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# OBSERVED AND POTENTIAL DOWNSTREAM EFFECTS OF LARGE STORAGE PROJECTS IN NORTHERN CANADA (*)

by Rolf KELLERHALS (1) and Don GILL (2)

CANADA

## 1. INTRODUCTION

During the late fifties improved transmission technology encouraged Canadian power producers to look northward, beyond the developed regions, in their search for new power supplies. Most of Canada's hydro-electric potential is located there, and the sparsity of settlement permits large-scale installations with reservoirs covering hundreds or even thousands of square kilometres (Fig. 1). During the last ten years several northern power developments became operational, the main ones being Churchill Falls in Labrador, several sites on the Outardes and Manicouagan Rivers north of the St. Lawrence estuary, several sites in the basin of the Moose River in Ontario, Kelsey and Kettle Rapids on the lower Nelson River in northern Manitoba, and W. A. C. Bennett Dam on the Peace River in northeastern British Columbia (D.E.M.R., 1970). Additional projects are being seriously considered. Some of the main ones are :

(i) the eastern tributaries to James Bay;

(ii) further development of the Nelson River including regulation of Lake Winnipeg and southward diversion of the Churchill River;

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(*) *Effets constatés et effets potentiels des grandes accumulations dans le Canada du Nord.*

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(iii) dams on the lower Peace River (British Columbia and Alberta) and on the Slave River at the Alberta-Northwest Territories border;

(iv) development of the Liard, Stikine and Yukon Rivers in British Columbia;

(v) the Great Bear River, N.W.T.

Besides these single-purpose hydroelectric projects there are many proposals for the southward diversion of northern rivers to alleviate water shortages in the southern Canadian Prairies or in the United States. These diversions have low priority at present for economic and political reasons but, unless current trends in water utilization are greatly altered, large-scale diversions will have to be seriously considered again.

Beginning of operation at the first large-scale power developments in northern Canada coincided with the sudden upsurge of interest in environmental matters in North America. It is therefore not surprising that a major controversy arose when regulation of the Peace River at Bennett Dam initiated certain environmental changes downstream. A beneficial side effect has been the initiation of numerous studies, some specifically directed at the downstream effects of Bennett Dam and others dealing in a more general way with problems caused by altering the flow regime of northern rivers.

The objectives of this paper are : (i) to focus attention on problems that have arisen or could arise in the future, and (ii) to review the results of studies relevant to the planning of future water resources projects in northern latitudes.

While most of the downstream effects of dams discussed here are detrimental, this should not be interpreted to mean that there are no benefits

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Fig. 1

Canada (from Dept. of Energy, Mines and Resources, 1970 *a*).

(1) Churchill Falls.
(2) Manicouagan and Outardes Rivers.
(3) Mattagami and Abitibi Rivers.
(4) Nelson River.
(5) W. A. C. Bennett Dam on Peace River.

(a) Peace-Athabasca Delta.
(b) Mackenzie Delta.
(c) Slave Delta.
(d) Extent of Canadian Shield.
(e) Eastern Boundary of Canadian Cordillera.
(f) Southern Limit of Continuous Permafrost.
(g) Southern Limit of Discontinuous Permafrost.

*Canada (du Département de l'Énergie, des Mines et des Ressources, 1970 a).*

*(1) Chutes Churchill.*
*(2) Rivières Manicouagan et Outardes.*
*(3) Rivières Mattagami et Abitibi.*
*(4) Rivière Nelson.*
*(5) Barrage WAC Bennett sur la rivière de la Paix.*

*(a) Delta Peace-Athabaska.*
*(b) Delta du Mackenzie.*
*(c) Delta de la rivière de l'Esclave.*
*(d) Étendue du Bouclier Canadien.*
*(e) Limites à l'est de la Cordillière Canadienne.*
*(f) Limites au sud du Pergélisol continu.*
*(g) Limites au sud du Pergélisol discontinu.*

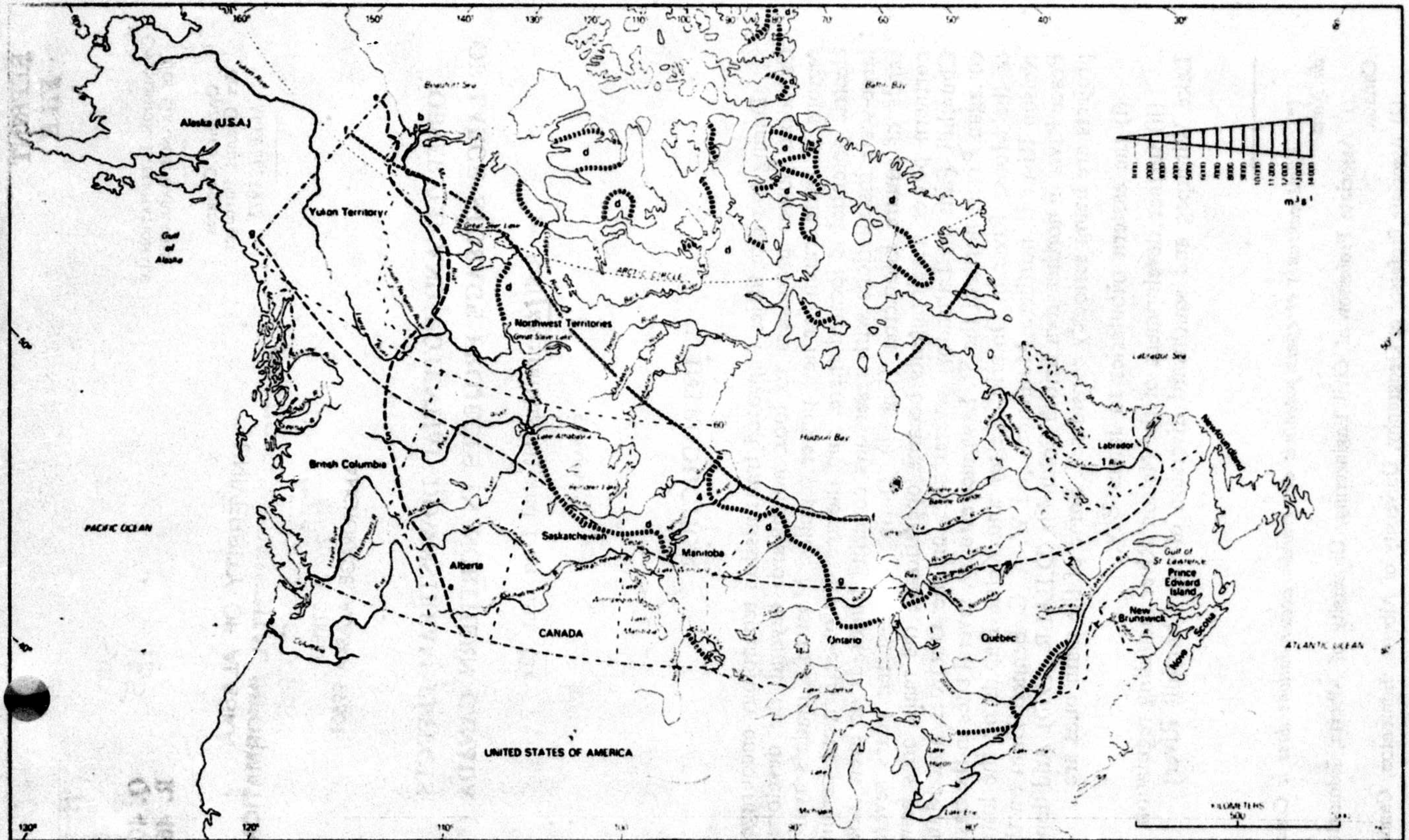
Alaska (U.S.A.)
Yukon Territory
Gulf of Alaska
Beaufort Sea
Baffin Bay
Northwest Territories
Great Slave Lake
Great Bear Lake
ARCTIC CIRCLE
Hudson Bay
Labrador Sea
Labrador
Newfoundland
British Columbia
PACIFIC OCEAN
Alberta
Saskatchewan
Manitoba
Ontario
Québec
CANADA
UNITED STATES OF AMERICA
Gulf of St Lawrence
Prince Edward Island
New Brunswick
Nova Scotia
ATLANTIC OCEAN
KILOMETERS
500
m³s⁻¹

Fig. 1

associated with dams on northern rivers. Most of the benefits are, however, separate from " downstream effects " and therefore fall outside the scope of this paper. The predominance of detrimental downstream effects is attributable to two main factors, (i) the biological richness of northern alluvial ecosystems, and (ii) the great importance of the unregulated river systems to the population of northern Canada.

## 2. NATURAL REGIME OF LARGE NORTHERN RIVERS IN CANADA

### 2.1. Natural Flows.

The hydrologic regime of northern rivers in characterized by extremely variable runoff from the land, which may or may not be modified by extensive natural storage in lakes and muskeg (1).

Rivers such as the Peace or Liard, which derive most of their flow from hilly or mountainous areas of the Canadian Cordillera where natural storage tends to be low, exhibit highly variable flow. Ratios of maximum to minimum flows of 50 to 100 are common. Two typical hydrographs (Peace River near Bennett Dam) are shown in Figure 2 a. The snow melt flood occurs in May and June and contains most of the runoff volume, but on some rivers rain-floods can produce the highest flood peaks. River flow gradually declines during late fall and winter and reaches a minimum in April.

At the other extreme are rivers such as the Churchill, the Nelson, and the Mackenzie, upstream of the Liard junction, whose basins contain such large amounts of natural storage that ratios of maximum to minimum flows drop below 5. Maximum flows still occur in late spring or summer but at least 3 factors can cause minimum flows : dry conditions in late summer, obstruction of lake outflow by ice jams in early or midwinter, or gradual depletion of storage in late winter.

A further distinct type of flow regime is found in the high Arctic where even major rivers may dry up completely in winter due to the elimination of groundwater storage by permafrost. Because no projects have been built on this type of river and due to lack of data and experience, they are not considered here.

### 2.2. Alluvial Processes and Sedimentation.

Most regions of northern Canada were covered by up to 2000 m of ice around 14,000 BP. Geologically speaking all Canadian rivers are extremely young. Furthermore, the entire region surrounding Hudson

(1) Organic terrain or peat bogs.

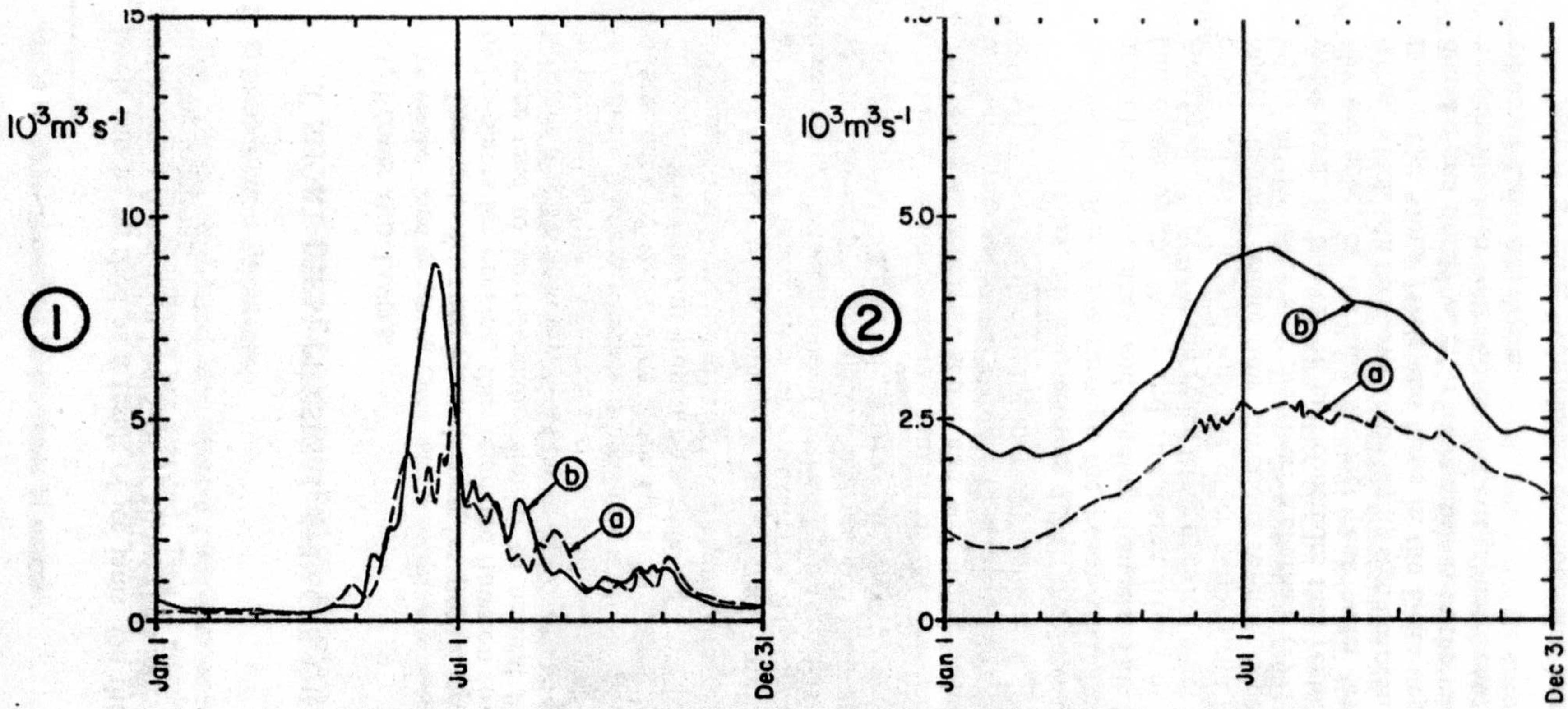


Fig. 2

Typical Hydrographs of Northern Rivers.

(1) Peace River near Bennett Dam.
(2) Nelson River, 100 km downstream from Lake Winnipeg.

(a) Average Year.
(b) High Flow Year.

*Hydrogrammes typiques des rivières du Nord.*

*(1) Rivière de la Paix près du Barrage Bennett.*
*(2) Rivière Nelson, 100 km du Lac Winnipeg, en aval.*

*(a) Année moyenne.*
*(b) Année de débit élevé.*

Bay is subject to glacial rebound and is rising at a declining rate, presently around 1 m per century, which partially accounts for the absence of large deltas at the mouths of tributaries to Hudson Bay and James Bay. On the Canadian Shield (Fig. 1) the result of young age, rapidly adjusting base level, and resistant bedrock is rivers with step-like profiles of slow-flowing pools alternating with rapids over boulders or bed-rock sills (Newbury, 1968). On a geological time scale the rivers are degrading but from an engineering point of view they are stable.

Farther west, in the plains and cordilleran regions and in the lower Mackenzie Valley, the rivers are equally young but bedrock is often less resistant. While most of the river channels are still entrenched, and bedrock is not far below the channel bed, there are important alluvial reaches where the rivers flow on great depths of their own sand deposits and are therefore free to adjust their slope and channel dimensions to the flow and sediment regime imposed from upstream. Alluvial reaches occur in the Peace-Athabasca and Mackenzie Deltas.

In comparison with most other large rivers of the world the sediment loads of all rivers considered here are low, but there are important variations. Sediment loads are closely related to the amount of natural storage in a basin. The rivers with little storage such as the Peace and Yukon carry significant, though small, suspended loads ranging from negligible values during winter to concentrations between 200 and 2000 mg per litre during floods. Bed-load consists mostly of gravel except for the short sand-bed reaches and the total amount of bed-load is generally a small fraction of the suspended load. The rivers with large natural storage, e.g. the Nelson and Churchill, carry negligible sediment loads during the entire year.

## 2.3. Ice Conditions.

Flow conditions are affected by ice over a period of 6 to 7 months starting November and ending late April to early June (Allen, 1964). The slow and evenly-flowing rivers of the plains region form a complete ice cover out of border ice and slush ice some 1-5 weeks after the first appearance of ice on the river. During the remainder of the winter the ice cover slowly grows thicker and smoother, and river stages therefore drop.

Rivers of the Canadian Shield, which are characterized by sequences of pools or lakes and rapids, develop ice covers only on the largest pools at freeze-up. The fast-flowing reaches remain open initially and generate large quantities of slush ice. Border-ice growth and slush-ice accumulation upstream of ice-bridged pools gradually extend the ice cover. Rapids freeze only when ice accumulations downstream have raised water levels and reduced local velocities to sufficiently low values for further upstream progression of the ice cover. Ice thicknesses of over 10 m are reported by Newbury (1968) for some locations below rapids on the Nelson River.

The brief period of break-up is in many respects the most significant part of the annual ice regime. At this time, stages in excess of highest flood levels can be reached as a result of ice jams. On the Nelson, moving ice maintains a forest trim-line 5-10 m above the highest ice-free flood levels at some locations.

## 3. SHORT-TERM PHYSICAL EFFECTS OF REGULATION

### 3.1. Flows and Levels.

The cost of transmission has so far prohibited the use of northern hydro-plants for peaking, thus regulated flows on rivers with large natural storage tend to be reasonably similar to natural flows. If peaking ever becomes feasible however, flows far in excess of natural flood stages would be imposed on the downstream river channels, which could have far-reaching effects. Little experience is available on this type of situation, but with enlargement of the outlets from Lake Winnipeg and diversion of the Churchill River (mean annual flow : 900 $m^3 s^{-1}$) to the Nelson River via the Burntwood River (90 $m^3 s^{-1}$) being planned, research is urgently needed.

The effects of regulating rivers with *small* natural storage is discussed by using the Peace River as an example. At Bennett Dam, unregulated flows varied between annual peaks of 3,500 to 9,000 $m^3 s^{-1}$ and lows of 150 to 250 $m^3 s^{-1}$. Regulation has reduced this range to between 2,000 and 500 $m^3 s^{-1}$ (Kellerhals, 1971).

Since the downstream channels of the Peace, Slave, and Mackenzie Rivers are all relatively stable and well defined, the immediate effects of regulation are easily predictable with standard flow-routing techniques and amount to a reduction in the annual variation of flows and stages.

Over its last 80 km, starting 1,200 km downstream from the dam, the Peace River flows through the Peace-Athabasca Delta, a 3,800 $km^2$ area of marshes, lakes, and winding channels. This large inland delta was laid down by the Peace and Athabasca Rivers in the post-glacial Lake Athabasca. At present the Peace River does not enter the lake but it remains connected with it (and with the other major delta lakes) through several outlet channels whose flow directions reverse, depending on the relative stages of the lakes and the river. Kellerhals (1971) examined flows and water levels in this region and concludes that regulation at Bennett Dam has the effect of reducing summer peak water levels by approximately 0.6 m, which will be shown to be highly significant in the flat terrain of that Delta. The winter levels and flows in the Delta depend mainly on unpredictable and highly variable ice conditions in the outlet channels, thus the unnaturally high winterflows of the regulated Peace have little immediate effect on Lake Athabasca.

Almost all large hydroelectric developments bring a measure of flood-protection to downstream settlements. Much flooding in northern Canada is associated with ice jams during spring break-up, however, thus local flooding would not always be alleviated by flow regulation.

### 3.2. Ice Effects.

During the freeze-up and break-up periods the difference between regulated and natural flows can be positive or negative on rivers such as the Peace, and it is therefore difficult to discuss downstream effects in general terms. On some rivers, break-up is accelerated by the rapid spring rise in discharge. In such situations regulation could delay break-up. Techniques for detailed ice-regime analysis of river reaches are available in the extensive literature on river ice, but successful application depends upon a certain amount of climatic data which is often lacking in northern Canada.

If winter flows are greatly reduced as a result of diversion projects or in the course of peaking operations at a power station, large-scale icings could conceivably be induced. Icings are thick accumulations of bottomfast ice in river channels. They occur naturally in certain northern rivers, where they may cover entire valley floors and persist all year. They are mainly the result of low flow, extreme cold, and the constricting effect of bedrock or permafrost below the channel bed.

### 3.3. Mesoclimate.

The 6,500 $km^2$ Mackenzie Delta (Fig. 1) serves as an example to discuss the potential effects of regulation on the meso-climate of northern deltas.

The summer temperatures of northern deltas are warmer than in the surrounding uplands; the Mackenzie Delta with a mean July average of 13.5 °C is warmer than any other portion of the Northern American continent at that latitude (Gill, 1971 a). One of the reasons for this anomalously high temperature is that weak low-pressure systems periodically develop during the June-August period in the Western Arctic (Thompson, 1967), which cause a wedge of warm air to extend down the Mackenzie Valley from the south (Abrahamsson, 1966, p. 21) but the physical action of spring floodwater in lifting up, breaking, and removing the winter accumulation of ice is also instrumental in causing a rapid increase in temperature (Gill, 1971 b). Thirty to fifty percent of the Mackenzie Delta is covered by lakes and channels, thus it follows that the change in albedo caused by " ice flushing " can be highly significant. Furthermore, with only the highest levees remaining above water during flood, high-albedo snow is inundated to further alter the gross energy balance of the Delta.

After flood-levels subside, relatively long cloudless days ensure that a considerable amount of short-wave radiation is absorbed and rapid warming of the soil results. Although most of the Delta is underlain by permafrost, the thawing isotherm penetrates rapidly to create a deep active layer (1) which enables many boreal forest species such as white spruce (*Picea glauca*) and balsam poplar (*Populus balsamifera*) to colonize successfully (Fig. 3), thereby creating one of the most northerly extensions of boreal forest in North America.

The low-Arctic tundra immediately adjacent to the Mackenzie Delta does not have the benefit of ice removal by flooding, and lakes which are only a few kilometres from the Delta remain ice-covered for as much as one month longer; air temperatures are correspondingly cooler.

If the lower Mackenzie River were regulated, channel and lake ice would remain several weeks longer in the Delta, maintaining a high-albedo surface. A general cooling of the Delta's mesoclimate could thus result.

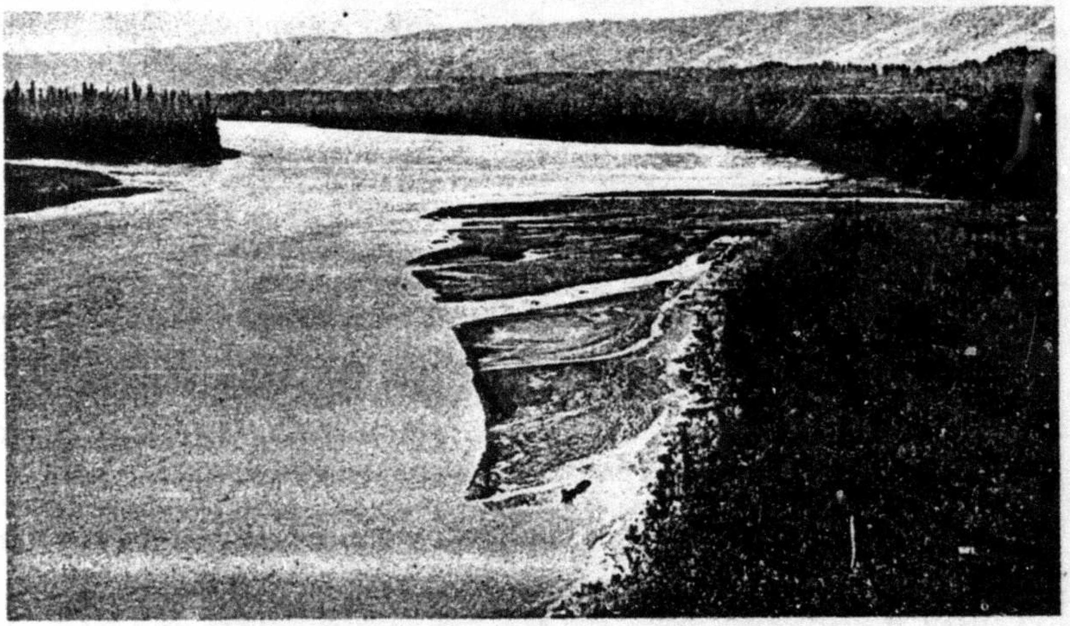

Fig. 3

New Delta of Farrell Creek in the Channel of the Peace River.
*Le nouveau delta du Farrell Creek dans le chenal de la rivière de la Paix.*

## 4. LONG-TERM PHYSICAL EFFECTS

### 4.1. Sedimentation Problems.

The projects considered here involve reservoirs of such size that virtually all incoming sediments are trapped. This is inconsequential in the nearly sediment-free rivers of the Canadian Shield, but in the more hea-

(1) Zone above permafrost which thaws in summer.

vily loaded plains and cordilleran rivers, downstream effects will depend largely on the location of a dam with respect to alluvial reaches.

Bennett Dam, the only project built on such a river to date, is located at the upstream end of a 50 km long bed-rock canyon. Father downstream the river flows for 800 km in a narrow valley, entrenched 100 to 300 m below the level of the surrounding plains. Except for occasional slumps of the valley walls, the channel is stable. The bed-material consists of gravel of gradually decreasing size for approximately 700 km and medium sand thereafter. Many of the deeper scour holes reach bedrock. The Peace is fairly typical of many northern rivers.

General channel degradation caused by a river's attempt to replace the missing sediment load with material picked up from the bed has occurred below dams on active sand-bed rivers but it is improbable along the gravel-bed reaches of the upper Peace. Even very conservative assumptions about initiation of movement show that the regulated flows are too low to move the coarser fractions of the bed material. The channel will therefore quickly become paved with a stable layer of coarse bed material, approximately one grain diameter in thickness.

The Peace River's suspended material is almost entirely wash-load, and its deposition in the reservoir is unlikely to have major consequences. By the time the Peace River reaches the Peace-Athabasca Delta, the effects of Bennett Dam on suspended load concentrations are probably low because many of the tributaries below the Dam are more heavily loaded than the main stem of the river.

If dams were built in or immediately upstream from alluvial reaches (e.g. on the lower Peace or on the lower Mackenzie) some degradation would have to be expected but it would probably take place at much slower rates than those reported for heavily loaded rivers in semi-arid or arid regions.

The sediment load plays an important role in the process of meander migration across alluvial plains by prograding the inside bank through point-bar construction from bed load and by aggrading the point bars to flood-plain levels through suspended load deposition in the emerging successional vegetation. A reduction of the sediment load could disrupt this process, which would result in at least local ecological changes. Widening of channels at meander bends and lateral instability might also be expected.

Although vertical degradation is unlikely to be a serious problem, there are two other processes associated with sedimentation which could gradually lead to difficulties : aggradation at tributaries and decreasing channel capacity. Large gravel-bed rivers tend to be relatively inactive morphologically and are unable to move most of their bed material until flows considerably exceed the long-term mean. Beyond this point, bed-load transport rates increase rapidly with discharge in a non-linear manner (Hollingshead, 1971). Regulation therefore reduces the capacity of a gravel river to transport bed material. Downstream of tributaries carrying significant gravel bed-loads, the main river becomes unable to handle the incoming material and aggrades. After 4 years of regulated flow several tributaries have built deltas into the channel of the Peace River, causing distinct breaks in its longitudinal profile (Fig. 3).

The channel properties of gravel-bed rivers such as the main reach of the Peace, appear to be principally determined by flows in the order of the 1.5 to 2 year flood, e.g. flows that persist on average for approximately one week each year (Bray, 1972). Regulation effectively reduces the size of the river without immediately changing the channel, but given sufficient time, certain channel properties will adjust to the new flow regime. The entrenched nature of the channel, proximity of bed-rock, and the resistant nature of the bed materials prohibit significant changes in width, depth, or slope (except near tributary junctions) but deep scour holes at bends will fill in to some degree, and gravel bars exposed above the new high-water mark will be colonized by vegetation, and could be well treed within 20 to 30 years. If an exceptional flood should ever make spillage necessary the reduced-capacity channel downstream will need to be taken into account.

Gravel bars on the Peace which were completely un-vegetated and obviously subject to active gravel transport under natural conditions were colonized by balsam poplar and willows (*Salix* spp.) 3 to 4 feet high after 4 years of flow regulation. Sections of the very steep and unvegetated river banks had collapsed and grown up in willows. Whether it is possible to maintain the river channel at more or less its natural size through periodic high spillages of short duration remains to be seen.

In deltaic areas, regulation could result in a wide variety of special sediment problems. As an example, the minimum level of Lake Athabasca is controlled by a silt bar across the lake outlet, consisting of material deposited by the Peace River during spring floods, when the outlet channels reverse flow direction and carry silty water into Lake Athabasca. Regulation has reduced the occurrence of flow reversals and the question now arises whether this important silt bar, which obviously represents an equilibrium between erosion and deposition, will remain. Erosion of this bar could further reduce water levels in Lake Athabasca.

### 4.2. Tributary Degradation.

The discharge regime of most northern rivers tends to be more or less in phase with the regime of their tributaries. Regulation of the main-stem river upsets this, with the result that floods in tributaries are more likely to occur at times when the stage at the junction is considerably lower than natural. The tributaries adjust by degrading their beds in the vicinity of the junction. Two highway bridges across tributaries of the Peace River had their foundations exposed due to this effect. In one case, the pier was protected with rip-rap and in the other the tributary was brought back to its former level by building up a boulder rapid between the bridge and the Peace River.

### 4.3. PERMAFROST.

Many lakes and channels in the zone of *continuous* permafrost (Fig. 1) do not freeze to the bottom and are consequently not underlain by permafrost. If regulation or diversion were to lower water levels in an area such as the Mackenzie Delta, permafrost would increase in areal extent and in depth. As discussed previously, deteriorating mesoclimate could aid the expansion of permafrost.

Permafrost aggradation is also encouraged by the build-up of organic material. Very little growth of mosses presently occurs on actively silting northern flood plains because the deposition of sediment during flood discourages its growth. Alluvium that contains little organic material retains less soil moisture, thus a drier and warmer soil is maintained. If regulation decreases flooding and siltation, organic build-up is no longer retarded, leading to increased waterlogging of the soil, reduced soil temperatures and reduced thickness of the active layer.

A similar sequence of events might follow regulation in deltas and flood plains that are underlain by *discontinuous* permafrost (Fig. 1). The recent drop of levels in the Peace-Athabasca Delta has reduced some lakes to one-quarter their former size (Dirschl, 1971) and this could permit permafrost, which is now of limited extent (Nielson, 1972), to become more widespread and to exert a deleterious effect on such factors as interior soil drainage, summer soil temperature, and depth of root penetration.

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**Fig. 4**

**Low-oblique Air-Photo Showing Typical Deltaic Plant Succession on a Point Bar in the Mackenzie Delta.**

The shoreline is shifting to the left as new alluvium is added to the growing point bar face during the annual spring flood. The pioneer community along the water's edge is dominated by equisetum (*Equisetum fluviatile*); the second sere is a pure stand of willow (*Salix alaxensis*); the third successional phase is a community dominated by balsam poplar (*Populus balsamifera*), easily seen by its lighter tone. The dark coniferous trees are white spruce (*Picea glauca*), which constitute the sole dominant of the climax ecosystem. Note the number of physiologically dissimilar communities in close juxtaposition creating ideal habitat.

***Photo aérienne prise à basse altitude et à un plan incliné à la verticale montrant la végétation typique d'un delta à la pointe d'une barre du Delta du Mackenzie.***

*Le rivage se déplace vers la gauche avec l'addition d'autres alluvions à la pointe de la barre au cours de l'inondation annuelle du printemps. La communauté des pionniers établie le long de la rive est dominée par l'equisetum* (Equisetum fluviatile); *la deuxième caractéristique est un groupe de saules* (Salix alaxensis); *la troisième caractéristique est une communauté dominée par des peupliers* (Populus balsamifera), *que l'on peut remarquer par ses teintes plus claires. Les conifères foncés sont des épinettes à bois blanc* (Picea glauca), *qui constituent l'élément dominant de l'arrangement de système écologique. Remarquez le nombre de communautés physiologiquement différentes en juxtaposition et créant un habitat idéal.*

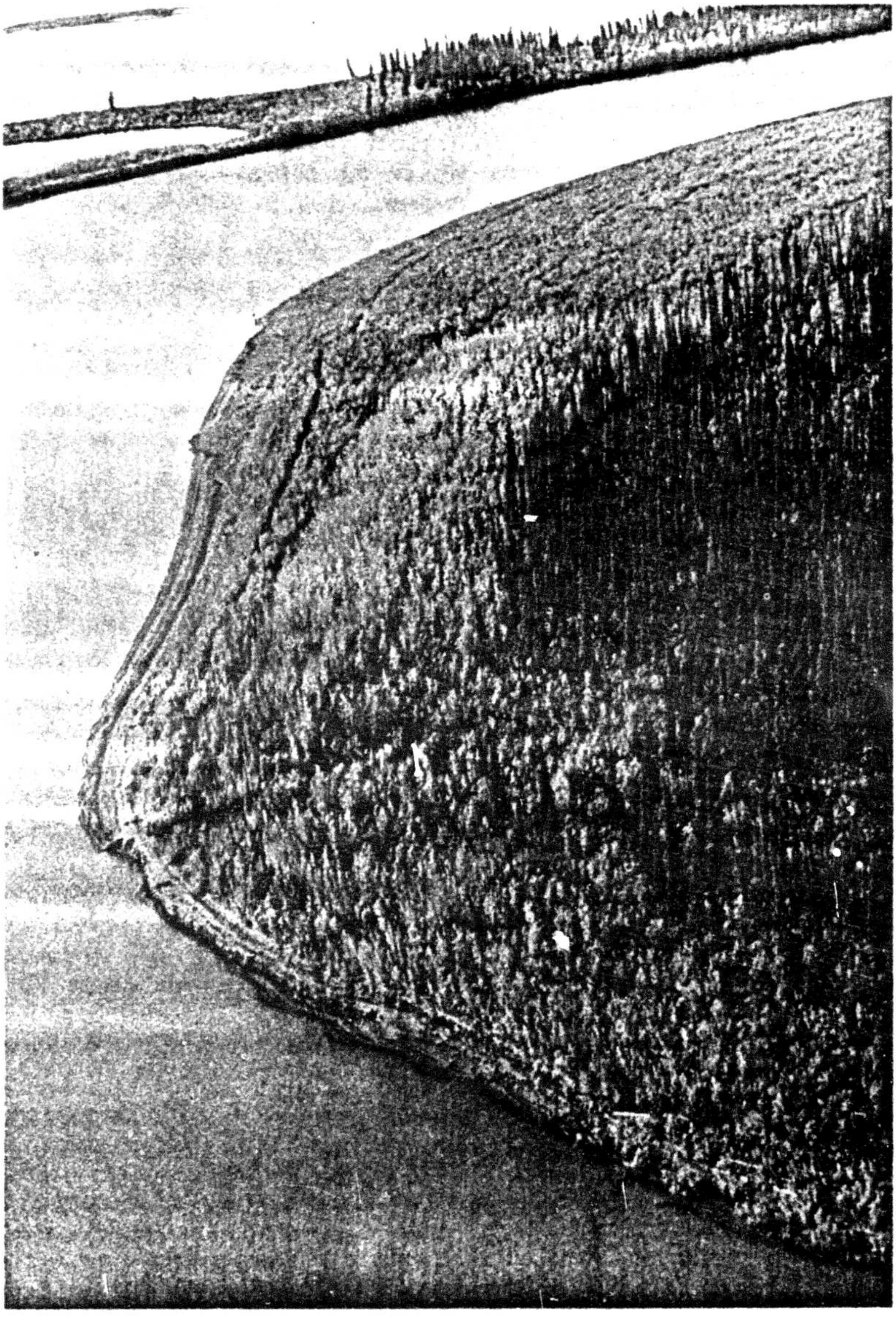

Fig. 4

# 5. ECOLOGICAL EFFECTS

## 5.1. Plant Succession and the Creation of Habitat.

The dynamic interaction of flooding and sedimentation that shapes the surface of floodplains and deltas is reflected in the distribution of its successional plant communities (Fig. 4). Plant succession refers to any unidirectional change that can be measured in the proportions of species in a stand, or, as is more often the case, the complete replacement of one plant community by another. Plant succession usually begins on a bare area soon after it has been created. An initial group of pioneer plants becomes established on the new site, and this group (or sere) is replaced in turn by other communities until the location comes under the control of species that are capable of reproducing themselves indefinitely (the climax association).

Along rivers, the process of plant succession is usually initiated on new ground formed by the deposition of sediment during flood-stage. It follows that to have new space for alluvium to be deposited, older sections of the floodplain must be periodically destroyed. It is this constant replacement of older soil-vegetation complexes by new successional sites that gives the northern floodplain its high primary productivity.

Successional floodplain communities occupy one point in space for a relatively short time. Allogenic (1) succession rapidly prepares a site for the later or autogenically-dominated (2) seres and the trend is toward a stable, more complex, but less productive ecosystem. If older portions of the floodplain are not periodically destroyed by lateral erosion, plant succession along northern rivers ultimately creates a closed-crown coniferous forest. Through the buildup of organic debris, this group of plants becomes increasingly more separated from the nutrient supply offered by flooding and siltation. As the organic mantle increases in thickness it retains more moisture and a colder soil environment results; the closed canopy reduces solar radiation at the forest floor to further cool the soil. The slow decomposition of organic material yields acid products and lowers the pH of the soil to make it less productive. This sequence of deteriorating ecologic conditions may be observed along most northern rivers by making a transect from a river's edge to the adjacent uplands.

The early seres in a successional sequence are nearly always the most productive for wildlife; biomass accumulation is rapid and proportionately more usable energy is fixed than is in most mature ecosystems. As a result

(1) A plant community where the replacement of one association by another results principally from changes in the substrate (such as caused by flooding and sedimentation), independent of the plants.

(2) A sere where the replacement of an association by another results chiefly from transformations induced by the plants themselves, such as that which occurs in the later stages of alluvial plant succession.

the northern floodplains and deltas form belts and islands of high productivity set within the less productive boreal forest and tundra landscapes. If a northern river with low natural storage is regulated, the perturbing effect of spring floods is reduced or eliminated and plant succession soon begins to reduce the productivity of the alluvial habitat. Without continued initiation of primary succession, the biological productivity of any northern floodplain or delta soon diminishes.

### 5.2. Migratory Waterfowl Habitat.

There is no lack of water in the northern landscape, but unfortunately, much of it is of little use to waterfowl. A large proportion of the smaller lakes is of the bog type-cold, deep, low in nutrients, often acidic, and support only limited aquatic vegetation; they are therefore avoided by most waterfowl.

The most productive inland waterfowl habitat is along rivers and floodplain or deltaic lakes, primarily because of the annual replacement of nutrients by flowing water, and by the continued initiation of productive successional vegetation. Although northern floodplains and deltas constitute a relatively small part of the total waterfowl production area of North America, they produce a high percentage of the annual waterfowl crop.

The number of breeding ducks in northern river lowlands has, however, varied between some one and two million in the past (Smith, *et al.*, 1964). This large range is a reflection of surface water conditions on the prairies to the south. When prairie surface water is abundant, northern breeding grounds support a normal population of ducks that seek northern habitats. During periods of drought on the prairies, northern floodplains and deltas function as a sanctuary for great numbers of waterfowl. A breeding stock is thus assured as long as these alluvial habitats are able to maintain normal water levels and flow regimes.

If regulation of a northern river eliminates spring flooding, the following factors could combine to modify waterfowl habitat.

(i) Nesting of numerous ducks and geese is now concentrated on low alluvial islands where waterfowl are protected from terrestrial predators. Lowering of river levels during spring and early summer could enlarge and coalesce some of these islands so that waterfowl might no longer find them suitable for nesting. Reduced flooding and ice scouring would enable rapid succession of densely-growing willow to further make such islands unsuitable for nesting.

(ii) A characteristic feature of many northern rivers, especially those of the Canadian Shield, is the distinct zone of sedges (*Carex* spp. and *Eriophorum* spp.) and semi-aquatic grasses (Gramineae) that parallel the shores. This cover is usually separated from the riparian woodland by a sharp boundary (trim-line) which is maintained by ice-scour during spring flood. The riparian grasses and sedges are excellent and easily-obtained sources of food for migrating and nesting waterfowl. If regulation were to eliminate ice scour (which may or may not occur), woody vegetation would no longer be eliminated from such areas and succession of species unusable as food by waterfowl would soon replace the nutrient-rich grasses and sedges.

(iii) An ice-free river provides an avenue of virtually continuous resting habitat for migrating waterfowl. If breakup is delayed artificially, the normal early-spring resting habitat could be reduced or even eliminated in some years.

(iv) A lake feature that offers protection from terrestrial predators is the " reverse delta " (Gill, 1972), an alluvial deposit that projects into delta and floodplain lakes which are joined to the river by a connecting channel. During flood stage, these small channels carry silty water into the lake to construct a small delta at the lake-channel junction. The apex of these deltas prograde outward more rapidly than willows can succeed, thus the points create relatively safe sanctuaries. Reduced flooding would lead to rapid colonization by willows, and the value of these points as terrestrial resting habitat would be lost.

(v) Floodplain and delta lakes that are not connected to rivers are destined to become increasingly nutrient-deficient unless the surrounding levees are periodically overtopped by silt-carrying floodwater. Regulation eliminates such overtopping as clearly demonstrated in the Peace-Athabasca Delta (Fuller and La Roi, 1971; Dirschl, 1971).

## 5.3. Aquatic Mammals.

Many of the statements concerning the value of northern floodplains to waterfowl hold equally for aquatic mammals. They too depend on the spring freshet to maintain the alluvial habitat in a state of high biological productivity.

The mammal that perhaps best characterizes northern river systems is the muskrat (*Ondatra zibethicus*). Its numbers in the Mackenzie, Slave, Peace-Athabasca, and Saskatchewan Deltas may reach 1,000,000 during peaks in its cyclic population (Fuller, 1951; Dirschl and Goodman, 1967; Stevens, 1971; Hawley, 1972). In these islands of suitable habitat, muskrats have shown remarkable adaptability to the northern environment. They become established in water bodies that, although ice-covered during winter, do not freeze to the bottom. According to Stevens (1971), a depth of 1.2 m of water is necessary for muskrats in Northern Canada to survive the winter. Surrendi and Jorgenson (1971) suggest that the optimum lake depth for the overwintering of muskrats in the Peace-Athabasca Delta is 1.4 m. In water much deeper than this the quantity of preferred aquatic vegetation necessary to support the animals over winter is not produced. The ice depth in lakes occupied by muskrats averages some 75 cm, thus only a shallow layer of water remains under the ice for the animals' feeding activities; a minor reduction in water level would cause the lakes to freeze to the bottom. Referring to this problem in the Peace-Athabasca Delta, Dirschl (1971, p. 185) concludes : " For muskrats, significant losses of breeding habitat are occurring through drying of many of the smaller water bodies, shrinkage of the large lakes, and lack of food and cover. More critical, however, is the fact that most of the remaining water areas are now so shallow as to freeze to the bottom and thus to make winter survival impossible ".

Stevens (1955) found that muskrats normally breed at breakup in the Mackenzie Delta but occasionally some older females produce a second litter. If breakup were artificially delayed, the possibility for second litters would probably be eliminated.

In northern Canada, beavers (*Castor canadensis*) also use flood-plains and deltas as habitat and depend on the successional vegetation as a food source. By contrast, the climax forest is virtually unused by this animal.

Gill (1971 c) demonstrates that as a response to sediment sorting, point bars of the Mackenzie Delta are colonized by a distinct ecosystem dominated by balsam poplar (Fig. 4), a preferred food of northern beaver. These animals are thus attracted to point bars where they may dam the outlet of an adjacent depression, construct a lodge, and use the poplar and willow as a food source. Again, if flooding were eliminated, this type of physical and biological interaction could not occur since sediment sorting during flood-stage *initiates* these responses.

## 5.4. Modification of Fish Spawning Habitat.

Flood elimination can immediately alter the quality of floodplain and deltaic spawning habitat. Spring-spawning fish such as northern pike (*Esox lucius*) are among the most numerous and important species of northern river systems. During flood stage, spawning pike take advantage of high water to enter many of the otherwise inaccessible delta and floodplain lakes where they spawn. From mid-summer to fall the fingerlings return to the main distributaries via small drainage outlets (Gill, 1971 a). Elimination of flooding would reduce the number of accessible lakes and it is reasonable to expect that populations would decrease due to the reduction in normal recruitment because of loss of spawning habitat.

Bidgood (1971) shows that the low water levels in the Peace-Athabasca Delta during the years 1968 to 1971, which are partly attributable to regulations of the Peace River (Kellerhals, 1971), are detrimental to the walleye (*Stizostedion vitreum*), another spring-spawning fish of considerable commercial value. The spring temperature in one shallow delta lake which is used by post-spawning walleyes has increased. After spawning, these fish are in weakened physiological condition, and when they are subjected to the warm water, fungus infection and an increase in post-spawning mortality results. In addition he suggests that altered lake outflow conditions cause the young-of-the-year to be trapped in shallow lakes where excessive summer temperatures cause some mortality. If the lakes completely freeze during winter, additional die-off would undoubtedly occur.

Autumn-spawning species, such as the lake whitefish (*Coregonus clupeaformis*), round whitefish (*Prosopium cylindraceum*) and inconnu (*Ste nodus leucichthys*), are less likely to be affected by flow regulation. Some cold-water species such as trout and char (*Salvelinus* spp.) would probably benefit from dams on northern rivers. The factors most likely to prove beneficial are (i) reduced suspended load, and (ii) reduced stream temperatures due to the deep reservoirs (Hynes, 1970).

## 6. SOCIAL AND ECONOMIC EFFECTS

### 6.1. Importance of Water-Based Activities to Northern Settlements.

With the development of fur trading in Northern Canada during the eighteenth century, rivers became the major transportation routes. An economy based largely on trapping with fishing and hunting as subsistence occupations led to the establishment of the majority of settlements near rivers and lakes. Although today only the Mackenzie River system remains as a major transportation route, the original settlement pattern still persists.

Trapping, especially of beaver and muskrat, was once the economic mainstay of most of these river and lakeside communities. Today there are fewer full-time trappers, although in many settlements a high proportion of residents trap on a part-time basis. Fishing has always been an important form of subsistence, and in many areas where dog teams were used in winter trapping operations it was essential for dog food. However, with the rapid decline of dog teams in favour of snowmobiles, the domestic demand for fish has decreased. Commercial fishing remains locally significant in northern portions of the provinces and in Great Slave Lake. Hunting was originally of a subsistence nature, but it has recently become more important as a form of recreation.

The most extensive study of the social and economic effects of changes in the hydrologic regime of northern rivers is associated with the declining water levels of the Peace-Athabasca Delta (Reinelt, *et al.*, 1971). Prior to 1968, the year of closure of the Bennett Dam, the settlement of Fort Chipewyan had already been beset by economic problems of unemployment, underemployment, and low educational levels. Cash income and prerequisites (food, clothing material, dog feed) from beaver and muskrat trapping, and from hunting and fishing formed the major indigenous economic base although there were substantial income flows from outside the community in the form of wages and social welfare payments. Persistently low water levels since 1968 moved Reinelt, *et al.* (1971, p. 7) to state :

" The fish and muskrat catches have been reduced substantially and wide dispersion of the muskrat population requires more travel effort, movement is made more difficult as available craft no longer suffice when lakes fall dry, fisherman must move many miles out in order to set their ice nets, the landing wharfs become unusable, boat loads must be carried to shore, etc. "

Although the low water levels served to merely hasten a move from traditional forms of livelihood that had already been going on for several decades, the accelerated economic and social changes affected not only the individual, but the entire fabric of the community. Similar conclusions were reached in a study done for Manitoba Hydro on the potential effects of the Churchill River diversion.

### 6.2. NAVIGATION.

The Mackenzie River system is the major form of heavy freight transportation to the Western Canadian Arcic. With one portage the river is navigable from Waterways, on the Athabasca, to the Arctic Ocean. Low water levels are a problem in the upper navigable reaches and a draught of only 75 cm is permissible; north of Hay River, N.W.T. a 1.8 m draught is possible. The duration of ice cover restricts river traffic to July and August in the northern sector and from early May to late September in the southern portions (Hall, 1969).

Regulation, which tends to shift large portions of the total runoff toward winter when rivers are ice covered, is almost certain to have some detrimental effects. Changes in freeze-up and break-up dates are also important to navigation and regulation could be beneficial or detrimental, depending on circumstances.

### 6.3. FUTURE POTENTIAL FOR RECREATION.

The traditional water-based activities of northern communities are without doubt declining, but there is a greatly increasing demand for sport-fishing and hunting and for non-consumptive water-oriented recreation (e.g. boating, canoeing, bird-watching and nature photography) from the urban sector of Southern Canada and the United States. The potential for recreational development in Northern Canada is therefore great and relatively untapped. This potential will increase in value in proportion to the increasing scarcity of wilderness areas in the more settled parts of the continent. As discussed previously, riparian wilderness is easily deteriorated by regulation-caused hydrologic changes, thus the potential of such deltas as the Peace-Athabasca for wildlife-based tourism, " the one enterprise that seems to offer a sound economic future, is in danger of being diminished " (Dirschl, 1971, p. 174).

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## SUMMARY

The recent start of regulation of the Peace River at the W.A.C. Bennett Dam in British Columbia, Canada, has initiated numerous environmental changes downstream. Indirectly it has also lead to extensive studies of the problems caused by regulating northern rivers. An attempt is made here to review these and other studies and to focus attention on the wide variety of downstream effects that should, in future, be considered.

The hydrologic regime of northern rivers is characterized by a snow-fed flood peak in spring or early summer and by minimum flows in late winter. The ratios between maximum and minimum flows depend on the amount of natural storage in a basin and vary from over 100 to less than 5.

Sedimentation problems caused by storage dams on northern rivers are poorly documented but indications are that they differ from problems encountered in arid or southern settings. Degradation-resistant gravel beds are common and sediment loads are generally low. The possible problem areas are tributary junctions, where aggradation of the main (regulated) river is likely, due to reduced carrying capacity. Initially, the tributary can degrade severely if, under natural conditions, the floods of the tributary had coincided with the floods in the main river.

Ice effects are also poorly documented. Delays in break-up could initiate a number of deleterious effects.

Active flood plains and deltaic wet-lands represent islands of high biological productivity in vast areas of less productive boreal forest. Many species of waterfowl and aquatic mammals depend on these islands of habitat for survival. Flow regulation can cause a reduction in the size and quality of these biologically significant areas.

A large segment of the population of inland Northern Canada lives in close proximity to rivers and deltas and depends on fishing, trapping, and hunting to supplement a relatively meager subsistence, one which can

e readily jeopardized by altering an appropriate hydrological regime. Iopes for improving the economic base of many northern settlements entre largely depends on developing their water-based recreational potential nd to a lesser degree on forestry and commercial fisheries, all of which epend on suitable hydrologic conditions.

## RÉSUMÉ

Le début récent de la régulation de la Rivière de Paix au barrage N.A.C. Bennett en Colombie Britannique, Canada, a déclenché plusieurs changements à l'environnement en aval. Indirectement ceci a aussi entraîné les études intensives aux problèmes causés par la régulation des rivières du nord. Un effort est ici fait pour les passer en revue ainsi que d'autres études, afin de porter l'attention sur la variété étendue des effets en aval qui devraient être considérés à l'avenir.

Le régime hydrologique des rivières du nord est caractérisé par le flot torrentiel provenant de la fonte des neiges au printemps ou au début de l'été, et par des écoulements minimaux plus tard en hiver. Le rapports entre les écoulements maximaux et minimaux dépendent du stockage naturel dans un bassin et varient de valeurs supérieures à 100 à des valeurs inférieures à 5.

La documentation concernant les problèmes de sédimentation causés par le stockage dans les barrages sur les rivières du nord est assez rudimentaire, mais est une indication que ces problèmes diffèrent de ceux rencontrés dans les endroits arides ou du sud. Les bancs de graviers résistant l'affouillement sont communs et les charges de sédiments sont généralement faibles. Les endroits pouvant créer des problèmes sont les jonctions d'affluents, où l'agrégation de la rivière principale (à débit contrôlé) est probable, due à la capacité de charriage réduite. Au début, l'affouillement de l'affluent peut être considérable à cause de conditions naturelles, les inondations de l'affluent coïncidant avec les inondations de la rivière principale.

Les effets de la glace sont aussi mal documentés. Des délais dans la rupture des glaces pourraient causer des dégâts.

Les plaines balayées par les inondations et les terres humides des deltas représentent des centres de productivité biologique intense dans de vastes régions de forêt boréale moins productives. Plusieurs espèces d'oiseaux aquatiques et de mammifères aquatiques dépendent de ces îles comme habitat pour survivance. La régulation du débit peut causer une réduction dans la superficie et la qualité de ces endroits biologiques importants.

Un gros secteur de la population demeure à l'intérieur au Nord du Canada à proximité des rivières et deltas, et dépend de la pêche, la trappe et

la chasse pour augmenter sa subsistance plutôt limitée. Elle peut être facilement mise en danger en modifiant le régime hydrologique correspondant.

Les espoirs pour améliorer la base économique de plusieurs établissements du nord se concentrent largement sur le développement de leur potentiel récréatif basé sur l'eau et à un degré moindre sur la sylviculture et la pêche commerciale. Tout cela dépend de conditions hydrologiques convenables.