CANADA CENTRE FOR INLAND WATERS

Environment Canada

ENVIRONMENTAL EFFECTS OF RESERVOIRS

R. M. Baxter

Canada Centre for Inland Waters

April 1974

Unpublished Manuscript

ENVIRONMENTAL EFFECTS OF RESERVOIRS

R. M. Baxter

Canada Centre for Inland Waters

April 1974

ENVIRONMENTAL EFFECTS OF RESERVOIRS

This review is in two parts. Part I "Reservoirs in general" is a brief summary of what is known of the limnology of reservoirs and of their broader ecological effects. It will be apparent that the subject is a complex one, involving many branches of fundamental and applied science. I have attempted to prepare a summary which will be comprehensible to the non-specialist, and consequently the expert may find my treatment of his particular specialty somewhat superficial and naive.

To make this part easier to read, I have not supported my statements with specific references. I have however provided a list of sources which should be of some help to anyone wishing to pursue any particular topic in more detail. I should like to call particular attention to the report of the symposium on man-made lakes sponsored by the American Geophysical Union. Anyone seeking more detailed knowledge of the properties of reservoirs should turn to this volume first.

Part I is meant to provide a general background for Part II, "Reservoir research in Canada". Without this background, the significance of the investigations that have been undertaken in Canada might not be very apparent. I hope I have referred to every major effort in this field in Canada in recent years or in progress at the present time. I have not attempted to list all existing publications.

I have been greatly helped by a number of scientists who have provided me with information about their own work or called my attention to other work of which I was not aware.

I. RESERVOIRS IN GENERAL

Until fairly recently, studies of the limnology and general ecology of reservoirs have been largely limited to matters of rather direct and immediate practical concern. If a reservoir erodes its banks rapidly, or if its volume is rapidly reduced by silting, its usefulness is obviously impaired. If the water in a reservoir is intended for irrigation, or for domestic or industrial use, the influence of impoundment on its quality becomes important. Such considerations have lead to a substantial amount of research in the physical and chemical limnology of reservoirs. The reservoirs of the Tennessee Valley Authority, and Mead Lake on the Colorado river behind Hoover Dam (formerly Boulder Dam) have stimulated numerous studies in the United States. Similar studies have been made in other countries, most notably perhaps in the Soviet Union, Czechoslovakia, and Poland.

If a reservoir is intended to support a commercial fishery, its biology is of obvious concern. This appears to be true in the Soviet Union, where an astonishing amount of research in this field has been done. In North America on the other hand this matter has received relatively little attention. Some work has been done in Sweden.

More recently the construction of very large reservoirs, and a growing general concern about the consequences of human modification of the environment, have aroused interest in the less direct and obvious consequences of the impoundment of water.

Reservoirs may be constructed in a variety of ways for a variety of purposes. From the environmental point of view the most important distinction (apart from the matter of size) is between those that are created by damming the outflow of a lake (lake reservoirs) and those produced by damming a river (river reservoirs). Other things being equal, the creation of a river reservoir is a more drastic alteration of the environment than the creation of a lake reservoir.

A distinction has been made between river reservoirs in which the water is largely confined to the river valley (channel type) and those in which the water spreads over a wide area of previously dry or marshy land (lobed type).

Reservoirs differ from natural lakes in several important respects.

In natural lakes the maximum depth may occur anywhere in the basin, whereas river reservoirs are almost always highly asymmetrical in longitudinal section, the deepest point being just behind the dam.

The retention time is usually shorter in reservoirs than in natural lakes.

In a lobed reservoir which receives water from more than one source, the chemical composition may be different in different places, depending on the chemical composition of the inflowing water.

The water levels in reservoirs are subjected to large and rapid periodic decreases (drawdown).

Natural lakes practically always discharge from the surface, whereas reservoirs commonly discharge from below the surface.

Physical and Chemical Limnology of Reservoirs

Reservoirs can develop stratification like natural lakes. This can be brought about by the formation of a thermocline as a result of solar heating and mixing of the upper water by the action of the wind in the usual way.

However since the rate of inflow into reservoirs is often much higher in relation to the total volume than in natural lakes, stratification can be produced in another way which is not usually of great importance in natural lakes. Inflowing water, according to its density, will flow over or under the water already present, or take up some intermediate position. Such strata of water will then flow down the reservoir with little mixing until they reach the dam. Such a flow is known as a density current.

The density of the inflowing water depends largely, but not exclusively, on its temperature. If it contains a large amount of suspended or dissolved material it may be dense enough to flow under water at a lower temperature.

Density currents have various effects. They may carry silt all the way to the dam, allowing it to settle over the entire bottom of the reservoir. Also if the reservoir discharges from some depth, the outflowing water may be turbid even though the lake appears to be clear.

If the inflow water is denser than the surface water of the reservoir it will sink beneath the surface, carrying a certain amount of surface water with it. This causes a balancing current of surface water to be set up, running in the upstream direction. If the inflow water is more turbid than the surface water, the position where the balancing current meets the sinking inflow may be visible as a convergence line. Even if the inflowing water is clear, the position of the convergence may be revealed by the presence of debris carried upstream by the balancing current and immobilized where the two flows meet.

If the reservoir discharges from below the surface and the density of the inflowing water is such as to cause it to form a density current at the level of the outflow, it will flow directly through the reservoir with scarcely any mixing with the water above it. In such a situation the upper part of the reservoir water is essentially a lake floating on a river, held in position by the dam.

The heat budget of a reservoir is often very different from that of a natural lake. During the warm part of the year, the amount of heat removed from a natural lake by its surface outflow is greater than the amount brought in by its inflow. In a reservoir discharging from the hypolimnion the reverse is true. A reservoir can therefore serve as an effective heat trap. One consequence of this is that the stream below the dam becomes cooler than it was before the dam was constructed. If on the other hand the reservoir discharges from the surface, the downstream water becomes warmer than before because the water has more opportunity to be heated by solar radiation in a broad slowly-moving reservoir than in a narrow fast-flowing river.

The gross chemical composition of the water in a reservoir depends upon that of the inflow. However when a reservoir is formed a more or less extensive area is flooded. Substances released by the decay of submerged vegetation, or leached from the submerged soil, will modify the chemical composition of the water to some degree. The changes may not be very striking on the basis of chemical analysis, and may be masked by seasonal and other variations. However they are often reflected in an increase in plankton biomass and primary productivity.

In a natural lake the biologically important substances follow a certain cycle, being carried down to the hypolimnion in dead organisms, released into the water when these decay, and returned to the epilimnion by the seasonal turnover of the water. In reservoirs discharging from the hypolimnion this cycle is broken. Nutrients are removed from the water and carried away downstream.

Consequently the high productivity of a new reservoir declines fairly quickly and the productivity of the stream below the dam may be increased.

As a rule water quality is improved by impoundment; suspended matter is given time to settle out, and organic pollutants have time to be degraded. However under certain circumstances water quality can be impaired, in particular when thermal stratification develops and the lower water strata becomes anoxic. In principle it is possible to avoid these ill effects by destratification, either by pumping up hypolimnetic water or by aeration.

A considerable literature exists on the prediction of the effects of impoundment, including both the hydrodynamic and thermal properties of the water body and the quality of the water. When a reservoir is formed, either from a river or from a lake, a new shoreline is established which is immediately subjected to erosion through the action of waves and variations in the water level. The shoreline deformation that results may be very extensive, and appears not to be readily predictable at the present time, although this matter is receiving considerable attention in various parts of the world.

The problem of erosion is related to that of sedimentation. Soil eroded from the banks of the reservoir will usually be deposited elsewhere in it. Moreover all reservoirs are more or less effective sediment traps, and much of the sediment in the inflowing water is usually deposited in the reservoir. The most obvious practical consequence of this is a reduction in the capacity and the useful life of the reservoir. However it is also important in other ways. Delta formation may lead to flooding upstream. The trophic status of the lake may be affected. If the sediment contains a substantial amount of organic material this may gradually decompose, releasing nutrients to the water over a period of time. On the other hand nutrients, in particular phosphate, may be adsorbed on sediment particles and removed from solution. Whether they are thereby rendered biologically unavailable is by no means certain however since there is probably an equilibrium between the adsorbed and the free form. Pollutants, notably pesticides, may be removed from the water by adsorption on particles and their subsequent sedimentation.

The quantity of sediment deposited in a reservoir, and the manner in which it is distributed, are influenced by a number of factors and their prediction is consequently difficult. The significance of density currents has already been mentioned. The nature of the watershed, and the extent to which soil conservation is practiced within it, greatly influence the quantity of sediment brought in. The extent of clearing of the reservoir bottom before flooding has an important effect on the redistribution of sediments within the reservoir.

The nature of the sediment particles and the chemistry of the water also have an effect. Clays of the montmorrilonite group are rather easily flocculated and precipitated under the influence of ions in the water. Under other circumstances they may form a semi-fluid mass which may travel down the reservoir as a density current. Clays of the kaolinite type are not easily flocculated by ions so they may remain in suspension, rendering the water turbid, for a much longer time.

The construction of a dam influences processes of erosion and sedimentation below it as well as above. The maximum water level in the stream below the dam is usually less than it was before the dam was built, which tends to decrease erosion. However if the water has deposited its sediment above the dam it will then be able to pick up another load below, so the net effect may be an increase in the amount of downstream erosion.

Biological effects of impoundment and the biological limnology of reservoirs

The typical biota of a river are not the same as those of a lake, in particular certain components of the benthic fauna. Hence when a stretch of a river is changed into a lake, a certain portion of the fauna will be adversely affected to some degree. When the outlet of a lake is regulated so as to convert it to a lake reservoir the effect is less catastrophic but still unfavourable for the benthos.

The effect of impounding rivers has received particular study in the U.S.S.R. The results of closing two reservoirs on the Volga may be taken as a somewhat extreme but still fairly typical example of what happens to the benthos in such situations.

These reservoirs were filled in the autumn. The first effect was a decrease in the biomass. Typically riverine organisms adapted to fast-flowing water and a sandy bottom, perished or drifted away. Organisms adapted to a muddy bottom were little affected. Organisms living on vegetation which had been submerged spread over the newly flooded areas, where terrestrial worms of various kinds also appeared in some numbers. By spring however virtually all these organisms had perished. This uninhabited, newly flooded area provided a particularly favourable environment for chironomid (midge) larvae. In the absence of competitors, and in a habitat enriched by the decay of flooded vegetation, these organisms appeared in such prodigious numbers that the adults, when they subsequently emerged, were a menace to navigation. The chironomid population was high in subsequent years, but not as high as in the year immediately after the closing of the reservoir, and their numbers gradually declined. At the same time the less motile organisms from the muddy parts of the bottom of the original river gradually spread over the newly flooded areas. The reservoir will be considered to have reached its final condition only when the entire bottom is covered with a layer of sediment. This may take several decades.

In lake reservoirs there is no riverine fauna to be destroyed. However the annual variations in the lake level are usually made larger by regulation, and in particular the annual lowering of the lake level occurs more rapidly, when the reservoir is drawn down. Organisms living near the shore may be unable to move rapidly enough to follow the retreating water line and so become stranded and perish.

Plankton populations usually increase shortly after the closing of a reservoir, as a result of the entry of nutrients to the water. However it usually declines after a few years, at least partly as a result of the loss of nutrients. At the same time the plankton population downstream often increases, in part because of the availability of these nutrients and in part because suspended matter has had an opportunity to settle out above the dam so the downstream water is clearer and more transparent.

The effects of impoundment on fish is a matter of considerable practical importance.

The behaviour of fish populations in new reservoirs, especially riverine reservoirs, has been very thoroughly studied by Soviet scientists. The general sequence which they have observed is as follows. During the first two or three years after the closing of the dam the fish population increases rapidly. However when the supplies of nutrients from the newly flooded soil and vegetation have been depleted, productivity decreases and may remain low for many years; Soviet scientists call this the "trophic depression phase". Finally, as the lake approaches a more or less stable condition its productivity may increase slightly. The length of the trophic depression phase depends on temperature. At high latitudes it may be 25 to 30 years and at lower latitudes only 6-10 years.

Formation of a reservoir is unfavourable for fish that spawn in shallow waters, since their spawning areas are likely to be laid dry when the reservoir is drawn down. Soviet scientists have attempted to avoid this problem by providing artificial breeding substrata suspended from rafts.

They have also attempted to increase the yield of fish from reservoirs by introducing exotic species of fish or of food organisms.

Impoundment may have considerable effects on fish downstream as well as upstream. In some cases the discharge of water from the hypolimnion has made a stream suitable for cold-water species such as trout which were unable to live there before. In other cases a stream has been made too cold even for cold-water fish. Downstream water temperatures can be controlled by providing two or more outlets at different depths, or by placing a barrier behind the dam in such a way as to cause water to be withdrawn from the epilimnion.

The decreased turbidity below a dam may make it easier for fish to capture their prey, but it may also make it easier for predators to capture them.

Anadromous fish, that is fish that live in the sea and spawn in freshwaters, will obviously be affected by the daming of the streams through which they proceed to their spawning grounds. Moreover these spawning grounds may themselves be rendered useless by flooding.

Pacific salmon are particularly sensitive to the effects of damming because of certain aspects of their biology. They return to the streams in which they were hatched, and their sojourn in the sea is not very long, as little as two years in some species. This means that a complete blocking of upstream migration for as little as two seasons (for example during the construction of a dam) could effectively eliminate salmon from a stream. Moreover they do not feed on the way to the spawning ground, but exist solely on the energy reserves in their tissues. This reserve is not much more than enough to get them to their spawning grounds before they die. If they are delayed they may perish before they arrive. It follows that the blockage of upstream migration need not be absolute to be fairly disastrous. Finally, since migrating adult salmon swim against the current, they may wander about aimlessly in a reservoir, even if they succeed in getting over the dam. It is technically possible to provide fish-ways to permit the fish to pass a dam, or to capture them below the dam and release them upstream, or to provide artificial spawning channels if their normal spawning grounds have been flooded or made inaccessible. Whether it is practically possible to do these things on the scale that would be required if the number of dams and their size were to be greatly increased appears to be open to question.

Dams also constitute an obstacle to salmon smolts returning to the sea, chiefly because they are likely to be killed if they pass through turbines. Devices to guide them away from turbine inlets have been used with some success.

When a waterfall flows into a deep plunge basin, entrained air bubbles may be carried to a considerable depth where the hydrostatic pressure causes some of the atmospheric gases to enter solution in excess of their solubilities at atmospheric pressure. When the water returns to the surface it will be supersaturated with oxygen and nitrogen and it will take some time for it to re-equilibrate with the atmosphere. The concentration of dissolved gases, particularly nitrogen, in the tissues of fishes tends to be in equilibrium with the water around them. Thus the tissue fluids of fishes may become supersaturated with nitrogen. This may eventually come out of solution as small bubbles within the tissues, causing more or less serious injury, particularly in young fish.

Supersaturation may occur below natural waterfalls, and it may also occur below the spillways of dams.

Water discharging from the hypolimnion of a reservoir is frequently low in dissolved oxygen and high in B.O.D. Consequently the oxygen content of the stream below the dam may be reduced. Moreover if a river is controlled by a number of reservoirs its rate of flow throughout its length will be lowered so that the rate at which it takes up oxygen from the atmosphere may be decreased.

Besides this, the construction of dams along a river is likely to be only one aspect of increased industrial activity in the area, and it is probable that the quantities of industrial wastes entering the river will be increased at about the same time. All these factors tend to lower the concentration of dissolved oxygen in the river, possibly to the detriment of the fish in it, especially the more desirable species.

Other effects

In October, 1963, in Italy, a portion of Mount Toc having a volume of about 350 million cubic meters slid into the reservoir above the Vaiont Dam. The water which was thus forced over the dam destroyed several villages in the valley below, and 2000 lives were lost.

This disaster occurred about a month after the water level in the reservoir reached the greatest height it had yet attained (over 700 m). During the period between the filling and the landslide a number of seismic disturbances occurred and it is believed by some that these shocks were a result of the filling of the reservoir and that they may have precipitated the landslide. It has also been suggested that the slide may have been facilitated by the penetration of water from the reservoir into a stratum of clay underlying limestone on the mountain, thus providing a kind of lubrication.

Whatever the circumstances may have been surrounding the Vaiont disaster, there seems to be no doubt that the impoundment of water may lead to seismic disturbances under certain conditions. The weight of a large mass of water may generate stresses which are subsequently relieved by seismic shifts, or may add their effect to that of existing stresses to bring about a still greater disturbance. Alternatively water may be forced to considerable depths through cracks or pores in the underlying bedrock, and exert sufficient pressure to fracture it. Doubtless reservoirs influence the local climate to at least as large an extent as natural lakes of the same size.

In some areas the construction of reservoirs is associated with various medical problems. The new body of water will provide a habitat for snails, including those that serve as intermediate hosts for schistosomiasis. There is a grave danger that this disease may become established in the vicinity of any new reservoir that is formed in the tropics. The formation of a new body of standing water will also be favourable to the breeding of mosquitoes, which may lead to an increase in malaria in the vicinity. On the other hand the creation of a lake is unfavourable to the breeding of blackflies, which breed in running waters, so the numbers of these disagreeable insects, and the incidence of diseases transmitted by them, are likely to be decreased by creating a reservoir.

These considerations are of considerable importance in the tropics, but probably not in temperate regions.

Any impoundment may exert specific effects peculiar to itself depending on its particular geographical location. By definition these effects are not subject to generalization and they may not be very easy to foresee. At the same time they may be extremely important.

The effects of the W.A.C. Bennett Dam, on the Peace River, may serve as an example. This dam was closed in 1968. The probable ecological characteristics of the lake that would be formed by such a dam had been previously considered. However as it turned out the most dramatic effects of the dam were seen some 730 miles downstream, in the Peace-Athabasca delta just east of Lake Athabasca.

The maintenance of the existing ecological conditions in the delta requires periodic flooding. The role of the Peace River in bringing this about is not immediately obvious from a casual examination of a map of the area. The river appears to skirt the northern edge of the delta until it joins the Slave River, which is practically a continuation of the Peace, and flows into Great Slave Lake.

The Athabasca, entering the delta from the south, appears to be the main source of water for the delta, as in fact it is.

Before the Peace River was dammed, the delta was frequently, but not always, flooded in early summer when the flood waters in the Peace River held back the water of the lake so that instead of flowing into the Slave River it backed up and flooded the delta. A certain amount of water from the Peace River sometimes also entered the delta. This almost annual flooding maintained wetland conditions in a large part of the delta. Since the dam was closed no flooding has occurred, and substantial changes are already evident in the ecology of the delta.

Concluding comment

Although it is not possible at the present time, there seems to be no reason why it should not eventually be possible to predict with reasonable accuracy the physical and biological consequences of the construction of any given reservoir. It should then be possible to determine whether the construction of a proposed dam would lead to a net economic gain or loss.

However, particularly in areas where the population is not very advanced technologically the construction of a reservoir may have very grave social consequences. It is presumably possible for example to estimate the cost of resettling the population of an area that is to be flooded, but the distress which these people may suffer can scarcely be assessed in economic terms. I have not discussed the social effects of reservoirs because this seemed to lie outside the scope of my assignment, not because I consider the matter unimportant.

This summary is based largely on the following sources:

Books

ACKERMANN, W. C., WHITE, G. F., and WORTHINGTON, E. B. ed. Man-made Lakes: Their Problems and Environmental Effects. American Geophysical Union, Washington, D.C. 1973.

BENNET, G. W. Management of Lakes and Ponds. 2nd ed. Van Nostrand Reinhold Company, 1971.

DAVIES, D. Fresh Water. Aldus Books, London, 1967.

FARVAR, M. T. and MILTON, J. P. The Careless Technology. The Natural History Press, 1972.

HALL, G. E. Reservoir Fisheries and Limnology. Special Publ. 8, American Fisheries Society, Washington.

HRBACEK, J. ed. Hydrobiological Studies I. Academia, Prague, 1966. (Volumes II and III of this series have also appeared, but I have not seen them.)

HYNES, H. B. N. The Ecology of Running Waters. University of Toronto Press, 1970.

LAGLER, K. F. ed. Man-made Lakes. FAO, Rome, 1969.

LOWE-McCONNELL, R. H. ed. Man-made Lakes. Academic Press, 1966.

RESERVOIR COMMITTEE, Southern Division, American Fisheries Society. Reservoir Fishery Resources Symposium. University of Georgia, 1967.

RICHARDSON, B. James Bay. Sierra Club and Clarke Irwin Company, 1972.

SCOPE WORKING GROUP on Man-made Lakes. Man-made Lakes as Modified Ecosystems. International Council of Scientific Unions, 1972.

SHTEGMAN, B. K. ed. Plankton and Benthos of Inland Waters (translated from the Russian) Israel Program for Scientific Translations, 1969.

SHTEGMAN, B. K. ed. Production and Circulation of Organic Matter in Inland Waters. (Translation from the Russian). Israel Program for Scientific Translations 1969.

SYMONS, J. M. ed. Water Quality Behaviour in Reservoirs. U. S. Dept. of Health, Education and Welfare, 1969.

TYURIN, P. V. ed. The Storage Lakes of the U.S.S.R. and their Importance for Fishery. (Translated from the Russian.) Israel Program for Scientific Translation 1966.

ZHADIN, V. I. and GERD, S. V. Fauna and Flora of the Rivers, Lakes, and Reservoirs of the U.S.S.R. (Translated from the Russian.) Israel Program for Scientific Translation, 1963.

Papers and Reports

BEZLER, F. I. Devising a method of forecasting the content of organic and biogenic substances, gas regime and water bloom in reservoirs. (Translated from the Russian.) F.R.B. translation series IV: 1247.

BURT, W. V. Verification of water temperature forecasts for deep, stratified reservoirs. Water Resources Research 10, 93-97 (1974).

CHAMBERLAIN, L. L. Primary productivity in a new and an older California reservoir. Calif. Fish. and Game 58, 254-267 (1972).

CYBERSKI, J. Erosion of Banks of Storage Reservoirs in Poland. Hydrological Sciences Bulletin 18, 317 (1973).

EBEL, W. J. Supersaturation of nitrogen in the Columbia River and its effect on salmon and steelhead trout. Fishery Bull. 68, 1 (1969).

EBEL, W. J. and KOSKI, C. H. Physical and Chemical Limnology of Browlee Reservoir, 1962-64. Fishery Bull. 67, 295 (1968).

GORDON, R. N. Fisheries Problems Associated with hydroelectric development. Canadian Fish Culturist, October, 1965, p. 17.

GRIMAS, U. The bottom fauna in Lake Blasjon, Northern Sweden. Inst. Freshwater Research Drottningholm Report 44, 14 (1963).

HARVEY, H. H. and COOPER, A. C. Origin and treatment of a super-saturated river water. Intl. Pacific Salmon Fisheries Comm. Progress Report No. 9 (1962).

HYNES, H. B. N. The effect of water-level fluctuations on littoral fauna. Verh. Internat. Verein. Limnol. 14: 652 (1961).

LINDSTROM, T. Life in a lake reservoir. Ambio, 2: 145 (1973).

LOVE, S. K. Relationship of impoundment to water quality. J.A.W.W.A. 53: 559 (1961).

MARKOFSKY, M. and HARLEMAN, D. R. F. A predictive model for thermal stratification and water quality in reservoirs. Environmental Protection Agency, Water Quality Office. Water Pollution Control Research Series 16130 DJH 01/71, Washington, D.C. 1971.

McHENRY, J. R. Reservoir sedimentation. Water Resources Bulletin 10, 329-337 (1974).

MORDUCHAI-BOLTOVSKOI, F. D. Die Entwicklung der Bodenfauna in den stausee der Wolga. Verh. Internat. Verein. Limnol. 14: 647 (1961).

NEEL, J. K. Impact of Reservoirs. In D. G. Frey, ed. Limnology in North America. University of Wisconsin Press, 1966.

PASTERNAK, K. Bottom sediments of the polluted dam reservoir at Otmuchow. Acta Hydrobiol. 12, 377-390 (1970).

PASTERNAK, K. and GLINSKI, J. Occurrence and accumulation of micro-components in bottom sediments of dam reservoirs of Southern Poland. Acta Hydrobiol. 14, 225-255 (1972).

PURCELL, L. T. The aging of reservoir waters. J.A.W.W.A. 31: 1775 (1939).

RODHE, W. Effects of impoundment on water chemistry and plankton in Lake Rausaren (Swedish Lapland). Verh. Internat. Verein. Limnol. 15: 437 (1964).

ROTHE, J. P. Fill a lake, start an earthquake. New Scientist, 39: 75 (1968).

SMITH, W. O., VETTER, C. P., CUMMINGS, G. B. and others. Comprehensive summary of sedimentation in Lake Mead, 1948-49. Geological Survey Professional Paper 295. U. S. Government Printing Office, Washington, D. C. 1960.

UNIVERSITY OF CALIFORNIA, Berkeley. Flow into a stratified reservoir. Office of Research and Monitoring, U. S. Environmental Protection Agency EPA-R2-72-037, Washington, D. C. 1972.

WALLIS, J. R. and O'CONNELL, P. E. Firm reservoir yield - how reliable are historic hydrological records? Hydrological Sciences Bull. 18, 347-365 (1973).

WRIGHT, J. C. and SOLTERO, R. A. Limnology of Yellowtail Reservoir and the Bighorn River. Office of Research and Monitoring, U. S. Environmental Protection Agency. EPA-R3-73-002, Washington, D. C. 1973.

Note: The following important source of information about reservoir ecology has not been available to me:

OBENG, L. ed. Man-made lakes: The Accra Symposium. University of Ghana Press, 1969.

II. RESERVOIR RESEARCH IN CANADA

Until recently, Canadian scientists have shown little interest in the ecology of reservoirs. Opportunities for interesting investigations have been missed. For example the Gouin reservoir on the St. Maurice river was for several decades the largest man-made lake in the world, yet I have found no reference to any research on the limnology or biology of this body of water.

Perhaps the most significant study of a general limnological character is one that has been carried out on the Kananaskis River system in Alberta over a period of several decades. (1, 2, 3, 4, 5, 6) This work is summarized in a very valuable forthcoming review by Geen (7). The effects of dams on fish, especially Pacific salmon, have received considerable attention (9, 10, 11, 12, 13, 14, 15). The specific problem of gas supersaturation has been studied (16, this paper contains a useful literature review and bibliography). Occasional papers of a more general limnological character have appeared (e.g. 17).

In January 1974 the programme of the Canadian Conference of Freshwater Fisheries Research included a group of eight papers under the general heading "Problems with the assessment of the impact of dams". Abstracts of these papers are available.

Most aspects of reservoir research now in progress were represented among these papers, as well as most centres where research is being carried out, except Quebec City. The full texts of the papers will be published shortly as a Bulletin of the Fisheries Research Board.

This volume, when it appears, should provide a very useful survey of reservoir research in Canada. The abstracts were very helpful to me in preparing this review.

The main centre of academic hydrobiological research on reservoirs in Canada is probably the Biology Department of the University of Waterloo. A number of papers have been published by Hynes, Fernando and Duthie, together with their students, mostly on the biological effects of rather small impoundments (18, 19, 20, 21, 22, 23, 24, 25). More recently Duthie has turned his attention to a much larger reservoir system, that associated with the hydroelectric project at Churchill Falls, Labrador. He and a graduate student, M. L. Ostrofsky, presented a paper on this work at the C.C.F.F.R. Another paper on their work is in press (26). Duthie and Ostrofsky have been mainly concerned with the effects of impoundment on trophic status and energy fluxes. If the C.C.I.W. should decide to enter the field of reservoir ecology, one possibility would be to collaborate with Duthie. A study of nutrient fluxes would usefully complement the biological work done and in progress.

The ecology of the spray zone of the Churchill Falls has been investigated by a group in St. John's, and the changes taking place as a consequence of the hydroelectric project are being studied (27).

Another centre of fundamental research on reservoir ecology is the Institut National de la Recherche Scientifique (INRS-Eau) in

Quebec City. Professor H. G. Jones and his colleagues have prepared a research proposal for the study of primary production in hydroelectric reservoirs of the Canadian Shield (28). This interesting document is a useful source of information on reservoirs in Quebec in general. Also in Quebec City, several scientists at Laval University have shown concern over a proposed hydroelectric development in the Laurentides Provincial Park (29). An attempt to predict the consequences of such a project has been undertaken (30) and will appear in the F.R.B. Bulletin on reservoirs although it was not presented at the meeting. This project has since been abandoned (31).

A symposium on the lakes of western Canada, held in November 1972, included several papers dealing with various aspects of reservoirs (32, 33, 34, 35).

Processes of erosion and sedimentation in Lake Diefenbaker, the reservoir famed by the blocking of the South Saskatchewan River by the Gardiner dam, have been under surveillance for a number of years (36).

Most of the other research on reservoirs in progress in Canada, with a few incidental exceptions (e.g. 37) is directed less towards gaining an understanding of the general environmental effects of impoundment than to anticipating and preventing the harmful consequences of proposed reservoirs or assessing and correcting damage that has already been done. Probably the most publicized instance of this has been the study of the effects of the W.A.C.

Bennett dam on the Peace-Athabasca delta. This work is well documented (38, 39, 40, 41) and need not be discussed here. In addition to the references cited above, a paper on the subject was presented at the C.C.F.F.R. by G. H. Townsend.

A very large hydroelectric power development program is being implemented in Manitoba. The program includes the diversion of the Churchill River into the Nelson River which is made possible by damming the outlet of Southern Indian Lake and raising the level of this lake on the Churchill River by approximately 10 feet. The original development proposal, the "high level" diversion scheme, which would have raised the lake level by approximately 35 feet, was criticized by professionals representing many disciplines including biologists such as Dr. Harold Welch of the University of Manitoba. Apparently these objections were a major factor contributing to the eventual rejection of this original scheme (42, pp 22-26). Dr. I. W. Dickson presented a paper on this subject at the C.C.F.F.R. The whole concept has been strongly criticized by Newbury (43).

F. M. Atton presented a paper at the C.C.F.F.R. on impact analysis of Saskatchewan hydroelectric reservoirs.

The impact of reservoirs on fisheries continues to be a matter of concern. Two papers at the C.C.F.F.R. dealt with this problem, one on the west coast and one on the east. G. H. Geen discussed the effects on Pacific Salmon of a proposed dam on the Fraser river. C. P. Ruggles and W. D. Watt discussed the effects on Atlantic Salmon of the existing dams on the Saint John River. This subject has also been recently reviewed elsewhere (44).

The development of watershed simulation models was discussed at the C.C.F.F.R. by C. Walters. His concern has been very broad, including such matters as recreational demand.

A paper on the influence of man-made lakes on the atmospheric boundary layer was presented at the A.G.U. conference by the late R. M. Holmes (45). This is the only study of the meteorological effects of reservoirs in Canada that I have found. I have been informed by Mr. K. L. Grandia of Intera Environmental Consultants (the company with which Mr. Holmes was associated) that this subject is still of interest to them.

A study by Sinclair, unfortunately only available in the form of a master's thesis (46) should be mentioned. This investigation provides useful information on the influence of different degrees of clearing before flooding on the subsequent physical and biological characteristics of the bottom.

Lake Koocanusa, the reservoir behind the Libby Dam on the Kootenay river in Montana, is being made the subject of a very large study by American scientists. This project has been described in an internal report by B. E. St. John of the C.C.I.W. Pacific Detachment. Since this lake will eventually extend almost 40 miles into Canada the study will obviously be of interest to Canadian scientists.

Public anxiety concerning the effects of large impoundments continues to be expressed (e.g. 47). A recent book (48) has strongly criticized the proposed James Bay hydroelectric development project. Certain of the legal aspects of this very complex problem were discussed at the C.C.F.F.R. by A. F. Penn.

It is possible that other research work in this field may be in progress in universities or government laboratories on a modest scale. However I think I have probably identified the major centres of activity.

It appears that many aspects of reservoir ecology are being considered somewhere in Canada, but generally on a rather small and limited scale. It is also possible that the results of investigations in one part of the country may be recorded in reports of limited circulation and so may not be available to workers in other parts of the country. This has been a major weakness in reservoir research in the U.S.A. (49). A central organization to compile and correlate all the data on reservoir ecology collected in Canada would probably be useful.

Both Westwater and the Pacific Region Detachment of C.C.I.W. have expressed interest in reservoir research but I understand no work has been begun yet.

I also understand that the Freshwater Institute is beginning to take an interest in this subject. A proposal for a reservoir ecology project, drawn up by the Prairie and Northern Regional Task Force of the Department of the Environment has recommended a very large scale undertaking. It therefore seems probable that activity in this field in Canada will increase very considerably in the near future.

For anyone proposing to undertake reservoir research the existing directory of Canada dams already built or under construction in 1970 (50) should be useful.

REFERENCES

1. NURSALL, J. R. The early development of a bottom fauna in a new power reservoir in the Rocky Mountains of Alberta. Can. J. Zool. 30, 387-409 (1952).
2. NELSON, J. S. Effects of fish introductions and hydroelectric development on fishes of the Kananaskis River system, Alberta. J. F. R. B. 22, 721-753 (1965).
3. FILLION, D. B. The abundance and distribution of benthic fauna of three mountain reservoirs on the Kananaskis River in Alberta. J. Appl. Ecol. 4, 1-11 (1967).
4. RADFORD, D. S. and HARTLAND-ROWE, R. A preliminary investigation of bottom fauna and invertebrate drift in an unregulated and a regulated stream in Alberta. J. Appl. Ecol. 8, 883-903 (1971).
5. RADFORD, D. S. and HARTLAND-ROWE, R. Some conservational problems posed by hydroelectric power installations in Alberta. Biological Conservation 4, 166-168 (1972).
6. RADFORD, D. S. Some effects of hydroelectric power installations on aquatic invertebrates and fish in the Kananaskis River system. Alberta Conservationist, Summer 1972, 19-21.
7. GEEN, G. H. The effects of hydroelectric developments in Western Canada on aquatic ecosystems. J. F. R. B. in press.

8. BRETT, J. R. Salmon research and hydroelectric power development. F. R. B. Bulletin 114, 1957.

9. PRITCHARD, A. L. The effects on fisheries of man-made changes in fresh water in the Maritime Provinces. Can. Fish. Cult., October, 1959, p. 3.

10. VLADYKOV, V. D. The effect on fisheries of man-made changes in freshwater in the Province of Quebec. Ibid. p. 7.

11. MILLER, R. B. and PAETZ, M. J. The effect of power, irrigation, and stock water developments on the fisheries of the South Saskatchewan River. Ibid. p. 13.

12. LARKIN, P. H. and Graduate Students. The effect on freshwater fisheries of man-made activities in British Columbia. Ibid. p. 27.

13. GORDON, R. N. Fisheries problems associated with hydroelectric development. Can. Fish. Cult., October 1965, p. 17.

14. DICKSON, I. W. The impact of impoundments on fisheries. Manitoba Dept. Mines, Res. and Env. Mgmt., Research Branch MS Rep. No. 72-8, 1972.

15. LARKIN, P.H. The environmental impact of hydro power. in I. E. Efford and B. M. Smith, ed. Energy and Environment. U. B. C. 1972.

16. HARVEY, H. H. and COOPER, A. C. Origin and treatment of a supersaturated river water. Int. Pac. Salmon Fish. Comm. Progress Report No. 9. 1962.

17. JOHNSON, M. G. and BERST, A. H. The effect of low-level discharge on the summer temperature and oxygen content of a Southern Ontario reservoir. Can. Fish. Cult., October 1965, p. 59.

18. PATERSON, C. G. and FERNANDO, C. H. The macro-invertebrate colonization of a small reservoir in Eastern Canada. Verh. Int. Ver. Limnol. 17, 126. 1969.

19. PATERSON, C. G. and FERNANDO, C. H. The effect of winter drainage on reservoir benthic fauna. Can. J. Zool. 47, 589. 1969.

20. PATERSON, C. G. and FERNANDO, C. H. Macro-invertebrate colonization of the marginal zone of a small impoundment in Eastern Canada. Can. J. Zool. 47, 1229. 1969.

21. PATERSON, C. G. and FERNANDO, C. H. Benthic fauna of a new reservoir with particular reference to the Chironomidae. J. F. R. B. 27, 213. 1970.

22. SPENCE, J. A. and HYNES, H. B. N. Differences in benthos upstream and downstream of an impoundment. J. F. R. B. 28, 35. 1971.

23. SPENCE, J. A. and HYNES, H. B. N. Differences in fish populations upstream and downstream of a mainstream impoundment. J. F. R. B. 28, 45. 1971.

24. DUTHIE, H. C. Ecology of phytoplankton in Lake Belwood, a storage reservoir in Southern Ontario. J. F. R. B. 25, 1229. 1967.

25. DUTHIE, H. C. and KIRTON, W. L. Pri[illegible]ry productivity and standing crops of phytoplankton in Belwoo[illegible]voir. Can. J. Bot. 48, 665. 1970.

26. DUTHIE, H. C. and OSTROFSKY, M. L. Plankton, Chemistry, and Physics of Lakes in the Churchill Falls region of Labrador. J. F. R. B. in press.

27. BRASSARD, G. R., FROST, S., LAIRD, M., OLSEN, O. A. and STEELE, D. H. Studies of the spray zone of Churchill Falls, Labrador. Biological Conservation 4, 13-18 (1971).

28. INRS-Eau. A research proposition to study the primary productivity of large hydro-electric reservoirs on the Canadian Shield. Quebec, 1973.

29. LEMIEUX, G. For sale: one provincial park, available immediately! Nature Canada 1 (4), 21-23, October/December 1972.

30. ABDELNOUR, R., AUDY, E., BEDARD, J., LeSAGE, R. and ROBITAILLE, J. La riviere Jacques-Cartier avec un amenagement hydroelectrique: impact potentiel sur l'environment. Bulletin of the F. R. B. in press.

31. SPECIAL BULLETIN: a supplement to Nature Canada. Vol. 1, No. 4, 1972.

32. BUCKLER, S. J. The temperature and evaporation regime on Lake Diefenbaker during 1972. Proc. Symposium on the Lakes of Western Canada, Edmonton, 1973. pp. 26-37.

33. DAVIS, E., SMITH, R. B. and GOOS, G. Predicting reservoir quality changes - a laboratory investigation. Ibid., pp. 40-54.

34. SMITH, S. B. Biological resources in relation to human ecology at Fort Chipewyan, Alberta. Ibid.,370-381.

35. DAY, J. C. The social feasibility of a multiple-purpose man-made lake: the Parkhill dam and reservoir, Ontario. Ibid., 401-420.

36. IHD Project Saskatchewan - 1. Progress report 1968.
IHD Project Saskatchewan - 2. Progress report 1969, 1970, 1971. Saskatchewan Water Resources Commission, Hydrology Division. Inland Waters Branch, Department of the Environment.

37. LEHMKUKL, D. M. Change in thermal regime as a cause of reduction of benthic fauna downstream of a reservoir. J. F. R. B. 29, 1329. 1972.

38. DRISCHL, H. J. Evaluation of ecological effects of recent low water levels on the Peace-Athabasca Delta. Occasional Paper No. 13, Canada Wildlife Service, Ottawa. 1972.

39. The Peace-Athabasca Delta. Summary Report, 1972. Prepared by the Peace-Athabasca Delta Project Group.

40. Technical Report. The Peace-Athabasca Delta Project. Prepared by the Peace-Athabasca Delta Project Group. 1973.

41. BENNETT, R. M., CARD, J. R. and HORNBY, D. M. Hydrology of Lake Athabasca. Past, present, and future. Hydrological Sciences Bulletin 18, 337. 1973.

42. DUNBAR, M. J. Environment and Good Sense. McGill-Queens University Press. 1971.

43. NEWBURY, R., and MALAHER, G. The destruction of Manitoba's last great river. Nature Canada 1 (4), 1-13, October/December 1972.

44. DOMINY, C. L. Recent changes in Atlantic Salmon (Salmo solar) runs in the light of environmental changes in the Saint John River, New Brunswick, Canada. Biological Conservation 5, 105-113 (1972).

45. HOLMES, R. M. Effect on the atmospheric boundary layer of three small man-made prairie lakes in Alberta. in W. C. Ackermann, G. F. White, and E. B. Worthington, ed. Man-made lakes: their problems and environmental effects. A. G. U., Washington, D. C. 1973, pp. 406-420.

46. SINCLAIR, D. C. The effects of water level changes on the limnology of two British Columbia coastal lakes, with special reference to bottom fauna. M. Sc. Thesis, U. B. C. 1965.

47. BOCKING, R. C. Water: visions and revisions. Ontario Naturalist 14 (1), 16-21, March 1974.

48. RICHARDSON, B. James Bay. Sierra Club and Clark, Irwin and Company. 1972.

49. FREY, D. G. Reservoir research - objectives and practices with an example from the Soviet Union in Reservoir Fishery Resource Symposium. University of Georgia, Athens. 1967. pp. 26-36.

50. PRATT, H. K. Register of dams in Canada. Published under the auspices of the Canadian National Committee of the International Committee on large dams. 1970.

APPENDIX

Names, addresses, and fields of interest of individuals concerned with reservoir research in Canada.

The information used in compiling this list has been obtained in various ways. In general, in the absence of any information to the contrary, I have assumed that anyone who has published a paper on some subject related to reservoir ecology since 1970 is probably still concerned with the subject.

I have obtained confirmation from some, but not all, of the scientists listed that their interests are as I have stated. I apologize for any errors I have made.

Some of the scientists listed are perhaps only incidentally or peripherally concerned with reservoir research. These are included because their specialized knowledge and skills may prove useful to anyone attempting to decide on a research programme on reservoir ecology.

The order of listing is geographical, from east to west.

G. R. BRASSARD

O. A. OLSEN

Dept. of Biology, Memorial University, St. John's, Newfoundland

Interest: Churchill Falls spray zone.

C. L. DOMINY

Environmental Protection Service, Dept. of the Environment, P.O. Box 5667, St. John's, Newfoundland

Interest: Atlantic salmon in the Saint John River.

C. P. RUGGLES

W. D. WATT

Resources Development Branch, Maritimes Region, Environment Canada, P.O. Box 550, Halifax

Interest: Saint John River.

H. G. JONES (and colleagues)

INRS-Eau, C.P. 7500, Quebec 10.

Interest: General limnology of reservoirs.

G. LEMIEUX

J. BEDARD (and colleagues)

Faculté des Sciences, Université Laval, Quebec

Interest: Environmental Impact of reservoirs.

A. F. PENN

McGill University, Montreal

Interest: Legal aspects of reservoirs.

H. B. N. HYNES

C. H. FERNANDO (abroad on sabbatical leave at the present time)

H. C. DUTHIE

Dept. of Biology, University of Waterloo

Interest: Biological effects of impoundment.

J. C. DAY

Dept. of Geography, University of Western Ontario, London, Ont.

Interest: Social aspects of reservoirs.

R. NEWBURY

Dept. of Civil Engineering, University of Manitoba, Winnipeg

Interest: Churchill-Nelson Project.

D. G. RAMSAY

Lake Winnipeg, Churchill and Nelson Rivers Study Board, Winnipeg

Interest: Churchill-Nelson Project.

S. J. BUCKLER

Environment Canada, Atmospheric Environment Service, Regina Airport

Interest: Evaporation from reservoirs.

F. H. ATTON

Dept. of National Resources, Saskatchewan Fisheries Laboratory, 30 Campus Drive, Saskatoon

Interest: Impact analysis of hydroelectric reservoirs and other developments affecting the aquatic environment.

E. DAVIS

R. B. SMITH

G. GOOS

Dept. of Civil Engineering, University of Saskatchewan, Saskatoon

Interest: Water quality in reservoirs.

J. R. CARD

Hydrology Branch, Alberta Dept. of the Environment, Edmonton.

R. M. BENNETT

Water Survey of Canada, Environment Canada, Edmonton.

G. H. TOWNSEND

Canadian Wildlife Service, Environment Canada, Edmonton

Interest: Peace-Athabasca Delta; assessment of effects of hydroelectric developments on wildlife.

These are three of the many scientists associated with this study. The first two are hydrologists and the last an ecologist. The names of others can be found in chapter 12 (summary of appendices and references) of the 1973 report (my reference 40).

S. B. SMITH

Environmental Conservation Authority, Edmonton

Interest: Human ecology of the Peace-Athabasca delta.

D. S. RADFORD

Dept. of Lands and Forests, Administration Building, Lethbridge

Interest: Biological effects of reservoirs.

R. HARTLAND-ROWE

Dept. of Zoology, University of Calgary

Interest: Biological effects of reservoirs.

G. H. GEEN

Simon Fraser University, Burnaby

Interest: Effects of reservoirs on fisheries.

C. WALTERS

Institute of Animal Resource Ecology, U. B. C., Vancouver

Interest: Development of simulation models.