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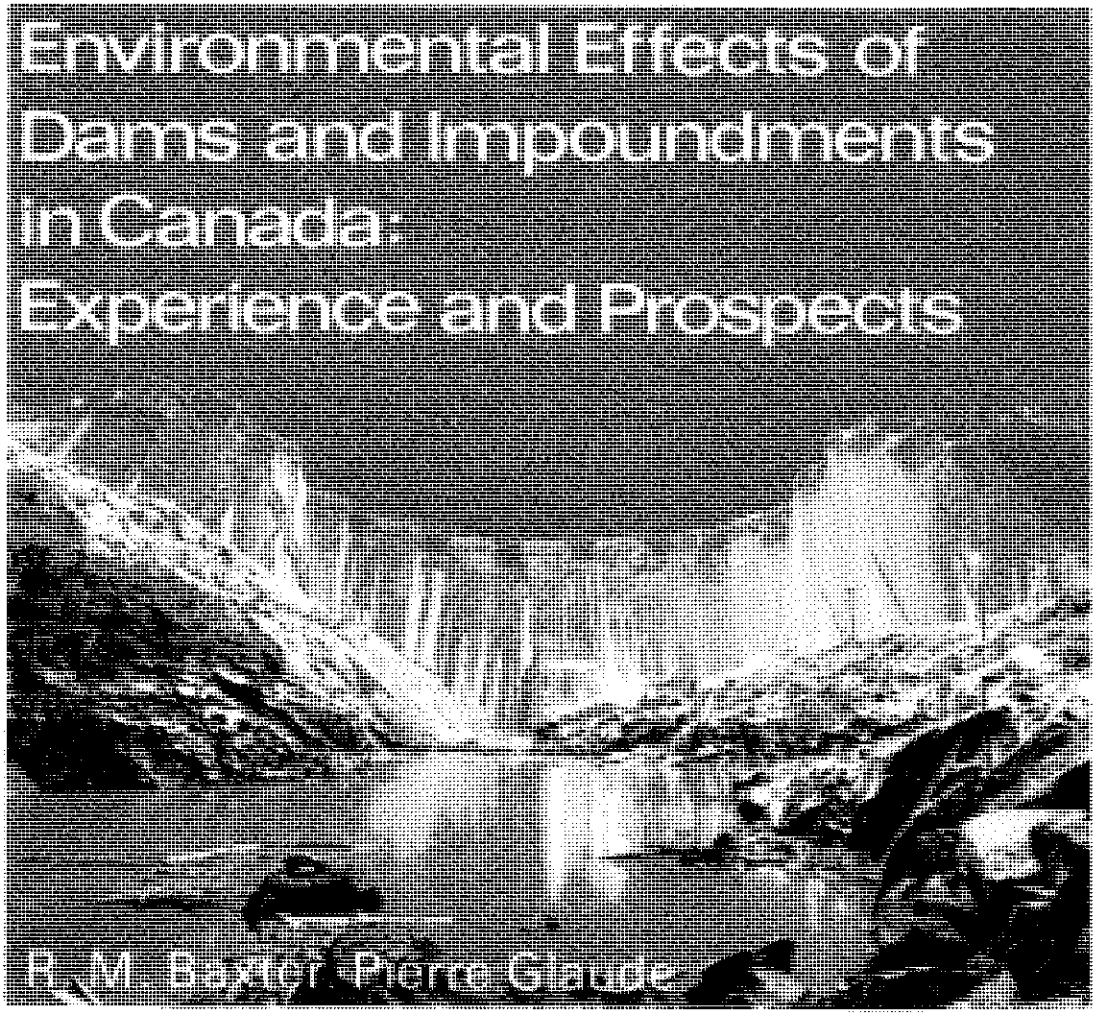
Environmental Effects of Dams and Impoundments in Canada: Experience and Prospects



R. M. Baxter, Pierre Glaude

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Environmental Effects of Dams and Impoundments in Canada

Experience and Prospects

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DEPARTMENT OF FISHERIES AND OCEANS
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Contents

Abstract

BAXTER, R. M., AND P. GLAUDE. 1980. Environmental effects of dams and impoundments in Canada: experience and prospects. Can. Bull. Fish. Aquat. Sci. 205: 34 p.

Although dams and reservoirs have contributed immeasurably to the well-being of Canadians they may have side effects which may be detrimental to the environment and to human welfare. In this Bulletin, the authors survey the environmental consequences that have ensued from dam construction and the impoundment of water in Canada in the past, and attempt to alert environmentalists and engineers to the types of problems that may be associated with such activities in the future.

Some of these effects are immediate, direct, and obvious, such as the loss of resources by flooding, interference with the passage of fish, and environmental damage and pollution as a result of construction activities. Others may manifest themselves only over a period of time, such as changes in water chemistry and modification of the new shoreline. This last is likely to be of particular importance in reservoirs on permafrost. Large impoundments may influence the climate in their vicinities and sometimes induce earthquakes. Still other consequences follow from the mode of operation of the reservoir. Low-level discharge through turbines may radically alter the temperature regime in the stream below. The induction of an unnatural seasonal pattern of water level fluctuation may lead to the formation of a virtually barren drawdown zone around the reservoir, and induce geographical and ecological changes downstream, sometimes at great distances.

Many of these effects act in various and sometimes opposing ways on the living organisms in the reservoir and the stream so that the ultimate biological consequences often cannot be confidently predicted.

It is sometimes difficult to reconcile the interests of those who stand to benefit from a given project and the interests of others who are likely to suffer a loss from it. This conflict is particularly acute when the project affects communities of native peoples following a traditional way of life. Such fragile societies are likely to be gravely disrupted unless particular care is taken.

Key words: dams, reservoirs, impoundments, man-made lakes, environmental impact, limnology, fisheries, water quality, permafrost, Canada

Preface

This review is based on an earlier paper entitled "Environmental Effects of Dams and Impoundments in Canada: a Review of the State of the Art" prepared at the request of the Management Committee of the Department of the Environment. The earlier paper was intended to outline the topics that should be covered in a proposed handbook on the subject. When it was decided not to proceed with the handbook at this time, it seemed worthwhile to revise the paper into a form suitable for wider publication.

D. A. Bondy, then of the Lands Directorate, assisted in the preparation of the earlier paper, and D. W. Phillips, of the Atmospheric Environment Service, provided a contribution on climatic effects of impoundments, which is included here in a slightly abridged form.

The task of revision has been made easier by many individuals who read and criticized the earlier review. We extend particular thanks to the following, who were especially generous with suggestions and information: R. Hecky, Freshwater Institute, Winnipeg; D. M. Kelly, Inland Waters Directorate, Halifax; R. Newbury, Freshwater Institute; G. S. Peck, Ocean and Aquatic Sciences, Burlington; and A. Soucy and his colleagues, James Bay Energy Corporation.

Introduction

No branch of engineering has contributed more to the development of civilization than the art and science of controlling the flow of water. It is also one of the oldest; as early as the fourth and third millennia B.C. fairly complex projects were being successfully undertaken in Egypt, India, and China (Biswas 1975). The benefits of hydraulic works are so great and so obvious that for a long time little thought was given to possible harmful effects, except for disasters resulting from dam failures. It appeared that any undesirable consequences could be avoided by appropriate design and management: the obstruction of fish migration by dams could be avoided by the construction of fish ladders; the breeding of malarial mosquitoes in impoundments could be prevented by periodic small fluctuations in water levels; and so on. The idea of harnessing large rivers for the benefit of man seems to have aroused a kind of popular euphoria, which found expression for example in a song by Woodie Guthrie praising the Grand Coulee Dam on the Columbia River (Guthrie 1976).

As more and larger dams were built and as more and more of the world's rivers were brought under control, it became apparent that unanticipated undesirable consequences could follow, often distant in space and time from the actual construction, and mediated by a chain of causes and effects that is often far from obvious (e.g. Ward 1977). These events, occurring as they have during a period of intense popular concern about the environment, have led to considerable opposition in some segments of the population to almost any further impoundment or regulation of natural waters.

In Canada, as elsewhere, natural water courses have long been used as transportation routes, and have been modified in various ways by the construction of canals and other structures. These have included some remarkable engineering achievements, such as the Jones Falls Dam (Fig. 1) on the Rideau Canal near Kingston. This dam, which is still standing, was the highest in North America (19 m) when it was completed in 1831 (Legget 1961). The development of agriculture in the Prairie Provinces required the impoundment and diversion of water for purposes of irrigation. Water power was used by the early settlers to drive saw mills and grist mills. When the potential of hydroelectric power began to be appreciated around the beginning of the present century, Canadian engineers played a leading role in the new technology, which in a few decades transformed the industrial and domestic life of the country (Encyclopedia Canadiana 1975). As larger and larger projects were proposed and constructed, the possibilities of undesirable environmental consequences gave cause for increasing concern. The effects on the Peace–Athabasca Delta of the W.A.C. Bennett Dam on the Peace River, discussed below, perhaps first served to bring these possibilities to the notice of the general public. At about the same time a

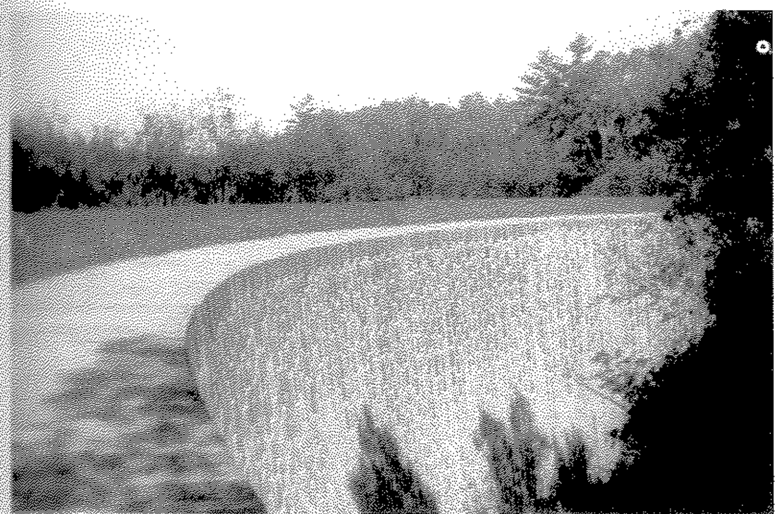

FIG 1. Jones Falls Dam (photo courtesy of Parks Canada).

proposal to divert much of the water of the Churchill River into the Nelson River became a major issue in a provincial election in Manitoba, and the announcement of the James Bay hydroelectric project by the premier of Quebec caused widespread concern. Not long after this, increasing anxiety in Canada about the possible environmental effects of the proposed Garrison diversion in North Dakota led to the appointment by the International Joint Commission of an international study board to examine the problem (International Garrison Study Board 1976). The study of reservoir effects is now generally recognized as an important topic in applied ecology.

The *Register of Dams in Canada* (Pratt 1970) gives a list and brief description of the major Canadian dams in existence or under construction in 1969 and Efford (1975b) lists the major Canadian hydroelectric projects up to 1974. The locations of sites discussed in the present paper are shown in Fig. 2.

In this review, we survey the environmental consequences that have been observed to result from dams and impoundments in Canada, or that may be expected on the basis of experience in other countries or of general physical and biological principles. Such a review may be of assistance to planners and managers in making the best possible decisions, in the light of existing knowledge, for the future development of Canada's water resources. It is only possible to indicate general areas of concern and general approaches to prevention or mitigation. The recognition and solution of specific problems at any particular site can only be achieved, if at all, by special on-site studies by specialists in the relevant disciplines and close collaboration between these and the people responsible for the planning, construction, and operation of the project.

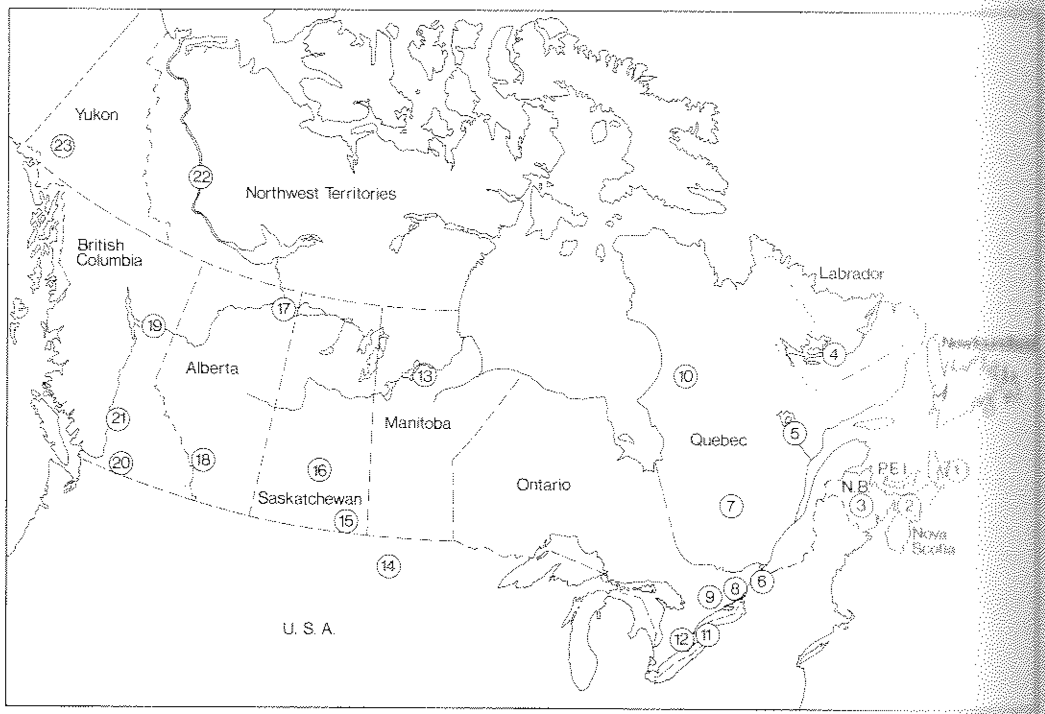

FIG. 2. Approximate locations of principal sites mentioned in the text. 1, Wreck Cove; 2, Minas Basin, possible site of Fundy tidal power project; 3, Saint John River; 4, Churchill Falls development (Smallwood Reservoir); 5, Manicouagan complex; 6, Moses–Saunders Dam; 7, Gouin Reservoir; 8, Jones Falls Dam; 9, Kawartha Lakes; 10, James Bay project — La Grande, Eastmain, and Caniapiscau rivers; 11, Niagara Falls; 12, Deer Creek; 13, Southern Indian Lake and Churchill River diversion; 14, proposed Garrison diversion (USA); 15, Boundary Reservoir, Estevan, Sask.; 16, Gardiner Dam (Lake Diefenbaker); 17, Peace–Athabasca Delta; 18, Bassano Dam, Bow River; Kananaskis River; Lake Minnewanka; 19, W.A.C. Bennett Dam (Williston Lake); 20, Skagit Valley; 21, Fraser River; 22, Mackenzie River; 23, Aishihik and Stevens lakes.

Environmental and ecological problems related to the intended function of the project will be considered. These include processes influencing the useful lifetime of a reservoir (silting and erosion) as well as those relating to the effectiveness of a reservoir for its intended purpose, such as the maintenance of fish populations where the provision of facilities for recreational or commercial fishing has been included among the benefits that the project will provide.

As far as possible, the discussion has been limited to matters that seem likely to be of concern in Canada. Such matters as the influence of impoundments on the spread of certain diseases, which are of great concern in some parts of the world, do not seem likely to be important here and have not been discussed. We have also refrained from discussing general water management problems that may arise in natural as well as in artificial water bodies. One such problem is the disposal of waste heat from thermoelectric generating plants. This has been discussed at length in two recent reports (James F. MacLaren Limited 1975, 1977). Recently the growth of the exotic Eurasian water milfoil (*Myriophylum spicatum*) in several regions of Canada has caused considerable concern. For example, it has appeared in the Kawartha Lakes, which are highly regulated and may be regarded as reservoirs. This problem, however, is not peculiar to reservoirs but is rather one of shallow, slow-moving waters in general. It is the subject of considerable research at the present.

Our aim here has been to emphasize practical considerations and to avoid matters of purely theoretical interest. However, a few general ecological concepts of rather wide applicability may be mentioned because of the light they throw on many of the consequences of impoundment. One of these is the concept of the ecotone, or border zone between two habitats, such as the edges of lakes or rivers. Everyone has probably observed the rich variety of living things found in such zones. Another very important region of this type is the estuary, the ecotone between freshwater and the sea. Both these types of habitat are very sensitive to any manipulation of the streams or lakes associated with them.

Another useful concept is that of pulse stabilization. This refers to the maintenance of long-term ecological stability by periodic perturbations. The maintenance of a lawn by regular mowing is a familiar example. Ecosystems along streams are largely maintained in their normal state by periodic flooding, and if the flood regime is changed, the ecosystem will change. Effects of this kind were responsible for the changes that occurred in the Peace–Athabasca Delta after construction of the W.A.C. Bennett Dam. The alterations of the flood regime above the dam brings about changes in that region too. For a discussion of these concepts, see Odum (1971).

It may also be useful to call attention to some of the differences between ecosystems in streams and in standing waters. As many of the organisms that live in streams cannot exist in standing water (and vice versa), when a stream is impounded many of the organisms in it will disappear, to be replaced by other forms. Blackfly (*Simulium*) larvae, for example, live only in running water, so when a stream is impounded there is likely to be a decrease in these pests in the vicinity. This has occurred in Lake Diefenbaker (Fredeen 1977). On the other hand, there may be an increase in mosquitoes, which breed in standing water.

Moreover, the ultimate source of energy to drive the ecosystems of standing waters is photosynthesis within the water body, particularly by the phytoplankton, whereas stream ecosystems are largely nourished by organic detritus derived from terrestrial plants within the watershed (Hynes 1975). The conversion of a stream to a lake is therefore a more drastic change than it may appear to the casual observer (McLachlan 1977).

It may also be helpful to bear in mind that the environmental effects of a dam on the environment above and below it show a certain symmetry, or complementarity. A decreased annual variation in water level below the dam is associated with an increased annual fluctuation above it; sedimentation above the dam leads to erosion below it; retention of heat in the impoundment causes cooling of the water downstream; and so on.

The arrangement of the various topics in a concise, lucid, and systematic way is not easy. Any primary effect of impoundment (such as the flooding of a given area of land) may produce effects of many different kinds, some of which may be removed by several cause-and-effect steps from the primary effect. Moreover, any ultimate effect of concern to man may be the result of a network rather than a chain of intermediate causes which may sometimes oppose each other. The important effects range from simple and direct consequences of impoundment, such as the loss of agricultural land and standing timber, to far-removed effects which may be difficult to predict, such as qualitative and quantitative changes in the fish population above and below the dam. They also range from consequences whose seriousness can be objectively assessed in a manner about which there is likely to be general agreement (the loss of farm land and timber again may be given as an example) to consequences which may appear trivial to some individuals, yet cause considerable concern to others, such as the possible extinction of a comparatively obscure species of plant or animal (e.g. Holden 1977) or the destruction of the spray-zone ecosystem below a waterfall by diversion of the stream above it (Brassard et al. 1971).

After a description of types of dams, the general geographical, physical, chemical, and biological consequences of the construction of a dam, both above and below it, will be discussed, followed by a discussion of the very complex way in which they may influence the populations of fish. Finally, some of the impacts that may be felt in the general vicinity of dams and impoundments but which are not necessarily restricted either to the new lake or the stream will be dealt with.

An attempt has been made to make the presentation easily comprehensible, and even interesting, rather than to impose any rigid framework upon it, which would be virtually impossible because of the complexity of our material. A review of the effects of impoundments written at this time is necessarily a kind of interim report. Studies currently in progress at several sites, especially perhaps at the various sites of the James Bay project, should yield results of great value for any subsequent undertakings.

Types and Purposes of Dams and Impoundments

The type of dam built at any particular site depends on such considerations as its intended purpose and the nature and location of the site. Earthfill and rockfill dams are embankments of earth or rock, usually with a core of impermeable material, sloping gently both upstream and downstream. Gravity dams are usually constructed of concrete and are held in place by their weight (Fig. 3). The upstream face is almost vertical and the downstream face tapers to a toe to prevent overtipping. Arch and buttress dams are also usually constructed of concrete, but are thinner than gravity dams. They are held in place either by the force of the water against their abutments (arch dams) or by a number of downstream buttresses. Arch dams are usually vertical on both faces, whereas buttress dams may be tipped in the downstream direction. A diagram of an arch dam is shown in Fig. 4.

A dam is usually provided with a spillway to permit water to escape from the reservoir at times of high flow without damage to the structure. To permit discharge of water when the level is below the spillway, a sluiceway is usually provided, and if the dam is part of a hydroelectric project, a penstock must be included to conduct water to the turbines. Sluiceways and penstocks often draw water from a point considerably below the surface of the impoundment. They may pass through either the dam or the adjacent hillside.

The commonest reason for constructing a dam is probably to make it possible to store water at times of high flow to be released when the natural flow is low. The purpose may be flood control, maintenance of navigation on rivers, generation of electricity, provision of a reliable supply of water for domestic, industrial, or agricultural use, or most commonly some combination of these. The most dramatic type of project is one in which a dam is constructed on a large river, thereby flooding a considerable area and converting a stretch of running water into a body of standing water. Such impoundments almost always have

Fig. 3. Moses–Saunders Dam on the St. Lawrence River (photo courtesy of Ontario Hydro).

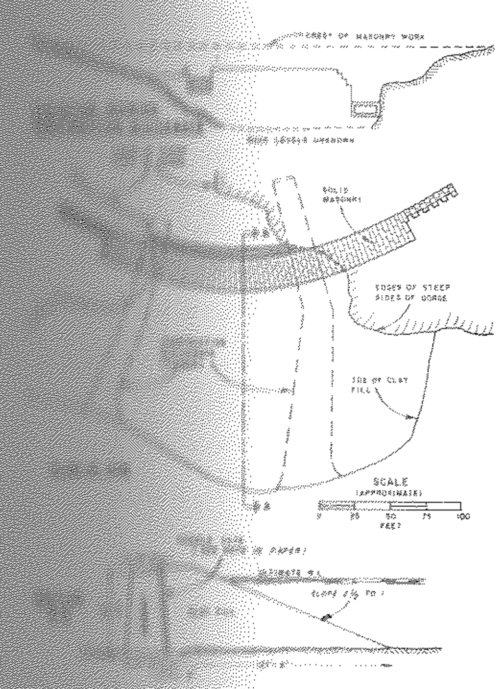

Fig. 4. Sketch of Jones Falls Dam, an arch dam (from Legget 1962).

the generation of electricity as at least one of their purposes, although the Gouin Reservoir on the Saint-Maurice River in Quebec, which was for a number of years the largest man-made lake in the world, was originally constructed to facilitate the transport of logs.

Not all hydroelectric projects involve the storage of large quantities of water, however. If the flow of a river is fairly constant throughout the year, either naturally or because of regulation upstream, a dam may serve mainly to provide a head of water and to direct its flow into a penstock. Generating stations of this type, operating on the normal flow of the stream, are referred to as run-of-the-river plants. Many rivers of the world are regulated throughout their length by a series of dams in cascade so that virtually all the hydraulic head is utilized. Often the dam furthest upstream forms a reservoir and those below are run-of-the-river. The three dams in the Canadian portion of the Saint John River constitute a cascade, and are of predominantly run-of-the-river type.

At the other extreme, an existing natural lake may be converted into a reservoir by regulating its outflow. If the lake is small, the impact of the project on the lake itself may be severe. However, large lakes such as Lake-of-the-Woods and Lac Saint-Jean, which are technically reservoirs in this sense, will be little influenced by such treatment.

Many large projects, such as the Churchill Falls project in Labrador, the James Bay project in Quebec, and the Churchill–Nelson project in Manitoba, involve both the production of new bodies of standing water and the modification of those already existing, and their impacts are correspondingly complex.

Many projects involve not only the impounding of water but the diversion of flows, sometimes even into different watersheds. The diversion of streams may be done for reasons unrelated to impoundment, and it has sometimes been difficult to decide where to limit the discussion. In what follows, the emphasis will be on diversions related fairly directly to impoundments.

Usually, water is impounded directly behind a dam so that the basin of the new lake, if one is formed, includes a portion of the original stream bed. Sometimes, especially when water is being stored for domestic or industrial use, it may be diverted from a stream into a natural or artificial basin to form an off-channel reservoir.

A particular type of hydroelectric generating station, the pumped-storage station, is increasingly important in the United States (American Fisheries Society 1976). In such a station, part of the electricity generated at one time is used to pump up water to generate more electricity at another time. Such stations have not yet come into use in Canada, although something similar is done at Niagara Falls, where the amount of water that may be withdrawn is regulated by international treaty, and more may be taken during the night than during the day. During the night, therefore, water is diverted and pumped into an off-channel reservoir (Friesen and Day 1977).

In some instances, the formation of a new body of standing water is the primary purpose of the undertaking. Instances of this are the construction of a cooling pond for a thermoelectric generating plant as at Estevan, Sask., or the construction of fish ponds on small coastal streams in Prince Edward Island.

The impoundment and regulation of salt water presents a group of problems different from those associated with freshwater impoundments. Up until now in Canada this has only occurred incidentally as a result of the construction of bridges or causeways across estuaries or bays. However, there is a strong possibility that extensive deliberate impoundment of sea water will sooner or later be undertaken in the Bay of Fundy in order to utilize tidal power for the generation of electricity (Clark 1978; Daborn 1977; Gordon and Longhurst 1979).

Effects of Flooding and the Question of Pre-clearing

The approximate extent of flooding will probably be known from surveys made before construction of the dam. The economic loss as a result of the flooding of agricultural land or standing timber should be calculable with reasonable accuracy by agricultural or forestry experts. The economic loss may not be limited to the flooded lands; the usefulness and value of lands adjacent to these flooded lands may be reduced, for example, if a continuous tract is broken up into a number of smaller tracts.

If the standing timber is not harvested before flooding it is not irretrievably lost, because techniques exist for harvesting it after the reservoir has been filled. The decision whether or not to harvest timber before filling will probably be based not only on the value of the timber, but on the use to which the reservoir is to be put. If the reservoir is to be used for boating, the timber should probably be removed even if it cannot be marketed. In some places, a certain amount of pre-clearing may be necessary for esthetic reasons. In the reservoirs of the James Bay project, the policy is to clear the areas that are visible from the roads, in the mouths of the tributaries, and where there is likely to be intensive fishing (Bollulo 1978).

The James Bay Energy Corporation has been carrying out interesting experiments on the clearing of reservoirs by natural agencies such as wind and ice. When flooded trees become frozen into ice, and the water level is lowered, the force thereby exerted is sufficient to break the trunks of trees of considerable size, which can be removed from the water after the ice has thawed (Bollulo 1978).

In flooded permafrost areas, it makes little difference whether the trees are cut, since they will in any case be carried into the water as the shoreline melts and slumps (see p. 12-13). In other areas, submerged vegetation may be useful in stabilizing the shoreline.

Fully submerged trees last a long time at the temperatures prevailing in Canadian waters. Tree trunks in the Gouin Reservoir showed little change 55 years after flooding (INRS-Eau 1978).

If the flooded area includes sphagnum bogs, these may rise to form floating islands (Fig. 5), which may persist for years. In the James Bay project, the possibility is being considered of clearing these near the shore, and anchoring them as refuges for wildlife and water fowl (Société d'Énergie de la Baie James 1978a).

The loss of wildlife as a result of flooding of their habitat is perhaps more difficult to estimate, but should be possible if sufficient time and resources are made available for surveys. The weight to be given to the loss of wildlife in the decision as to whether to proceed with the project will vary from one part of the country to another. Other things being equal, it will be of more importance on the central plains, where the valleys of the relatively few rivers provide almost the only habitat for most ungulates, than in the forests, in areas where hunting and trapping are important to the local economies than in areas where this is not the case; and where the area to be flooded is close to urban populations, which may thereby be deprived of a highly valued recreational resource, than in more remote areas. The Skagit Valley in British Columbia may illustrate this last point (Adams et al. 1971).

The shoreline ecotone is important as a habitat for many species. In the James Bay region, for example, it provides food and shelter for ptarmigan (*Lagopus lagopus*), beaver (*Castor canadensis*), muskrat (*Ondatra zibethica*), and various species of waterfowl. It follows that the linear extent of shoreline flooding may be as important for its influence on wildlife as the areal extent of flooding. The development of a new shoreline ecotone will take longer the more severe the climate, and is likely to be made more difficult by the process of drawdown (see next section).

During the filling of certain large tropical impoundments, large rescue operations were organized to save as many animals as possible in the area being flooded (e.g. Walsh and Gannon 1967). Obviously this is only feasible if there is an unoccupied place available where the animals can be released. Some attempts have been made to relocate beaver in areas affected by the James Bay project (Joliquelin 1978). In general it would seem reasonable to harvest as many as possible of economically useful animals before flooding. At the same time particular care must be taken to avoid the destruction of populations of rare or endangered species or of unique or unusual habitats.

Sites of archaeological or historical interest may be threatened by flooding. When the Aswan High Dam was built in Egypt, a very complex and costly international operation was undertaken to move to higher ground a number of temples and monuments that would otherwise have been submerged (e.g. Keating 1975). Although problems of such magnitude will not occur in Canada, many sites occupied by prehistoric and early historic man are near streams and would become inaccessible if the water level was raised. Such considerations were taken into account by the Lake Winnipeg, Churchill, and Nelson Rivers Study Board (1975). The area to be flooded should be surveyed by archaeologists to locate significant sites and to excavate those likely to yield important information. Many rock paintings and petroglyphs (Fig. 6) are located near water, and many of these in the USA have already been lost as a result of dam construction (Grant 1967). It might be desirable to consider moving threatened paintings to higher ground.

The increased head of water produced when a stream is impounded will often force more water into underlying aquifers. Although this represents a loss of water from the reservoir, it may be desirable under some circumstances, especially in arid regions, by making water available for drinking or irrigation some distance away (Lagler 1969).

In humid regions it is likely to be undesirable. The rise in the water table may waterlog the soil and consequently kill trees around the reservoir. The rate of rise in the water table, which may take several years, and the nature and extent of the changes in soil and vegetation, which may extend for a kilometre or more from the reservoir, depend on the previous height of the water table, the nature and permeability of the soil, the nature of the terrain, and similar factors (Avakyan 1975). If the quality of the impounded water is poor, the quality of the water in the aquifer may be impaired (Hoffman and Meland 1973).

This topic has received relatively little attention in Canada. A fairly thorough study of the influence of Lake Diefenbaker on adjacent groundwater has been made by van Everdingen (1967, 1972), but little attention appears to have been given to the broader environmental considerations.

FIG. 5. Floating peat islands in area flooded by Churchill River diversion (courtesy of Freshwater Institute, photo by G. McCullough).

Problem of the Drawdown Zone

The operation of a hydroelectric generating station usually requires that the reservoir be filled when the rate of flow in the river is high, and gradually drawn down through the turbines throughout the rest of the year. In Canada, this means that it is most commonly filled in the late winter or early or late spring, whenever the snow melts at the sources of the streams, and gradually drawn down during the summer, fall, and most of the winter. This poses certain problems. Under natural conditions, the highest levels of water in rivers and lakes last only for a short time, and drop before the growing season is far advanced, so the banks are clothed during the summer in their characteristic vegetation. In a reservoir, however, the water level may remain high well into the growing season so that, especially if the surrounding relief is relatively flat and the lateral variation in the position of the shoreline consequently extensive, it may be surrounded during a large part of the year by a wide, virtually barren zone (Fig. 7). Swedish ecologists, who are also confronted with this problem, refer to this zone as the "aridal" (Lindström 1973). Under these circumstances the restoration of the littoral ecotone is extremely difficult. This region is unpleasant to look at and in dry and windy

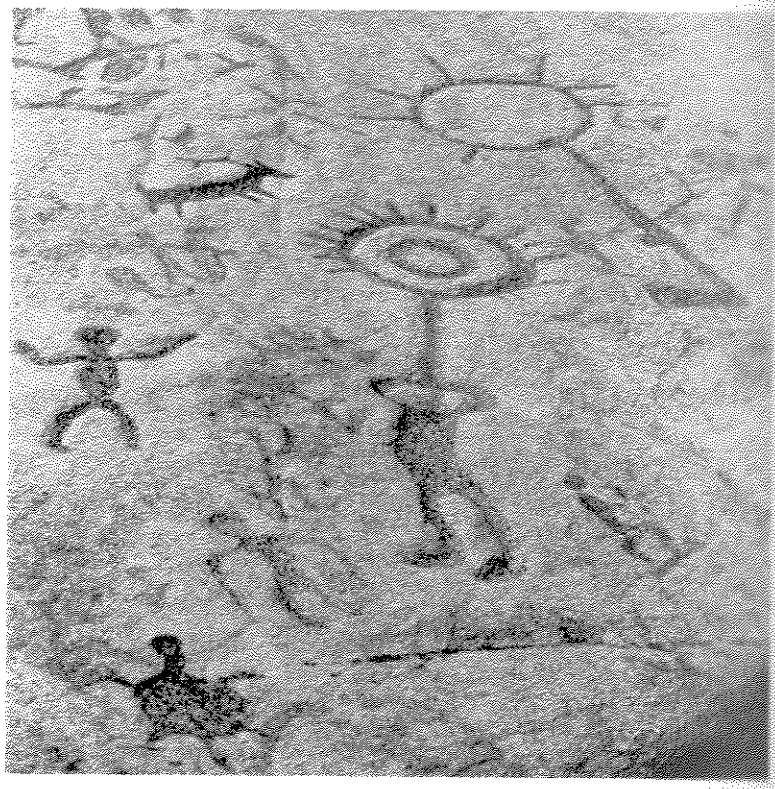

FIG. 6. Petroglyphs near Peterborough, Ont. (courtesy of NFB Photothèque, photo by Jeanne White).

weather may be the source of disagreeable amounts of dust.

In relatively mild climates the appearance can be improved by planting the drawdown zone with flood-resistant shrubs and trees. Some experiments along these lines have been made in England (Gill and Bradshaw 1971), and in the southern USA (Fowler and Hammer 1976; Fowler and Maddox 1974); a long review on the subject is available (Gill 1977) which should have some applicability to Canadian conditions. The British Columbia Hydro and Power Authority (1978) has experimented with the seeding of the drawdown zone to alleviate the problem of dust. The restoration of a suitable littoral habitat for wildlife, particularly at high latitudes, appears to be a more difficult matter. Experiments in progress in the James Bay region (Bollulo 1978) may perhaps contribute to a solution of this problem.

The practice of drawdown poses other problems, particularly in relation to the spawning of fish. These are discussed in the section on biological effects.

Impoundments and Water [illegible]

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[illegible] Indian Lake project [illegible] appears to have caused [illegible] including an increase in [illegible] in the lower Churchill [illegible] has been diminished, and [illegible] the flow of which has [illegible] et al. 1979).

[illegible] nutrients may lead to [illegible] of phytoplankton [illegible] and in primary produc[illegible] but not necessarily. [illegible] (1978) found the primary [illegible] Reservoir to be [illegible] natural lakes. On the [illegible] Kelly (1978) found no [illegible] in spite of the large in[illegible] this to a concur[illegible] which decreased the [illegible] synthesis, and absorption [illegible] particles.

[illegible] may also be released from [illegible] recent study in North [illegible] Cumbie (1977), com[illegible] mercury in the tissues of [illegible] *salmoides*) from [illegible] that the fish from the [illegible] contained the highest [illegible] and those from the oldest [illegible] were made in a [illegible] reservoir in Illinois [illegible] concentration of mer[illegible] low, but the element [illegible] through the activities of microorganisms in the soil and eventually found its way into the fish. In Canada, surprisingly large amounts of mercury have recently been found in fish from the Smallwood Reservoir in Labrador, and from Southern Indian Lake in Manitoba following the increase in the level of the lake as a result of the Churchill diversion (Bodaly and Hecky 1979), although mercury has never been produced or used industrially in either of these regions.

Effects such as these are temporary, and diminish as the reservoir matures. In small reservoirs it may be practicable to hasten the process of maturation by removing the topsoil before the reservoir is filled. A study of the effect of topsoil stripping on water quality in water supply reservoirs has been made by scientists at INRS-Eau in Quebec City (Campbell et al. 1975, 1976). A somewhat similar study on the effects of various Saskatchewan soils on water quality was carried out at the University of Saskatchewan (Davis et al. 1973).

There are other effects of impoundment on water quality, however, which are persistent, arising as they do from the structure and manner of operation of many reservoirs. In the temperate regions natural lakes of sufficient depth develop a sharp thermal stratification during the summer months with a warmer epilimnion separated from the cooler hypolimnion by a narrow thermocline. When the lake cools during the autumn and winter, the water is first mixed, then develops a different stratification with the lower water at the

[illegible] Shand Dam, an earthfill-gravity dam, and Belwood Reservoir, on the Grand [illegible] Guelph, Ont., showing the drawdown zone (photo by R. M. Baxter).

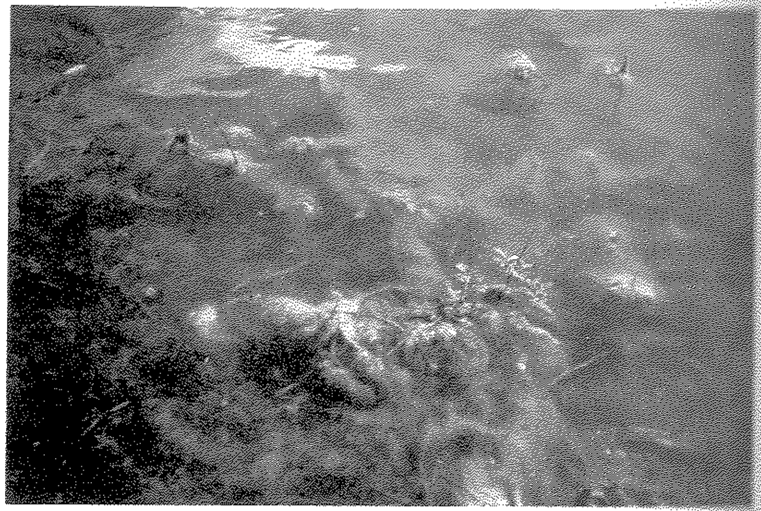

FIG. 8. Algal growth on submerged vegetation, Southern Indian Lake (courtesy of Freshwater Institute, photo by R. Hecky).

temperature of maximum density (4°C) and above it cooler water (down to 0°C). In the spring, the water is again mixed, and the summer type of stratification is reestablished. Because the discharge from a natural lake is always from its surface, water in a stream leaving a lake is relatively warm during the summer and near the freezing point during the winter.

A much more complex situation may prevail in reservoirs particularly if water is drawn from a penstock well below the surface. Complex systems of horizontal currents may thereby be set up such as are rarely, if ever, found in natural lakes. If the inflowing water is denser, by virtue of its temperature or load of dissolved or suspended material, than is the surface water of the reservoir, it may retain its identity for a considerable distance through the reservoir without mixing much with the water already there, or even pass directly through and out, while the water lying about it moves very little. If a thermocline develops it may be tilted (Kittrell 1959). If the upstream face of the dam is vertical, or nearly so, a mass of stagnant water may accumulate at the bottom of the reservoir against the dam face (Fiala 1966). Decomposition of organic matter already present on flooded ground, or entering the hypolimnion by the settling of planktonic organisms from the epilimnion, may lead to the depletion of dissolved oxygen near the bottom of the reservoir and an increase in the concentration of reduced substances such as sulphide, ferrous, and manganous ions. If the resulting poor quality water is then discharged through a low-level penstock, it may pass many kilometres down the river before becoming reoxygenated sufficiently to restore its quality. This is a matter of continuing concern in the reservoirs of the Tennessee Valley Authority (e.g. Kittrell 1959) and in other warm areas of the USA (e.g. Hannan et al. 1979).

This situation can sometimes be remedied in fairly small impoundments by mixing and thereby destratifying the water body. The energy required for this can be calculated since it is equivalent to the work that would be done in raising the centre of gravity of the stratified water body to the position it would occupy if the body were of uniform density (Ruttner 1963). In Canada, P. H. Bouthillier and his colleagues in the Department of Civil Engineering, University of Alberta, have been carrying out research in this subject (Bouthillier and Hrudey 1979).

There will probably be changes in water quality in the reservoirs of the James Bay project. Preliminary studies have been carried out on a small reservoir, and both nutrient enrichment and oxygen depletion have been observed (Soucy 1978b).

The withdrawal of hypolimnic water may also affect the thermal characteristics of the water below the dam, causing it to be cooler in summer and warmer in winter than water leaving the epilimnion of a natural lake in the normal way. This matter has received a great deal of attention in the USA (e.g. Park and Schmidt 1973; Wunderlich and Elder 1973; Troxler and Thackston 1975; Burt 1974). Much of this work should be applicable in some degree to Canadian conditions. In Canada, research relating specifically to the thermal behaviour of reservoirs under cold conditions is lacking (Roberts 1978). The James Bay hydroelectric project has provided an impetus to studies of this kind (Marcotte 1977; Soucy 1978a). The effect may be substantial: it is predicted that the LG 2 Dam on La Grande River will lower the maximum downstream temperature by 4°C and raise the minimum by about 1°C and delay the peak temperature by about a month.

Hypolimnetic cooling can be decreased or eliminated by artificial destratification (Burns 1977) or by the use of penstock intakes at more than one level so that warmer or cooler water may be drawn as the situation demands. It is technically feasible to install a high-level intake on an existing dam constructed with a low-level one (Fraser 1979). The interesting suggestion has also been made that it may be possible to use the temperature gradient between the hypolimnion and the epilimnion to generate additional power by the use of a suitable heat engine (Wilson et al. 1979).

Shallow, unstratified reservoirs, especially those which are fed by cool groundwater, and deeper reservoirs that discharge from the epilimnion, would tend to have a warming effect, if any, on the river below them.

Reservoirs constructed to provide cooling water for thermal electric generating plants present special problems. Because these are built where other water sources are not available, they are usually located in regions where the annual precipitation is low, streamflows are intermittent, and the concentration of total dissolved solids (TDS) in the water is fairly high. The TDS may be increased further by the leaching of salts from the flooded ground and by forced evaporation as a result of the heating of the water. There is a danger that downstream water quality may be seriously impaired. This possibility gave rise to concern in connection with a reservoir at Estevan, Sask. However, the effect of forced evaporation is apparently more than compensated for by the beneficial effect of retention of poor quality water in the reservoir and release of low TDS at the time of the spring runoff, so that the quality of the water below the reservoir is fairly constant and acceptable throughout the year (Allan 1978; Allan and Roberts 1978).

When impounded water is used for irrigation and the water returned to the river further downstream, its quality may be seriously impaired by salts and nutrients leached from the soil. This is one of the major Canadian concerns in relation to the Garrison diversion project in North Dakota (Bouchard 1977; Weber 1977).

The construction of a reservoir on a river is often only one manifestation of increased industrialization and urbanization within its basin. Consequently, it is often accompanied by increased loads of industrial and domestic waste in the river. The impact of these will be increased by the reservoir because the reduced current velocity will cause a reduced rate of oxygenation of the water and hence a decreased rate of oxidation of foreign organic matter. This seems to have happened in the Saint John River (Dominy 1973).

Hydroelectric plants may be additional sources of environmental contaminants. This seems to have happened at the Churchill Falls hydroelectric project in Labrador, where the concentrations of polychlorinated biphenyls (PCBs) in fish taken below the dam were many times higher than those in fish taken above it (Musial et al. 1979). PCBs were formerly used as insulating liquids in transformers and other electrical devices so it is likely that they had escaped from the generating station in some way, although their precise source is not yet known.

A literature review on water quality in impoundments, with particular reference to Canada, has been prepared by Park (1975). There is also a useful survey in Kelly's (1978) thesis. The development of simulation models for the prediction of water quality changes in reservoirs is proceeding in various parts of the world. Canadian scientists who have been active in this field include Dr P. E. Wisner, University of Ottawa, and Dr E. A. McBean, University of Waterloo (Hodgins et al. 1977; McBean and DeLucia 1979).

Erosion, Sedimentation, and Modification of the New Shoreline

The shoreline of a new body of water is exposed to erosive forces that modify it more or less rapidly until an equilibrium is approached. The most important of these forces are those exerted by moving water and ice; groundwater may also have some effect. The rate and extent of shoreline erosion depend on the nature of the material of which it is composed and the amount of energy available. Since most of this energy is derived from the wind, the direction, velocity, and duration of winds blowing over the reservoir and the length of the fetch are of great importance.

Bank erosion in reservoirs affects their usefulness in a number of ways. Since it leads to an increase in total surface area, it will indirectly cause an increase in the rate of evaporation. Its most important effect, however, is to change the storage capacity. How the storage capacity is changed will depend on where the eroded material comes from and where it goes. If material is eroded from above the maximum water level into the reservoir, the total storage capacity will obviously be decreased. Transport of material from between the maximum and minimum water levels into deeper water will not change the total storage capacity, but it will increase the usable storage capacity (e.g. the Lake Diefenbaker study by Coakley and Hamblin 1967).

Erosion also may lead to the formation of beaches, which may make the reservoir more useful for recreation purposes.

Engineers and hydrologists have devoted much effort to the development of formulas for the prediction of the extent of erosion in reservoirs, taking into account both the magnitude of the erosive forces and the nature of the bank material (e.g. Kondratjev 1966; Kachugin 1966). In Canada, these principles have been applied to Lake Diefenbaker by van Everdingen (undated). He concluded that erosion during the early life of the reservoir will cause a substantial decrease in the total storage capacity, but an increase of as much as 7.4% in its usable storage. Evaporation will also be increased and a 200-m wide, essentially barren fluctuation zone will be produced on both sides of the reservoir, with corresponding shallows extending up to 90 m from the lower waterline.

A matter that is of particular concern in Canada is the evolution of the shoreline of reservoirs on permafrost. The southern limit of continuous permafrost in western Canada is represented roughly by a line stretching from the Ontario–Manitoba border just south of Hudson Bay to the Arctic Circle at the Alaskan border. Continuous permafrost in eastern Canada occurs only in the tip of the Ungava peninsula. Discontinuous permafrost, however, may occur anywhere north of an arc running westward from the eastern tip of Labrador to the southern tip of James Bay, then northwestward to the 60th parallel about where British Columbia, the Yukon, and Alaska meet. Consequently, throughout a considerable part of the country there is a possibility that permafrost may be present. At least one project, the Churchill-Nelson development in Manitoba, already involves the flooding of large areas of permafrost, and probably more such projects will be undertaken in the future. (There is little or no permafrost in the area of the James Bay project.)

The events that ensue when permafrost is flooded have been studied by Newbury and his colleagues (Newbury and Malaher 1972; Newbury et al. 1978) at Southern Indian Lake in northern Manitoba. The level of this lake was raised about 2 m as a consequence of the Churchill River diversion, flooding about 600 km^2 of adjacent terrain, involving about 2900 km of shoreline. The site lies on the Canadian Shield, and part of the shoreline consists of bedrock, bare, or covered with an organic layer. A large part of it, however, consists of fine-grained varved clay, mostly covered with an organic layer. Permafrost occurs in much of this region.

When the water level was raised, erosion of the shoreline proceeded very rapidly. Typically, a notch appeared at the water's edge, above and below the waterline, as a result of the combined effects of mechanical erosion by waves and melting and liquefaction (solifluction) of the frozen clay. As the notch grew deeper, the undercut soil above it, along with the trees and other vegetation on it, slumped into the lake and the process was repeated (Fig. 9). In some areas, the shoreline receded as much as 12 m in a single season, releasing into the water about 20 m^3 of material per metre of shoreline. There is a striking contrast between these slumped shorelines and new shorelines on bedrock which were partly cleared before flooding and are almost indistinguishable from natural shorelines. Although the process of erosion will be slowed somewhat by the protective action of the barrier produced by the fallen trees, it appears that it will continue until the shoreline recedes to bedrock or becomes paved with gravel and boulders.

This is a new field of research as the very extensive studies on permafrost in Canada (e.g. Brown 1970) have not considered the problems associated with reservoirs. Further research in this field should be given every encouragement, if the construction of hydroelectric installations is to continue to move northward.

Much of the northern part of the USSR is in the zone of permafrost and a great deal of work on engineering projects, including reservoirs, has certainly been done in that country. However, Canadian conditions are significantly different from conditions in the USSR. Most of the Canadian arctic was glaciated during the Pleistocene. Under the ice sheet, there was a relatively thin layer of permafrost, much of which was dissipated under the extensive areas of flooding that occurred as the ice retreated and did not reform until this standing water receded. A large part of the Soviet arctic was not glaciated and a much thicker layer of permafrost was produced and has persisted. The permafrost zone extends further south in the eastern hemisphere than in the western, and the layer of unfrozen soil lying above it is thicker. The problems which Canadian engineers must face are therefore somewhat different from those confronting their Soviet counterparts.

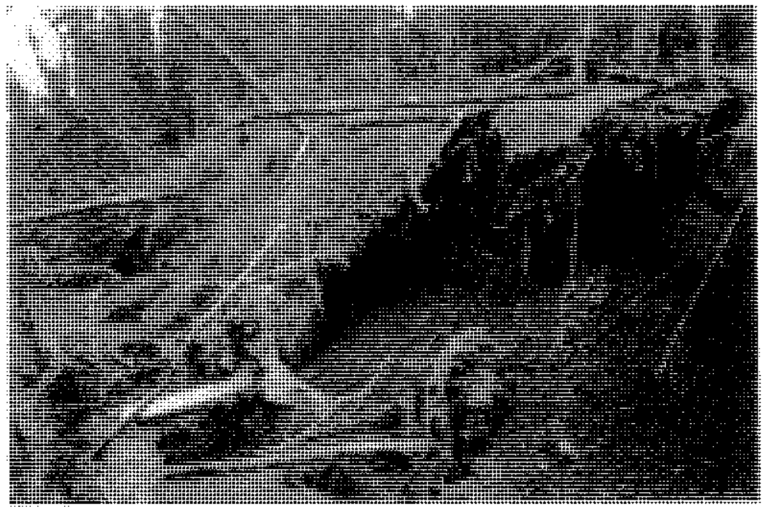

FIG. 9. Erosion and slumping of new shoreline on permafrost, Southern Indian Lake (courtesy of Freshwater Institute, photo by G. McCullough).

Sedimentation, like erosion, is of immediate concern to reservoir engineers because of its influence on the storage capacity and useful life of reservoirs. A review of this topic, with particular reference to Canada, was written in 1973 and is readily available and generally valid (Wiebe and Drennan 1973), so only a brief outline of some of the main points seems to be needed here. The amount of sediment carried by a stream depends on the amount of sediment entering it, which, in turn, depends on the size and nature of the watershed and the type of land-use within it, and on the capacity of the stream to carry it, which depends on the velocity and turbulence of its flow. When the rate of flow decreases, the sediment will be deposited according to its size, but in reservoirs (as opposed to natural lakes), the spatial distribution of the material will be greatly influenced by the practice of drawdown because sediment deposited when the water level is high will be eroded away again and deposited elsewhere when the water level is lowered. Until recently, there has been little information available in Canada on rates of loss of storage capacity of reservoirs as a result of sedimentation. In one instance, the reservoir formed by the Bassano Dam on the Bow River in Alberta, the storage capacity was reduced from 34 X 10^6 m^3 to 11 X 10^6 m^3 in about 60 yr (1911–1970). Techniques for collecting and processing data have been considerably improved in subsequent years (K. Wiebe personal communication), but the main conclusions of the 1970 review still stand, namely:

1. There is still no way of predicting the pattern of sedimentation in a reservoir before it is built, except in a very general way.
2. The best ways of minimizing sedimentation in a reservoir are by a judicious selection of the site and the control of erosion in the watershed. This involves, for example, selecting a site with the lowest possible stream gradient (Kerr 1973) and encouraging careful agricultural practices within the watershed. In some places the construction of roads within the watershed has increased the sediment load of streams very substantially (Anderson 1974).

Sedimentation in reservoirs has other consequences besides the loss of storage capacity. Sedimentation and delta formation in the upper part of a reservoir, known as aggradation in the backwater zone, raise the water level and may cause flooding if the banks are low (Kerr 1973). At the same time, the opposite process, known as degradation, may occur in the stream bed below the dam, as the stream picks up a new load of sediment to replace what was deposited in the reservoir. As the finer material is washed away the bed becomes paved with heavier nonmovable material so that bed erosion stops (Hammad 1972). Bank erosion may then occur, increasing the meander of the stream and sometimes leading to damage to the banks which may require extensive remedial measures (Kerr 1973).

Research on these topics in Canada includes study of aggradation and degradation associated with Lake Diefenbaker, carried out during the International Hydrological Decade (Anon. 1975) and a 5-yr study of changes in channel morphology below Deer Creek reservoir in southwestern Ontario (Buma and Day 1977).

Although it is usual for reservoirs to act as traps for sediments, discharging clearer water than they receive, this is not necessarily true for new impoundments on highly erodable material. Bank erosion following the raising of the water level in Southern Indian Lake has produced large quantities of sediment (Fig. 10), thus probably increasing the amount in the streams leaving it. The water has an opalescent appearance, due presumably to the presence in suspension of extremely fine material, which must settle out very slowly if at all.

The construction of a tidal barrage for power generation in the Bay of Fundy will be associated with a new set of problems. Some of these have been discussed by Amos (1977). Sediment is not only carried seaward by rivers, but landward by tidal currents, so sedimentation will be expected to occur on both sides of the dam. Observations on the Windsor Causeway, which is in effect a dam across the estuary of the Avon River, indicate that extensive and rapid siltation can occur on the seaward side of such structures, leading to the formation of extensive mudflats.

The material carried in suspension by running water is an extremely complex mixture of particles of various types of clay and other inorganic material as well as organic detritus derived from terrestrial and aquatic organisms. These components interact with each other in various ways (e.g. Hyne 1978; Jackson et al. 1978; Thomas 1969). A variable but significant fraction of the total amounts of nutrients in the water may be associated with suspended material and removed from the water when the sediment settles (Gill et al. 1976; McKee at al. 1970; Schreiber and Rausch 1979).

Other substances, such as pesticides (Pionke and Chesters 1973) and metal ions (Frenet-Robin and Ottman 1978; Pita and Hyne 1975) may be absorbed onto the particles and removed in the same way. Reservoirs therefore act as traps for a variety of important chemical substances. Some of these can probably be returned to the water as a result of changes in the pH, redox potential, or other characteristics of the sediment, but more information is needed before the effects of reservoirs on the nutrient dynamics and environmental toxicology of aquatic ecosystems is thoroughly understood.

The biological consequences of reservoir sedimentation are discussed below in the section on biological effects.

Fig. 10. Plumes of sediment from newly flooded ground, Southern Indian Lake (courtesy of Freshwater Institute, photo by G. McCullough).

Downstream Effects of Changes in the Flow Regime

The imposition of a new and in some respects unnatural pattern of variation in water levels can have effects below the dam that are at least as dramatic as those above it. The changes that may occur are of two kinds: an increase in the diurnal variation of flow, and a decrease in the annual variation. The former results from variations in the amount of water passing through the turbines in response to diurnal variations in the demand for power. This may lead to large and rapid changes in the water level downstream, which can be very destructive to aquatic organisms (Fisher and LaVoy 1972; Ward 1976a, b), induce changes in the morphology of the stream channel, impede access to downstream islands, and impair the usefulness of the stream for such activities as boating, angling, and swimming.

The longer term or annual changes are the result of the storage of water at times of high natural flows and its gradual release throughout the rest of the year. This may induce changes hundreds of kilometres below the dam. Degradation and aggradation at the mouth of tributaries are often observed. Abolition of high flows in the main stream when the tributaries are in spate increases the flow velocity in these near their mouths, with consequent degradation of their channels. At the same time materials deposited in the main stream by the tributaries can no longer be swept away, leading to the formation of bars and deltas, which eventually become stabilized by the growth of vegetation on them. Such changes have been observed in the downstream portion of the Peace River since the construction of the W.A.C. Bennett Dam (Kerr 1973; Kellerhalls and Gill 1973).

This dam had an even more dramatic impact on the Peace-Athabasca Delta. Because most environmentalists would probably agree that this was the most serious unplanned consequence of the construction of a dam that has occurred in Canada, and because it provides an almost classical example of its kind, it is worthwhile to outline what happened. More detailed accounts are readily available (Anon. 1972, 1973, 1974). A study published in 1962 when construction of the dam was just beginning foresaw changes in the delta, but the authors did not offer any predictions as to the nature of these (Anon. 1962). The delta is largely a great marsh or series of marshes interspersed with lakes and ponds of various sizes. Before the dam was built, it persisted in this state because it was flooded almost every year so that vegetation characteristic of drier grounds was unable to establish itself; it was a typical pulse-stabilized ecosystem.

The hydrological situation was complex. The Peace River, passing to the north of the delta, contributed little to the annual flooding, but the flood waters of the Peace served to block the exit of the Athabasca, entering from the south, the waters of which caused the actual flooding. Shortly after the dam was closed, it was observed that the delta was drying up and that dry-ground vegetation was beginning to establish itself. This was an immediate cause of concern because the residents of the area (mostly Cree, Chipewyan, and Métis) depended largely on trapping and fishing in the delta for their livelihoods.

There was some uncertainty at first as to the importance of the dam in bringing this about because of lower than average precipitation for some years previously. It was eventually concluded that the dam was at least a major contributing factor. After consideration of various possibilities, a weir was constructed which, it was hoped, would allow the original conditions to restore themselves. Although it is probably still too early to judge whether this has been entirely successful, the results so far appear encouraging.

This example is instructive because it includes many of the features often associated with environmental impacts of dams. The effect was far removed in space from the dam; it was not immediately obvious that the effect was caused by the dam and not by something else (in this case, a decrease in precipitation) which happened to occur at the same time; and the effect (the drying up of a marsh) was one that, in another situation, might well have been considered desirable.

Deltas appear to be particularly vulnerable to the effects of alterations in the flow patterns of rivers entering them. Regulation of the Mackenzie River would probably produce rather extensive changes in its delta (Gill 1971, 1972, 1973, 1975; Gill and Cooke 1974; Kellerhalls and Gill 1973).

Estuaries too may be influenced by the regulation of their rivers, and effects may be produced for some distance away in the ocean (Elliott 1976). Estuaries are ecotones between fresh and salt water, hydrologically complex because they are zones of interaction between freshwater carried seaward by rivers and salt water carried landward by tides (e.g. Fischer 1976). Because of this, they are rather sensitive to disturbance; for example, fairly extensive changes have been induced by a relatively small disturbance of a British Columbia estuary (Pomeroy and Stockner 1976). They are highly productive of many forms of life, including a number of organisms of great commercial importance.

An account of four important Canadian estuaries and a discussion of the problems involved in their management has recently been published (Fox and Nowlan 1978).

The influence of the St. Lawrence River on the oceanographic characteristics of its gulf, and even beyond, has recently been discussed (Sutcliffe 1972; Sutcliffe et al. 1976; Trites and Walton 1975) and the probable effects of its regulation have been pointed out (Hassan 1975; Neu 1975). There is evidence that some changes have already occurred (Sutcliffe 1973). Concern has been expressed regarding the changes that might occur in the Strait of Georgia if the Fraser River in B.C. were regulated (Geen 1975).

Much of the concern about these regions relates to possible effects on fish, which are discussed in the section on biological effects. However, one other possible consequence of regulating river flow may be discussed, namely, the possibility of downstream climatic changes. Gill (1971) has shown that the spring breakup of ice in the lower, more northerly parts of the Mackenzie River is hastened by the spring floods, which, by their hydrostatic pressure, crack the ice and allow water to flow up and over it. Less radiant energy is reflected by wet ice than by ice covered with snow, so the rate of heating and melting is increased. He has suggested that any reduction in the height of the spring floods might well cause a significant delay in the coming of spring along the lower Mackenzie and in its delta.

Even more dramatic consequences of the regulation of large northward-flowing rivers in high latitudes have been suggested. Aagaard and Coachman (1975) have discussed the possible results of regulating the flow of freshwater into the Eurasian basin of the Arctic Ocean. They suggest that this might alter the stratification pattern, leading to increased mixing, an upward transport of heat, and the disappearance of a significant amount of ice from this area. Since plans are being drawn up in the USSR for the regulation of the Ob, one of the largest rivers entering the Eurasian basin (Rich 1976), these speculations are of more than theoretical interest.

There is almost no previous experience to serve as a guide here, since until recently no one has regulated a large river flowing northward to the sea in high latitudes. The James Bay project involves the regulation of La Grande River and the diversion into it of most of the flow of the Eastmain River. Both of these rivers flow westward into James Bay. It also involves the diversion into La Grande of about a quarter of the flow of the Caniapiscau River which flows northward into the Koksoak River and hence into Ungava Bay. It will be interesting to see what effect, if any, this will have on the oceanography of the Ungava Bay region.

The Caniapiscau diversion will only increase the total amount of freshwater entering James Bay by 6.5% (S. J. Prinsenberg unpublished data). A more important effect of the project will be to change the seasonal pattern of inflow by greatly increasing the flow during the winter. This will undoubtedly change the pattern of surface currents (Peck 1977; Prinsenberg unpublished data; El-Sabh and Koutitonsky 1977), but the wider consequences for the oceanography of James Bay and Hudson Bay are not yet known. Also unknown are the possible oceanographic effects of the Churchill–Nelson diversion on the west side of Hudson Bay, and their possible interaction with the effects of the James Bay project.

When a reservoir is being filled, the stream below it may be almost completely shut off for a time. If it is near the sea, salt water may be carried by tidal action for some distance up the river to the detriment of the flora and fauna. Engineers in high latitudes enjoy an advantage over their colleagues in warmer regions because the extent of saltwater intrusion may be reduced by delaying the closing of the dam until the lower river has frozen, providing a partial barrier. This policy was followed on LG 2, the largest impoundment on La Grande River.

The diversion of water from one river to another has effects on both streams, depending on the relative decrease and increase in the respective flows, the nature of the terrain, and the prevailing climatic conditions. A valuable review of this topic based on a study of 11 Canadian interbasin diversions has recently been published by Kellerhalls et al. (1979). The effects on the depleted stream are similar to those induced by reducing the maximum flow. An important effect in high latitudes is the formation of channel icings if the flow is shallow enough, where deep accumulations of ice may spread over the floodplain. The possible effects along the diversion channel include greatly increased erosion with consequent increases in the sediment load, which may be deposited further downstream. The magnitude and character of these effects can be predicted only to a very limited extent.

A tidal power plan in the Bay of Fundy would have various oceanographic consequences which cannot be predicted in detail at the present time. The pattern of stratification and mixing in the affected area would be altered (Garrett et al. 1978). Moreover, the tidal regime in the Bay of Fundy and the Gulf of Maine (which appear to behave as a single system) is controlled not only by the approximately semidiurnal tidal period, but also by the natural oscillation period of the system. Hence a tidal barrage, by changing the length of the system, would change its natural period and hence the pattern of resonance between this and the tidal cycle, with changes in the tidal regime that might be perceptible as far away as Boston (Greenberg 1977).

This is another area in which there is little foreign experience to provide guidance. The only tidal power plant in operation at present is in France, at La Rance near St. Malo. Some studies have been made in relation to a proposed installation on the Severn Estuary in England (e.g. Robinson 1978).

Biological Effects of Dams and Impoundments

The biological effects are many and complex, both above and below the dam, and have given rise to much concern in Canada as elsewhere. Various aspects of the problem in Canada have been discussed previously by Brett (1957), by the contributors to a symposium on the effects on fisheries of human activities in general (Larkin et al. 1959; Miller and Paetz 1959; Pritchard 1959; Vladykov 1959), in a lecture by Larkin (1972), in two reviews by Geen (1974, 1975), and for four important species (lake whitefish, *Coregonus clupeaformis*; northern pike, *Esox lucius*; yellow walleye, *Stizostedion vitreum vitreum*; and lake trout, *Salvelinus namaycush*) in a series of bibliographies and literature reviews by Machniak (1975).

It has long been known that fish populations are often very large in new impoundments during their first few years (e.g. Ellis 1941). It has been claimed that the effect of the activities of the Tennessee Valley Authority (TVA) on fisheries in that region have been wholly positive (Wiebe 1960). The great impoundments of the USSR (Zhadin and Gerd 1963) and Africa (Ryder and Henderson 1975; Goodwin 1976) have provided important new fishery resources for their respective regions. In Canada, Lake Diefenbaker has provided opportunity for sportfishing in a region where such opportunities were scanty before the reservoir was constructed (Richards 1975).

In all regions mentioned above, however, the fish involved have been nonmigratory species. In eastern and western Canada, anadromous fish (i.e. those that are hatched in freshwater and spend their adult lives in the sea), especially various species of salmon (*Salmo* and *Oncorhynchus*), are an important resource and the effects of dams on stocks of these species is almost certain to be deleterious unless special precautions are taken.

In Canada there seems, until recently, to have been little interest in developing new commercial fisheries (as opposed to recreational fishing) in new impoundments, probably because the fishery resources of our many natural lakes have been adequate to meet the demand. The emphasis appears to have been on maintaining existing resources in waters that have been modified by damming and flooding. A recent plan to establish a commercial fishery in the Smallwood Reservoir in Labrador suggests that this emphasis may well shift in the future.

The rapid increase in fish populations often observed in new impoundments is probably the result of a number of causes. The increase in reproduction rate by the provision of secure spawning sites and the protection of young fish against predators by the vegetation in the flooded area is probably one. The increased provision of food is another. When a stream is impounded, the decreased flow rate allows a population of phytoplankton to develop, which is further enhanced by an increased supply of nutrients leached from the flooded soil and vegetation. This is followed (or accompanied) by an increased population of zooplankton, and so on up the food chain. The benthic population also increases, utilizing the resources of organic matter provided by flooded vegetation.

Considerable work has been done in Canada on the development of the algal and invertebrate populations of new impoundments. Laberge and Mann (1976) have studied the phytoplankton of Mactaquac Reservoir on the Saint John River. The University of Waterloo has been a center for such research with work by Hynes, Fernando, and their colleagues on benthos (e.g. Fernando and Galbraith 1973; Paterson and Fernando 1970; Spence and Hynes 1971a, b), and Duthie and his colleagues on plankton (e.g. Duthie and Kirton 1969; Duthie and Ostrofsky 1975; Ostrofsky and Duthie 1975; Duthie 1979). Valuable work has also been done in the Kananaskis Reservoir in Alberta by Nursall (1952, 1969).

Not all the species of fish originally present in an impounded stream will thrive; some may be eliminated altogether. The case of the snail darter (*Percina tanasi*), a small fish found only in a stretch of the Little Tennessee River, has become famous (e.g. Kinkead 1979). Because this species would almost certainly have been exterminated if its habitat had been flooded, the completion of the Tellico Dam just downstream from its habitat was delayed for several years. The freshwater fish fauna of Canada is much poorer than that of the United States, so it seems unlikely that a comparable situation will occur here, but the danger of the elimination of a valuable species from a particular area still exists.

Comparatively little research has been done in Canada on these matters, but from the general literature on the subject, reviewed by Machniak (1975) the following problems can be discerned.

Drawdown can be very destructive to populations of fish that spawn in shallow water if the operating regime is such as to lay these areas bare when the nests contain eggs or small fry. Some success has been achieved in other countries in reducing the damage done by providing floating spawning platforms (Zhadin and Gerd 1963) or by the construction of subimpoundments that remain filled with water when the reservoir is drawn down (Grimås 1965).

The opposite effect, the raising of the level of the water over habitual spawning grounds, may discourage reproduction in some species, although Cuerrier (1954) found in Lake Minnewanka, Alta., that lake trout continued to spawn in their accustomed places even after the water level had been raised.

Changes in the seasonal temperature pattern following impoundment may change the time of spawning to the detriment of some species. This possibility is being investigated in Southern Indian Lake by scientists from the Freshwater Institute, Winnipeg.

If much sediment is released into the impoundment, the effect will almost certainly be detrimental. At very high suspended sediment loads, adult fish are killed because their gills become clogged. At much lower concentrations, many invertebrates, including species important as food for fish, will die or attempt to move out of the affected area. Hynes (1973), in a useful review of this topic, has concluded that loads greater than about 80 mg/L are likely to be harmful. Rosenberg and Wiens (1978) found that addition of a few mg/L of suspended sediment to a stream in the Northwest Territories caused a significant increase in the drift of several species of macrobenthos.

Deposition of silt can cause great damage to sessile benthic invertebrates and to the eggs and young of certain species of fish, especially those, such as certain salmonids, that spawn in redds in gravel. Deposited silt is likely to interfere with the circulation of the water through the gravel, causing suffocation (Hynes 1973). This topic is also being investigated at Southern Indian Lake where, as was previously noted, the silt load is very high.

Another danger to which fish are subjected in reservoirs is deoxygenation of water. The unusual longitudinal profile of most reservoirs, with the deepest water lying just behind the dam, favors the accumulation of a layer of stagnant bottom water in this part. This may become deoxygenated, especially in new impoundments where flooded soil and vegetation exerts a considerable oxygen demand. If, for some reason, this water becomes mixed with the upper water, the effect on fish may be disastrous (Ellis 1941).

The population of fish parasites may be increased as a result of impoundment. This problem in Canada has been discussed by Lawler (1970) with special reference to lake whitefish, although the general principles involved should be applicable to other species. The factors involved are not clearly understood, but include changes in the relative abundance of various species of fish, changes in their feeding habits, and increase in the numbers of the species of zooplankton that are intermediate hosts of the parasites. If a project involved diversions of rivers between watersheds, there would be serious danger that parasites might be introduced into regions that have previously been free of them, as pointed out for British Columbia by Lindsey (1957) and for certain Yukon rivers by Arthur et al. (1976). This is one of the possible undesirable consequences of the Garrison diversion (Weber 1977).

Diversions may also introduce objectionable species of fish to waters where they were not found before, to the possible detriment of desirable species (Weber 1977; Loch et al. 1979).

In the Maritimes, small impoundments have been constructed on coastal streams for the specific purpose of providing habitats for Atlantic salmon (*Salmo salar*) and brook trout (*Salvelinus fontinalis*). Saunders (1960) and Smith and Saunders (1967, 1968) have described the effects of one such impoundment on Ellerslie Brook, P.E.I. The movement of the fish was modified to some degree, but no sustained increase in yield occurred.

Extensive changes in biota are frequently observed below dams. The physical changes responsible for these have already been discussed. They include increased short-term and decreased long-term fluctuations in the water level, increased transparency resulting from sedimentation in the reservoir, and changes in the temperature regime. If the reservoir is deep enough to stratify, and if it discharges from the hypolimnion, the downstream temperature will be lowered and the time of maximum temperature delayed. With shallow reservoirs or those discharging from the epilimnion, the temperature may be increased. There may also be an increase in the amount of organic detritus derived from plankton in the reservoir. It is not always easy to disentangle the effects of these various factors.

Ward (1976a) reviewed 13 studies (10 in the USA and 3 in Canada) on the effects of changes in the flow regime on benthos. The diversity of the benthos was commonly decreased, but the standing crop increased about as often as it decreased. The species composition often changed considerably. Increased constancy of flow usually increased the standing crop. An increase in the long-term constancy, by providing a stable substrate, can increase the standing crop even though the short-term constancy is moderately decreased. Extreme short-term fluctuations, however, are very destructive to many species (Fisher and LaVoy 1972; Trotzky and Gregory 1974).

Lehmkuhl (1972, 1979) found decreases both in diversity and biomass of insect larvae in the South Saskatchewan River below Lake Diefenbaker; this effect could be observed as far as 110 km downstream. He attributed it to the cooling effect of hypolimnion discharge. Spence and Hynes (1971a) found changes in the species composition of the benthos below a dam on the Grand River in southern Ontario. Some of these seemed to be due to temperature changes, but other factors played a part: an increase in particulate organic matter favored detritus feeders, and an increased growth of attached algae favored species that live and feed on these.

Certain species of insects appear to be particularly sensitive to alterations of the thermal regime because the various stages in their metamorphoses are triggered by temperature changes: if these do not occur, or occur at the wrong time, their life cycles will be disrupted (Ward 1976b; Gore 1977). This matter is of practical importance because many of the susceptible species are important as food for fish.

Fredeen (1977) has described some of the changes that have occurred in the South Saskatchewan River below Lake Diefenbaker. The increased clarity of the water has led to extensive increases in the growth of attached aquatic plants, especially filamentous algae. More surprisingly, the blackfly species *Simulium arcticum* has been almost completely replaced by two other species, *S. luggeri* and *S. vittatum*.

The diversity of fishes is often reduced below impoundments. Spence and Hynes (1971b) observed that four species that occurred above the dam were absent below it. These were all southern species so the effect seems to have been due to cooling. In warmer streams, such as some of the rivers regulated by the TVA, below-dam temperatures have been reduced sufficiently to allow salmonid populations to develop in place of the less desirable species that were there before (Wiebe 1960), but such benefits seem unlikely in the cooler streams of Canada.

A decrease in turbidity as a result of the deposition of suspended sediment in the reservoir may favor an increase in primary productivity and a consequent increase in food supplies for fish, but may also expose them to a greater risk of predation. The net effect of these changes is difficult to predict (Geen 1974).

Depletion of oxygen and the consequent increase in the concentrations of reduced chemical species such as manganous and sulphide ions can render the hypolimnic water very dangerous to downstream life (Hagan and Roberts 1972). The effect can be disastrous if the water is used to supply a fish hatchery (Oglesby et al. 1978). Excessive cooling of the water can also do great damage to young fish in hatcheries by making them more susceptible to infections (Hagan and Roberts 1972).

When water mixed with air passes through turbines, or when water plunges over a spillway carrying entrained air to a considerable depth, it may become supersaturated with gases, especially nitrogen. If these come out of solution within the bodies of fish, the resulting bubbles may cause more or less serious injury, or death, depending on their location (gas bubble disease) (Fig. 11). H. H. Harvey of the University of Toronto is a recognized expert on gas bubble disease and recently published a review (Harvey 1975). In the United States, gas bubble disease has been observed in salmon in the Columbia River on a scale sufficient to cause considerable concern, and at least three reviews have been published recently (Boyer 1973; Rucker 1972; Stroud et al. 1975). Supersaturation in turbines can probably be decreased or eliminated by modifying the air valve system (Ruggles and Watt 1975), and supersaturation below spillways by judicious spillway design (Smith 1974; Smith 1976). Government policy in Canada has not permitted the construction of dams on important salmon streams on the west coast (Harvey 1976) so the problem appears not to have been serious there. It has occurred in Atlantic salmon on the Saint John River (MacDonald and Hyatt 1973).

If increasing energy needs make it necessary to change the existing policy and permit the use of salmon rivers for hydroelectric development, serious problems will arise. Some of these have been mentioned above. However, anadromous

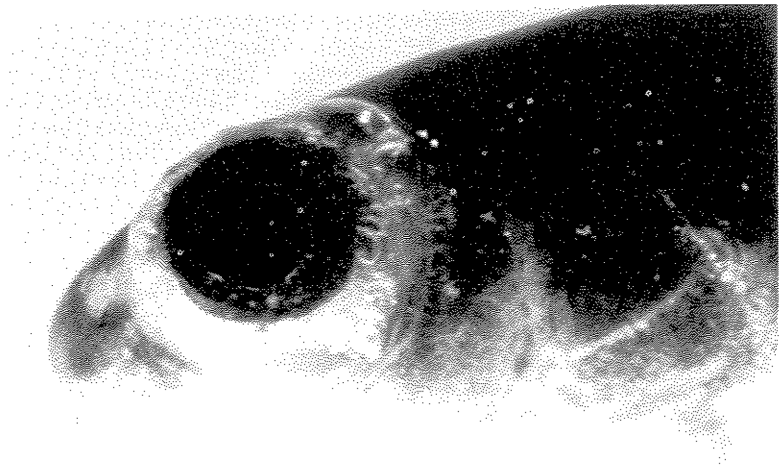

FIG. 11. Exophthalmia in rainbow trout (*Salmo gairdneri*) caused by gas bubble disease (photo courtesy of H. H. Harvey).

fish have their own particular problems. They return from the sea to the streams in which they are hatched. They find their way back by following subtle olfactory and tactile clues. Some species, including all species of Pacific salmon, do not feed once the migration to the spawning ground has begun.

These give rise to the following practical considerations. If a stream is blocked, even temporarily (if the blockage lasts for a period equal to or longer than the period of sojourn of the fish in the sea), the fish stock of the stream may be effectively wiped out. If a stream is partially blocked, the clues leading to the spawning ground may be obscured so that the fish are delayed and may perish before reaching their destination. If a reservoir is built on their route, they may seek the cooler, deeper water and be unable to find their way out again. Engineers have devoted a great deal of effort to the design of structures to permit fish to pass dams and other obstacles. A book is available dealing with this with particular reference to Canadian conditions (Clay 1961). However, there appears to be disagreement among fisheries experts as to the compatibility of dams and andromous fish. It has been said that "[the] problems . . . all can be solved if enough effort is made" (Collins 1976) but also that "likely the salmon populations upstream of a Moran-type dam [on the Fraser River] could not be saved" (Geen 1974). In some instances in Canada the provision of an unsupervised fish-ladder has only made poaching easier (Scott and Crossman 1973, p. 281–282; The Spectator 1977).

On the Saint John River, the practice of capturing fish below dams and taking them upstream for release has met with some success. However, if a large number of fish arrive during a short period of time, the practical and economic problems may be severe. Young salmon going down to the sea are likely to suffer considerable mortality if they pass through turbines. In Nova Scotia, louver deflectors have been fairly effective in guiding them away from the turbines (Ducharme 1972). On the Saint John River a hatchery has been established below the Mactaquac Dam to provide smolts to replace those killed in the turbines and lost in other ways (Ruggles and Watt 1975).

Dams also obstruct the movement of catadromous fish (those that are hatched in the sea and spend their adult lives in freshwater). The only commercially important catadromous fish is the American eel (*Anguilla rostrata*). When the Moses-Saunders hydroelectric dam was constructed on the Saint Lawrence Seaway in 1958, it was expected that it would prevent young eels (elvers) from entering Lake Ontario, thereby eventually destroying the eel fishery there (Eales 1968). Although the passage is harmful both to the eels (Lefolii 1970) and the turbines (Eales 1968), apparently the installation is not a serious obstacle for the elvers. By 1971 there was still no evidence of the anticipated decline in eel catches (Ontario Ministry of Natural Resources 1972), and catches were still high in 1974 (Ontario Ministry of Treasury, Economics, and Government Affairs 1975). However, the young eels were a nuisance because they gathered in great numbers just below the turbine outlets. When the turbines were shut down for repairs they would immediately swim into the turbine housings, clogging the intakes of the pumps that are used to remove the water from the housings. A temporary eel ladder was therefore installed in 1974 and since then half a million to a million eels have passed up it every year (Whitfield and Kolenosky 1978). A permanent structure will be installed shortly (Anon. 1978).

The physical changes brought about in estuaries and adjoining parts of the ocean by regulation of the rivers entering them have already been alluded to. There are grave difficulties here. The extent of the physical effects is itself not easy to predict, and the impact that any change may have on fish stocks is even more difficult to foresee. The ecosystems of estuaries, like those of streams, ultimately derive most of their energy from organic detritus produced elsewhere. It has recently been found that young chum salmon (*Oncorhynchus keta*) in estuaries feed largely on detritivorous crustaceans (Healey 1979; Naiman and Sibert 1979; Sibert 1979; Sibert et al. 1977). Therefore, any diminution of the amount of organic detritus reaching the estuary might have serious results.

The LG 2 Dam of the James Bay project will certainly affect the fauna of the estuary of La Grande River (Dadswell 1974) but the effect will probably not be severe (Hunter et al. 1977; Grainger and McSween 1976; Grainger 1977). The partial diversion of the Caniapiscau River into La Grande River is not expected to affect the salmon fishery in the Koksoak River, into which it runs (Soucy 1978c).

On the other hand, there is reason to believe that regulation of the Fraser River would have adverse effects on young salmon in the Strait of Georgia (Geen 1974, 1975), and there is evidence to suggest that the regulation of the St. Lawrence River and other rivers entering the Gulf of St. Lawrence may already have reduced the catches of some species in the gulf (Sutcliffe 1973). A tidal barrage in the Bay of Fundy would certainly cause changes in the invertebrate population of the affected area, which might, in turn, have deleterious effects on the fish and birds which feed on these organisms (Risk et al. 1977).

Seismic Activity Induced by Impoundments

During the past decade or so, there have been a number of instances throughout the world of earthquakes occurring during or after the filling of large impoundments, and it is now generally agreed that in most, if not all, of these instances the shocks have been a result of the impoundment (Gupta and Rastogi 1976). For discussions on the possible mechanisms involved, see Gough and Gough (1970), Kisslinger (1976), Simpson (1976), and Bell and Nur (1978).

The most important single factor in determining whether an impoundment will induce seismic activity appears to be the depth of the water; if this exceeds about 100 m, there is an appreciable risk that quakes may occur (Rothé 1973). This phenomenon is not confined to regions of recent spontaneous seismic activity, although in most instances, there has been a history of such activity at some time in the past. Induced quakes have not been large (maximum magnitude about 6 on the Richter scale) and have not usually caused serious damage. However, a quake near the Koyna Dam in India in December 1967 caused considerable destruction and loss of life. Geophysicists disagree as to whether this quake was indeed induced by the impoundment. Induced seismicity may also have been involved in the most appalling dam disaster of modern times, which occurred in October 1963, when a huge landslide fell into the reservoir behind the Vaiont Dam in Italy. This caused an enormous wave which overtopped the dam and killed more than 2000 people in the valley below. It has been reported that the filling of a large reservoir in Soviet Tadzhikstan had to be halted because of increased seismic activity (Rich 1977).

There is one well established instance of induced seismicity following an impoundment in Canada. This was a shock of magnitude 4.3 that occurred in October 1975 during the filling of the Manicouagan 3 Reservoir in Quebec (Milne and Berry 1976; Buchbinder 1977). No induced seismicity was observed in connection with any of the other dams of the very large Manicouagan complex.

A number of scientists in Canada have had experience in this field. Besides the geophysicists in the Department of Energy, Mines and Resources who investigated the Manicouagan earthquake, Dr D. I. Gough of the University of Alberta is an internationally recognized authority on induced seismicity.

Climatic Effects of Impoundments

Flooding a large tract of land or damming a stream in order to amass a considerable volume of water may have a significant effect on climatological characteristics near the body of water and at various distances above and downwind of the project. The magnitude and importance of these effects depend primarily upon the morphology of the water body, its geographical setting, and the type of conversion of land use. The physical and biological consequences, both beneficial and harmful, which result from the climatic change, may be difficult to assess and will certainly be different for different environments.

Few man-made lakes or reservoirs have been in existence long enough for the collection of enough meteorological data to determine whether the creation of a reservoir can result in a significant change in climate. When the subtle changes in local climate caused by the construction of a reservoir are superimposed upon the natural variability of the atmospheric circulation, it becomes difficult to make definite statements that link these changes to the alteration of the earth's surface. It is possible that no definite and permanent change will take place. Vendrov and Malik (1965) estimate that the smallest quantitative criterion for the extent of the influence of a reservoir is about 0.3°C, which is in the order of magnitude of random climatic fluctuations.

Much of the influence is of less practical importance for the reservoir itself than it is for the surrounding ecosystem. Small changes in meteorological variables such as temperature, precipitation, and wind may have a serious impact on human activities such as agriculture, transportation, construction, and urbanization. Attention should be directed to the possible environmental consequences of the changes in climate, and to suggest how wise planning of reservoir design could minimize the undesirable effects and maximize the advantages offered by more favorable effects. For example, reservoir evaporation may be minimized by selecting the reservoir site so as to reduce exposed surface area, and by positioning of discharge outlets in order to withdraw warm surface water rather than cooler, deep water. Similarly, the collocation of residential, business, industrial, and recreational facilities is best done with a knowledge of the manner in which air and water interact to influence the potential for air pollution.

Another difficulty arises out of the need to be able to separate the magnitude and the importance of each effect. For example, flooding a forest stand in southern Canada may produce a moderation in local temperature of 3°C, which may be less destructive to the environment than the same construction in northern latitudes, where the temperature change may be only 1°C, but the local ecosystems may be more vulnerable.

The extent of the zone of climatic influence depends upon the type of land-use substitution and the character of the reservoir and shoreline landscape. However, a simple rule of thumb is that the influence will extend across the surrounding terrain for a distance equal to the distance the wind has travelled over water.

Until the James Bay hydroelectric development project, little interest was shown in Canada in the climatic effects of water impoundments. Opportunities for the establishment of observing networks before and after construction have been missed at many large projects. Efforts in Canada have concentrated on measuring lake effects, but the task of translating them into possible environmental impacts has been largely neglected. For more than a decade, research has been conducted by the Lakes and Marine Applications Section of the Atmospheric Environment Service into the effects of the Laurentian Great Lakes on weather, and conversely, on the influence of weather elements on the lakes themselves (Richards 1969). One must be cautious in transposing to other areas what we know about the Great Lakes. To a large degree, the same physical factors are at work, but the magnitude of the effects is much smaller. The largest area to be flooded in the James Bay project will be only 20% of that of Lake Ontario, the smallest of the Great Lakes.

There exists a considerable literature on the temperature effects that result from the construction of small lakes and reservoirs in temperate regions, no doubt because modification of air temperature is easily detected. (For a Canadian study, see Holmes 1972.) For small bodies of water, extremes of air temperature are generally suppressed, mean temperatures are slightly cooler than those inland in spring, and slightly warmer in fall. Reservoirs also influence diurnal temperature range. On the average, reservoirs raise nighttime temperatures and lower daytime values from May to July and warm the surrounding air from September to November, regardless of the hour. One positive effect of water impoundment is that nighttime temperatures are generally higher near the water, so that local frost-free seasons are extended by 5-15 days at the shoreline, depending on the heat storage capacity of the reservoir.

Studies on the Great Lakes show that large lakes may inhibit the growth of convective clouds and reduce the occurrence of showery precipitation during spring and early summer (Phillips and McCulloch 1972). The opposite appears to be true in fall and early winter. Few studies of the cloud and precipitation regimes over small lakes and reservoirs have been made. Natrus (1964) concluded that summer precipitation at Lake Omega on the Volga River is 5–7% lower over the lake than at shore stations. For the Rybinsk Reservoir, D'yakonov and Reteyum (1965) discovered that in July, in some areas, the reservoir is responsible for increases in precipitation of up to 90 mm, but there is a decrease of 10 mm over the reservoir itself. In addition, there is a small diurnal difference in these numbers. Furthermore, the intensity of precipitation is about two thirds of the intensity measured at inland stations. In Canada, for a small reservoir in the Fraser Valley, R. W. Verge (unpublished data) found that in July rainfall may be reduced by as much as 20% downwind from the reservoir. For the same limited area, winter precipitation was estimated to be about 10% higher.

With the creation of a reservoir wind roses usually would be elongated in the direction of the longest fetch. Probably the number of days with strong winds would increase, the frequency of light winds would decrease, and differences in wind speed over lake and land would be greatest at night and least during the day (Phillips and Irbe 1977).

Considering the size of some of the reservoirs, local winds in the form of land breezes and lake breezes are sure to develop. Their intensity will depend directly on the magnitude of the air–water temperature contrast and inversely on the general circulation. For the most part, the local circulation of onshore lake breezes during the day and offshore land breezes at night will prevail during the warming season (Phillips 1980).

Soviet studies indicate that humidities are slightly higher in the area immediately surrounding the lake, compared with downwind land stations (Vendrov 1965). However, Buckler (1973) found, for Lake Diefenbaker, that the configuration of the lake was such that the effect of the lake on specific humidity was too small to determine. Schaefer (1976) made a similar observation for Williston Lake. For the Great Lakes, Phillips and Irbe (1978) found that differences in dew point temperature between lake and land were negative throughout the year, except during May and June when dew points over the lake were 1 or 2°C less than those over land.

Perhaps one of the most complex subjects involved in the assessment of the climatic effects of new water impoundments is the difference in the evaporation regime of an open-water body and that of a vegetative cover, such as a lichen surface, or a coniferous forest. The problem is complicated because several meteorological variables are involved. Some of these are soil moisture, humidity, atmospheric pressure, radiation, and wind. Vowinckel and Orvig (1974), in assessing the implications of the James Bay development project, concluded that evaporation would be reduced after the creation of a reservoir. They cite three reasons: a prolonged ice cover in spring would reduce the absorption of solar radiation; water would have a smaller evaporativity rate than thick vegetation; and during the fall when turbulent fluxes are at a maximum over the lake, a larger portion of energy would be expended as sensible heat flux so that the annual lake evaporation would be reduced.

There is ample evidence to suggest that occurrences of fog increase after the construction of man-made lakes or reservoirs. Fog may result from the passage of cold air over warm water or from the advection of warm, moist air across a cold lake. Besides the reservoir itself, ancillary developments such as cooling towers or ponds may become sources of steam fog under certain meteorological conditions.

Shortly after breakup, the water receives condensed water from overriding moist, warm air. This contact may create persistent fog banks, especially where the water is coolest. The fog could be subsequently advected over the surrounding terrain.

Before freezeup, cold air coming into contact with the warm water of the reservoir may cause deposition of ice on nearby surface features. Under such conditions, accompanied by moderate or strong winds, icing by spray may be a hazard for a few hundred metres downwind of the open water. Under similar conditions, and temperatures near freezing, heavy wet snow can be expected to accrete on exposed objects such as vegetation and transmission wires. Accumulations of as much as 125 mm can be expected (Chainé et al. 1975). Temperatures below -30°C and light winds provide ideal conditions for ice fog to form near sources of moisture, such as compressor sites or idling traffic. On occasions with low-level fog, severe rime icing may accumulate on structures. Buckler (1973) reported an incident on Lake Diefenbaker in which steam fog produced "walls" of cloud which moved onshore and deposited 50–75 mm of ice crystals on trees and other objects within 3 km of the lakeshore.

Results of reservoir-impact climatologies are generally not applicable from project to project. Each construction requires site-specific analyses, since the effects will depend upon the morphology of the lake and the regional climatology. Nemec

(1973) calls for the systematic collection of hydrometeorological data as the first and most important task for further understanding of the interaction between man-made lakes and the atmosphere.

Other Effects of Impoundments

The construction of dams, or of roads, airports, or anything else, has incidental effects that require no ecological insight to recognize. In populated areas, noise, dust, and increased traffic will cause some inconvenience and annoyance to the residents. In more remote areas, wildlife will be disturbed and tempting opportunities for poaching may be provided. Removal of vegetation and topsoil for road construction, and excavation of construction materials from quarries and borrow pits are likely to leave unsightly scars on the landscape and cause increased erosion and an increase in the sediment load in the streams of the watershed affected. When a large amount of construction activity is concentrated in a relatively small area, as in the Wreck Cove hydroelectric project in Nova Scotia (Kelly 1978), these impacts can be severe. Rockfill and earthfill dams in particular require large volumes of material; for example the LG 2 Dam of the James Bay project required about 150×10^6 m^3 of fill. Disposal of waste materials of all kinds can be a problem, especially in remote areas. Unless rigorous rules are imposed and strictly enforced, the area is likely to become littered with debris such as discarded fuel drums, used tires, and garbage of all kinds. The uncontrolled disposal of liquid wastes, such as wastewater and used engine oil, can cause even more serious problems.

Considerable damage of this kind was done during the early stages of the James Bay project (Gauquelin 1978). Subsequently, the corporation adopted a policy of preparing directives for the protection of the environment which the various contractors were required to respect, and assuring compliance with these through the establishment of a surveillance team which supervised all construction activities and provided advice where needed (Dufort 1978).

At the same time the corporation undertook a research project to determine the best ways to restore areas affected by construction activities by replanting them either with local plants or with exotic species capable of thriving in the region (Brouillette and Marceau 1978).

Dams sometimes fail, often leading to the loss of human lives and almost always with more or less disastrous consequences for the environment. The sudden release of water and sediment may cause significant changes in the downstream channel (Chen and Simons 1979). When the Teton Dam in Idaho broke in 1976, this not only caused great destruction below the dam, but also dispersed many thousands of pounds of pesticides and other chemicals over the flooded area and in the river below the dam. Concentrations of some of these compounds in fish subsequently approached the maximum permissible levels for food fish (Perry 1979). The failure rate has been estimated (Mark and Stuart-Alexander 1977) at 1×10^{-4} to 5×10^{-4} per dam-year. In assessing the possible environmental effects of dams, the possibility of failure should be kept in mind.

In cold climates, dams can alter the ice regimes of rivers. The reduced current velocity above the dam generally favors earlier freezeup and later breakup than in unregulated rivers. Below the dam, on the other hand, the discharge of relatively warm hypolimnic water tends to keep the river free of ice for some distance. This topic has received considerable attention in the USSR (Rossinsky and Lubomirova 1975) but little appears to have been published on it in Canada, although Kerr (1973) has pointed out that ice jams can seriously disrupt the operation of hydroelectric stations. Water intakes on the Great Lakes have, on occasion, been almost completely blocked by ice (Foulds 1974). The general problem of preventing and clearing ice jams has received much study from engineers, and the general technology is probably applicable around dams as elsewhere.

Effects of Impoundments on Man

Dams are built because it is expected that they will be beneficial to society as a whole. They may also be detrimental in ways described above. In the southern agricultural and industrial parts of Canada it is possible, in principle, to weigh the benefits against the deleterious effects and arrive at a rational decision as to whether or not to proceed with any proposed undertaking. The practical difficulties of achieving this may be severe. For example, it has not yet been possible to devise an overall plan for the management of the Fraser River that would provide adequate flood control without causing unacceptable damage to salmon runs (Sewell 1977). When the anticipated loss is not a purely economic one such as the flooding of land, but a less tangible one such as the destruction of a site of natural beauty, the problem becomes more difficult, but techniques of cost-benefit analysis may give some guidance (e.g. Bohm and Henry 1979).

In the northerly parts of Canada, the situation is very different. Here the inhabitants, mostly Indians and Inuit, still for the most part live in their traditional way, supporting themselves by hunting, fishing, and trapping. These fragile societies are in danger of severe disruption if their traditional hunting and trapping grounds are flooded, if the fish populations in their streams are destroyed, or if their communities are invaded by large numbers of outsiders whose cultural values differ from those of the residents. Ecological research in these regions may serve to define the problems, but it can offer few solutions.

The largest northern development to date, the James Bay project, has dealt in length with these problems, particularly through the native land claims settlement process. Early in the project development stage, the matter of outstanding native land claims arising out of aboriginal rights presented legal problems, which were resolved through the negotiation of a detailed agreement by the federal government, the government of Quebec, representatives of the Crees and the Inuit, and the three Crown corporations involved (James Bay and Northern Quebec Agreement 1976). In addition to monetary compensation, this comprehensive agreement establishes the configuration of the hydro project, provides measures to mitigate effects on traditional hunting, fishing and trapping, and includes measures for the protection of the social and cultural values of the native people. The social evolution of these communities will be followed with great interest by all those concerned about the impact of development on Canadian northern peoples.

The problems discussed in this section have been treated at much greater length in an unpublished paper prepared for Environment Canada, Lands Directorate, by P. Boothroyd.

Concluding Remarks

What was probably the first general review on the environmental aspects of impoundments was published almost 40 yr ago (Ellis 1941). The topic received little further attention for a number of years, except perhaps in the USSR, but from the mid-sixties onward it has attracted increasing interest and has been the subject of numerous reviews and symposia (e.g. Ackerman et al. 1973; American Fisheries Society 1967; Baxter 1977; Geen 1974; Larkin 1972; Lowe-McConnell 1966; Obeng 1969, 1977; Efford 1975a). A consideration of environmental consequences of impoundments must not be limited to the immediate vicinity of the reservoir, but should take into account possible events a long distance, perhaps hundreds of kilometres, downstream. Such a consideration must also take into account a wide variety of scientific disciplines, from the biology of phytoplankton to the biogeography of deltas and estuaries, from the physical chemistry of gases in solution to meteorology and geophysics.

Probably the general nature of the impacts of dams is now reasonably well understood, but we are still a long way from being able to predict, specifically and quantitatively, the impact of any given project.

Most of the suitable sites for hydroelectric projects in southern Canada are already being used or are in the course of development. When, if ever, more remote sites will be developed will depend to a large extent on a complex interplay of economic forces relating to the total energy need and the relative costs of the various options. There are many grave environmental problems that will have to be considered in addition to the purely economic ones. The construction of reservoirs for other purposes (flood control, water supply, heat dissipation from the thermoelectric installations) will continue with their associated environmental problems.

It would be unwise to rely too heavily on foreign experience in seeking solutions to the problems that will arise in Canada. Canadian engineers and environmentalists who are concerned with reservoirs are probably most familiar with work in the United States, among foreign countries. Much American experience is doubtless applicable here, but lower temperatures in Canada should dictate caution. Many important problems in Canada do not occur in the United States (except perhaps in Alaska), such as problems of shoreline evolution on permafrost and the effects of regulating large northward flowing rivers. Experience in Scandinavia and the USSR may be of some assistance here, but again, it will be necessary to exercise caution.

Fortunately there appears to exist in the Canadian scientific community the knowledge and experience necessary to treat authoritatively virtually all the problems discussed in this review. Some problems, such as those related to sedimentation and erosion, and to fisheries, have been considered by scientists in government laboratories. Others have been considered by university scientists pursuing their own particular interests. In at least one instance, that of the problem of the Peace-Athabasca Delta, an ad hoc group assembled to deal with the problem has gained experience that should be of considerable value in dealing with future problems. Current research at Southern Indian Lake should contribute greatly to our understanding of what happens when permafrost is flooded and how this influences the biological communities of the affected area. Above all, studies carried out in the James Bay project area by Environment Canada, the James Bay Development Corporation, and particularly, the Environmental Service of the James Bay Energy Corporation can be expected to be of the greatest value to anyone undertaking similar projects in the north, both for initial baseline surveys (Anonymous 1977; Société d'énergie de la Baie James 1978b) and mitigation techniques (Soucy 1978a).

A combination of ecological understanding and sympathetic consideration of the feelings and aspirations of the people likely to be affected should go a long way towards the prevention of undesirable environmental and social consequences of the further development of Canada's water resources.

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