraulic node in the delta channel-lake system, thereby creating backwater which would inundate the surrounding perched-basin environment. The natural levels around such basins would retain the water after the backwater recedes.

The best hydraulic node for the construction of a flow obstruction within the PAD is near the Quatre Fourches Dog Camp. Notably, this was the site of one of the early rockfill weirs; a structure that was successful in significantly raising lake water levels during a large spring-runoff event in 1971, but also one that proved to be ecologically unsuitable because it impaired the migration of fish. As part of the PADTS (see section 3.8.2), an artificial ice dam was constructed overtop of the old weir. The objective was to use the temporary ice structure the passage of spring snowmelt runoff through the Delta, thereby creating backwater that would flood basins adjacent to the large delta lakes. Since construction of the early weirs, a significant percentage of the Athabasca flow has been diverted naturally into the Delta lakes through development of the Embarras River breakthrough to Mamawi Creek. This has increased the possibility of obstructing spring flow in the delta lakes. Success of using an artificial ice dam at this site is dependent on the vagaries of winter climate (specifically the magnitude, rate and timing of spring snowmelt) and the winter flow strategies of B.C. Hydro. For example, it appears that sudden winter decreases in upstream flow over the winter of 1994/95 hampered the ability of the artificial ice dam to elevate water levels to flood stage. If such an attempt is undertaken again, agreements should be made regarding winter flow operations.

An alternative to using an artificial ice dam would be to employ a gated structure. This, like the ice dam, would minimize problems associated with fish migration among the lakes and channels but problems may exist about the construction of such a permanent feature within a National Park.

It should be stressed again, however, that the above medium-scale approaches still only have the possibility of affecting perched basins close to the backwater effect that could be established near the Dog Camp hydraulic node. Such flooding will not affect the northern perched basins close to the Peace River - ones that are believed to have experienced the most drying since 1974.

4.9.2.3 *Macro-Scale Flooding from the Peace River*

Introducing macro-scale flooding of the PAD is possible only through disruption of flow on the large Peace or Slave rivers. Again, a permanent gated structure could be used but construction/engineering costs would be enormous. The possibility of constructing an artificial ice dam has also been considered by the PADTS. Recognizing the need for an environmental impact assessment of related effects, early community information meeting were also held by the PADTS.

Similar to the meso-scale approach, the success of an artificial ice dam depends very much on the vagaries of climate, especially as they affect the magnitude of spring runoff produced by tributaries downstream of the Bennett dam, such as the Smoky and Wabasca rivers. Given this, the most practical recommendation is "[5] Ice Jam Enhancement" outlined in Section 4.8.1. The success of an artificial ice jam could be enhanced further if there was a concurrent attempt near the PAD to increase the resistance of the Peace River ice cover to breakup. This could include increasing thickness using spray-ice techniques and/or the retardation of melt through the application of insulating materials.

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The Northern River Basins Study was established to examine the relationship between industrial, municipal, agricultural and other development and the Peace, Athabasca and Slave river basins.

Synthesis Report

Over four and one half years, about 150 projects, or "mini studies" were contracted by the Study under eight component categories including contaminants, drinking water, nutrients, traditional knowledge, hydrology/hydraulics, synthesis and modelling, food chain and other river uses. The results of these projects, and other work and analyses conducted by the Study are provided in a series of synthesis reports.

This Synthesis Report documents the scientific findings and scientific recommendations of one of these components groups. This Synthesis Report is one of a series of documents which make up the North River Basins Study's final report. A separate document, the Final Report, provides further discussion on a number of scientific and river management issues, and outlines the Study Board's recommendations to the Ministers. Project reports, synthesis reports, the Final Report and other NRBS documents are available to the public and to other interested parties.