Water Budgets for Southern Indian Lake, Manitoba, Before and After Impoundment and Churchill River Diversion, 1972 - 1979

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WATER BUDGETS FOR SOUTHERN INDIAN LAKE, MANITOBA, BEFORE AND AFTER IMPOUNDMENT AND CHURCHILL RIVER DIVERSION, 1972-1979

by

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Water budgets have been determined for Southern Indian Lake in northern Manitoba, for the whole lake and for individual basins, to quantify changes in patterns of flow and water exchange times due to impoundment and diversion of the Churchill River. Calculated natural exchange times for various basins of Southern Indian Lake vary from 0.012 to 4.2 years. The budgets indicate that in basins along the path of the Churchill River both before and after diversion exchange times are not greatly changed. In those basins isolated from the Churchill River both before and after diversion exchange times are doubled due to increased lake volume. In two northern basins away from which 80% of the Churchill River flows have been diverted exchange times are increased by an order of magnitude. In South Bay, through which the Churchill River has been newly diverted, the gross exchange time has been decreased by two orders of magnitude.

Key words: diversion; flushing; impoundment; reservoir hydrology; water budget; water exchange time; water residence time.

RESUME

McCullough, G.K. 1981. Water budgets for Southern Indian Lake, before and after impoundment and Churchill River diversion, 1972-79. Can. MS Rep. Fish. Aquat. Sci. 1620: iv + 22 p.

Le bilan hydrologique pour le Southern Indian Lake (nord du Manitoba) a été établi pour le lac dans son ensemble et pour des bassins pris séparément, afin d'évaluer quantitativement les variations dans le mode d'écoulement et les durées d'échange d'eau, provoquées par l'aménagement du lac en réservoir et par le détournement de la Churchill River. On a constaté que la durée d'échange d'eau pour divers bassins du Southern Indian Lake varie de 0.012 à 4.2 années. L'étude du bilan hydrologique pour les bassins situés le long de la Churchill River, tant avant qu'après le détournement de la rivière, révèle que la durée d'échange n'a pas beaucoup varié. Quant aux bassins isolés de la rivière étudiés avant et après le détournement, la durée d'échange a doublé par suite du volume accru du lac. Dans deux bassins nord qui ne reçoivent que 20% du débit de la rivière, la durée d'échange n'a augmenté que d'un ordre de grandeur. Dans la South Bay qui vient de commencer à recevoir l'eau du détournement, la durée a diminué de deux ordres de grandeur.

Mots-clés: détournement; inondation; bassin; hydrologie (réservoir); bilan hydrologique; durée d'échange de l'eau; durée de séjour de l'eau.

INTRODUCTION

Southern Indian Lake lies at 57°N 99°W in northern Manitoba. (Fig. 1,2). It is an irregular broadening of the Churchill River infilling depressions in the rolling bedrock-controlled terrain of the Precambrian Shield, 285 km in length and 6 to 30 km in width. Where it enters Southern Indian Lake, the Churchill River has drained 148,400 km^2 in the Shield and 93,600 km^2 in the adjacent Great Plains. An additional 14,000 km^2 of Shield terrain drains into Southern Indian Lake via streams directly tributary to the lake.

To facilitate the diversion of the Churchill River southwards in 1976, the mean level of Southern Indian Lake was raised by a dam across the outlet at Missi Falls. The level was raised from 255 m MSL with a natural range from 254.5-256 m, to 258 m MSL with a regulated range of 1 m (Fig. 3). The surface area of the lake was increased from 1977 km^2 to 2391 km^2. The Churchill River was diverted southwards through South Bay into the Rat-Burntwood River system, to supply additional water to hydroelectric plants on the lower Nelson River. With diversion operating at the limit of licence to Manitoba Hydro, approximately 816 m^3s^{-1} are diverted from the mean annual Churchill River discharge of 958 m^3s^{-1}.

Limnological and biological studies have been undertaken on Southern Indian Lake to document the effects of impoundment and diversion. To interpret these studies and to quantify changes in patterns of flow and water exchange times in the basins of the lake, water budgets have been determined for the period 1972 to 1979, for the whole lake and individually for each of 8 regions within the lake. These water budgets are presented in Tables 9, 10 and 11.

METHODS

DETERMINATION OF THE WHOLE LAKE WATER BUDGETS

The water budget of a lake is an expression of the equality of the rate of change in lake volume with the rate of water input minus the rate of water loss (Chow, 1964, p. 1-4. Hutchinson, 1957, p. 231). For a discrete time period the equality can be expressed as:

Input = output ± Change in storage

Considering significant sources of input and output individually, the water budget for Southern Indian Lake can be expressed as:

$$Q_{LR} + Q_{local} + P = Q_{MF} + Q_{SB} + E \pm \Delta S$$

where:

Q_{LR} = Churchill River flow at Leaf Rapids

Q_{local} = Flow from all other streams and direct runoff areas discharging into Southern Indian Lake.

P = Precipitation falling on the lake surface.

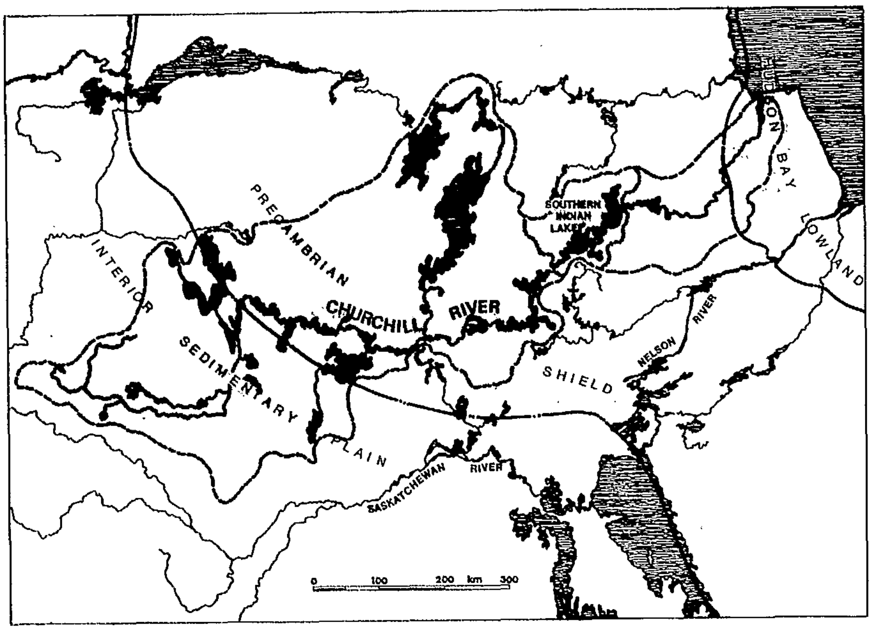

Fig. 1. Southern Indian Lake showing the Churchill River drainage basin bounded by a dashed line. Local drainage area influent to Southern Indian Lake is indicated by dotted lines.

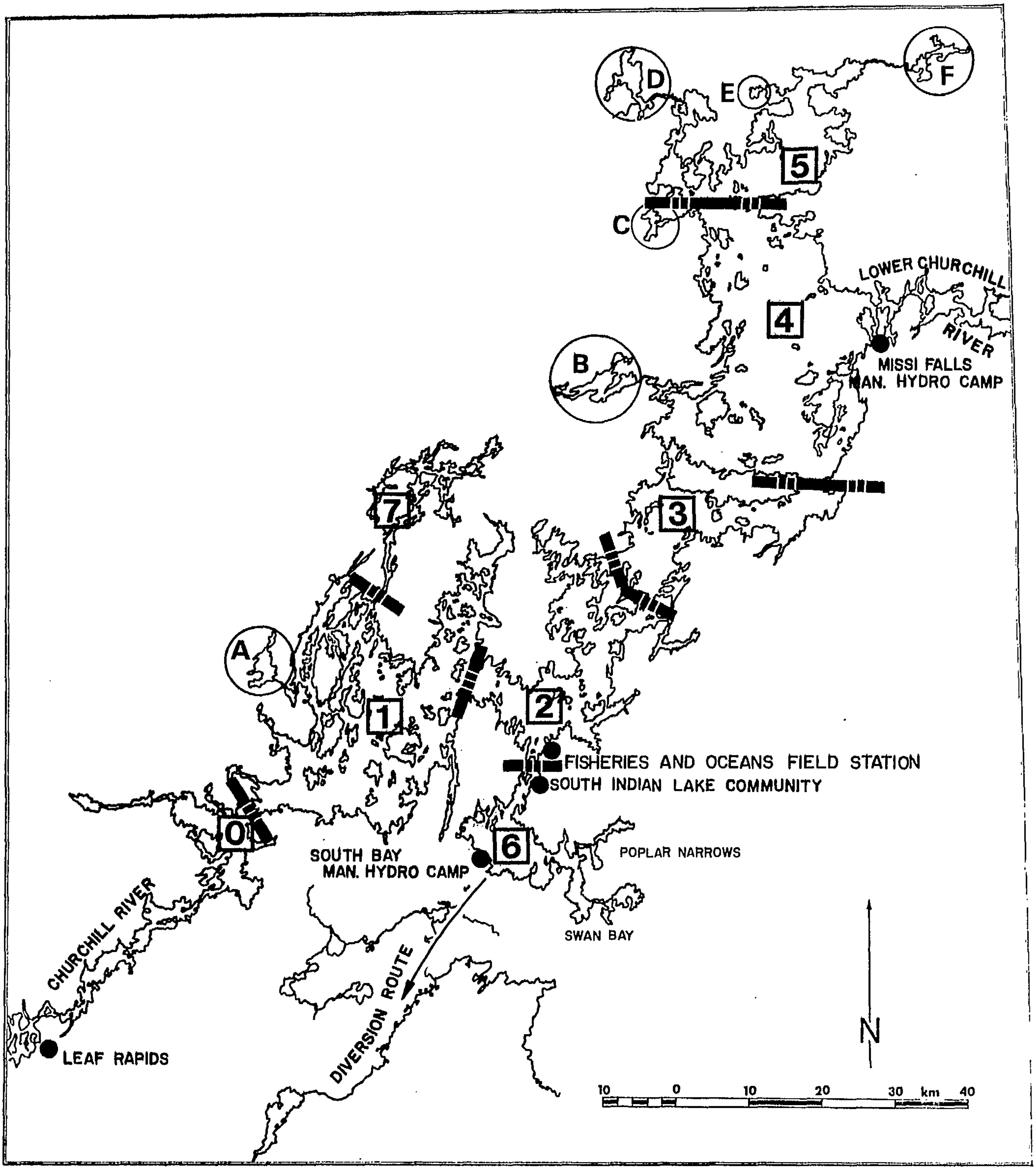

Fig. 2. Southern Indian Lake indicating regional subdivision. Precipitation, temperature and wind records have been maintained for various periods at the Manitoba Hydro camps at Missi Falls and South Bay and at the Freshwater Institute camp near the South Indian Lake community. Circles indicate adjacent lakes incorporated into Southern Indian Lake by impoundment.

Q_{MF} = Churchill River flow at Missi Falls.
Q_{SB} = Diversion route flow at South Bay outlet.
E = Net evaporation from the lake surface.
ΔS = Storage change in Southern Indian Lake where + ΔS corresponds to a rise in lake level.

Groundwater flow into Southern Indian Lake is not considered independently. It is a minor component of the total input as most of the nearshore areas are underlain by impervious bedrock covered by a thin mantle of clay till and/or lacustrine clay of low permeability. Local inflow calculations are based on measured streamflows which include essentially all the groundwater input as baseflow.

Evaporation calculations compute net evaporation; thus condensation is not considered separately. Based on estimates using a mass transfer formula developed by Kuzmin in the U.S.S.R. (Gray 1970), winter snow sublimation is assumed negligible. This agrees with results reported by Meyer (1915, Fig. 12) based on data from lakes in the northern United States.

Redistribution of snow on the lake surface by wind erosion is neglected as the effect would be within error of stage measure and the spring snowmelt estimate.

Churchill River Inflow (Q_{LR})

For the period 1973 to 1979 Water Survey of Canada (1973-79) discharge data for the Churchill River at Leaf Rapids were used.

As no discharge data is available for the Churchill River at Leaf Rapids before 1973, the mean monthly discharges for 1974 and 1975 were correlated with corresponding data for the Churchill River at Granville Falls to give the following regression equation:

$$Q_{LR} - 1.10\ Q_{GF} - 265\ (n = 24,\ r^2 = 0.97)$$

where:

Q_{LR} = Churchill River monthly discharge at Leaf Rapids (ft^3s^{-1})
Q_{GF} = Churchill River monthly discharge at Granville Falls (ft^3s^{-1}).

Water Survey of Canada (1972) mean monthly discharges for the Churchill River at Granville Falls were inserted into this regression equation to estimate discharges at Leaf Rapids during 1972.

Local Inflow (Q_{local})

First estimates of monthly local inflow to Southern Indian Lake were based on drainage area-discharge correlations for the rivers and streams listed in Table 1. These rivers and streams lie in a band in the latitude of the Southern Indian Lake local drainage area stretching approximately 400 km to east and west. Regressions were calculated for each month according to the model:

$$\text{Monthly discharge} = a\ (\text{drainage area})^b$$

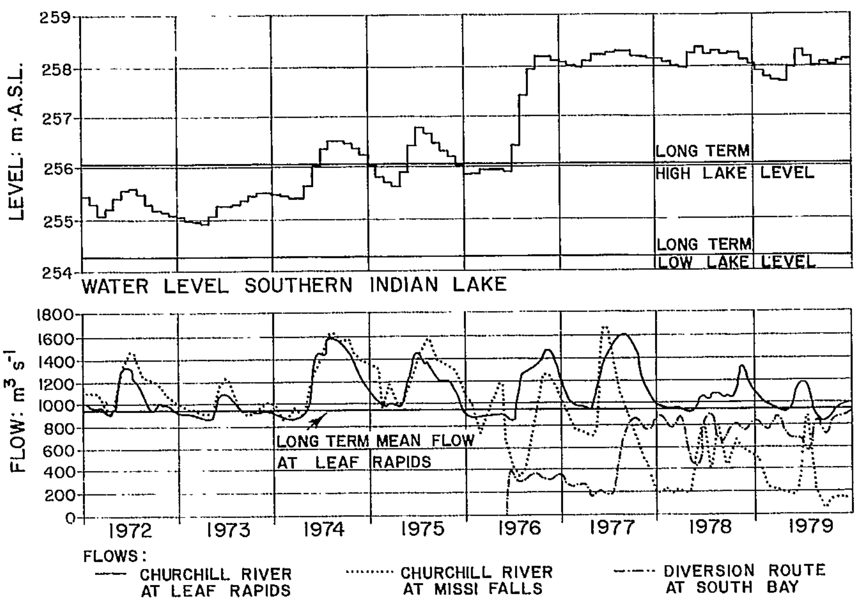

Fig. 3. Hydrographs of Southern Indian Lake levels, Churchill River flows at Leaf Rapids and Missi Falls, and Diversion Route flows at South Bay, based on Water Survey of Canada (1956-79) data. Flows at Leaf Rapids are estimated from a regression relationship with Churchill River flows at Granville Falls.

Table 1. Rivers and streams for which flow records were used in drainage area - discharge correlations. Discharge and drainage data for all rivers except Tumblewell and Sandhill are from Water Survey of Canada (1972-79). For Tumblewell and Sandhill Streams data are from unpublished records of the Freshwater Institute, Canada Department of Fisheries and Oceans. The latter discharges are based on continuous stage records and stage-discharge relationships established for a weir on Tumblewell stream and for a section of rapids on Sandhill stream. (x = complete annual records, i = partial record only.)

	Periods of record								
River	1972	1973	1974	1975	1976	1977	1978	1979	Drainage Area (km^2)
Tumblewell						i	i		4.23
Sandhill							i		101.7
Footprint						i	x	x	598.3
Pagato		i	x	x	x	x	x		973.8
Barrington			i	i	i	x	x	x	1770
Kettle	x	x	x	x	x	x	x	x	1958
Wheeler		i	i	i	i	x	x		2437
Limestone	x	x	i	i	x	x	x	x	3160
Little Beaver	i	i	x	x	x	x	x	x	4248
Little Churchill	x	x	x	x	x	x	x	x	5439
Upper Burntwood								i	6656
South Seal	x	x	i	x	x	x	i	i	12170

where "a" and "b" are regression coefficients determined from available stream flow data.

The local drainage area was subdivided according to drainage area/stream as indicated in Tables 2 and 3. Mean drainage area/stream was then applied to the monthly regressions and discharges were summed to give an estimate of total monthly local inflow.

Table 2. Local drainage area: Rivers. Drainage area data are from Cleugh (1974). Cleugh's drainage areas have been altered for the Barrington River (data from Water Survey of Canada Winnipeg office, personal communications), and for the MacBride River (area determined by planimeter measurement on 1:250,000 scale N.T.S. map).

Name	Region[a]	Drainage Area (km^2)
Muskwesi River	5	2353
Grandmother River	7	1904
Barrington River	0	1770
Waddie River	5	1035
	4	619
	7	505
MacBride River	0	362

[a] Southern Indian Lake is subdivided into seven regions. See Fig. 1.

For the calculation of the regression parameters, data from four to eleven streams were used as available, resulting in coefficients of correlation averaging 0.7 but ranging from 0.2 to 0.98. The dearth of data, especially in the early years of the period considered, and the presence of some very low coefficients of correlation made a test of the results advisable. Calculated monthly local inflows (converted to mm depth/watershed) were plotted against hydrographs for the Barrington, South Seal, Little Churchill and Pagato Rivers for the available periods of record (Fig. 4). Some divergence was to be expected in these hydrographs as the watersheds vary in area, climatic regime and, to some extent, physiography. It was assumed that the local inflow hydrograph need not equal the mean of the hydrographs but should fall approximately in the range plotted. The Southern Indian Lake local inflow has a much smaller average drainage area per stream than the rivers used to calculate regression parameters, and has a smaller potential for storage. Thus it was further expected that deviations from the mean of the hydrograph plot would be those associated with shorter response time to precipitation and snowmelt events and with generally low winter discharge.

Adjustments were made to the first estimates of monthly local inflow calculated from the regressions based on inspection of the plotted hydrographs and of the residual value of the Southern Indian Lake water budget equation when all other components had been applied. The second estimate had to fulfill two requirements:

1. change from the first estimate must improve the balance of the water budget equation.
2. change from the first estimate must improve the fit of the local inflow hydrograph with the other plotted hydrographs in accordance with the previously discussed considerations.

Monthly local inflow values as determined above are plotted in Fig. 4.

Precipitation (P)

Depth of precipitation was multiplied by lake area (Cleugh et al. 1974, Tables 2, 5) to

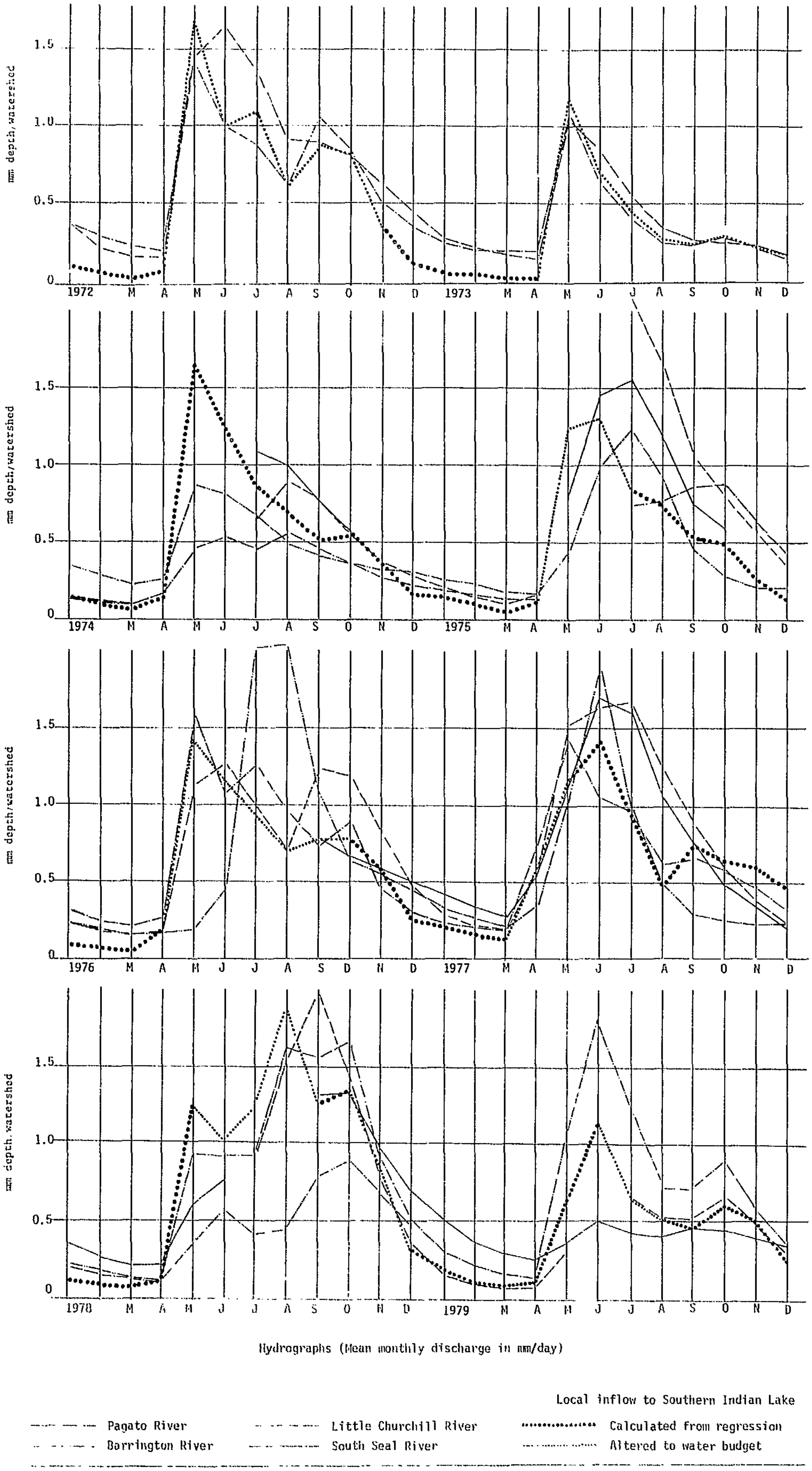

Fig. 4. Hydrographs of calculated monthly local inflow to Southern Indian Lake and rivers nearby. Data for the Pagato, Barrington, Little Churchill and South Seal Rivers is from Water Survey of Canada (1972-79).

Table 3. Local drainage area: Streams and direct runoff areas. Drainage area data are from Cleugh et al. (1974). Cleugh lists 180 km^2 of drainage area in the <10 km^2/stream class but does not include direct runoff areas. Estimate of additional small stream and direct runoff area is based on planimeter measurement on 1:250,000 scale N.T.S. maps.

Range of drainage areas/stream (km^2)	Mean drainage area/stream (km^2)	Drainage area (km^2)
160 - 360	232.71	698
80 - 160	111.01	888
40 - 80	51.69	827
20 - 40	27.67	498
10 - 20	14.74	443
Pre-impoundment <10	-	2146
Post-impoundment <10	-	1790

Total local drainage area, including areas listed in both Tables 2 and 3. (km^2):
Pre-impoundment: 14048 Post-impoundment: 13692

Table 4. Comparison of precipitation data from various stations, using concurrent observations.

Number of months	Mean of monthly precipitation at S.I.L. (mm)	Standard deviation (mm)	Mean of monthly difference in precipitation (mm)	Standard deviation (mm)
(Mean of Southern Indian Lake stations) - (mean of Lynn Lake and Thompson)				
Winter 19	19.7	10.5	-0.7	5.3
Summer 33	63.1	33.6	0.3	18.4
(Mean of South Bay and Freshwater Institute Stations) - (Missi Falls Station)				
Winter 6	-	-	-11.9	8.6
Summer 16	-	-	- 6.4	21.6

give monthly volume of water precipitated on the lake surface. Precipitation data (Atmospheric Environment Services, 1972-79) from the nearest operating weather stations were used. Mean values were calculated from data from stations as listed below:

Period	Stations
Jan. 1972 - Oct. 1973	LL, T
Nov. 1973 - May 1976	MF, SB
Jun. 1976 - Sep. 1976	MF, SB, SIL
Oct. 1976 - Apr. 1977	LL, T
May 1977 - Nov. 1977	SIL
Dec. 1977	LL, T
Jan. 1978 - Sep. 1979	SIL
Oct. 1979	LL, T
Nov. 1979 - Dec. 1979	SIL

where:

LL = Lynn Lake
T = Thompson
MF = Missi Falls, Hydro camp
SB = South Bay, Hydro camp
SIL = South Indian Lake community, Freshwater Institute camp.

As indicated in Table 4, the average difference in precipitation between the Southern Indian Lake stations and the mean of the Lynn Lake and Thompson stations is small, although the standard deviation of the difference exceeds 25% of the mean monthly precipitation. Thus use of Lynn Lake and Thompson data may have resulted in a considerable error in the monthly value.

Mean monthly precipitation at Missi Falls is higher than at South Indian Lake community for the short period of concurrent observation. Use of community data only for most of 1977 to 1979 may have resulted in an underestimate of precipitation for the whole lake; however insufficient data exists to justify calculating a correction factor.

Churchill River Outflow (Q_{MF})

As no discharge data is available for the Churchill River at Missi Falls before 1976, mean monthly discharges for 1976-1978 were correlated with corresponding data for the Churchill River at Fidler Lake. Outflow at Missi Falls was controlled by Manitoba Hydro during this period; thus only those months for which month to month discharge fluctuations were within a natural range were used in calculating the relationship.

Regression equation:

$$Q_{MF} = 0.82\ Q_{FL} + 2530 \quad (n = 9,\ r^2 = 0.90)$$

where:

Q_{MF} = Churchill River monthly discharge at Missi Falls (ft^3s^{-1})

Q_{FL} = Churchill River monthly discharge at Fidler Lake (ft^3s^{-1})

Water Survey of Canada (1972-75) mean monthly discharges for 1972-1975 for the Churchill River at Fidler Lake were inserted into this regression equation to estimate discharges at Missi Falls. Measured discharge data supplied by Manitoba Hydro were used for the period 1976-79.

Diversion Route Outflow (Q_{SB})

All discharge data for the South Bay diversion were supplied by Manitoba Hydro. These data are calculated from measured level differences between South Bay and the Notigi Reservoir and a calculated channel roughness.

Manitoba Hydro data as supplied indicate 0 m^3s^{-1} discharge for the months of August, September and October, 1976. As flow had begun in the diversion channel in June and could not have been stopped without lowering of Southern Indian Lake level (which did not occur), or raising the Notigi Reservoir level to Southern Indian Lake level while stopping flow at the Notigi Dam (which also did not occur), the residuals of the water budget equation when all other components had been applied were assigned entirely to the diversion route outflow.

Evaporation (E)

Monthly evaporation was calculated using the Meyer (1942, p. 12) form of mass transfer equation:

$$E = 53\ (1+0.1V_{7.6})(e_s - e_a)$$

where:

- E = evaporation (mm)
- $V_{7.6}$ = wind velocity at 7.6 m A.G.L. ($km\ h^{-1}$)
- e_s = vapour pressure of saturated air at the temperature of the water surface (kPa)
- e_a = actual vapour pressure of the air (kPa)

The coefficient 53 is the coefficient developed for small lakes near Kenora, Ontario based on comparison with water budget derived evaporation data (Newbury and Beaty, 1977). The coefficient 53 is the equivalent of 7 in the mass transfer equation where wind is measured in mph, pressure in inches of mercury and evaporation in inches per month. Comparison with Meyer's (1942, p. 12) coefficients for lakes and ponds indicates that this is a suitable value for a large lake, and implies that many adjacent small lakes (the northwestern Ontario case) are like an isolated large lake in their capacity to saturate the near surface atmosphere.

Evaporation calculated as depth of water over the lake surface was multiplied by lake surface area (Cleugh et al. 1974, Tables 2,5) to give monthly volume of water evaporated.

To bracket the periods during which a liquid surface was open to the atmosphere, ice break-up and freeze-over dates as calculated by R. Hecky (unpublished manuscript) and tabulated below were used. Date of break-up is considered to be the intersection of the forty day running mean temperature (mean of Lynn Lake and Thompson data) with 5°C and freeze-over the intersection with 0°C. Such calculated dates have corresponded well with observed dates of break-up and freeze-over in 1977-79.

Year	Date of Break-up	Date of Freeze-over
1972	25 May	20 October
1973	28 May	5 November
1974	7 June	20 October
1975	29 May	3 November
1976	26 May	3 November
1977	12 May	18 November
1978	31 May	7 November
1979	10 June	7 November

Wind ($V_{7.6}$): Wind speed data (Atmospheric Environment Service 1972-79) from operating stations as listed below were used.

Period	Stations
Jan. 1972 - Jun. 1974	LL, T
Jul. 1974 - May 1976	LL, T, MF
Jun. 1976 - Sep. 1976	LL, T, MF, SIL
Oct. 1976 - Dec. 1979	LL, T, SIL

where:

- LL = Lynn Lake
- T = Thompson
- MF = Missi Falls, hydro camp
- SIL = South Indian Lake community, Freshwater Institute camp

Wind speed data from each station was corrected to a standard 7.6 m above ground level (A.G.L.) using a power relationship with an exponent of 0.25 as determined by Buckler (1969) for various prairie sites in western Canada.

Use of 0.25 gives the following correction factors:

	Anemometer height (m A.G.L.)	Factor used to correct to 7.6 m A.G.L.
Thompson	15.2	0.84
Lynn Lake	10	0.93
Missi Falls	9	0.96
South Indian Lake community to November 1978	3[a]	1.3
South Indian Lake community after December 1978	9	0.96

[a]Measured above surrounding tree tops

The mean of the corrected wind speeds was assumed to represent mean monthly wind speed over land and was corrected to over water values using factors for the Great Lakes region reported by Richards and Phillips (1970).

Month	Correction Factor
June	1.3
July	1.2
August	1.4
September	1.8
October	2.0
November	2.0

Vapour Pressure: Ambient vapour pressure (e_a) data from Atmospheric Environment Service stations at Thompson and Lynn Lake were used (Atmospheric Environment Service 1972-79). Vapour pressure data for the Freshwater Institute station at South Indian Lake community exist for only the summer months of 1977 and 1978. Comparison of 8 mean monthly values, June to September indicate a mean difference between South Indian Lake values and the Lynn Lake-Thompson mean of -0.049 kPa (LL.T-SIL) with a standard deviation of 0.053 kPa. The mass transfer equation term (e_s-e_a) varies from 0.2 - 0.4 kPa in midsummer and back to 0.3 - 0.4 kPa near the end of the open water season. Thus the potential error in the term varies from about 17% in spring through about 8% in the midsummer months to about 14% near the end of the open water season. However, insufficient comparable data exists to justify applying correction factors to the term.

Frequent limnologic surveys of Southern Indian Lake in the open water periods from 1974 to 1979 included surface water temperature measurements (Hecky et al. 1979). Surface water temperature was used to calculate vapour pressure (e_s) according to the formula:

$$e_s = \exp. (52.58 - A - B)$$

where:
A = $6790 \div (T_w + 273.2)$
B = $5.029 \times \ln (T_w + 273.2)$
T_w = surface water temperature (°C)
e_s = vapour pressure at surface water temperature (kPa.)

Mean monthly water mass temperature, corrected for morphometry, was calculated for each region of Southern Indian Lake using graphic interpolation to the 15th day of each month from all available survey data (R. Hecky, personal communication). Temperatures at ice-out and at freeze-up were assumed to be 2°C. Inspection of lake temperature profiles indicated that for most months the difference between mean monthly water mass temperature and surface water temperature (T_w) was negligible. For June, 2°C were added to Region 4 and 1°C to Region 5 to allow for stratification. For July, 1°C was added to Region 4. Vapour pressure was calculated for each basin individually and then the weighted mean was calculated for the whole lake. As inadequate surface water temperature data exist to make the calculations for Regions 0, 3 and 7, mean monthly vapour pressures for Region 3 were assumed equal to those for Region 2; for Region 0 and 7 they were assumed equal to those for Region 1.

Mean monthly surface water temperature (Hecky et al. 1979) averaged for Southern Indian Lake for June through October, 1974-1978, was regressed against mean monthly air temperature for the concurrent and for the preceding month. The resulting equation was used with Atmospheric Environment Service (1972-73) data from Lynn Lake and Thompson to predict mean monthly surface water temperature, (T_w), for the open water months of 1972, 1973.

$$T_w = 0.83 + 0.40\,T + 0.54T_a \quad (n = 22,\ R^2 = 0.6)$$

where:
T_w = mean monthly surface water temperature, °C
T = mean monthly air temperature (°C) for the concurrent month
T_a = mean monthly air temperature (°C) for the preceding month

(Based on a comparison of Southern Indian Lake, Lynn Lake and Thompson temperatures, T and T_a were considered to be the mean of the Thompson and Lynn Lake data minus 0.5°C).

Change in Storage (ΔS)

Monthly changes in the volume of water stored in Southern Indian Lake were calculated as the product of the difference in lake level between the beginnings and ends of months multiplied by the lake surface area.

For the first half of 1972, Water Survey of Canada level data (Water Survey of Canada, 1972-79) for the station at South Indian Lake community exist only for the dates: 11 December 1971, and 3 February, 27 March, 30 June 1972. Monthly storage change was estimated by distributing the gross change for these periods proportionately according to the monthly residual in the water budget equation calculated without a storage change term. Backcalculating to determine monthly lake levels produced a hydrograph that compares favorably with the hydrograph for measured data for the same period on Granville Lake upstream of Southern Indian Lake.

For the period July, 1972 to December, 1975, level data from the Water Survey of Canada gauge at South Indian Lake community were used as an estimate of whole lake level changes. The mean of the level on the last day of the month and the first day of the following month was used as an estimate of lake level at each months end.

From 1976 to 1979, level data as above were used to determine change in storage for the south half of Southern Indian Lake only. Level data from the Manitoba Hydro gauge at Missi Falls (Manitoba Hydro, unpublished data) were used to determine change in storage for the northern half and a weighted mean change in storage term was calculated.

Location of the gauges at South Indian Lake community and at Missi Falls are shown in Fig. 1. The South Indian Lake community gauge lies near the centre of that part of the lake south of Long Point. It is well situated to avoid extremes of level changes due to set-up and seiche that are maximized at the ends of lake basins. Thus the level record at South Indian Lake community should give a fair representation of changes in storage for the whole south half of the lake. Similarly, the Missi Falls gauge is located near the centre of the northern basins, although the level record there could be seriously affected by east or west winds. Other level gauges on Southern Indian Lake either have a shorter period of record than those used in the storage calculation, or are less ideally situated; data from these gauges would add little to the reliability of the calculated storage term.

Table 5. Analysis of the residual term (n = 93).

	Monthly residual term (10^9 m^3)	Absolute value of Monthly residual term (10^9 m^3)	Absolute value of residual term as % of mean monthly outflow
Mean	0.19	0.22	7.3
Maximum	0.69	0.69	31
Minimum	-0.23	0	0
Standard deviation	0.20	0.17	5.5

Table 6. Relative contribution of components to the water budget.

	Absolute mean monthly value (10^9 m^3)	% of mean monthly outflow	Range of % of monthly outflows
Churchill River inflow	2.85	93	71 - 99
Local inflow	0.21	7	1 - 21
Precipitation	0.09	3	1 - 18
Churchill River outflow[a]	1.47	48	18 - 92
Diversion Route outflow[a]	1.60	52	8 - 93
Evaporation	0.06	2	0 - 9
Change in storage	0.09	7	0 -108

[a]June, 1976 to December, 1979 only. For the period January, 1972 to May, 1976, 100% of the Southern Indian Lake outflow (3.08 x 10^9 m^3/month) was via the Churchill River at Missi Falls.

Lake surface areas used in the storage calculation are from Cleugh et al. (1974). Surface areas for intermediate levels of Southern Indian Lake during some months of 1974, 1975 and 1976 were estimated by linear interpolation based on mean monthly lake levels.

DISTRIBUTION OF THE RESIDUAL ERROR COMPONENT IN WHOLE LAKE WATER BUDGETS

Because all terms of the water budget equation were determined independently, a residual error term resulted. This term is described in Table 5. Balancing of the water budget equation required distribution of this residual term among the components of the budget.

The residual term is positive in 78 months of the period and negative in only 13 months.

A major consideration in this distribution is the contribution of each component to the total water input (or output). The relative contribution is noted in Table 6. Churchill River inflows, and Churchill River and Diversion Route outflow comprise most of the input and output to the water budget, in all but a very few months of record. Because greater confidence was placed in the measured inflow values, the monthly residual term was added to outflow values. The considerations governing this decision are as follows:

1) Churchill River discharge data at Leaf Rapids is based on a continuous level record converted to a flow record from a level-discharge relationship based on measured data. The Churchill River inflow term should be the most accurate of the water budget equation.

2) Estimation of local inflow has considerable potential for large relative monthly errors. However, local inflow is also a minor term in water budget equation, never exceeding 21% of total monthly water input. As residual error is commonly almost as large as or equal to local inflow (Tables 5,6) no significant portion of the error can be absorbed by the local inflow term without a large relative alteration in the value of that term. Furthermore, calculation of the second estimate of local inflow in some months incorporated adjustments that tended to reduce the water budget residual based on the first estimate. (See previous discussion of the local inflow component and Fig. 4).

The combined value of local inflow and evaporation can be tested against precipitation in a simplified terrestrial water budget:

$$P = RO + E \pm \Delta S$$

where:
P = annual precipitation
RO= annual runoff
E = annual evapotranspiration
ΔS = change in storage

The annual change in storage between the end of each winter season can be assumed to be small in small basins with short response times. The precipitation values in Table 7 are the means of precipitation recorded at Lynn Lake and Thompson (Atmospheric Environment Service, 1972-79). Snow is assumed to enter the budget in May of the year following its precipitation. Tabulated annual runoff is the sum of local inflows

Table 7. Comparison of sums of calculated runoff and evaporation with measured precipitation. Runoff is calculated local inflow into Southern Indian Lake between April of each successive year (this paper). Evaporation is calculated annual lake evaporation (this paper). Precipitation is the mean of measured annual precipitation at Lynn Lake and Thompson.

Year	Runoff (mm)	Evaporation (mm)	Runoff + Evaporation (mm)	Measured Precipitation (mm)	Percent Error $100\frac{(E+R.O.)-P}{P}$
1972	195.7	249.6	445.3	515.9	-14
1973	111.3	298.0	409.3	499.3	-18
1974	186.4	319.7	506.1	464.6	+ 9
1975	173.7	328.4	502.1	579.9	-13
1976	206.9	338.2	545.1	584.2	- 7
1977	198.3	374.2	572.5	557.3	+ 3
1978	294.1	188.6	482.7	522.3	- 8
1979	120.9	277.8	398.7	484.1	-18

to Southern Indian Lake between April of each successive year, converted to mm depth over the watershed. Annual lake evaporation is used as an estimate of evapotranspiration. If evaporation from a large lake can be assumed to be an underestimate of nearby terrestrial evapotranspiration (due to the lesser surface area available to the atmosphere) then the approximate agreement of values of columns 4 and 5 of Table 7 implies that the sum of calculated annual runoff and evaporation are reasonable approximations of actual annual runoff and evaporation.

3) A considerable potential for error results from using data from Lynn Lake and Thompson as an estimate of monthly precipitation at Southern Indian Lake. The standard deviation of the difference between Southern Indian Lake and mean Lynn Lake-Thompson data is 18 mm or 29% of mean monthly rainfall of 63 mm. However the monthly residual term commonly exceeds precipitation; no significant amount of the residual could be absorbed by the precipitation term without a large relative effect.

4) The discharge of the Churchill River is based on measurements made at Missi Falls from 1976 to 1979 only. Values for previous years depend on a regression relationship with monthly discharge at Fidler Lake, based on data obtained under an unnatural flow regime. Thus a considerable potential for error exists in the Churchill River outflow term. As it accounts for most of the total water output in the years previous to construction of the South Bay diversion, the residual error was assigned to Churchill River outflow, effectively increasing the estimates by an average monthly value of 8%. During the months when the Diversion Route outflow was operating, the monthly residual term was proportioned between the Churchill River and Diversion Route outflow terms with the result that the Churchill River outflow estimate was increased by an average monthly value of 3%, and the Diversion Route outflow by 7%. (See Point 5).

5) Diversion Route monthly discharges were supplied by Manitoba Hydro and are calculated figures. Among the terms of the water budget, the Diversion Route outflow term has probably the greatest potential for error. It varies from 8 to 93% of the total monthly outflow; thus in some months it can absorb a large share of residual error without a correspondingly large relative effect on its value.

The period of August to October, 1976 is an exception; all of the residual error was assigned to the Diversion Route for these months. (See the discussion of the Diversion Route outflow component above).

6) The accuracy of the evaporaton term is discussed in Point 2, above. It is typically exceeded in value by the residual term and could not absorb any significant portion of the residual without a large effect on its value.

7) On a large lake the monthly storage term can easily have a large error. Potential wind set-up at each of the stage recorders can be estimated based on a formula developed for lakes in Holland (Fair and Geyer 1965):

$$h_s = \frac{w^2 f}{1400\ d}$$

where: h_s = wind set-up above mean lake level (ft), w = wind velocity (mi h^{-1}), f = fetch (mi), and d = mean basin depth (ft). A common wind speed of 45 km h^{-1} can create a set-up of 0.051 m at Missi Falls. Such a set-up corresponds to an error of 0.04 x 10^9 m^3 of storage on the north half of the lake. A smaller potential set-up of 0.033 m at the South Indian Lake community corresponds to a potential storage error of 0.06 x 10^9 m^3 for the period in which there was only one level gauge on the lake. Smaller monthly errors can occur during the winter as a result of set-up due to atmospheric pressure differentials.

However, the residual error was positive in 78 of the 96 months in question, with a mean

Table 8. Local terrestrial drainage area influent to each basin of the lake. Drainage area data are from Cleugh et al. (1974). Some additional small stream and direct runoff area is based on planimeter measurement on 1:250,000 scale N.T.S. maps. Terrestrial drainage area loss due to impoundment is calculated by subtraction of increased lake surface area.

Basin	Pre-impoundment terrestrial drainage area (km^2)	Post-impoundment terrestrial drainage area (km^2)
0	3250	3235
1	981	935
2	811	755
3	499	447
4	1155	1039
5	4172	4076
6	522	503
7	2716	2702
Total	14106	13692

value of 0.19×10^9 m^3s^{-1}, suggesting some systematic error, probably in river discharge data. Applying a constant positive error to the storage term would have implied a constantly increasing error in measurement of lake level; level errors should logically vary randomly about 0. Thus none of the residual error was assigned to the storage term.

The period of January to June, 1972 is an exception in that the values of the monthly residual term were used as an index of monthly storage changes. (See the previous discussion of the change in storage component).

DETERMINATION OF THE REGIONAL WATER BUDGETS

To facilitate limnological and biological studies, Southern Indian Lake has been divided into the 8 regions shown in Fig. 2. Each region is separated from the others by topographic constrictions and can be considered as an independent basin of water. To understand the effects of impoundment and diversion on the limnology of Southern Indian Lake, it is necessary to study the balance of inputs and outputs to each basin separately. The general expression for the basin water budgets is:

$$Q_{i-j} + Q_{local} + P = Q_{j-k} + E \pm \Delta S$$

where:

Q_{i-j} = Inter-basin net flow from i = basin upstream to j = basin being described.

Q_{local} = Flow from streams and direct runoff areas discharging into the basin.

P = Precipitation on basin surface.

Q_{j-k} = Inter-basin net flow from j = basin being described, to k = basin downstream.

E = Evaporation off basin surface.

ΔS = Storage change in basin where + ΔS corresponds to a rise in lake level.

As noted in Table 2, basins have one or more source of inflow and outflow. For Basin 0, Q_{i-j} = Q_{LR} of the whole lake budgets; for Basin 4, Q_{j-k} = Q_{MF}, and for Basin 6 after diversion, Q_{j-k} = Q_{SB}.

The regional annual water budgets were derived from the whole lake annual water budgets. Annual Churchill River discharges at Leaf Rapids (Q_{LR}) and at Missi Falls (Q_{MF}), and diversion route discharges at South Bay (Q_{SB}) were transferred unaltered to the regional water budgets.

Total annual local inflows into Southern Indian Lake were proportioned among the basins according to the ratio of the drainage area of each basin to the local drainage area of the whole lake. Regional drainage areas are listed in Table 8. Potential errors due to yield differences were ignored. Such errors would have negligible effect on the exchange time as local inflow is typically less than 5% of total outflow. Basins 5 and 7, and Basin 6 in the period 1972 to 1975, are exceptions where local inflow comprises the total inflow.

Total annual precipitation and evaporation were proportioned according to the ratio of water surface area of the basin to the water surface area of the whole lake. It was assumed that precipitation and evaporation occur homogeneously throughout the area. Available data suggest that, in fact, precipitation is higher at Missi Falls than at the South Indian Lake community (see discussion of the precipitation component of the whole lake water budget) and evaporation is less from the northern basins. However, neither equal more than 1% of total inflow or outflow. Basin 5 is an exception where precipitation and evaporation equal 72% and 44% respectively of outflow.

Total annual changes in storage (ΔS) for 1972 to 1975 were subdivided among basins according to the ratio of basin surface water area to whole lake area. For the period 1976 to 1979, level data from the Manitoba Hydro level gauge at Missi Falls were assumed representative of level changes in Basins 4 and 5. Data from the Water Survey of Canada gauge at Southern Indian Lake were used to estimate storage changes on all other basins.

Net inter-basin flow (Q_{i-j}) was considered to be the residual of the budget equation for each basin. Thus for example, for Basin 0:/

$$Q_{LR} + Q_{local} + P = Q_{0-1} + E + \Delta S$$

$$Q_{0-1} = Q_{LR} + Q_{local} + P - (E + \Delta S)$$

where:

Q_{LR}	=	Churchill River discharge at Leaf Rapids
Q_{local}	=	Flow from all other streams discharging into the basin
P	=	Precipitation
E	=	Evaporation off the basin
ΔS	=	Change in storage
Q_{0-1}	=	Net flow out of Basin 0 into Basin 1.

Net outflow from Basin 0 is net inflow to Basin 1. Thus proceeding from all headwater regions down the path of net flow, the residual term of each regional water budget equation was determined.

DETERMINATION OF TYPICAL WATER BUDGETS UNDER NATURAL AND CONTROLLED REGIMES

The typical annual water budgets presented in Table 10 under natural and controlled conditions were calculated because:

1) discharges from Notigi through the diversion route can be expected to be approximately 850 m^3s^{-1}, the maximum rate allowed under the terms of licence of Manitoba Hydro. In the period 1976 to 1979 this mean annual discharge was not achieved.
2) the mean annual discharge of the Churchill River at Leaf Rapids from 1972 to 1979 was 1085 m^3s^{-1}. The long term mean annual discharge is 958 m^3s^{-1}.
3) the 30 year normal precipitation for Lynn Lake is 458 mm per year compared with a mean annual precipitation of 487 mm for the period 1972 to 1979. Higher normal precipitation is reflected as well in greater local runoff.

For the purpose of calculating typical regional water budgets, the long term mean annual discharge of the Churchill River at Leaf Rapids of 958 m^3s^{-1} = 30.20 x $10^9 m^{-3}y^{-1}$ was used. This figure is based on the mean of 27 years of Water Survey of Canada (1952-78) discharge data for the Churchill River at Granville Falls corrected by a regression based on 1973 to 1978 annual data for the two locations.

$$Q_{LR} = 1.065\ Q_{GF} + 1840 \quad (n = 6,\ r^2 = 0.92)$$

where:

Q_{LR}	=	Churchill River annual discharge at Leaf Rapids (ft^3s^{-1})
Q_{GF}	=	Churchill River annual discharge at Granville Falls (ft^3s^{-1}).

The long term mean annual precipitation for the area was considered to be 85% of the mean annual precipitation for the period 1972 to 1978 based on the mean of Lynn Lake and Thompson records (Atmospheric Environment Service, 1972-78). Local runoff was corrected by the same factor on the assumption that the mean annual yield was not greatly different for the two periods. The increased value of the precipitation term after impoundment is a consequence of increased surface area of each basin of the lake. The value of the local inflow term was decreased by an amount corresponding to this increase in the precipitation term to reflect the decrease in terrestrial drainage area.

A mean annual discharge at Notigi of 850 m^3s^{-1} was assumed in estimating the diversion route outflow at South Bay. A typical annual water balance for the Notigi Reservoir was estimated assuming long term mean annual local runoff, precipitation and evaporation were the same per unit area as for Southern Indian Lake. Mean annual inflow at South Bay, calculated as the residual of a typical annual water budget for the Notigi Reservoir, is 816 m^3s^{-1} = 25.73 x 10^9 m^3y^{-1}. This is assumed to be the mean annual discharge under controlled conditions of the diversion route outflow at South Bay.

The mean annual evaporation for the period 1972 to 1978 was considered to be an adequate estimate of evaporation. The increased value of the evaporation term after impoundment is a consequence of increased lake surface area.

Net inter-basin flow and the Churchill River outflow at Missi Falls were then calculated progressively through the system as the residual of each basin water budget.

RESULTS AND DISCUSSION

THE WHOLE LAKE BUDGETS

Annual and monthly water budgets for Southern Indian Lake from 1972 to 1979 are presented in Table 9.

Effects of impoundment and diversion on the whole lake are emphasized in the typical annual water budgets under natural and controlled regimes shown in Table 10. Values listed for each term are the tums of values for each basin listed in Table 11. Typical water budgets under natural and controlled conditions are based on long term mean Churchill River discharge at Leaf Rapids, and normal precipitation data for the region.

The change in water budgets is reflected in the gross exchange time for the lake. Expressed in years, the exchange time is estimated as the lake volume divided by the annual outflow. The increase in water exchange time from 0.51 to 0.72 years for the whole lake is due to:

1) increased evaporation off the larger lake surface, decreasing the annual outflow, (accounts for 1.2% of total increase in exchange time), and
2) increased volume of the lake (accounts for 98.8% of total increase).

It should be noted that post impoundment volume calculations are based on area measurements at the 850 ft MSL contour, or 259.1 m MSL, and thus constitute some exaggeration of the real value. On the other hand, shoreline erosion will reduce this error in the long term. The size and significance of this exaggeration is discussed in Appendix 1.

Table [illegible] Southern Indian Lake annual and monthly water budgets, 1972-1979. Units of volume: 10^9 m^3.

	INFLOW		PRECIPITATION	OUTFLOW		EVAPORATION	CHANGE IN STORAGE
Month	Churchill River	Local Drainage		Churchill River	Diversion Route		
1972							
Jan	2.66	0.04	0.02	2.84	0	0	-0.12
Feb	2.45	0.02	0.03	2.81	0	0	-0.31
Mar	2.58	0.01	0.02	2.78	0	0	-0.17
Apr	2.44	0.03	0.04	2.46	0	0	0.05
May	3.20	0.69	0.06	3.27	0	<0.01	0.68
Jun	3.43	0.41	0.16	3.52	0	0.06	0.42
Jul	3.25	0.45	0.12	3.86	0	0.11	-0.15
Aug	2.84	0.24	0.08	3.40	0	0.10	-0.34
Sep	2.44	0.34	0.20	3.17	0	0.17	-0.36
Oct	2.69	0.34	0.05	3.13	0	0.05	-0.10
Nov	2.58	0.13	0.04	2.84	0	0	-0.09
Dec	2.52	0.05	0.04	2.69	0	0	-0.08
Total	33.08	2.75	0.86	36.77	0	0.49	-0.57
1973							
Jan	2.43	0.02	0.04	2.58	0	0	-0.09
Feb	2.18	0.02	0.02	2.32	0	0	-0.10
Mar	2.34	0.01	0.05	2.45	0	0	-0.05
Apr	2.24	0.01	0.07	2.35	0	0	-0.03
May	2.64	0.49	<0.01	2.53	0	<0.01	0.60
Jun	2.86	0.28	0.10	3.05	0	0.10	0.09
Jul	2.85	0.18	0.18	3.17	0	0.07	-0.03
Aug	2.54	0.11	0.17	2.55	0	0.11	0.16
Sep	2.43	0.09	0.09	2.35	0	0.19	0.07
Oct	2.46	0.12	0.16	2.38	0	0.09	0.27
Nov	2.41	0.09	0.07	2.52	0	0.03	0.02
Dec	2.46	0.07	0.06	2.64	0	0	-0.05
Total	29.84	1.49	1.01	30.89	0	0.59	0.86
1974							
Jan	2.40	0.06	0.04	2.57	0	0	-0.07
Feb	2.09	0.04	0.02	2.23	0	0	-0.08
Mar	2.32	0.03	0.01	2.44	0	0	-0.08
Apr	2.33	0.06	0.02	2.34	0	0	0.07
May	3.19	0.63	0.06	3.04	0	0	0.84
Jun	3.66	0.47	0.16	3.42	0	0.03	0.84
Jul	4.13	0.32	0.17	3.94	0	0.11	0.57
Aug	4.24	0.26	0.10	4.24	0	0.25	0.11
Sep	3.93	0.20	0.09	4.08	0	0.23	-0.09
Oct.	3.72	0.22	0.07	4.10	0	0.08	-0.17
Nov	3.25	0.14	0.10	3.73	0	0	-0.24
Dec	3.06	0.07	0.06	3.53	0	0	-0.34
Total	38.32	2.50	0.90	39.66	0	0.70	1.36
1975							
Jan	2.83	0.06	0.05	3.46	0	0	-0.52
Feb	2.39	0.04	0.02	2.75	0	0	-0.30
Mar	2.67	0.02	0.03	2.96	0	0	-0.24
Apr	2.54	0.05	0.10	2.64	0	0	0.05
May	3.16	0.53	0.12	2.81	0	<0.01	1.00
Jun	3.66	0.56	0.25	3.23	0	0.03	1.21
Jul	3.69	0.32	0.18	3.94	0	0.16	0.09
Aug	3.49	0.28	0.12	4.05	0	0.22	-0.38
Sep	3.14	0.21	0.07	3.69	0	0.19	-0.46
Oct	3.19	0.19	0.06	3.52	0	0.13	-0.21
Nov	2.81	0.10	0.04	3.38	0	0.01	-0.44
Dec	2.50	0.05	0.04	2.87	0	0	-0.28
Total	36.07	2.41	1.08	39.30	0	0.74	-0.48
1976							
Jan	2.36	0.04	0.06	2.57	0	0	-0.11
Feb	2.21	0.03	0.04	2.01	0	0	0.27
Mar	2.37	0.02	0.04	2.28	0	0	0.15
Apr	2.30	0.06	0.02	2.61	0	0	-0.23
May	2.37	0.57	0.10	2.99	0	<0.01	0.05
Jun	2.22	0.47	0.22	1.20	0.99	0.07	0.65
Jul	2.95	0.37	0.31	0.91	0.77	0.14	1.81
Aug	3.47	0.28	0.16	1.11	0.86	0.19	1.75
Sep	3.43	0.32	0.09	1.92	0.96	0.24	0.72
Oct	3.82	0.28	0.15	3.15	0.85	0.16	0.09
Nov	3.74	0.22	0.08	3.14	0.84	0.01	0.05
Dec	3.37	0.09	0.11	2.90	0.90	0	-0.23
Total	34.61	2.75	1.38	26.79	6.17	0.81	4.97
1977							
Jan	2.76	0.08	0.03	2.31	0.73	0	-0.17
Feb	2.36	0.06	0.05	1.95	0.66	0	-0.14
Mar	2.57	0.05	0.05	1.93	0.71	0	0.03
Apr	2.50	0.25	0.05	1.85	0.40	0	0.55
May	3.28	0.44	0.16	3.14	0.54	0.02	0.18
Jun	3.74	0.54	0.19	4.25	0.38	0.09	-0.25
Jul	4.13	0.36	0.18	3.46	0.92	0.16	0.13
Aug	4.25	0.18	0.19	2.69	1.68	0.23	0.02
Sep	3.97	0.28	0.12	2.13	2.18	0.16	-0.10
Oct	3.52	0.18	0.19	1.53	2.18	0.16	0.02
Nov	2.85	0.13	0.04	1.09	1.99	0.12	-0.18
Dec	2.66	0.08	0.03	0.55	2.20	0	0.02
Total	38.59	[illegible]	1.28	26.88	14.57	0.94	0.11

Table 9. Southern Indian Lake annual and monthly water budgets, 1972-1979. Units of volume: 10^9 m^3. (cont'd)

Month	INFLOW: Churchill River	INFLOW: Local Drainage	PRECIPITATION	OUTFLOW: Churchill River	OUTFLOW: Diversion Route	EVAPORATION	CHANGE IN STORAGE
1978							
Jan	2.54	0.05	0.03	0.50	2.25	0	-0.13
Feb	2.30	0.04	0.01	0.46	2.07	0	-0.18
Mar	2.52	0.03	0.07	0.52	2.24	0	-0.14
Apr	2.33	0.05	0.14	0.50	1.72	0	0.30
May	2.62	0.48	0.16	1.20	1.10	0	0.96
Jun	2.70	0.46	0.06	1.88	2.04	0.02	-0.72
Jul	2.83	0.51	0.22	1.03	2.36	0.07	0.10
Aug	2.75	0.77	0.34	2.01	1.72	0.13	0
Sep	2.70	0.48	0.12	1.19	1.89	0.14	0.08
Oct	3.05	0.52	0.10	1.68	2.12	0.11	-0.24
Nov	3.32	0.33	0.03	1.44	2.20	0.01	0.03
Dec	3.07	0.11	0.06	1.37	2.12	0	-0.25
Total	32.73	3.83	1.34	13.78	23.83	0.48	-0.19
1979							
Jan	2.79	0.06	0.02	1.20	2.14	0	-0.47
Feb	2.34	0.04	0.04	0.61	1.98	0	-0.17
Mar	2.57	0.03	0.08	0.51	2.25	0	-0.08
Apr	2.39	0.03	0.03	0.49	2.06	0	-0.10
May	2.58	0.21	0.06	0.44	1.67	0	0.74
Jun	2.98	0.36	0.14	1.02	1.79	0.01	0.66
Jul	2.92	0.20	0.26	2.20	1.45	0.14	-0.41
Aug	2.44	0.16	0.23	0.82	2.13	0.19	-0.31
Sep	2.13	0.14	0.14	0.14	1.91	0.18	0.18
Oct	2.29	0.19	0.11	0.28	2.17	0.17	-0.03
Nov	2.48	0.15	0.07	0.30	2.27	0.01	0.12
Dec	2.63	0.07	0.04	0.32	2.38	0	0.04
Total	30.54	1.64	1.22	8.33	24.20	0.70	0.17

Table 10. Southern Indian Lake typical annual whole lake budgets under natural and controlled conditions. Exchange time is calculated by division of volume by total liquid outflow. Units of volume: 10^9 m^3.

	INFLOW: Churchill River	INFLOW: Local Drainage	PRECIPITATION	OUTFLOW: Churchill River	OUTFLOW: Diversion Route	EVAPORATION	CHANGE IN STORAGE	AREA (km^2)	VOLUME	EXCHANGE TIME (years)
Natural	30.20	2.41	0.82	32.84	0	0.59	0	1977	16.8	0.51
Controlled	30.20	2.16	1.08	6.93	25.73	0.78	0	2391	23.4	0.72

Table 11. Southern Indian Lake annual water budgets subdivided by basins, 1972-1979. Units of volume: $10^9 m^3$.

	INFLOW			PRECIPITATION	OUTFLOW	EVAPORATION	CHANGE IN STORAGE	MEAN[h] BASIN AREA (km^2)	MEAN[h] BASIN VOLUME	EXCHANGE[i] TIME (years)
Basin 0	Q^a_{LR}		Q^b_{local}		Q^c_{0-1}					
1972	33.08		0.74	0.03	33.85	0.02	-0.02	77	0.38	0.011
1973	29.84		0.40	0.04	30.23	0.02	0.03	77	0.38	0.013
1974	38.32		0.67	0.04	38.95	0.03	0.05	81	0.44	0.011
1975	36.07		0.65	0.04	36.75	0.03	-0.02	81	0.45	0.012
1976	34.61		0.74	0.07	35.15	0.04	0.23	84	0.49	0.014
1977	38.59		0.70	0.08	39.31	0.05	0.01	92	0.63	0.016
1978	32.73		1.03	0.07	33.81	0.03	-0.01	92	0.63	0.019
1979	30.54		0.39	0.05	30.94	0.03	0.01	92	0.63	0.020
Natural[f]	30.20		0.60	0.03	30.80	0.03	0	77	0.38	0.012
Controlled[g]	30.20		0.58	0.06	30.79	0.05	0	92	0.63	0.020
Basin 1	Q_{0-1}	Q_{7-1}	Q_{local}		Q_{1-2}					
1972	33.85	0.52	0.18	0.21	34.79	0.11	-0.14	475	3.78	0.11
1973	30.23	0.26	0.10	0.24	30.48	0.14	0.21	475	3.78	0.12
1974	38.95	0.43	0.17	0.22	39.27	0.17	0.33	486	4.14	0.11
1975	36.75	0.45	0.16	0.26	37.56	0.18	-0.12	488	4.22	0.11
1976	35.15	0.39	0.18	0.29	34.73	0.17	1.11	495	4.43	0.13
1977	39.31	0.49	0.17	0.27	40.02	0.20	0.02	521	5.27	0.13
1978	33.81	0.72	0.25	0.28	34.99	0.10	-0.03	521	5.27	0.15
1979	30.94	0.34	0.11	0.26	31.46	0.15	0.04	521	5.27	0.17
Natural	30.80	0.49	0.15	0.20	31.50	0.14	0	475	3.78	0.12
Controlled	30.79	0.48	[illegible]	0.2[illegible]	31.47	0.1[illegible]	0	521	5.27	0.17

Table 11. Southern Indian Lake annual water budgets subdivided by basins, 1972-1979. Units of volume: $10^9\ m^3$. (cont'd)

	INFLOW			PRECIPITATION	OUTFLOW		EVAPORATION	CHANGE IN STORAGE	MEAN[h] BASIN AREA (km^2)	MEAN[h] BASIN VOLUME	EXCHANGE[i] TIME (years)
Basin 2	Q^c_{1-2}	Q_{6-2}	Q^b_{local}		Q_{2-3}	Q_{2-6}					
1972	34.79	0.15	0.15	0.10	35.19	0	0.06	-0.06	223	1.70	0.048
1973	30.48	0.03	0.08	0.11	30.53	0	0.07	0.10	223	1.70	0.056
1974	39.27	0.02	0.14	0.10	39.30	0	0.08	0.15	237	1.88	0.048
1975	37.56	0.13	0.13	0.12	37.91	0	0.08	-0.05	239	1.92	0.051
1976	34.73	0	0.15	0.16	28.05	6.33	0.09	0.57	248	2.03	0.059
1977	40.02	0	0.14	0.15	25.72	14.47	0.11	0.01	279	2.45	0.061
1978	34.99	0	0.21	0.16	11.68	23.64	0.06	-0.02	279	2.45	0.069
1979	31.46	0	0.09	0.14	7.47	24.12	0.08	0.02	279	2.45	0.078
Natural[f]	31.50	0.10	0.14	0.09	31.76	0	0.07	0	223	1.70	0.054
Controlled[g]	31.47	0	0.10	0.13	5.97	25.64	0.09	0	279	2.45	0.078
Basin 3	Q_{2-3}		Q_{local}		Q_{3-4}						
1972	35.19		0.09	0.09	35.38		0.05	-0.06	200	1.74	0.049
1973	30.53		0.05	0.10	30.54		0.06	0.08	200	1.74	0.057
1974	39.30		0.08	0.09	39.26		0.07	0.14	213	1.91	0.049
1975	37.91		0.08	0.11	38.08		0.07	-0.05	215	1.94	0.051
1976	28.05		0.09	0.14	27.68		0.09	0.51	223	2.04	0.074
1977	25.72		0.09	0.13	25.83		0.10	0.01	252	2.42	0.094
1978	11.68		0.13	0.14	11.91		0.06	-0.02	252	2.42	0.20
1979	7.47		0.05	0.13	7.56		0.07	0.02	252	2.42	0.32
Natural	31.76		0.09	0.09	31.88		0.06	0	200	1.74	0.055
Controlled	5.97		0.06	0.11	6.06		0.08	0	252	2.42	0.40
Basin 4	Q_{3-4}	Q_{5-4}	Q_{local}		Q^d_{MF}						
1972	35.38	0.87	0.21	0.27	36.77		0.15	-0.19	625	7.59	0.21
1973	30.54	0.38	0.12	0.32	30.89		0.19	0.28	625	7.59	0.25
1974	39.26	0.58	0.20	0.29	39.66		0.22	0.45	653	8.09	0.20
1975	38.08	0.76	0.19	0.34	39.30		0.23	-0.16	659	8.19	0.21
1976	27.68	0.25	0.21	0.42	26.79		0.25	1.52	676	8.49	0.32
1977	25.83	0.78	0.21	0.39	26.88		0.28	0.05	741	9.64	0.36
1978	11.91	1.23	0.30	0.41	13.78		0.15	-0.08	741	9.64	0.70
1979	7.56	0.54	0.12	0.38	8.33		0.22	0.05	741	9.64	1.2
Natural	31.88	0.68	0.21	0.26	32.84		0.19	0	625	7.59	0.23
Controlled	6.06	0.64	0.15	0.32	6.93		0.24	0	741	9.64	1.4
Basin 5			Q_{local}		Q_{5-4}						
1972			0.77	0.09	0.87		0.05	-0.06	211	1.04	1.2
1973			0.42	0.11	0.38		0.06	0.09	211	1.04	2.7
1974			0.70	0.10	0.58		0.07	0.15	234	1.23	2.1
1975			0.68	0.11	0.76		0.08	-0.05	239	1.27	1.7
1976			0.77	0.18	0.25		0.11	0.59	253	1.38	5.5
1977			0.74	0.17	0.78		0.12	0.01	307	1.81	2.3
1978			1.08	0.18	1.23		0.06	-0.03	307	1.81	1.5
1979			0.49	0.16	0.54		0.09	0.02	307	1.81	3.4
Natural			0.65	0.09	0.68		0.06	0	211	1.04	1.5
Controlled			0.60	0.14	0.64		0.10	0	307	1.81	2.8
Basin 6	Q_{2-6}		Q_{local}		Q^e_{SB}	Q_{6-2}					
1972	0		0.10	0.05	0	0.15	0.03	-0.03	120	0.42	2.8
1973	0		0.05	0.06	0	0.03	0.03	0.05	120	0.42	14
1974	0		0.09	0.05	0	0.02	0.04	0.08	125	0.52	26
1975	0		0.08	0.06	0	0.13	0.04	-0.03	126	0.53	4.1
1976	6.33		0.10	0.08	6.17	0	0.05	0.29	128	0.59	0.096
1977	14.47		0.09	0.07	14.57	0	0.05	0.01	139	0.81	0.056
1978	23.64		0.13	0.08	23.83	0	0.03	-0.01	139	0.81	0.034
1979	24.12		0.06	0.07	24.20	0	0.04	0.01	139	0.81	0.033
Natural	0		0.09	0.04	0	0.10	0.03	0	120	0.42	4.2
Controlled	25.64		0.07	0.06	25.73	0	0.04	0	139	0.81	0.031
Basin 7			Q_{local}		Q_{7-1}						
1972			0.50	0.02	0.52		0.01	-0.01	46	0.19	0.37
1973			0.27	0.02	0.26		0.01	0.02	46	0.19	0.73
1974			0.46	0.02	0.43		0.02	0.03	49	0.23	0.53
1975			0.44	0.02	0.45		0.02	-0.01	50	0.24	0.53
1976			0.50	0.03	0.39		0.02	0.12	52	0.26	0.67
1977			0.48	0.03	0.49		0.02	0	60	0.35	0.71
1978			0.70	0.03	0.72		0.01	0	60	0.35	0.49
1979			0.33	0.03	0.34		0.02	0	60	0.35	1.03
Natural			0.48	0.02	0.49		0.01	0	46	0.19	0.39
Controlled			0.47	0.03	0.48		0.02	0	60	0.35	0.73

a) Q_{LR} = Churchill River flow at Leaf Rapids, discharging into Southern Indian Lake.

b) Q_{local} = Flow from all other streams and direct runoff areas discharging into the basin.

c) Q_{i-j} = Inter-basin net flow where i = basin discharging flow, j = basin receiving flow.

d) Q_{MF} = Churchill River flow at Missi Falls, discharging from Southern Indian Lake

e) Q_{SB} = Diversion Route flow at South Bay, discharging from Southern Indian Lake.

f) "Natural": calculated water budget based on pre-impoundment. pre-diversion conditions and a long-term mean annual Churchill River discharge at Leaf Rapids = $30.20 \times 10^9\ m^3\ y^{-1} = 958\ m^3 s^{-1}$.

g) "Controlled": calculated water budget based on post-impoundment, post-diversion control conditions, a long-term mean annual Chorchill River discharge at Leaf Rapids = $30.20 \times 10^9\ m^3\ y^{-1} = 958\ m^3 s^{-1}$ and the present maximum allowable diversion flow at Notigi minus local drainage into, precipitation on, and plus evaporation from the Notigi Reservoir $(26.79 - 0.94 - 0.30 + 0.18) \times 10^9 = 25.73 \times 10^9\ m^3\ y^{-1} = 816\ m^3 s^{-1}$

h) Areas and volumes: see Appendix 1.

i) Exchange time = volume ÷ outflow.

Decreased local inflows due to flooding of some terrestrial drainage area are balanced by increased precipitation on the larger lake surface.

Only the gross exchange time can be calculated based on water budget analysis. There is biological and chemical evidence that there were somewhat discrete water masses in the lake (Patalas and Salki, 1974) and that the Churchill River flow followed a defined plume along the southeast side of the lake (Cleugh, 1974). Cleugh noted that movement of sodium and silicon ions indicated an exchange time of about 0.27 years for the Churchill River plume compared with 0.51 years calculated by the water budget method. This implies a much longer exchange time for areas of the lake off the main path of the Churchill River. Only further study based on suitable chemical or biological tracers of water masses will resolve this unknown.

THE REGIONAL WATER BUDGETS

Annual values based on measured data, and theoretical annual values given normal climatic conditions with natural and controlled flow patterns are listed in Table 11.

The water exchange times indicated are for the whole volume of each basin. In fact the main flow of Churchill River water follows a reasonably discrete path through each basin, as through the whole lake, (Cleugh, 1974; Patalas and Salki, 1974) and mixing with lake waters is incomplete and not described by these water budgets. Furthermore, water exchange times are calculated from net outflows. Especially, in basins off the main flow of the Churchill River, intermittent inflow and outflow due to wind or pressure induced set-up and seiche may have a significant effect on water exchange between basins. For example, pre-diversion annual exchange times fluctuated in Basin 6 because the small inflow from the terrestrial drainage area is easily exceeded on a short-term basis by wind-induced flows through the channel into Basin 2. Cleugh (1974) noted that higher sodium and potassium concentrations in Basin 5 than Basin 4 could not be derived simply from sodium and potassium inflow from the two major tributary rivers. The chemical evidence implied that 25% of the water in Basin 5 flowed north from Basin 4 in an exchange not predicted by simple water budget analysis.

Data in Table 11 indicate that only minor changes have resulted in Basins 0, 1 and 2 where the flow of the Churchill River continues unchanged. The increased residence time is mostly due to increased lake volume. It should be noted that the main flow of Churchill River water through Basin 2 is diverted through the southwest half and through the channel to South Bay.

Basins 5 and 7 remain separated from the main flow of the Churchill River. Exchange times of the water in these basins have approximately doubled because impoundment nearly doubled the volume of each basin. As noted above, wind induced currents probably have a relatively large effect on water exchange between Basins 4 and 5. As Basin 7 is a region of many islands and narrow channels, wind probably has less effect on water movement.

Basins 3 and 4 were on the main path of flow of the Churchill River before diversion. Only about 20% of the Churchill River now flows north. The combination of dramatically decreased flow and increased lake volume result in an increase of approximately an order of magnitude in water exchange time: from 0.055 to 0.40 years in Basin 3 and from 0.23 to 1.4 years in Basin 4. Most of the Churchill River flow passes along the east side of Basin 4 (Patalas and Salki, 1974) so that the exchange time is probably considerably less in the eastern third of the basin and somewhat longer in the western two-thirds.

Diversion has its greatest effect on Basin 6 which has a small terrestrial drainage area relative to its volume and through which the Churchill River did not flow until diverted in 1976. Exchange time decreased two orders of magnitude from 4.2 to 0.031 years. As a considerable portion of the basin is still isolated from the main path of flow, the exchange time is actually much less in the western portion of the basin and only slightly affected in the eastern Poplar Narrows and Swan Bay areas.

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APPENDIX 1

DISCUSSION OF DISCREPANCIES IN PREVIOUSLY REPORTED AREAS OF SOUTHERN INDIAN LAKE

The Southern Indian Lake water budget was initially prepared using lake areas as reported by Cleugh et al. (1974, Tables 1 and 5). Several reviewers expressed concern about the accuracy of these figures, as they differ from the areas of Southern Indian Lake earlier reported by Underwood-McLellan (1970, Fig. A-3) and as they imply a larger increase in area due to impoundment than is apparent to several researchers familiar with the lake. Investigation of available sources of area measurements suggests to this reviewer that Cleugh et al. (1974) provides the most reliable estimate of the pre-impoundment area of Southern Indian Lake (1977 km^2), and that adjustment of data reported by Cleugh et al. (1974) to the actual mean post-impoundment level of 258 m MSL gives the best estimate of post-impoundment area (2391 km^2). Use of these data implies minor adjustments to reported lake volumes. These adjusted areas and volumes are reported in Tables 1-1 and 1-2.

In Table 1-3 are listed areas of Southern Indian Lake measured independently by Underwood-McLellan (1970) and Cleugh et al. (1974) who used copies of the same photo-mosaic, reproduced at a scale of 1:63,360. Cleugh checked this reported scale by surveying 3 tri-sects, at South Bay, near Missi Falls and at the north end of the lake (Cleugh, personal communication). The post-impoundment shoreline was assumed to be the 850 ft. MSL (259.1 m MSL) contour as plotted on this photo-mosaic. The discrepancies between the resulting figures are about 4% of the total area.

Flanders et al. (1974), using 1:31,680 scale photo-mosaics compiled from 1969, 1970 aerial photographs, measured the area of forested and non-forested land between the pre-impoundment shoreline of Southern Indian Lake and the 850 ft. MSL (259.1 m MSL) contour. The total flooded terrestrial area computed from their data (Flanders et al. 1974, Table V) is 460 km^2. Approximately 68 km^2 of adjacent lakes were inundated by impoundment of Southern Indian Lake (Table 1-4). When this figure is subtracted from the total flooded areas calculated from Underwood-McLellan (1970) and Cleugh et al. (1974), the latter figure agrees very closely with the flooded terrestrial area computed from Cleugh et al. (1974). Because of this close agreement the figures of Cleugh et al. (1974) are preferred by this author as giving the best estimate of the areas of Southern Indian Lake at the natural mean level of 255 m MSL and the 259.1 m MSL.

The photo-mosaic used by Underwood-McLellan (1970) and Cleugh et al. (1974) was compiled from aerial photographs taken in the summer of 1954 and 1955. As no level gauge existed on Southern Indian Lake prior to 1956, the lake level at the time of photography cannot be precisely known. However the mean June-July-August level of Southern Indian Lake (Water Survey of Canada, 1956-73) can be correlated with mean June-July-August Churchill River discharge at Granville Falls (Water Survey of Canada, 1956-73). The linear regression expression of this correlation (r^2 = .77, n=11) predicts a summer, 1954 mean level of 255.2 ± .9 m MSL and a summer, 1955 mean level of 255.5 ± .9 m MSL with 95% confidence. Thus the lake level at the time of photography was probably at or slightly above the natural mean level of 255 m. MSL and the measured area can be assumed to be the natural mean area. Gauged lake level at the time of photography used in the Flanders et al. (1974) study was 254.9 to 255.3 m MSL (Water Survey of Canada, 1954-55).

The terms of reference of the Lake Winnipeg, Churchill and Nelson Rivers Impact Study Agreement (Canada-Manitoba, 1974) signed by the federal and provincial governments directed the participants to assume that Southern Indian Lake would be raised to 259.1 m MSL. All authors cited above assumed this level in defining the post-impoundment shoreline of Southern Indian Lake. However, since impoundment the mean lake level has been 258 m MSL. Figure 1-1 is a hypsometric plot for Southern Indian Lake based on areas reported by Underwood-McLellan (1970, Fig. A-3) and Cleugh et al. (1974, Tables 2 and 5). Examination of Fig. 1-1 indicates that the post-impoundment surface area can reasonably be adjusted to 258 m MSL by straight line interpolation. In this manner the post-impoundment areas reported in Table 1-1 have been estimated.

Discrepancies in lake area figures affect estimation of several components of the water budget: precipitation, evaporation and change in storage. As residual error in the water budget equation is assigned to the outflow term, a change in any of these affects calculated outflow. Precipitation and evaporation never exceed 18% of the monthly outflow; thus the effect of a 5% difference in lake surface area on the outflow calculation is less than .05 x 18 = 1% of monthly outflow; furthermore the error in precipitation tends to cancel the error in evaporation. Average monthly storage change is 5% of the mean monthly outflow; only during 5 months does the storage change exceed 30% of the total outflow. During May and June, 1975 and July and August, 1976, the elevation of Southern Indian Lake was intermediate to the natural and controlled levels. Areas for intermediate levels were estimated by interpolation and in these months differ from corrected areas by only 1 to 2%. In May, 1978, the only other month in which the change in storage exceeded 30% of outflow, the effect of a 5% difference in area is to increase estimated outflow by only 3%. For all other months the effect on outflow is less than 2%.

In general the water budget for Southern Indian Lake is not greatly affected by adjustment to the value reported for area at the controlled mean level. Water budget calculations for this paper were completed using unadjusted area data reported by Cleugh et al. (1974).

Calculation of the volume data in Table 5 was based on the adjusted surface areas reported in Table 1-1 and isobath area data from

Table 1-1. Areas of regions of Southern Indian Lake at pre-impoundment and post-impoundment mean levels. Sources discussed in text. Units: km^2

Region Elevation	0	1	2	3	4	5	6	7	Total
258 m MSL	92	521	279	252	741	307	139	60	2391
255 m MSL	77	475	223	200	625	211	120	46	1977

Table 1-2. Volumes of Southern Indian Lake by region and depth at natural historic mean level and post-impoundment historic mean level. Sources as discussed in text. Units: 10^9 m^3.

Region Elevation (m MSL)	0	1	2	3	4	5	6	7	Whole Lake
258.0									
	.25	1.49	.75	.68	2.05	.77	.39	.16	6.54
255.0									
	.22	1.73	.78	.75	2.44	.61	.34	.13	7.00
250.6									
	.09	1.27	.53	.58	2.16	.28	.08	.05	5.04
245.6									
	.04	.61	.27	.31	1.66	.10	<.01	.01	3.00
240.6									
	.02	.15	.10	.09	1.02	.03		<.01	1.41
235.6									
	<.01	.02	.02	.01	.29	.01			.35
230.6									
	<.01	<.01	<.01	<.01	.02	<.01			.03
225.6									
		<.01	<.01		<.01	<.01			.01
220.6									
Post-impoundment total volume:	.63	5.27	2.45	2.42	9.64	1.81	.81	.35	23.38
Pre-impoundment total volume:	.38	3.78	1.70	1.74	7.59	1.04	.42	.19	16.84

Table 1-3. Areas of Southern Indian Lake (including Opachuana Lake) and flooded area as reported by various authors.

Source	Pre-impoundment area (km^2)	Post-impoundment area (km^2)	Total flooded area (km^2)	Flooded terrestrial area (km^2)
Underwood-McLellan (1970)	2064[a]	2440[b]	376	308[c]
Cleugh et al. (1974)	1977[a]	2520[b]	543	475[c]
Flanders et al. (1974)				460[d]

a Pre-impoundment area measured on photo-mosaic compiled from 1954, 1955 aerial photographs at 1:63,360 scale, with Southern Indian Lake level at approximately 255 m MSL.
b Post-impoundment area measured on above mosaic at the plotted 850 ft MSL (259.1 m MSL) contour.
c Calculated by subtraction of area of flooded lakes (68 km^2) from total flooded area.
d Flooded land measured on township photo-mosaics compiled from 1969, 1970 aerial photographs at 1:31,680 scale, with Southern Indian Lake level 254.9 - 255.3 m MSL and with assumed post-impoundment level at the 850 ft. MSL (259.1 m MSL) contour.

Table 1-4. Areas of lakes flooded by impoundment of Southern Indian Lake. Areas measured by author on photo-mosaic at 1:63,360 scale, with plotted 850 ft. MSL (259.1 m MSL) contour.

Figure 1 designation	Pre-impoundment lake level (m MSL)	Pre-impoundment area (km^2)	Post-impoundment area (km^2)
A	258	10	11
B	256	24	35
C	-	5	8
D	255	17	24
E	-	2	3
F	-	10	24
Total	-	68	105

Cleugh et al. (1974, Table 2) for all other depths. As the bathymetric survey which served as source for these data was done in June and July of 1972, when the lake surface elevation was approximately 255.6 m MSL, the 5 m isobath (at 250.6 m MSL) is only 4.4 m below the historic mean level of 255 m MSL. Volume of each segment was calculated by the formula (Hutchinson, 1957):

$$V = \frac{h}{3}\,(A_1 + A_2 + \sqrt{A_1 A_2})$$

where: V = volume (m^3)
h = thickness of segment (m)
A_1 = area inside upper isobath (m^2)
A_2 = area inside lower isobath (m^2)

This calculation assumes that each segment is in the shape of a frustrum of a cone.

Volumes thus calculated are reported in Table 1-2. As these volumes differ slightly from those reported by Cleugh et al. (1974, Tables 2,5), and as exchange time as calculated from the water budget is inversely proportional to lake volume, the adjusted volumes reported in Table 1-2 were used in calculating the exchange times reported in Tables 1 and 3 in the text of this report.

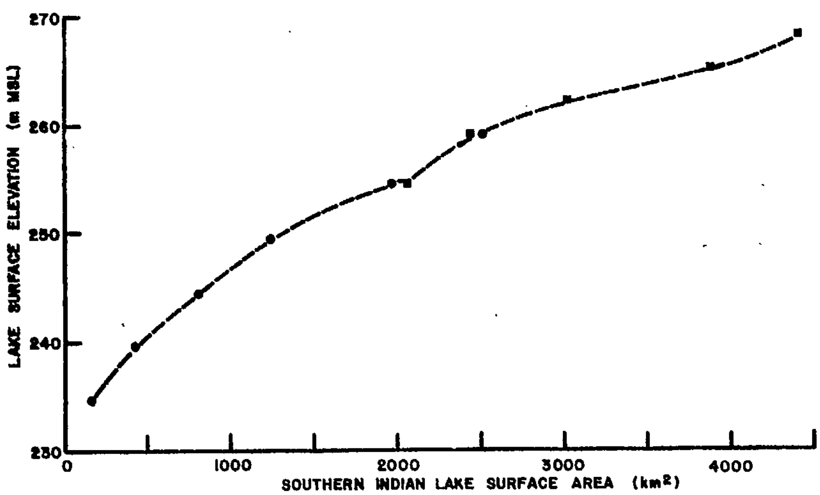

Fig. 1-1. Hypsometric plot for Southern Indian Lake. Data from Underwood-McLeann (1970) (squares), and Cleugh (1974) (dots).

APPENDIX REFERENCES

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