Effects of Pollutants at the Ecosystem Level
Edited by P. J. Sheehan, D. R. Miller, G. C. Butler and Ph. Bourdeau

CASE 7.4

Ecological Effects of Hydroelectric Development in Northern Manitoba, Canada: The Churchill–Nelson River Diversion

R. A. BODALY[1], D. M. ROSENBERG[1], M. N. GABOURY[2],
R. E. HECKY[1], R. W. NEWBURY[1] and K. PATALAS[1]

[1] *Canada Dept. Fisheries and Oceans, Freshwater Institute,*
501 University Crescent, Winnipeg, Manitoba R3T 2N6
[2] *Manitoba Dept. Natural Resources, Box 40, 1495 St. James Street,*
Winnipeg, Manitoba R3H 0W9

7.4.1 INTRODUCTION

Planning for hydroelectric development on the Churchill and Nelson rivers began almost two decades ago and major dams, diversions and power stations were operational by 1977. Extensive pre-development ecological studies and environmental impact predictions were carried out (Lake Winnipeg, Churchill and Nelson Rivers Study Board, 1971–1975: 1974, see especially Appendix 5). Studies on selected portions of the affected area encompassing the physical, chemical and biotic levels have continued to the present, using data from the pre-development period as ecosystem baselines. Emphasis has been on the impact of aquatic ecological changes on the harvest of fish by man. Although these studies are not strictly ecotoxicological, the study of perturbations at the ecosystem level is common to other case studies presented in this volume.

This case study has the following objectives:

1. To describe overall features of the Churchill and Nelson Rivers hydroelectric development.
2. To summarize ecological effects of the development.
3. To recommend future planning needs for hydroelectric development in subarctic areas.

7.4.2 THE ECOSYSTEMS BEFORE DEVELOPMENT

The lentic ecosystems affected by the Churchill and Nelson Rivers hydroelectric development are a set of boreal, Precambrian Canadian Shield lakes in northern Manitoba, Canada (Figure 7.4.1). Much of the bedrock in the area is overlaid with fine-grained glacio-lacustrine deposits, many of which are affected by permafrost. The area is characterized by a subarctic climate with short, cool summers and long, cold winters. Mean January daily temperatures are -22.5 to -27.5°C while mean July daily temperatures are 12.5 to 17.5°C. Annual precipitation is 400–500 mm of which approximately one-third falls as snow. Annual evaporation from lakes of the area ranges from approximately one-third to three-quarters of precipitation. The ice-free season is about 5 months (June–October).

Lake surface areas varied from small ($< 10\,km^2$) to very large (approximately $2000\,km^2$). The lakes were generally riverine and relatively shallow for their surface area. This, together with such factors as the glacio-lacustrine shore and bottom sediments and strong winds, caused relatively high turbidity. Residence times of water ranged from a few days (lakes on the lower Churchill River) to 2–3

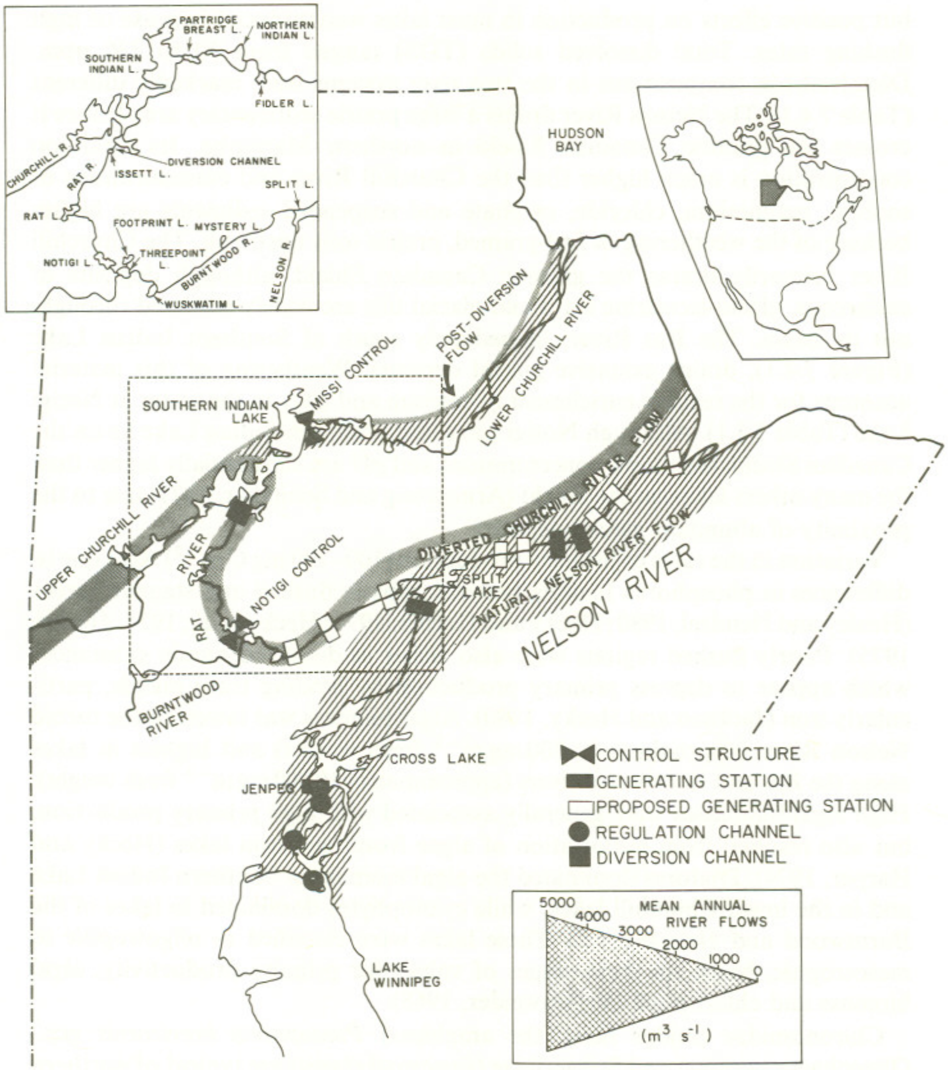


Figure 7.4.1 The Churchill and Nelson rivers hydroelectric development, northern Manitoba. Pre- and post-diversion flows, the locations of generating stations, control structures, artificial channels, and study lakes are shown

years (some basins of Southern Indian Lake). The lakes were generally isothermal during the ice-free season, with water temperatures usually < 20°C. Oxygen levels generally were near saturation throughout the water column, especially during the summer.

The riverine nature of the lakes imposed a high nutrient supply per unit area but positive effects on production in most lakes were reduced because of high flushing rates. Total dissolved solids (TDS) ranged from 50 to 230 ppm. Dissolved ion compositions in the two river systems were markedly different (Table 7.4.1). The Nelson River drains a large prairie sedimentary area before it crosses the granitic Canadian Shield in northern Manitoba. Its total ion concentration is much higher than the Churchill River and concentrations of sodium, magnesium, chloride, sulphate and suspended sediments are higher because of the weathering of fine-grained, prairie soils upstream. The Churchill River primarily drains the granitic Canadian Shield, although deposits of calcareous, glacio-lacustrine clays and glacial tills are widely scattered throughout its basin. The Rat River, immediately south of Southern Indian Lake (Figure 7.4.1), drains extensive glacial deposits. Weathering of this material accounts for the relative enrichment of calcium and CO_2 in the water at Notigi Lake (Table 7.4.1). Although Notigi Lake and Southern Indian Lake lie on the Canadian Shield, their ionic concentrations and pH are substantially higher than for many others lakes on the Shield (Armstrong and Schindler, 1971) due to the proximity of abundant glacial deposits.

Variation in the rates of primary production (100–700 mg C m^{-2}) were due to differences in phosphorus loading between rapidly flushed and stagnant areas (Healey and Hendzel, 1980; Hecky and Harper, 1974; Hecky *et al.*, 1974; Hecky, 1975). Poorly flushed regions were also richer in dissolved humic substances which appear to depress primary production by binding trace metals, particularly iron (Jackson and Hecky, 1980). Algal biomass was lowest in the turbid Nelson River (approximately 300 mg m^{-3} fresh weight) and highest in lakes along the Rat and Burntwood rivers (approximately 10 000 mg m^{-3} fresh weight). High algal biomasses were generally associated with high primary production, but also resulted from importation of algae from upstream lakes (Hecky and Harper, 1974). Diatoms dominated the algal biomass in Southern Indian Lake and in the lower Churchill lakes, while cyanophytes dominated in lakes of the Burntwood and Nelson rivers. These lakes were classified as oligotrophic to mesotrophic, based on their ranges of values for primary productivity, algal biomass and chlorophyll (Vollenweider, 1968).

Chironomidae (midge flies), the amphipod *Pontoporeia brevicornis* grp., Oligochaeta (worms) and Sphaeriidae (fingernail clams) are typical of northern boreal lakes and dominated the benthic macroinvertebrate fauna. Mean standing crops of benthic macroinvertebrates were higher in lakes of the lower Churchill River (approximately 11 500 m^{-2}) than in Southern Indian Lake (about 3000 m^{-2}) or lakes along the Rat and Burntwood rivers (approximately 3000 m^{-2}). The Churchill River had a positive influence on the production of macrobenthos in the lakes through which it passed (Hamilton and McRae, 1974). Mean standing crop of macrobenthic invertebrates in Southern Indian Lake was two to ten times higher than in other large lakes in the same general region, and benthic macroinvertebrate standing crops in lakes of the lower

Table 7.4.1 Chemical composition of Churchill River water at Southern Indian Lake, the Rat River at Notigi Lake, and the Nelson River at Cross Lake during the ice-free season prior to hydroelectric development. Concentrations are mean values for the open-water season (Cleugh, 1974). TSS: = total suspended sediments

Station	Na	K	Ca	Mg	Si	Cl	SO_4	Total CO_2	pH	Total N	Total P	TSS
				(mg L^{-1})				(μmole L^{-1})		(μg L^{-1})		(mg L^{-1})
Churchill River (Southern Indian Lake outlet, 1973)	2.6	1.1	9.4	3.5	1.0	1.1	4.3	830	7.8	400	28	2
Rat River (Notigi Lake, 1973)	2.0	1.0	16	4.3	1.6	1.1	3.8	1130	7.9	740	27	6
Nelson River (Cross Lake outlet, 1972)	15.0	2.4	29	10.7	0.7	18.2	24.7	1740	8.2	475	34	15

Churchill River were considerably higher than would be expected for lakes of that size and at that latitude (Hamilton and McRae, 1974).

The crustacean zooplankton of these lakes were typical limnetic species and were dominated by copepods. Total community abundance was strongly affected by water exchange times. A high degree of similarity existed between the fauna of lower Churchill River lakes, Southern Indian Lake and lakes of the Rat-Burntwood system. Generally, copepods comprised approximately 80 per cent of total numbers while cladocerans comprised the remaining approximately 20 per cent. In Southern Indian Lake, total abundance in the main lake basins was comparable to more southerly lakes such as Lake Ontario and Lake Winnipeg (Patalas, 1975). The lowest numbers of crustaceans occurred in the inflow regions of Southern Indian Lake (approximately $10\,l^{-1}$) while higher numbers (approximately $100\text{–}200\,l^{-1}$) were encountered in some well-protected bays. Short water exchange times tended to reduce severely total abundance of the community. Lakes in the Rat-Burntwood system which had water exchange times of 30–200 days tended to have lower crustacean abundance (about $15\text{–}80\,l^{-1}$) than the main basins of Southern Indian Lake but higher than the rapidly flushed lakes along the lower Churchill River ($1\text{–}6\,l^{-1}$) which had exchange times of 1–9 days.

The fish fauna of these lakes was typical of relatively shallow boreal Canadian lakes (Koshinsky, 1973). Diversity of fish was relatively low and the community was dominated by a relatively small number of cool-water adapted benthivores (lake whitefish *Coregonus clupeaformis*, white sucker *Catostomus commersoni* and longnose sucker *C. catostomus*), planktivores (ciscoes *Coregonus artedii* and related species), and piscivores (northern pike *Exos lucius*, walleye *Stizostedion vitreum* and burbot *Lota lota*).

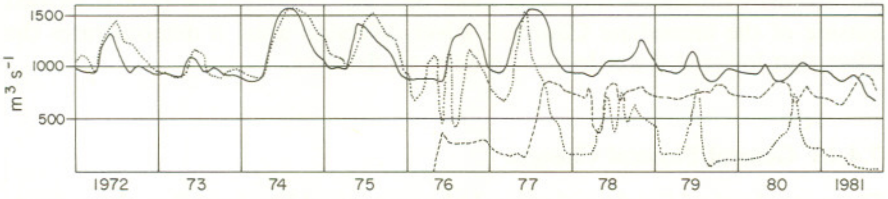
Sport fishing was not important in the area but many lakes supported commercial and domestic fisheries with modest yields (up to approximately $4\,\text{kg ha}^{-1}$). Walleye, pike and whitefish were the valuable commercial species. Yields were strongly influenced by economic factors such as access, cost of production and the availability of alternate employment, so over-exploitation generally was not a problem in these fisheries. Standing crops of commercially valuable species were relatively high, compared to other Canadian Shield lakes, probably reflecting the relatively shallow depths of these lakes and high nutrient loading due to riverine conditions.

7.4.3 HYDROELECTRIC DEVELOPMENT OF THE CHURCHILL AND NELSON RIVERS

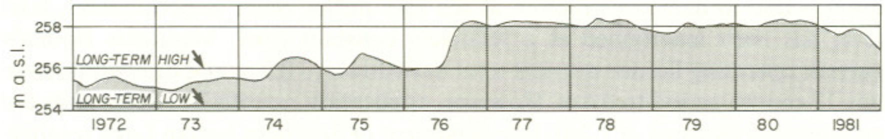
Hydroelectric development of the Churchil and Nelson rivers is a major energy producing project with a total designed capacity of approximately 8400 MW. The scheme utilizes the combined flow of two of the major rivers of Canada. Most of the flow of the Churchill, the smaller and more northerly of the two rivers, has been diverted into the Nelson, the larger and more southerly river

(Figure 7.4.1). The Churchill River, near the point of diversion (Missi Falls), has a drainage basin of 250 000 km^2 and a long-term mean flow of 1010 $m^3 s^{-1}$. It flowed through Southern Indian Lake, a large (pre-impoundment surface area: 1977 km^2), multibasin lake. A control dam was placed at the natural outlet of the lake (Missi Falls) in 1976 and the level of the lake was raised 3 m above the long-term mean level (Figure 7.4.2A, B). Water from the Churchill River now leaves the lake through a channel constructed between South Bay and the headwaters of the Rat River in the Nelson River basin. A control structure at the outlet of Notigi Lake regulates flows down the Rat River Valley. The control structure was closed in 1974, retaining local runoff water until water levels in the Rat River Valley and Southern Indian Lake were similar (Figure 7.4.2C). The diversion channel was then opened in 1976, and the diversion was operating at full design capacity by late 1977. The diverted flow joins the Burntwood River at Threepoint Lake, below the Notigi control structure, and enters the Nelson River at Split Lake. The amount of water diverted out of the Churchill River basin generally has been held constant at near 760 $m^3 s^{-1}$ or 75 per cent of the long-term mean flow.

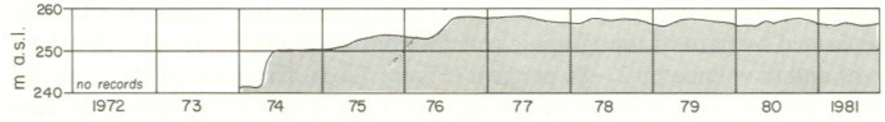
Hydroelectric power from the project is produced on the lower Nelson River where the combined annual mean flow of the Churchill and Nelson rivers is



A. FLOWS: CHURCHILL RIVER – AT SOUTHERN INDIAN LAKE INFLOW (LEAF RAPIDS) ——
AT SOUTHERN INDIAN LAKE OUTFLOW (MISSI FALLS) ············
AT DIVERSION CHANNEL OUTFLOW (SOUTH BAY) -------



B. LEVEL: SOUTHERN INDIAN LAKE



C. LEVEL: NOTIGI FOREBAY

Figure 7.4.2 Churchill River flows at the Southern Indian Lake inflow, outflow and diversion channel outflow (A); water levels of Southern Indian Lake (B) and the forebay of Notigi Reservoir (C), 1972–1981 about 3500 $m^3 s^{-1}$. Smaller generating plants are planned for the Burntwood River, below the Churchill River diversion (Figure 7.4.1). Power production also involves the regulation of Lake Winnipeg (surface area approximately 23 750 km^2) for winter storage. The level of Lake Winnipeg is controlled by a generating station at Jenpeg, and midwinter flows out of the lake are regulated by various artificial channels, control dams and dikes. Downstream of Jenpeg, the three generating stations currently in place have created large reservoirs, flooding existing lakes and the Nelson River Valley. About 30 per cent (approximately 2600 MW) of the total potential of the Nelson River has been developed, with a further 1100 MW currently under construction.

7.4.4 ECOLOGICAL EFFECTS OF HYDROELECTRIC DEVELOPMENT-SOUTHERN INDIAN LAKE

Our studies of the ecological effects of the Churchill–Nelson diversion have emphasized the response of Southern Indian Lake to impoundment and diversion. Therefore, we will treat Southern Indian Lake in detail and then outline the physical changes resulting from Churchill River diversion in lakes along the lower Churchill valley and the diversion route, and briefly describe the results of some biological studies in Notigi Lake. We also include an outline of the downstream effects on Cross Lake because, although the lake is located outside of the immediate Churchill River diversion area, it demonstrates the effect that lowered water levels can have on fisheries.

7.4.4.1 General Physical Changes

The water level of Southern Indian Lake was raised by about 3 m above long-term mean levels in 1976 (Figure 7.4.2B). Water levels in the summers of 1974 and 1975 exceeded the 20-year recorded high level by approximately 0.5 m for about 5 months due to dam construction at the lake outlet. Since impoundment, lake level has been maintained at a relatively constant level. Manitoba Hydro's current operating licence restricts total drawdown to 0.9 m and drawdown over any 12-month period to 0.6 m. However, application recently has been made for an annual drawdown of 1.2 m. Impoundment of Southern Indian Lake resulted in a 20 per cent increase in surface area and a 39 per cent increase in volume over long-term mean values (McCullough, 1981). Individual basins of the lake, separated by natural topographic constrictions, increased in area by 10–45 per cent and in volume by 27–84 per cent (Figure 7.4.3). Diversion of the Churchill River from its natural outlet altered water budgets of the various basins, the most extreme change occurring in South Bay (through which the Churchill now flows) where residence time changed from 4 years to 11 days.

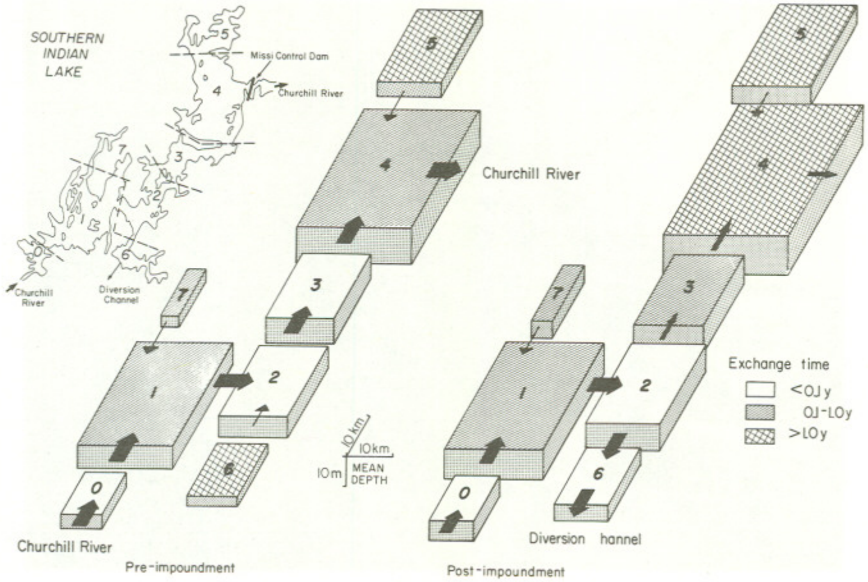


Figure 7.4.3 Schematic diagram of basins of Southern Indian Lake showing surface area, volume, mean depth and water exchange times before and after impoundment and river diversion. Each basin is represented by a three-dimensional block. Surface areas are shown by the horizontal scale, mean depths are shown by the vertical scale and water exchange times are shown as toning on the horizontal surface of each block. Inter-basin water exchanges are shown as arrows, the widths of which are proportional to mean annual flow

7.4.4.2 Shoreline Erosion

Shoreline forms and erosion rates also were altered by impoundment. Before 1976, 76 per cent of the water–land contact consisted of water-washed bedrock beaches. Shorelines along unconsolidated overburden occurred only where there was protection from long wave fetches or in deep deposits of proglacial sands and gravels and glacio-lacustrine clays. Less than 5 per cent of total shoreline length was actively eroding. Impoundment raised the lake level above the water-washed bedrock beaches and into overlying unconsolidated glacial deposits. Over 80 per cent of the shoreline immediately after impoundment occurred in fine-grained tills and lacustrine silty-clays which previously existed in permafrost. Lakewide, approximately 25 MW of power in the form of wave energy was directed against the shoreline during the open-water season (Newbury, 1981). This has caused retreats of up to 10 m yr^{-1}, removing up to 25 m^3 of material per metre of shoreline (Newbury and McCullough, in press). Along shores bounding large basins, erosion proceeded in a repeating sequence of the melting of

Figure 7.4.4 Eroding bank following a storm, at a shoreline affected by relatively high incident wave energies. Wave action has removed slumped material, cutting a vertical bank in frozen clay

permafrost and slumping of bank materials during periods of relative calm, followed by removal during storms (Figures 7.4.4, 7.4.5). Where the shore is exposed to smaller fetches ($<$ 2k m), erosion of the shoreline was retarded by the protective moss and root mat of the former forest floor. In these cases, melting of permafrost in the inundated zone initiated widespread settling, indicated by slump scars and fallen trees in the backshore zone.

An average erosion index was determined by calculating wave energy using wind records from Southern Indian Lake, and by monitoring erosion rates at 20 survey sites surrounding the lake. The sites were chosen to represent a range of materials and fetches for the lake. Using shoreline survey and wind data from 1978–80, the rate of erosion was 0.00035 m^3 per tonne-m of wave energy per metre of shoreline. Subtraction of peat volume and ice content from this figure yielded an index of erosion of mineral materials of 0.00012 m^3 per tonne-m of wave energy per metre of shoreline.

Although grain size analyses indicated that these shoreline materials were 70–95 per cent clay, only a portion of the material eroded was carried offshore in suspension. Wave energy breaking up the clay mass did not reduce all the material to colloidal particles; rather, clay 'balls' were formed ranging from 2 cm diameter through sand and silt sizes. Bottom cores taken adjacent to eroding banks indicated that these clay balls were deposited in the nearshore zone in a pattern of decreasing size with increasing distance from shore.

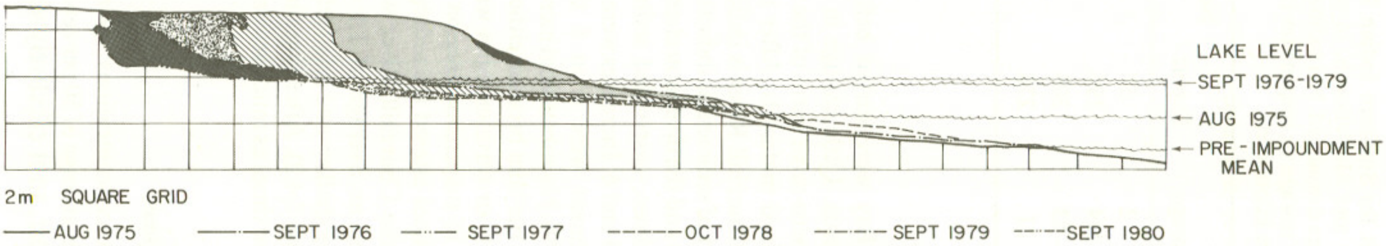


Figure 7.4.5 Surveyed profiles of the shoreline in Figure 7.4.4 indicating the quantities of material eroded annually

Table 7.4.2 Sediment budget for Southern Indian Lake before and after impoundment (from Hecky and McCullough, in press). Only sediments $> 1\ \mu m$ (nominal diameter) are considered. Net sedimentation/erosion (N) is calculated from import (I), storage in suspension (S), and export (E) as $N = I - S - E$. All values are kilotonnes

Year	Import	Storage	Export	Net sedimentation (+)/ net erosion (−)
1975	124	2	57	+65
1976	115	124	195	−204
1977	148	−83	305	−74
1978	103	21	278	−196

7.4.4.3 Sediment Budgets

The eastern basins of South Bay were turbid before impoundment due to resuspension of bottom sediments. Little change in suspended sediment concentration occurred in the northern-most basin of the lake because the shoreline was predominantly coarse-grained materials. After impoundment, dilution of sediment in lake waters by the Churchill River is indicated (Figure 7.4.6) by the dark plume at the inflow; export of sediment is indicated by the light tones of the outflowing waters at Missi Falls and the diversion channel. Despite the inefficient dispersion of clay from shorelines, suspended sediment concentrations rose dramatically in regions 1, 2, 3, 4 and 6. Increases were greatest in region 4 where concentrations after impoundment were 6 to 8 times higher than before impoundment (Hecky *et al.*, 1979). No substantial increases occurred in regions 5 and 7 and many small bays on the lake because either fine-grained overburden materials were lacking (region 5) or wave energies were too low to cause bank erosion or maintain sediments in suspension (region 7 and small bays).

Material from eroding shorelines altered the sediment budget of the lake. In 1975, prior to impoundment, the Churchill River was the primary source of sediment to the lake, supplying an average of 1.1×10^5 tonnes of sediment annually. The lake, despite being shallow and relatively rapidly flushed, retained > 50 per cent of this input (Table 7.4.2). After impoundment and diversion, the lake exported approximately five times as much sediment as compared to before impoundment.

7.4.4.4 Light and Thermal Regimes

Increased suspended sediment concentrations altered the underwater light regime over much of the lake. An average of 50 per cent of the suspended offshore material was $> 1\ \mu m$ in diameter, so it effectively scattered light (Kullenberg,

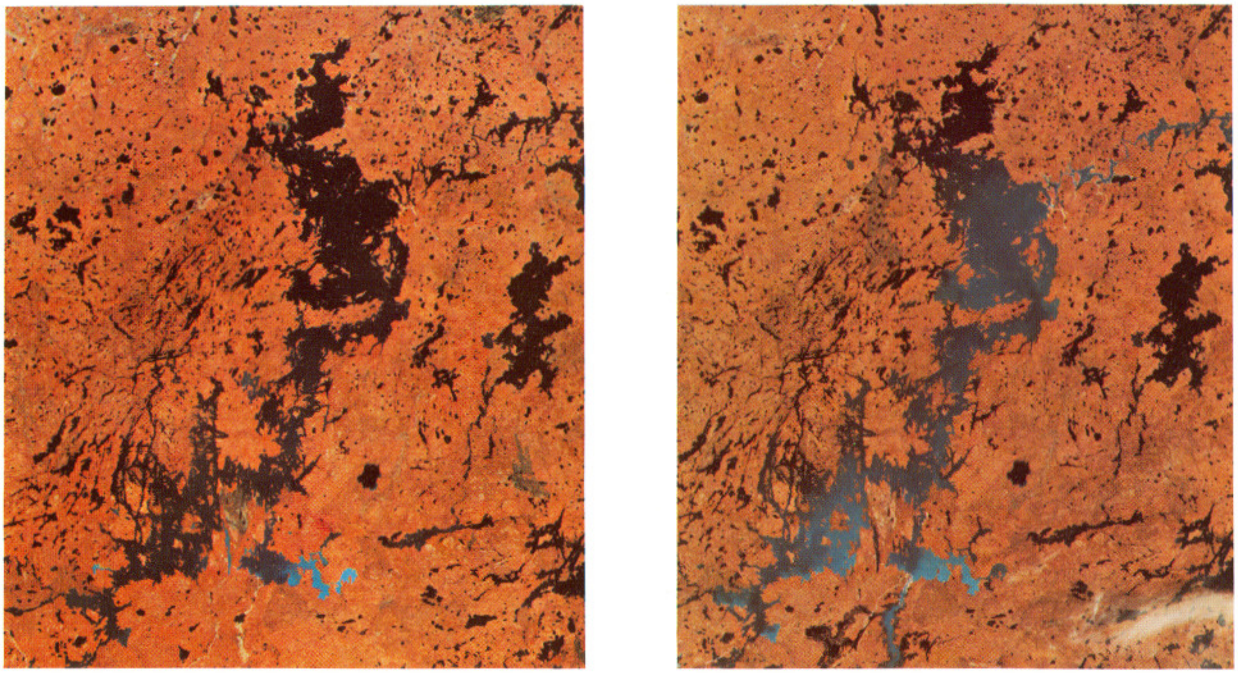


Figure 7.4.6. Composite Landsat images (bands 4, 5 and 7) of Southern Indian Lake in 1973 (left) and 1978 (right). Lighter tones indicate high reflectivity due to high concentrations of suspended sediments

1974). Increased light scattering after impoundment was apparent in Landsat photographs of the lake (Figure 7.4.6). Light penetration was reduced by mean values of 30–50 per cent in regions 2, 3, 4 and 6 (Hecky *et al.*, 1979). Since the large regions of Southern Indian Lake are unstratified throughout the open water season, the mean water column irradiance ($\bar{I}$) defines the light regime for freely circulating phytoplankton. $\bar{I}$ is calculated using the equation:

$$\bar{I} = \frac{1}{\bar{z}} \int_{0}^{Z_m} I_o e^{-kz} \, dz$$

where z is depth (m), $\bar{z}$ is the mean depth of the basin, Z_m is the maximum depth of the basin, I_o is the incident photosynthetically active radiation at $z = 0$ and k is the vertical light extinction coefficient. Mean water column irradiance declined in all regions of the lake after impoundment (Figure 7.4.7). For regions in which light penetration was similar before and after impoundment (e.g. region 5), observed decreases in mean water column irradiance were due mainly to increased mean basin depth. For regions in which light penetration decreased due to increased suspended sediment levels (e.g. regions 2, 4 and 6), observed decreases in mean water column irradiance were due to the combined effect of decreased light penetration and increased mean depth (Figure 7.4.7).

Impoundment and diversion had no obvious effect on vertical thermal

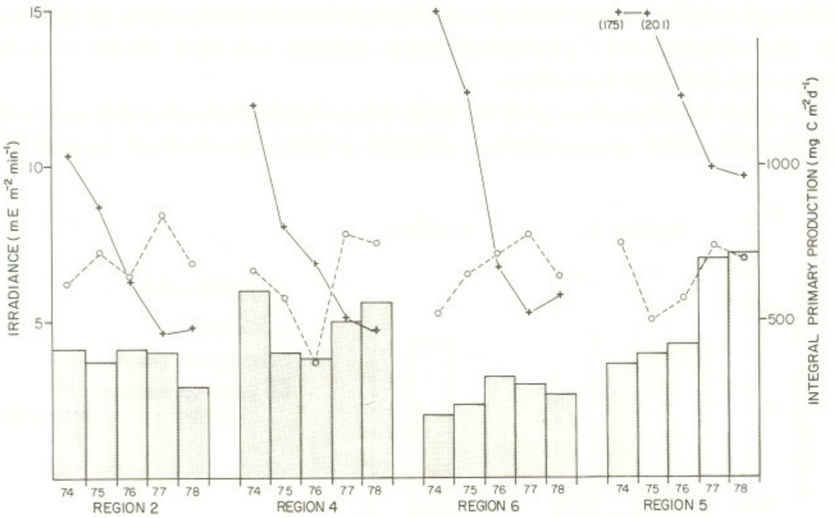


Figure 7.4.7 Mean water column irradiance during daylight ($\bar{I}$) (—+—), mean onset of light saturation (I_k) (---o---) and mean integral primary production (bars) for four regions of Southern Indian Lake, 1974–1978. Mean values are for 5 July–4 September for all five years. Mean onset of light saturation and mean integral primary production were measured using the incubator technique and digital computation programme of Fee (1973)

structure of the lake. Surface waters typically were 2–3 °C warmer than deep waters during June and July of the open-water season, but no persistent stable stratification was observed before or after impoundment. However, impoundment and river diversion did alter the horizontal distribution of heat in the system. For example, region 6, which received diversion flows, was cooled by 1 °C below its pre-impoundment temperature in the open-water season and by 2–3 °C in winter. Region 4 was cooled by 1 °C during the open-water season because of reduced heat input from the river and loss of radiant energy due to backscattered light. The ice-out pattern of the lake imposed a natural southwest to northeast thermal gradient (2 °C between regions 1 and 4 in July) and river diversion increased this gradient (Hecky *et al.*, 1979).

7.4.4.5 Primary Production

The productivity of phytoplankton in Southern Indian Lake demonstrated a variable response to impoundment. In the main regions of the lake (1, 2, 3, 4), there was no significant change in integral primary production (Figure 7.4.7). Production of phytoplankton in these regions was phosphorus limited before impoundment (Guildford, 1978; Healey and Hendzel, 1980) but was light limited after impoundment as the mean water column irradiance, $\bar{I}$, fell below the irradiance required for light saturation, I_k (Hecky and Guildford, in press). Although soluble reactive phosphorus concentrations increased in all regions in the lake (Figure 7.4.8), phytoplankton in regions 1–4 were unable to benefit because of this light limitation.

In region 5 and small bays of the lake, where light penetration did not change significantly after impoundment, integral primary production increased by

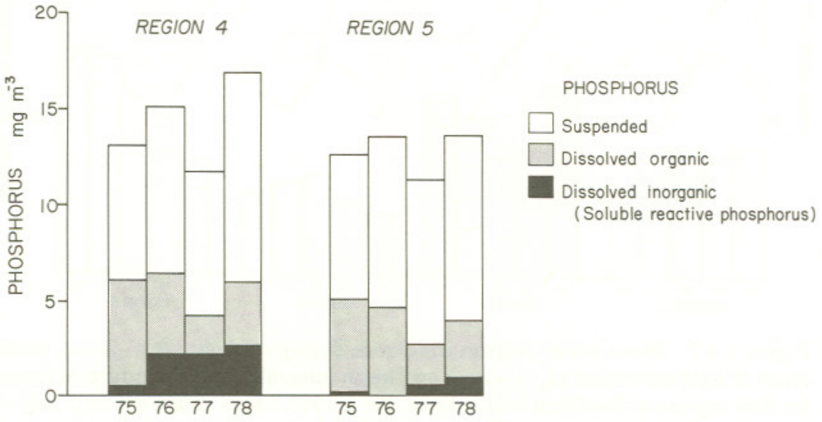


Figure 7.4.8 Concentrations of suspended, dissolved organic and soluble reactive phosphorus in regions 4 and 5, Southern Indian Lake, 1975–1978

50–100 per cent. Phytoplankton in region 5 did not become light limited because $\bar{I}$ exceeded I_k before and after impoundment (Figure 7.4.7) so the phytoplankton were able to use the increased soluble reactive phosphorus concentration (Figure 7.4.8). Primary productivity increased in region 6, despite a decline in $\bar{I}$ below I_k (Figure 7.4.7), because diversion linked this region with region 2 which was more productive than region 6 before diversion.

7.4.4.6 Macrobenthic Invertebrates

Profundal macrobenthos in Southern Indian Lake were surveyed before impact (1972), after flooding and partial diversion (1977), and after full diversion (1979) using methods described in Wiens and Rosenberg (in press). Lakewide standing crop (mean number $m^{-2} \pm$ SE) of macrobenthos increased from 3227 (369) m^{-2} before flooding (1972) to 5592 (493) m^{-2} just after flooding (1977), and decreased to 4817 (477) m^{-2} just after diversion (1979). This pattern has been observed commonly in newly created reservoirs all over the world (McLachlan, 1974; Wiens and Rosenberg, in press). Increased standing crop is ascribed to additions of nutrients and organic matter from newly flooded land (e.g. McLachlan, 1974; Baxter, 1977) while subsequent declines in standing crop may be due to depletion of the flooded organic matter (e.g. McLachlan, 1974). The response of macroinvertebrates to flooding was rapid in Southern Indian Lake as has been observed in many other reservoirs.

Mean standing crops of macrobenthos remained virtually unchanged for the three surveys in regions 1 and 6-east of Southern Indian Lake (Table 7.4.3). However, mean standing crops in the other regions increased markedly between 1972 and 1977; by 1979 densities had stabilized in regions 0 and 2, had increased in region 6-west, and had decreased in the other regions (3, 4, 5, 7), in relation to the 1977 levels. Four interrelated changes that occurred in Southern Indian

Table 7.4.3 Mean standing crops (number of individuals $m^{-2} \pm$ SE) of profundal macrobenthos in regions of Southern Indian Lake in 1972, 1977 and 1979

Region	Year 1972	 1977	 1979
0	1712(401)	3587(1223)	3394(1377)
1	6239(1017)	5512(880)	5823(760)
2	2304(737)	4849(1338)	4457(1871)
3	3789(941)	6360(1335)	3468(749)
4	3832(740)	8311(955)	6903(1489)
5	2769(1350)	6123(1451)	5006(1267)
6-west	1019(588)	1503(18)	2044(770)
6-east	1770(1006)	1585(342)	1251(528)
7	3273(1231)	6717(1037)	4117(622)

Lake (additions of nutrients, additions of particulate organic matter, changes in suspended sediment concentrations and changes in integral primary production) largely explained the observed responses of macrobenthic standing crops in each region (Wiens and Rosenberg, in press).

Increased mean standing crops of macrobenthos in the first year after impoundment (1977) were proportionally highest in the 5–10 m depth zone (approximately 200 per cent) as compared to standing crops in the 0–5, 10–15 and 15–20 m depth zones. By 1979, standing crops stabilized at 10–15 m, declined at 5–10 m and 15–20 m and increased only at 0–5 m (approximately 30 per cent). Greater increases in standing crops of macrobenthos in shallower as compared to deeper zones of the lake after flooding were attributed to preferential deposition of allochthonous organic matter in these shallow areas (Wiens and Rosenberg, in press).

Four taxa of macrobenthos comprised >95 per cent of total standing crop before and after impoundment: Diptera (mainly Chironomidae), *Pontoporeia brevicornis* grp. Oligochaeta and Pelecypoda (mainly Sphaeriidae). Responses of these major taxa to the flooding of Southern Indian Lake differed in many ways from those reported for other newly formed reservoirs (cf. Wiens and Rosenberg, in press). *P. brevicornis* grp. remained the most abundant organism; there was no evident succession of macrobenthic taxa, and a high diversity of profundal species was maintained in Southern Indian Lake. These results, together with the relatively slight changes in standing crop observed after flooding, indicate only a marginal impact on Southern Indian Lake macrobenthos. This minimal impact is probably related to the environmentally less disruptive type of reservoir formation in Southern Indian Lake (i.e. low-level flooding) compared to that normally occurring when reservoirs are formed by damming a river.

7.4.4.7 Zooplankton

Planktonic crustaceans in Southern Indian Lake were surveyed before impact (1972), during a period when water levels exceeded previously recorded high levels (1975) (Figure 7.4.2) and then yearly after diversion (1977–1980), using methods described by Patalas and Salki (in press). No dramatic changes were observed in the list of species present but lakewide average abundances (expressed as individuals per litre) of crustacean plankton following diversion decreased from 76 ind. l^{-1} in 1972 to 40–46 ind. l^{-1} in the four post-diversion years (1977–1980) (Table 7.4.4A). The abundance of plankton in 1975, an intermediate period, was 61 ind. l^{-1}. The degree to which zooplankton responded to diversion differed in various parts of the lake. No significant changes occurred adjacent to the Churchill River inflow (region 0) where post-diversion abundance was approximately 36 ind. l^{-1} compared to approximately 35 ind. l^{-1} in 1972. Abundances in the main water bodies north of the diversion route (regions 2, 3, 4) declined from 89 ind. l^{-1} in 1972 to 34 ind. l^{-1} during

Table 7.4.4 Changes in abundance of planktonic crustaceans in Southern Indian Lake from 1972 to 1980. Values are lake averages for late summer in A: number of individuals l^{-1} and B: percentage composition

	1972	1975	1977	1978	1979	1980
A: Individuals l^{-1}						
Calanoida	25.2	32.7	24.8	21.0	21.2	25.2
Cyclopoida	35.2	18.9	15.6	16.4	15.0	18.5
Cladocera	15.6	9.0	3.9	4.5	3.9	2.6
Total	76.1	60.6	44.3	41.9	40.1	46.3
B: Percentage composition						
Calanoida	33.2	53.9	56.0	50.1	52.8	54.4
Cyclopoida	46.3	31.3	35.2	39.1	37.5	39.9
Cladocera	20.5	14.8	8.8	10.8	9.7	5.7
Total	100.0	100.0	100.0	100.0	100.0	100.0

1977–1980. These changes coincided with other effects of impoundment (e.g. lower midsummer chlorophyll-*a* concentrations, decreasing water transparency) and of diversion (e.g. decreasing water temperature) in these regions (Patalas and Salki, in press). In South Bay (region 6), through which the main flow was diverted, zooplankton abundance declined from 83 to 40 ind. l^{-1} because of higher flushing rates.

Not all groups of crustaceans responded in the same way to impoundment. Lakewide average numbers of cladocerans declined from 16 ind. l^{-1} before impoundment to 4 ind. l^{-1} following impoundment; cyclopoids declined from 35 to 16 ind. l^{-1}; but calanoids remained relatively stable at around 24 ind. l^{-1}. Percentage composition of cladocerans, cyclopoids and calanoids changed from 20, 46 and 33 per cent, respectively, in 1972, to 9, 38 and 53 per cent, respectively, in the four post-diversion years (1977–1980) (Table 7.4.4B). Although absolute numbers of calanoids did not change during this period, their percentage composition increased because of the decline in abundance of the other two groups.

A significant increase occurred in the abundance and distribution of some large species after diversion (e.g. *Limnocalanus macrurus, Senecella calanoides, Mysis relicta*) *Mysis relicta* was absent in pre-diversion catches, but from 1977 to 1980 it became more abundant and its distribution expanded. These large species are a preferred food item for both whitefish and cisco; they are cold-water stenotherms and they inhabit deeper layers of water. Increased abundance of these species could be due to decreased water transparency which offered better protection against predatory fish, decreased water temperatures which created more favourable conditions and increased depth of the lake which expanded the volume of deeper waters suitable for these species.

7.4.5 ECOLOGICAL EFFECTS OF HYDROELECTRIC DEVELOPMENT-OTHER LAKES

7.4.5.1 Lakes of the Lower Churchill River

The mean annual natural discharge of the Churchill River at Missi Falls has decreased, under average regulated conditions, from 1010 to 220 $m^3 s^{-1}$ (McCullough, 1981) (Figure 7.4.2A). However, Manitoba Hydro's licence allows reduction of discharge to as low as 14 $m^3 s^{-1}$ during the open-water period and 42 $m^3 s^{-1}$ under ice conditions. No upper limit has been placed on the discharge released at Missi Falls. Since diversion, the annual range of releases has exceeded 600 $m^3 s^{-1}$ (Figure 7.4.2A). Reduced mean flows have lowered lake levels dramatically on Partridge Breast, Northern Indian and Fidler lakes downstream of Missi Falls (Figure 7.4.1), and have increased annual water level fluctuations from a natural range of 1 m to post-diversion ranges of 2–3 m (Brown, 1974). Pre-diversion lake areas have been halved, exposing a total of 96 km^2 of former lake bottom on the three lakes along the lower Churchill. Natural water exchange times for each of the lower Churchill River lakes originally were only 1 to 9 days. The combination of decreased lake volumes and decreased annual flows yielded only small changes in exchange times, with a range of 1–16 days under average post-diversion flow conditions.

7.4.5.2 Diversion Route Lakes (Rat and Burntwood River Valleys)

General description

The upper Rat River Valley is now flooded by the Notigi Reservoir and water levels in lakes of the lower Rat River Valley and lower Burntwood River Valley have increased due to the Churchill River diversion. A chain of eight lakes extended along the Rat and Burntwood rivers prior to Notigi impoundment and Churchill River diversion (Figure 7.4.1). The lakes were relatively small, ranging from 3.7 km^2 (Issett, the headwater lake) to 85.3 km^2 (Wuskwatim, on the lower Burntwood River). The lakes were shallow (mean depth 1.7–5.3 m), rapidly flushed (residence times 37–136 days), and turbid (Secchi disc depths 0.5–1.5 m) because of extensive fine-grained glacial sediments in the basin, shallow mean depths, low residence times and frequent interconnecting riverine stretches.

Formation of the Notigi Reservoir united five of the lakes at a common water level and flooded 409 km^2 of terrestrial soils and vegetation. Pre-existing lake area within the reservoir boundary was 67 km^2 so 86 per cent of the reservoir surface area is underlaid by former land. Water levels of the forebay area of

Notigi Lake were raised 16 m (Figure 7.4.2C); mean depth of the reservoir after flooding was 7 m. Rat River natural mean annual discharges of $2\,m^3\,s^{-1}$ at Issett Lake and $35\,m^3\,s^{-1}$ at its confluence with the Burntwood River were augmented by $300\,m^3\,s^{-1}$ through 1976, increasing to mean monthly discharges as high as $820\,m^3\,s^{-1}$ in late 1977 (Figure 7.4.2A). Clearing was performed only for hydraulic purposes on the immediate course of the diverted water through the reservoir and also for aesthetic purposes in the vicinity of road crossings. Standing black spruce dominate this flooded area and large peat mats have floated free in headwater bog regions. Shoreline erosion within the reservoir is minimal because the dendritic shape of the reservoir results in short wind fetches (maximum 10 km) and low wave energies.

Water levels on the Burntwood River lakes below Notigi Reservoir are now 3–5 m above their pre-impoundment mean due to an increase in discharge from $100\,m^3\,s^{-1}$ to $880\,m^3\,s^{-1}$. Winter ice-dams raise lake levels further. Erosion in the river channel below Notigi has been significant because of the dramatic increase in flow.

Notigi Lake

Limnological observations were concentrated on Notigi Lake before, during and after impoundment and diversion. Notigi Lake and two basins connected by a relatively shallow, narrow channel. The western basin was flushed rapidly by the Rat River prior to impoundment and by the Churchill River after diversion, whereas the eastern basin was relatively poorly flushed before and after impoundment (Hecky and Harper, 1974).

The western basin was isothermal throughout the open-water period (Cleugh, 1974) prior to impoundment. Greatly increased water levels in the two basins during 1974 and 1975, combined with reduced flushing and minimal change in fetch, allowed summer thermal stratification to develop (Hecky *et al.*, 1979). With the onset of full diversion flow in 1978, the western basin became isothermal again while a thermocline persisted in the eastern basin (Hecky *et al.*, 1979).

These changes in thermal structure, combined with the gradually increasing amounts of flooded terrestrial organic matter with its high oxygen demand, have resulted in unique oxygen stratification patterns. Prior to impoundment, dissolved oxygen in Notigi Lake was vertically homogeneous with about 75 per cent saturation during the winter and near saturation throughout the open-water period (Cleugh, 1974). After impoundment, winter dissolved oxygen concentration in the eastern basin declined with depth, indicating the interaction between warmer bottom waters and the oxygen demand of flooded substrate (Figure 7.4.9). In summer, contact of the relatively warm water of the metalimnion with flooded terrain resulted in midwater oxygen minima (Figure 7.4.9). The depths of these summer minima tended to decrease over the post-impoundment period, probably in relation to the length of time the soil had

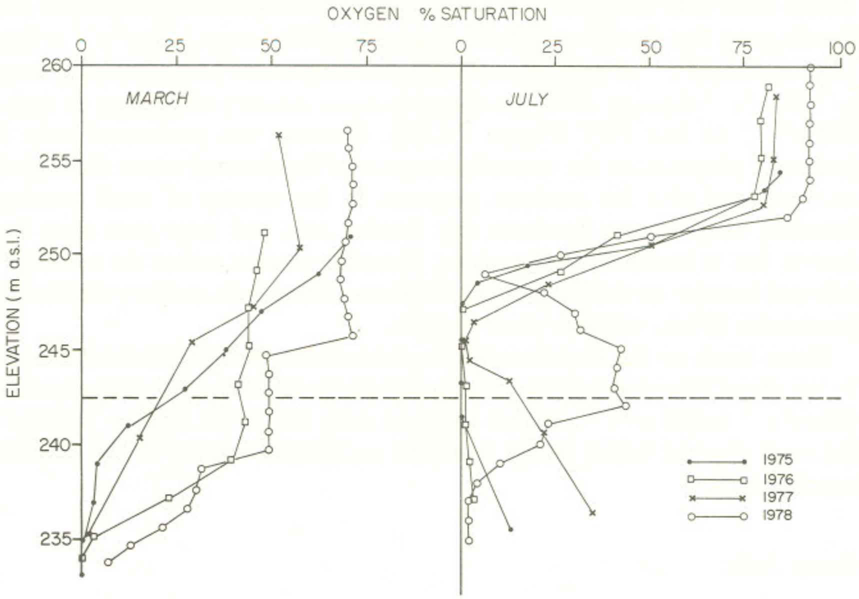


Figure 7.4.9 Winter (March) and summer (July) oxygen profiles for the eastern basin of Notigi Lake, 1975–1978. Because water levels rose steeply from 1975 through 1976, concentrations are plotted against elevations so that homologous strata may be compared from year to year. Pre-impoundment lake level is indicated by the dashed horizontal line

been flooded. The severity of oxygen depletion decreased from 1975 to 1978, during both summer and winter, perhaps indicating depletion of readily oxidizable material.

Flooding released nutrients from the soils and stimulated algal growth and accumulation. Mean chlorophyll concentrations after impoundment (16.8 mg m^{-3}) more than tripled from pre-impoundment concentrations (5.4 mg m^{-3}) and maximum chlorophyll concentrations in 1975 and 1976 (32.4–35.0 mg m^{-3}) were about four times the pre-impoundment maximum (8.6 mg m^{-3}) (Jackson and Hecky, 1980). Chlorophyll concentrations declined in subsequent years from the post-impoundment maximum. Integral primary production peaked in 1976 with rates of up to 1.76 g C m^{-2} d^{-1}. Algal biomass reached a high of 12 000 mg m^{-3} and was dominated by *Aphanizomenon flos-aquae*. Rates of primary production have been declining since 1976.

Oxygen profiles and algal production figures indicate that the reservoir experienced a rapid and intense increase in bacterial and primary production with flooding and that, subsequently, productivity declined rapidly, a response similar to more southerly reservoirs (Lowe-McConnell, 1973). The dramatic increase in flushing of the system from 1974–75 to 1978 may have hastened the decline of the productive upsurge.

7.4.5.3 Cross Lake

Cross Lake is located on the Nelson River, upstream of the confluence of diverted Churchill River water with the Nelson (Figure 7.4.1). The Jenpeg generating station was constructed at the main inflow of Cross Lake in 1974 to regulate the level of Lake Winnipeg. The flow entering Cross Lake, and the water level of the lake, are controlled by discharges through Jenpeg. Prior to regulation, Cross Lake had a mean depth of 2.4 m (open-water season) and a surface area of 460 km^2. After regulation, a minimum discharge of around 700 $m^3 s^{-1}$ into the lake resulted in a drawdown of 1.7 m below the historic mean open-water stage of 207.1 m (Gaboury and Patalas, 1981). Drawdown decreased lake volume by 53 per cent, decreased lake area by 26 per cent and decreased mean water depth to 1.5 m.

The regulation of Cross Lake has resulted in a number of severe environmental effects. Submergent vegetation was scarce prior to regulation (Driver and Doan, 1972; Ayles *et al.*, 1974), but proliferated after regulation (Gaboury and Patalas, 1981). Oxygen depletion in winter occurred only in isolated bays prior to regulation (Driver and Doan, 1972; Koshinsky, 1973), but now the decay of extensive areas of submergent vegetation can result in low dissolved oxygen levels ($< 3 mg l^{-1}$) during the winter. Surface water temperatures in the lake usually were <20 °C prior to regulation, whereas after regulation surface water temperatures of 21–26 °C are common. The frequently shallow post-regulation mean depth of the lake also apparently has resulted in high turbidity (Secchi disc transparency approximately 45 cm) through resuspension of the bottom sediments by wind (Gaboury and Patalas, 1981).

7.4.6 EFFECTS OF HYDROELECTRIC DEVELOPMENT ON FISHERIES

In this section, we present results of the following fisheries studies made along the Churchill and Nelson Rivers:

1. Catches and grade in the Southern Indian Lake whitefish fishery.
2. The effects of early spring drawdown on whitefish and cisco populations in Cross Lake.
3. Fish mercury levels in Southern Indian Lake and the diversion route lakes.

7.4.6.1 Grade of Whitefish Catch in Southern Indian Lake

Commercial catches of lake whitefish from Southern Indian Lake, the largest whitefish fishery in northern Manitoba, have changed since impoundment. The pre-diversion catch was characterized by A grade (Export) light coloured fish and relatively high mean catch per unit effort (CPE), but 5 years after impoundment, classification of the fishery was lowered to B grade (Continental) and CPE is only one-third of the pre-impoundment mean.

Prior to impoundment, top grade was maintained by selectively fishing certain basins of the lake. Effort was concentrated in region 4 (between Sand Point and Long Point) for fish landed at the Loon Narrows packing plant which received 80–85 per cent of the fish shipped from the lake (Figure 7.4.10A). After

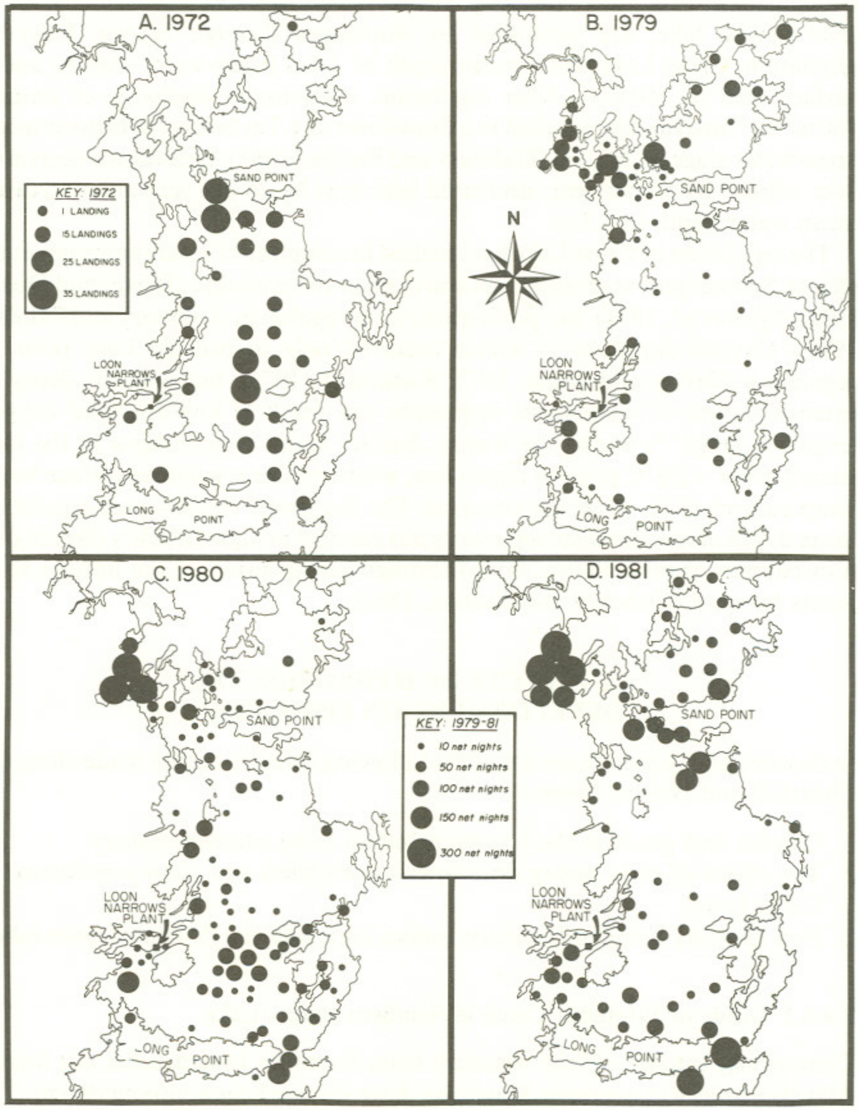


Figure 7.4.10 Geographical distribution of summer fishing effort for fish landed at the Loon Narrows packing plant, Southern Indian Lake, before impoundment (A: 1972) and after impoundment (B-D: 1979–81). From Bodaly *et al.* (in press, b). See Bodaly *et al.* (1980) for sampling methods

impoundment, this pattern of selective exploitation changed. In 1979, 1980 and 1981, the proportion of fishing effort expended in region 5 (north of Sand Point), outside of traditional areas, was 62 per cent, 30 per cent and 33 per cent, respectively (Figure 7.4.10B,C,D). Fish stocks being exploited in region 5 were composed largely of dark coloured, more heavily parasitized whitefish (Bodaly *et al.*, 1980; Bodaly *et al.*, in press, b). As a result of these changes, the total lake catch was composed of up to 81 per cent lower grade fish.

The change in the geographic distribution of fishing effort was a response by fishermen to sharp declines in CPE on traditional fishing grounds. Lake whitefish CPE on traditional fishing grounds for the summer fishery in 1972, prior to impoundment, was 23 kg standard net^{-1} 24 h^{-1} but declined to 14, 10.5 and 7.5 kg standard net^{-1} 24 h^{-1} in 1979, 1980 and 1981 (Figure 7.4.11). A corresponding decline has occurred in whitefish CPE for the winter fishery. Winter CPE on traditional fishing grounds decreased from 19 kg standard net^{-1} 24 h^{-1} in 1972–73 to 4 kg standard net^{-1} 24 h^{-1} in 1980–81 (Figure 7.4.11). Apparently, these catch declines are not the result of excessive fishing pressures

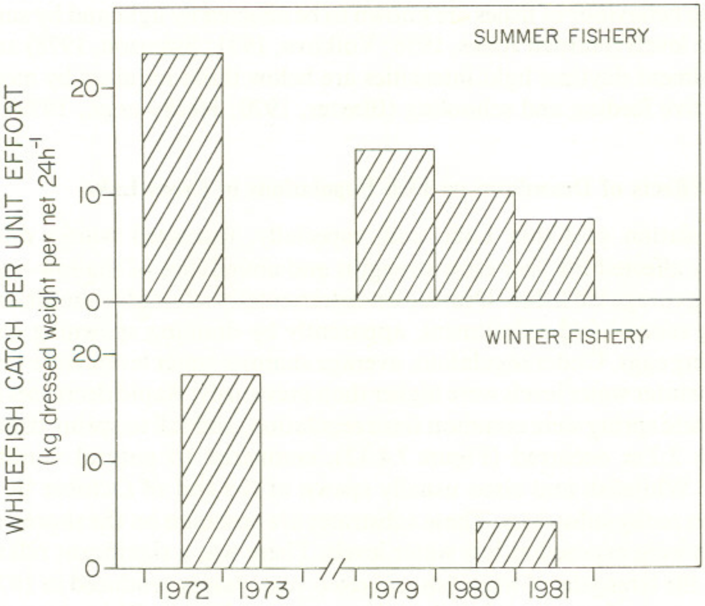


Figure 7.4.11 Lake whitefish catch per unit effort for the pre-impoundment (1972 summer and 1972–3 winter) and post-impoundment (1979, 1980, 1981 summer and 1980–1 winter) Southern Indian Lake commercial fishery. From Bodaly *et al.* (in press, b). Data are from traditional fishing areas adjacent to the Loon Narrows packing plant (see Figure 7.4.10). See Bodaly *et al.* (1980) for sampling methods

prior to impoundment (Bodaly *et al.*, 1980). Whitefish stocks before impoundment were relatively slow growing and old, had moderate mortality rates and, therefore, showed no signs of over-exploitation (Ayles, 1976). The whitefish catch had declined in the decade prior to impoundment as a result of decreased fishing effort, making depletion of stocks due to continued high fishing effort at the time of impoundment unlikely (Bodaly *et al.*, 1980). Furthermore, the age distribution of the post-impoundment whitefish catch has not changed significantly since flooding and the catch continues to be composed of relatively old fish with a number of year classes being represented (Bodaly *et al.*, in press, b).

Declines in whitefish CPE may be due to major movements of fish out of Southern Indian Lake in response to changes caused by lake impoundment. Large numbers of whitefish have been found congregating immediately below the Missi Falls control dam. Similar whitefish congregations were reported at the Lobstick control dam in Labrador (Barnes, 1981). Large numbers of fish have been noted also in the Southern Indian Lake diversion channel at South Bay. Emigrations of whitefish from Southern Indian Lake may have occurred in response to reduced light penetration in major lake basins. The distribution and schooling behaviour of fishes are known to be affected by light and by suspended sediment levels (Harden Jones, 1956; Volkova, 1971; Swenson, 1978) and post-impoundment daytime light intensities are below those required by most fishes for effective feeding and schooling (Blaxter, 1970; Hecky *et al.*, 1979).

7.4.6.2 Effects of Drawdown on Fish Populations in Cross Lake

The regulation of Cross Lake and, especially, increased winter drawdown adversely affected the year class strengths and abundance of shallow-water fall-spawning coregonid fishes. Drawdown detrimentally affected whitefish and cisco hatching success and recruitment, apparently by draining spawning areas and desiccating eggs. Under regulation, average summer water levels were lower and average winter water levels were higher than previously. Rapid decreases in water levels in late spring were common since regulation, and fall to spring drawdowns of up to 2.2 m occurred (Figure 7.4.12), compared to natural variations of < 0.5 m. Whitefish and cisco usually spawn at the end of October in shallow depths on rocky substrates. These substrates are common on the shores of Cross Lake but were exposed at low water levels. There was a significant relationship between the strengths of whitefish and cisco year classes produced in 1971–1980 and the extent of winter-spring drawdown (Figure 7.4.12). Weak year classes of whitefish and cisco resulted from years with a marked winter drawdown and strong year classes tended to result from years with little winter drawdown.

Catches of adult whitefish declined substantially after lake regulation, both in relative and absolute abundance. The relative abundance of whitefish declined 65 per cent from levels before regulation in 1965 and 1973 catches (Driver and

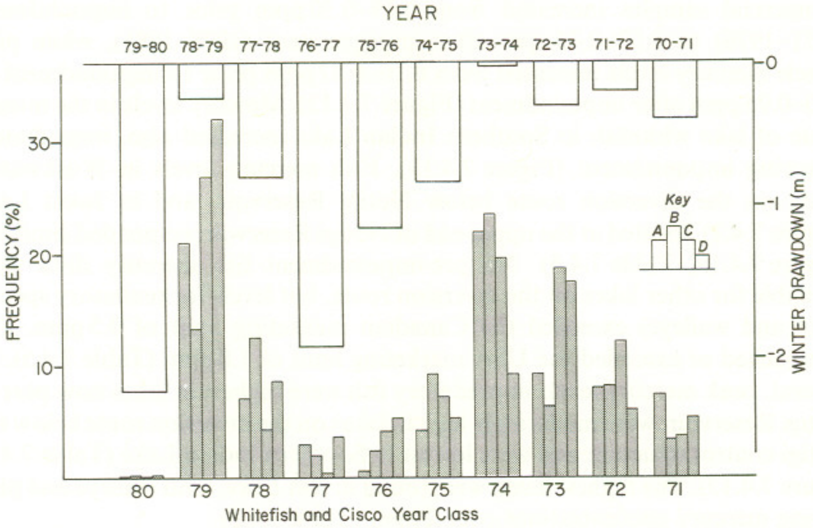


Figure 7.4.12 Relationship between winter and spring drawdown (white bars) and whitefish and cisco year class success (dark bars) in Cross Lake, 1971–1980. Winter and spring drawdown calculated as minimum level between October 28 and May 31 subtracted from level on October 28. A: per cent frequency of whitefish from 1980 gillnet catches; B: per cent frequency of whitefish from 1981 gillnet catches; C: per cent frequency of cisco from 1980 gillnet catches; D: per cent frequency of cisco from 1981 gillnet catches. See Gaboury and Patalas (1981, 1982) for sampling methods and ageing procedures

Doan, 1972; Ayles *et al.*, 1974), compared to catches in 1980 and 1981 (Gaboury and Patalas, 1981, 1982). Catch per unit effort of whitefish in 13.3 cm mesh declined from 35 fish 91 m net^{-1} night^{-1} in 1977 to 9 fish in 1980 and 4 fish in 1981 (B. Wright, personal communication; Gaboury and Patalas, 1981, 1982). Probable factors contributing to the decline in whitefish abundance include the effect of winter drawdown on year class strengths and recruitment, sudden declines in water levels which result in stranding and suffocation of fish in shallow bays and channels, and movements of fish out of Cross Lake.

7.4.6.3 Fish Mercury Levels

Reservoir formation has frequently been implicated as the cause of elevated mercury levels in fish (Potter *et al.*, 1975; Abernathy and Cumbie, 1977; Bruce and Spencer, 1979; Meister *et al.*, 1979). Increased fish mercury levels coincided with the creation of impoundments in the Churchill and Nelson River drainage basins and these higher levels led to restrictions on the commercial marketing of fish from ten impounded lakes.

In Southern Indian Lake, walleye muscle mercury concentrations from commercial samples increased from 0.19–0.30 ppm prior to impoundment (1971–1976) to 0.57–0.75 ppm after impoundment (1978–1981), while pike muscle mercury levels increased from 0.16–0.47 ppm prior to impoundment to 0.50–0.95 ppm after impoundment (Figure 7.4.13). Mercury levels in the muscle tissue of lake whitefish in Southern Indian Lake increased also, immediately following impoundment (Figure 7.4.13). Fish mercury levels in Wuskwatim Lake, on the diversion route below Notigi Reservoir, and in Issett Lake (Figure 7.4.1), located at the upper end of Notigi Reservoir, responded similarly (Figure 7.4.13, Table 7.4.5). No pre-impoundment fish mercury data were available for other lakes on the diversion route, but levels for predatory species (pike and walleye) exceeded the Canadian marketing limit of 0.5 ppm, and approached or exceeded the USA marketing limit of 1.0 ppm (Table 7.4.5). In general, peak mercury levels in predatory fish were highest in lakes now part of Notigi Reservoir, were moderately high in lakes on the diversion route below the Notigi control structure and were lowest in Southern Indian Lake (Table 7.4.5, Figure 7.4.13). The highest levels were found in Rat Lake, with walleye and pike having mercury concentrations over 2 ppm (Table 7.4.5).

Apparently, the fish mercury level increases observed following impoundment were due to the bioaccumulation of naturally occurring mercury. Neither agricultural activity nor known industrial mercury sources exist in the immediate vicinity of the lakes. Other lakes in the region unaffected by hydroelectric development have not experienced recent increases in the levels of mercury in fish and, therefore, atmospheric transport does not appear to be the cause of observed changes.

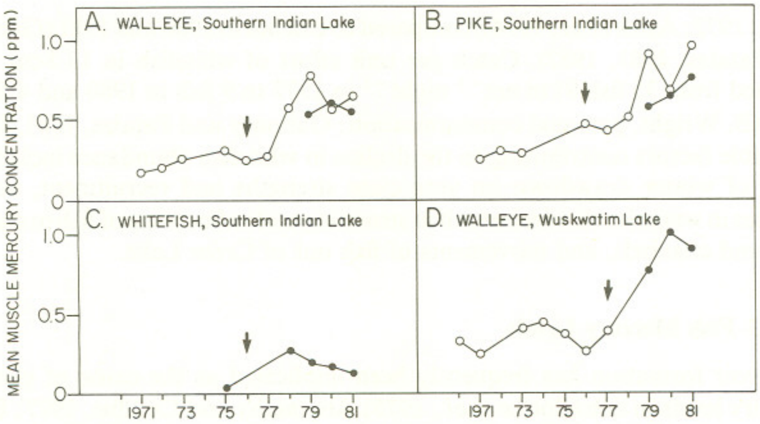


Figure 7.4.13 Fish muscle mercury levels from Southern Indian Lake and Wuskwatim Lake, 1970–1981. Arrows indicate year of impoundment. Open circles are means from one or more commercial samples; closed circles are means for survey samples (2–4 regions of the lake). See Bodaly and Hecky (1979) and Bodaly *et al.* (in press, a) for methods

Table 7.4.5 Fish mercury concentrations in lakes flooded by the Churchill River diversion project. S: survey sample; mercury concentration determined for individual fish. C: commercial sample; mercury concentration determined for a pooled sample of fish muscle tissue. See Bodaly and Hecky (1979) for details of sampling methods and analyses

Lake	Species	Year	Mean mercury concentration (ppm)	Number of samples and type of sample
Notigi Reservoir				
Issett	Whitefish	1975	0.15	24 S
		1978	0.32	5 S
	Pike	1978	0.61	5 S
Rat	Walleye	1978	2.56	26 S
		1979	2.32	25 S
		1980	1.15	22 S
	Pike	1978	2.05	24 S
		1980	2.32	1 C
Notigi	Walleye	1978	1.41	19 S
		1980	2.90	4 S
		1981	1.88	29 S
	Pike	1977	1.59	1 C
		1980	1.99	1 C
		1981	1.70	50 S
Below Notigi Reservoir				
Wapisu	Walleye	1977	1.17	91 S
	Pike	1977	1.08	38 S
Footprint	Walleye	1978	0.82	40 S
		1980	0.92	12 S
		1981	1.10	30 S
	Pike	1978	0.60	36 S
		1980	1.38	8 S
		1981	1.12	14 S
Threepoint	Walleye	1980	1.18	10 S
		1981	1.35	42 S
	Pike	1980	1.28	10 S
		1981	1.33	28 S
Mystery	Walleye	1979	1.13	33 S
	Pike	1979	0.79	45 S

Hypotheses concerning causes of elevated fish mercury levels in new impoundments have emphasized either increased amounts of potentially available mercury due to natural mercury present in inundated soils (Abernathy and Cumbie, 1977; Meister *et al.*, 1979) or increased retention of naturally transported mercury found on sediment (Potter *et al.*, 1975). Regional differences in peak mercury concentrations in fish from lakes affected by the Churchill River diversion suggest that the primary cause of elevated fish mercury levels is the mobilization of natural mercury from flooded soils. Highest fish mercury levels in the Churchill River diversion area occurred in lakes in Notigi Reservoir where ratios of area of flooded land to reservoir volume were greatest. The presence of flooded vegetation and soil organic matter promotes bacterial production and, therefore, may increase the rate of mercury methylation since it is well known that bacteria can methylate inorganic mercury under aerobic conditions (Jensen and Jernelov, 1969; Fagerstrom and Jernelov, 1971; Furutani and Rudd, 1980).

Recognition of enhanced mercury bioaccumulation as a result of reservoir formation is relatively recent. Mercury concentrations in predatory fish from new reservoirs can exceed 2 ppm, leading to the restriction of commercial marketing (McGregor, 1980) and to potential health problems for persons consuming large amounts of affected fish (Wheatley, 1979).

7.4.7 STABILIZATION OF THE ECOSYSTEMS

Under natural conditions, the potential energy of a river is expended by fluvial processes that carve and transport sediment from a myriad of channels that combine to form a river system. At any point in the system, the size and form of the river channel reflect the quantity of water conducted, the geological materials of the basin and the length of time that this particular combination of water and land has been in existence. The balance between the creation of land masses through crustal movements and the removal of the land surface by river erosion occurs over geological epochs that far exceed the record of man's observations. This natural rate of evolution is in strong contrast to the nearly instant change of diverting a river or flooding a lake. Such rates of rapid change are observed only during earthquakes or other catastrophic events and even these are seldom on the basin-wide scale of a river diversion. The rapid adjustment of a hydraulic regime is not followed by a rapid establishment of new stable values of other characteristics of the ecosystem. Instead, changes in the environment take place as natural forces which act on a geological time scale change the nature of their influence in the environment. Long-term instabilities occur through permafrost melting, erosion, sedimentation, turbidity changes and new flow regimes. The evolution of aquatic systems after river diversion and impoundment is not towards the original state before development, but rather towards a new state, the form of which depends on the nature of the water flow and water level manipulations as imposed by the hydroelectric utility involved.

This section summarizes our observations on the evolving, impacted ecosystems in the Churchill-Nelson diversion. The period of observation has extended for only 2–4 years after flooding and diversion and, therefore, it is difficult to predict the final form of these ecosystems or even to estimate how long it will be until they stabilize. Moreover, the ability to predict changes varies among trophic levels, being more accurate for organisms with life histories shorter than the period of observation than for more long-lived species.

7.4.7.1 Physical Stabilization

The rate of re-stabilization of the diversion systems can be estimated only at Southern Indian Lake where erosion data are available. Here, with the exception of shoreline monitoring sites in coarse granular materials (4 per cent of the total shoreline length), nearshore deposition of eroded materials has had no apparent effect in decreasing the rate of erosion. The melting, slumping and eroding sequence has not diminished for most of the shoreline and average annual erosion indices have been constant since the first full year of impoundment. Re-stabilization appears to depend upon the rate at which erosional retreat exposes bedrock underlying the backshore materials. Based on the assumption that the shoreline monitoring sites are representative of the eroding shorelines on Southern Indian Lake, a minimum restabilization period of 40 years has been estimated (Newbury and McCullough, in press).

7.4.7.2 Primary Production

The response of primary production in the reservoirs created by the Churchill-Nelson diversion has varied considerably and has depended on light, nutrients and other factors. In the two major basins of Notigi Reservoir, algal productivity followed a classical response to impoundment (Lowe-McConnell, 1973): an upsurge of productivity during flooding followed by a decline of algal biomass and oxygen demand to pre-impoundment levels within 2 years of impoundment. Backwater areas of Notigi Reservoir which have experienced poor flushing were still highly productive in 1981, relative to the main portion of the reservoir (Hecky, unpublished data), but primary production was depressed in humic back-water areas of the 3-year old Kettle Reservoir on the Nelson River (Jackson and Hecky, 1980). In Southern Indian Lake, no such surge was observed in regions with light limitation after impoundment (see section 7.4.4).

An upsurge of productivity can be expected if light conditions are adequate to allow effective utilization of nutrients from flooded soil. The intensity and duration of this productivity upsurge will depend on the relation between the area flooded and flushing time of the basin. Minimal flooding and rapid flushing will result in short periods of high production while more extensive flooding in a less rapidly flushed area will result in longer periods of high production. Humification also may occur in extensively flooded poorly flushed areas of northern reservoirs and this accumulation of dissolved humic materials may lead to lower productivity as essential trace metals become unavailable for algal growth (Jackson and Hecky, 1980). In Southern Indian Lake, where light limited conditions were caused by sediments eroding from shorelines, improvement in light conditions—and stabilization of algal productivity—will depend on shoreline stabilization.

7.4.7.3 Macrobenthic Invertebrates

It is difficult to generalize about the recovery period of macrobenthos in reservoirs (Wiens and Rosenberg, in press). Responses of individual taxa reported from other reservoirs did not occur in Southern Indian Lake but the relatively quick increase and decrease of overall standing crops after impoundment indicate that standing crops may stabilize soon. We believe this marginal impact in Southern Indian Lake to be due to an environmentally less disruptive type of reservoir formation but further monitoring should continue to determine the role of natural variation in the Southern Indian Lake Reservoir.

7.4.7.4 Zooplankton

The quantitative response of planktonic Crustacea to new conditions in Southern Indian Lake was rapid. In 1975, a period of unusually high water levels, plankton abundance decreased to 61 ind. l^{-1} from 76 ind. l^{-1} in 1972. With full impoundment in 1977, plankton abundance dropped to 44 ind. l^{-1} and remained at this level (40–46 ind. l^{-1}) from 1977 to 1980, the post-impoundment period. The zooplankton community should stabilize at its present level as long as dramatic changes are not made in present flow patterns and water levels in Southern Indian Lake.

7.4.7.5 Fish Populations

Fish species composition in temperate reservoirs depends largely on physical conditions affecting spawning success (Beckman and Elrod, 1971; Aass, 1973; Walburg, 1977). In Southern Indian Lake, spawning conditions probably will be affected by the characteristics of both flooded shores and flooded terrestrial vegetation, and sedimentation resulting from shore erosion. Since current estimates of the time until shorelines stabilize are in the range of several decades, fish populations probably will not stabilize for some time. The current period of observation on Southern Indian Lake has been too short to observe changes in recruitment due to impoundment because the fish species of interest have long generation times.

It has been hypothesized that elevated fish mercury levels resulting from lake impoundment may decline within 5–10 years as source mercurials in terrestrial material are depleted (Meister *et al.*, 1979) or become less available to the aquatic systems (Abernathy and Cumbie, 1977). However, there are still no clear trends towards decreasing fish mercury levels after 5 years of post-impoundment observations on lakes affected by the Churchill River diversion.

7.4.7.6 Conclusion

Shoreline erosion and altered light penetration have been the most dramatic physical changes resulting from creation of the Southern Indian Lake Reservoir. Biological changes have differed greatly, depending on trophic level. There have been some shifts and/or compensation to the new environment in production of algae, zoobenthos and zooplankton. In contrast, fish stocks have apparently undergone dramatic redistributions and their mercury levels have affected marketing. It has been hypothesized that these biological changes have co-occurred independently of trophic relationships, but that each is dependent directly on physical changes in the new reservoir. However, continuing research on the Southern Indian Lake Reservoir is needed to elucidate possible altered trophic relationships.

7.4.8 MITIGATION AND PLANNING

Instabilities caused by river diversion and lake impoundment can be corrected only partly by remedial works that follow project construction because of the dramatic reorganization associated with hydroelectric development (Newbury, 1981). Weirs and control structures to adjust lake levels have been suggested but not yet implemented at several lakes outlets in the Nelson and Lower Churchill rivers. Studies on Cross Lake, for example, demonstrate the importance of the maintenance of fall water levels for producing strong coregonid year classes. A weir constructed at the outlet of Cross Lake could maintain an acceptable minimum water level during the open-water season, minimize the loss in water volume and area, and improve fish production. A controlled stage could improve hatching success of whitefish and cisco in years of restricted flows and would decrease the possibility of fish kills through stranding and suffocation, by damping the rate of drawdown. A weir would not restore the natural water level regimes (increased water levels during spring), so spawning success of walleye and pike might not benefit, but weirs could be operated to manage primary production by optimizing water retention time relative to nutrient loading (Vollenweider, 1976).

Bank and shoreline protection works were successfully constructed at communities, graveyard sites and highway crossings affected by impoundment and diversion. However, the cost of extending these protective works to all lakes and channels of the diverted system was considered prohibitive. Major pre-impoundment clearing of the forested backshore was undertaken for aesthetic reasons along short sections of the Southern Indian Lake impoundment. However, this clearing was rendered useless at many sites by the erosion and elimination of the cleared backshore zone in the first 2 years after impoundment.

Independent development of hydroelectric potentials on the lower Churchill River would have displaced 2000 MW less energy than the Churchill River diversion by avoiding the impoundment of Southern Indian Lake, flooding of the

Rat and Burntwood valleys and abandonment of the lower Churchill River (Newbury, 1981). The lower Churchill River is a potentially favourable site, environmentally, for reservoir creation because it has a high, ice-scoured bank and impounded levels usually would not exceed bank height. The decision to divert the Churchill River was made solely on the basis of favourable relative cost estimates, but compensation costs for resources lost due to the project were not considered and will probably be substantial over the long term.

Many of the major environmental effects of hydroelectric development documented here were completely unpredicted or only poorly predicted by pre-development impact studies. Experience with more southerly reservoirs has not been easily transferred to this case history study. The comparison of actual to predicted impacts becomes increasingly important as hydroelectric development continues in subarctic and arctic areas. Furthermore, reservoir studies should progress beyond a case history approach and rely more on experimental manipulations to test hypotheses concerning underlying causes for observed changes.

7.4.9 SUMMARY AND CONCLUSIONS

1. Lakes impacted by the Churchill–Nelson hydroelectric development are located on the Canadian Shield, within the boreal forest zone. They were generally relatively shallow and rapidly flushed and were classified as oligotrophic or mesotrophic. The benthic macroinvertebrate faunas were dominated by chironomids, amphipods, oligochaetes and sphaeriids and standing crops were generally enhanced by rapid water renewal times. The crustacean zooplankton communities were dominated by copepods and standing crops were reduced by rapid water renewal times. Diversity of fish was low and the fauna was dominated by relatively few cool-water species. The most important commercial species were lake whitefish, walleye and northern pike.
2. Hydroelectric development of the Churchill and Nelson rivers has a potential total generating capacity of 8400 MW. Most of the flow of the Churchill River was diverted into the Nelson River for power production on the lower Nelson. The natural outlet of Southern Indian Lake, through which the Churchill River flowed, was dammed and the level of the lake was raised 3 m above long-term mean levels. The lower Churchill River valley was abandoned. A newly excavated channel diverted flow from the lake into the headwaters of the Nelson River drainage (Rat and Burntwood River valleys).
3. Abandonment of the lower Churchill River valley resulted in halving of pre-diversion mainstem lake areas. A total of 409 km^2 of land was flooded in the Rat River Valley to create the 476 km^2 Notigi Reservoir. Lakes on the Burntwood River were flooded by 3–5 m due to greatly increased diversion flows. Spring and summer drawdown on Cross Lake (upper Nelson River) resulted in a 26 per cent decrease in lake area.

4. Impoundment of Southern Indian Lake caused severe erosion of fine-grained glacial clays along shorelines. Light penetration was reduced in the main basins because of eroded clay in suspension. In contrast, shoreline erosion in the Rat and Burntwood River valleys was minimal, despite extensive glacial clay deposits throughout the area, because of relatively short wind fetches.

5. The response of primary production to impoundment and diversion depended on specific conditions within the manipulated ecosystems. In the main basins of Southern Indian Lake, increased suspended sediment levels reduced light penetration so increased concentrations of soluble reactive phosphorus from flooded shorelines could not be used and integral primary production remained unchanged. Light penetration was unaffected in Notigi Reservoir and in small bays of Southern Indian Lake and integral primary production increased significantly in response to increased nutrients originating from flooded soil and vegetation. Sequestration of essential trace metals by humic substances depressed primary production in some humic-rich backwater areas.

6. Macrobenthic invertebrate standing crops in Southern Indian Lake increased after impoundment and, within 3 years, decreased towards pre-impoundment abundances. A high degree of species diversity was maintained and there was no evidence of a succession of macrobenthic taxa due to impoundment. The crustacean zooplankton community of Southern Indian Lake responded to impoundment with reduced standing crops, especially in areas of the lake subjected to significant changes in post-diversion flows. Significant increases occurred in the abundance of some large species after impoundment.

7. Fish mercury levels increased soon after impoundment in Southern Indian Lake and lakes in the Rat and Burntwood River valleys. Post-impoundment predatory fish mercury levels ranged from approximately 0.5 ppm to > 2.5 ppm, appeared to be related to the severity of flooding in the various new reservoirs, and appeared to be due to the mobilization of natural soil mercury. Mercury levels in predatory fish had not declined 5 years after impoundment.

8. The grade of the commercial whitefish catch in Southern Indian Lake declined significantly immediately following impoundment. Lower grade fish constituted from 12 to 72 per cent of catches in the 4 years following impoundment whereas they were nearly absent from pre-impoundment catches. Catch per unit effort of top grade whitefish on traditional fishing grounds decreased to one-third of pre-impoundment values.

9. Late spring drawdown of Cross Lake reduced year class strengths and abundance of shallow-water autumn-spawning coregonid fishes. There was a significant relationship between the strengths of whitefish and cisco year classes produced in 1971–1980 and the extent of winter-spring drawdown, due probably to desiccation of spawning areas and eggs.

10. A shoreline restabilization period of at least 40 years is estimated for Southern Indian Lake so elevated suspended sediment levels will continue. Stabilization of biological processes such as primary production and fish reproductive success will

depend on reduction of suspended sediment levels and sedimentation rates. Biological changes observed at different trophic levels in Southern Indian Lake appear to have co-occurred independently and in response to physical changes in the lake environment.

11. The widespread nature of changes caused by hydroelectric impoundment and river diversion renders most remedial measures impractical and uneconomic. Bank protection measures over long distances and timber clearing of land to be flooded are prohibitively expensive. As well, a cleared shore zone can be quickly eliminated by bank erosion in areas of high wave exposure. However, weirs can be effective to restore or maintain levels in lakes subject to reduced flow or drawdown.

12. Flooding and river diversion disrupt the natural rate of evolution of aquatic systems. Deleterious environmental effects can be minimized if predicted environmental impacts and alternative development schemes are seriously considered in the planning process. Alternate schemes can be evaluated by comparing the amount of energy displaced by each.

13. Many of the major environmental effects of flooding and river diversion were either poorly predicted or completely unpredicted in the Churchill–Nelson system, despite extensive pre-development studies. Comparisons of actual to predicted impacts are necessary to improve impact prediction for arctic and subarctic hydroelectric developments.

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