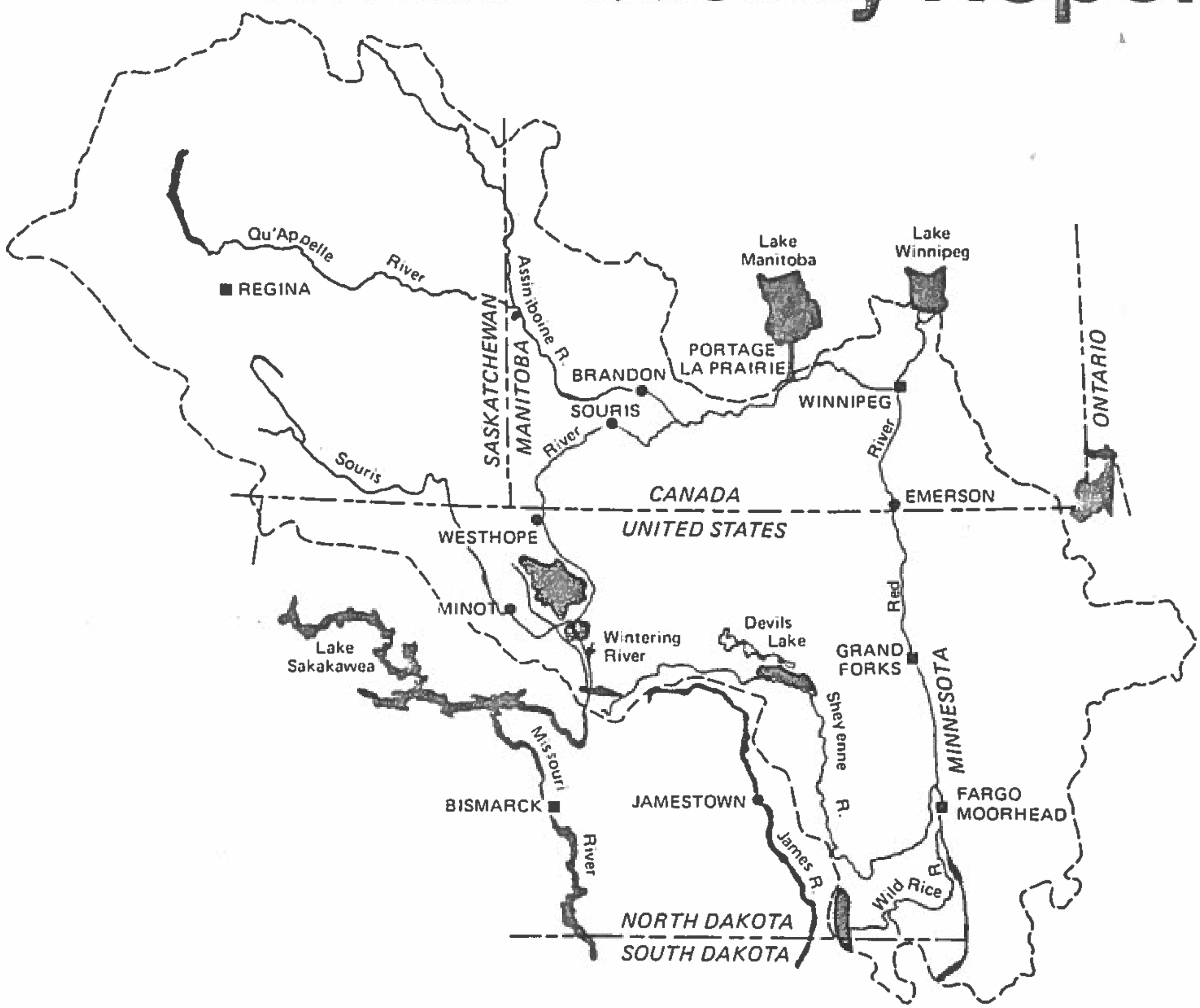
INTERNATIONAL GARRISON DIVERSION STUDY BOARD

APPENDIX A
Water Quality Report



REPORT TO THE INTERNATIONAL JOINT COMMISSION - 1976

VI WATER QUALITY OF LAKES

A. Introduction

Lake Winnipeg is located between 96°20' and 99°20' W longitude and 50°20' and 53°51' N latitude and Lake Manitoba is located between 98°00' and 99°40' W longitude and 50°00' and 51°40' N latitude, in south central Manitoba. Both lake basins are remnants of Glacial Lake Agassiz. The entire Lake Manitoba basin is situated on Paleozoic and Mesozoic sedimentary strata whereas the Lake Winnipeg basin is situated on the boundary between the Precambrian Shield on the east and north and sedimentary strata on the west and south. Rivers flowing to Lake Winnipeg from the east are generally low in concentrations of nutrient elements, major ions (specific conductivity <100 μmhos cm^{-1} at 25°C) and suspended material. Rivers flowing to Lake Manitoba and to Lake Winnipeg from the west and south generally have higher concentrations of nutrient elements, major ions (specific conductivity 300 to 1700 μmhos cm^{-1}) and suspended material. Major tributaries to Lakes Manitoba and Winnipeg are identified in Figures A-47 and A-48 . Since 1970, water has been diverted during high flow periods from the Assiniboine River to Lake Manitoba via the Portage La Prairie Diversion. Water flows out of Lake Manitoba through the Dauphin River to Lake Winnipeg. Lake Winnipeg empties into Hudson Bay via the Nelson River.

Basic morphometric parameters (surface areas, volumes, mean depths and maximum depths) for Lake Manitoba and Lake Winnipeg are reported in Tables A-43 and A-44 . Both lakes are large in surface area compared to mean depth; as a result, thermal stratification is rare during the open water season. It is possible to divide the Lake Winnipeg Basin into three distinct regions, namely the South Basin, the Narrows and the North Basin. Delineation of these regions is outlined in Figure A-48. Similarly, it is informative to consider separately the South Basin and North Basin of Lake Manitoba (Figure A-47). Drainage areas of major tributaries to Lakes Manitoba and Winnipeg are reported in Tables A-45 and A-46 , respectively. These data were obtained from Surface Water Data reports published annually by Water Survey of Canada. Other drainage areas reported in Tables A-45 and A-46 were obtained by planimetry.

Brunskill (1973) and Crowe (1972) reported that Lakes Winnipeg and Manitoba, respectively, are eutrophic.

The purpose of this part of the report is (1) to describe the present water quality of Lakes Manitoba and Winnipeg and, (2) to predict future water quality with and without the imposition of irrigation return flows, canal system seepage, operational wastes, municipal and industrial effluent and fish and wildlife return flows related to the planned Garrison Diversion Unit in North Dakota.

Descriptions of present and predictions of future water quality of the lakes will be approached in two ways: 1) in terms of loading rates to the lake basins and, 2) in terms of constituent concentrations within the lake basins. Parameters which will be emphasized are total suspended solids, major anions and cations in solution, and nutrients.

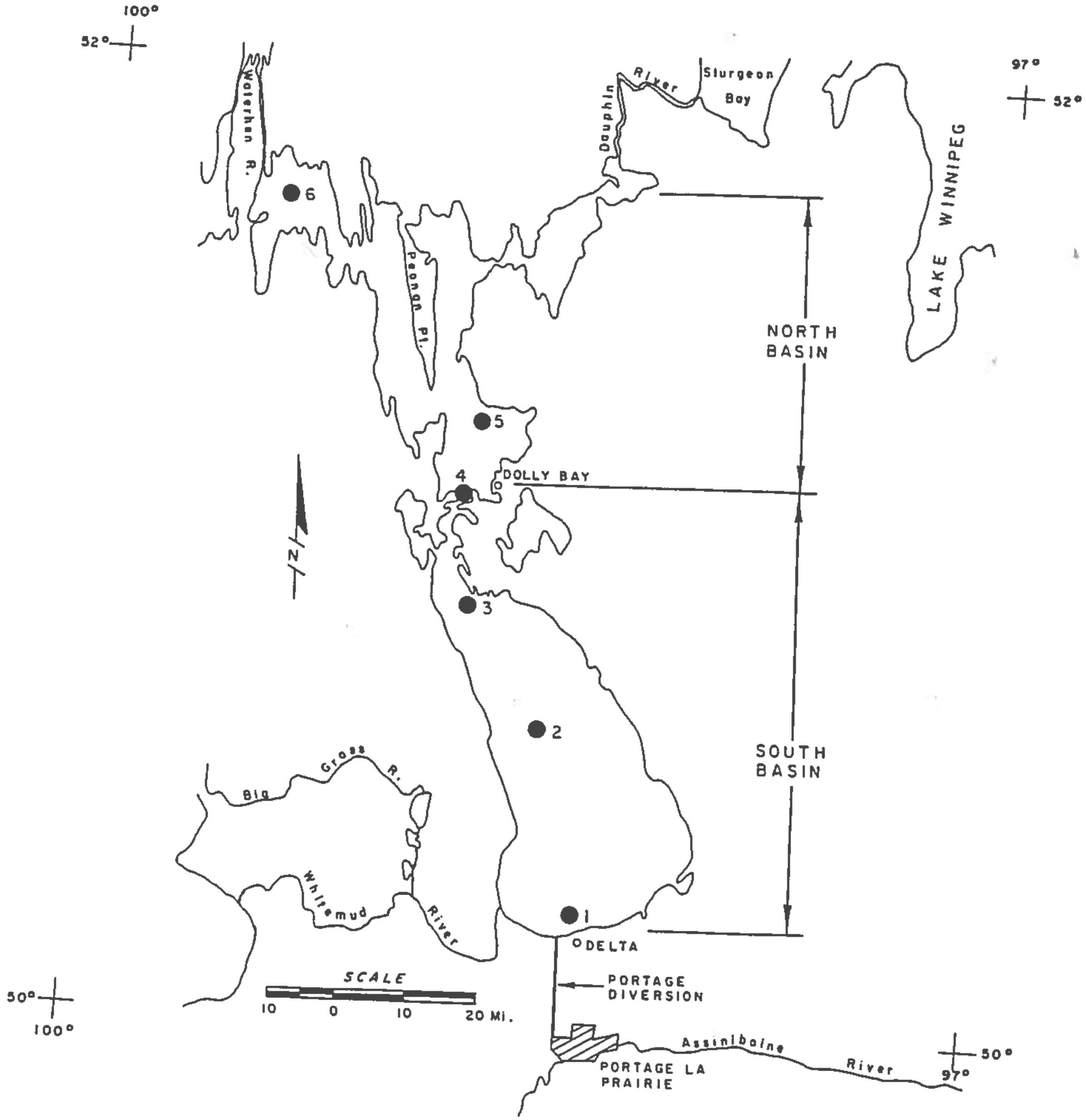


FIGURE A- 47 - Locations of Sampling Stations in Lake Manitoba

FIGURE A-48 - Locations of Sampling Stations in Lake Winnipeg

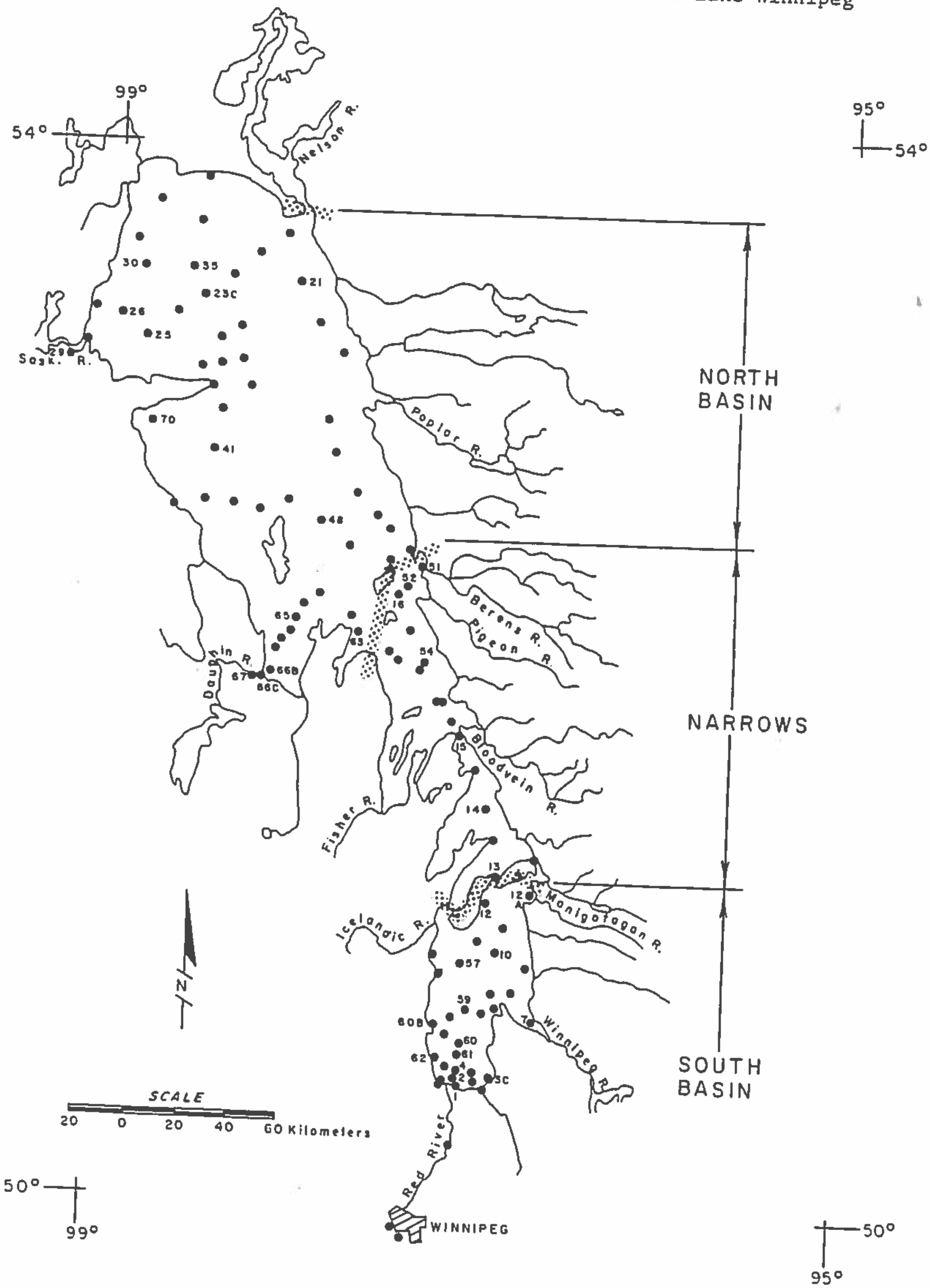


Table A-43. Morphometry of Lake Manitoba.*

	Surface Area (km^2)	Volume (km^3)	Mean Depth (meters)	Maximum Depth (meters)
SOUTH BASIN	2860	14.6	5.1	6.6
NORTH BASIN	1800	5.6	3.1	5.7
ENTIRE LAKE	4660	20.2	4.3	6.6

* Lake surface taken to be 247.8 meters above sea level. Surface areas were measured by planimeter. Depths and volumes courtesy of J. A. Crowe.

Table A-44. Morphometry of Lake Winnipeg.*

	Surface Area (km^2)	Volume (km^3)	Mean Depth (meters)	Maximum Depth (meters)
SOUTH BASIN	2780	27.0	9.7	14.2
NARROWS	3450	24.6	7.1	38.0
NORTH BASIN	17520	232.4	13.3	19.9
ENTIRE LAKE	23750	284.0	12.0	38.0

* Morphometric data courtesy of G. J. Brunskill, Lake surface taken to be 218.3 meters above sea level. Computations of morphometric parameters were done after Hutchinson (1957).

Table A-45 Terrestrial drainage areas of the Lake Manitoba watershed.

	Drainage Area (km^2)
SOUTH BASIN	
Whitemud River	6,220
Other	8,240
	14,460
NORTH BASIN	
Waterhen River	56,980
Other	3,700
	60,680
TOTAL TERRESTRIAL DRAINAGE AREA	75,140

Table A-46 . Terrestrial drainage areas of the Lake Winnipeg watershed.

	Drainage Area (km^2)
SOUTH BASIN	
East side - Precambrian Shield	
Winnipeg River	126,400
Other	6,300
West and South sides - approx. 85% sedimentary	
Red River	287,500
Other	10,400
	430,600
NORTH BASIN AND NARROWS	
East side - Precambrian Shield	
Poplar River	6,790
Berens and Pigeon Rivers	19,700
Manigotogan River	1,800
Other	12,760
West side - approx. 98% sedimentary	
Saskatchewan River	340,400
Dauphin River	80,000
Fisher River	1,360
Other	59,840
	522,650
TOTAL TERRESTRIAL DRAINAGE AREA	953,250

B. Present Water Quality

Methodology of Computing Water Budgets 1969-74

Monthly and annual water budgets were computed for the South Basin and Narrows/North Basin of Lake Winnipeg for the years 1969-1974. Total inflow to the South Basin was computed by summing runoff from the terrestrial watershed and precipitation falling directly on the lake surface. Evaporation was estimated to be 0.5 meters $year^{-1}$ (Newbury, personal communication) and subtracted from the total annual flow to the South Basin in order to obtain annual estimates of flow from the South Basin into the Narrows/North Basin. Flow from the South Basin was added to contributions from surface runoff and precipitation to obtain total inflow to the Narrows/North Basin. A storage-evaporation residual for the Narrows/North Basin was computed by subtracting outflow via the Nelson River from total inflow.

Only approximate annual and monthly water budgets could be prepared for the north and south basins of Lake Manitoba due to the paucity of meteorological stations in the area and the relatively high fraction of unmeasured terrestrial drainage into the south basin. Representative budgets were prepared for the period 1970-1974 by first balancing inflows and outflows for the whole lake and assigning unmeasured residual terms to each basin in proportion to their relative areas (Newbury and Beaty, Freshwater Institute, Environment Canada). The residual terms (comprised of evaporation, storage, and errors in all measured and estimated terms) were combined with the inflows and outflows for each basin to obtain the net exchanges in flows required between each basin. In general, an excess of inflow as compared to outflows and storage during the winter months produced the major source of error in the whole lake budget.

Flow data were obtained from annual Surface Water Data reports of Water Survey of Canada (Mr. P. Abel of Manitoba Hydro provided flow data for the Saskatchewan River at Grand Rapids). Flow from unmonitored areas was estimated by extrapolation from adjacent monitored watersheds. Precipitation data was obtained from Monthly Record Meteorological Observations of the Canadian Atmospheric Environment Service. Precipitation recorded at Gimli, Pine Dock and Grand Rapids was applied, respectively, to the South Basin, the Narrows and the North Basin of Lake Winnipeg. The Delta and Vogar stations were used, respectively, to estimate precipitation to the surface of the South Basin and North Basin of Lake Manitoba. Estimates of annual eastward and westward groundwater inflows to the North Basin and South Basin of Lake Manitoba were provided by Mr. F. Render of the Manitoba Department of Mines, Resources and Environmental Management.

For each lake basin, estimates of theoretical water renewal times (residence times) were computed by dividing the volume of the basin by the annual outflow from the basin (excluding evaporation).

Sources of Physical and Chemical Data

Unpublished physical-chemical data collected during 1968-70 by Dr. G. J. Brunskill of the Freshwater Institute, Winnipeg, Manitoba were used to describe the present water quality of Lake Winnipeg. Sampling locations on Lake Winnipeg are denoted in Figure A-48 . Data of Ms. J. A. Crowe (1972 and unpublished) and of Mr. M. Morelli (unpublished) of the Manitoba Department of Mines, Resources and Environmental Management which were collected during the periods 1966-69 and 1973-75 were used in describing Lake Manitoba. Lake Manitoba sampling stations are shown in Figure A-47 . Mr. Bill Gummer of the Water Quality Branch, Canadian Environmental Management Service, provided data on chemical determinations carried out on tributaries to and outflows from Lakes Winnipeg and Manitoba for the period 1969-74. The quality of groundwater flowing into Lake Manitoba was estimated by using chemical analyses of water from wells within 10 km of the lake shore; the analyses were provided by Mr. F. Render of the Manitoba Department of Mines, Resources and Environmental Management.

Methodology of Calculating Loading Rates - 1969-1974

Loading rates to the South Basin and the North Basin of Lake Manitoba and to the South Basin and Narrows/North Basin of Lake Winnipeg of suspended sediment (SS), dissolved calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO_4), chloride (Cl), bicarbonate (HCO_3), and total (dissolved plus particulate) nitrogen (TN) and phosphorus (TP) were computed annually for the periods 1970-74 and 1969-74, respectively. Inputs of any given parameter from the terrestrial drainages were computed by taking the product of instantaneous concentration and total monthly discharge. Monthly rates of transport (or seasonal rates of transport, if a paucity of data) were summed to obtain annual rates of transport. Specific tributaries on which loading rates were computed are listed in Tables A-47 and A-48 . Loading rates from unmonitored drainages was estimated by extrapolation from adjacent monitored drainages . Transport of an element through the Narrows of Lake Manitoba were estimated seasonally and summed to obtain annual rates. In the case of Lake Winnipeg, concentrations measured at Station 14 (Figure A-48) during 1969 only were averaged and multiplied by annual outflows from the South Basin in order to estimate annual rates of transport from the South Basin into the Narrows/North Basin. Loading rates direct to the lake surfaces by wet and dry fallout were estimated on an annual basis by extrapolation from a watershed near Kenora, Ontario (Schindler *et al.*, 1976). The averages of analyses from 6, 24 and 11 wells were used to compute annual inputs of major cations and anions to Lake Manitoba *via* groundwater from the east, southwest and northwest shores, respectively. Total annual rates of transport to a basin were obtained by summing annual inputs from surface runoff and precipitation (as well as transport from an adjacent lake basin or groundwater where applicable).

Water Budgets, 1969-1974

Annual water budgets for the South Basin and North Basin of Lake Manitoba and the South Basin and Narrows/North Basin of Lake Winnipeg for the periods 1970-74 and 1969-74, respectively, are reported in Tables A-47 and A-48. In general (exception, South Basin of Lake Manitoba), maximum total annual inflows occurred in 1974. Minimum annual inflows to all basins occurred in 1973. An analysis of flows for the 60-70 year period of record on the Winnipeg River and Red River suggests that the water budgets presented here account for about 50 percent of the "present-day" range of total annual inflows to the lake basins. The upper end of the range is covered well; however, approximately 50 percent of the annual flows measured over the entire historical period of record were less than those of the lowest flow year (1973) considered here.

Although only approximately 25 percent of the terrestrial drainage basin of Lake Winnipeg is Precambrian Shield, it was found to contribute, on an average, 55-60 percent of the runoff water to the lake. Annual runoff from the Precambrian Shield ranged from 0.19 to 0.35 meters $year^{-1}$ whereas annual runoff from the sedimentary drainages ranged from 0.03 to 0.07 meters $year^{-1}$ during the six year period considered here. When the South Basin of Lake Winnipeg was considered by itself, the annual contribution of runoff water (m^3 $year^{-1}$) from the Precambrian Shield (primarily the Winnipeg River) was found to be 4 to 9 times that from the sedimentary drainage to the west and south (primarily the Red River). As a rule, it was observed that variation in annual discharge from year to year in rivers lacking major control structures was greater for those on sedimentary drainages than those on the Precambrian Shield. On an average, 10-15 percent of the total annual inflow to Lake Winnipeg was accounted for by precipitation direct to the lake surface.

Annual runoff to Lake Manitoba (exclusively sedimentary drainages) ranged from 0.01 to 0.10 meters $year^{-1}$. From 0-20 percent of the total annual inflow to the South Basin of Lake Manitoba came via the Portage Diversion. The largest single contribution of water to the South Basin was precipitation; precipitation direct to the lake surface accounted for 40-65 percent of the total annual inflow. In the case of the North Basin of Lake Manitoba, however, precipitation accounted for only 10-25 percent of the total annual inflow. The largest inflow component to the North Basin was flow from the Waterhen River (50-65 percent of total annual inflow). In 2 of the 5 years from 1970-1974, it was observed that there was no net transfer of water from the South Basin to the North Basin via the Narrows. In dry years, then, (probably at least 50% of the time), evaporation is the sole outflow component from the South Basin of Lake Manitoba.

Table A-47. Annual water budgets for Lake Manitoba, 1970-1974.

	(m^3 year^{-1} X 10^6)				
	1970	1971	1972	1973	1974
SOUTH BASIN					
Inflow					
Portage Diversion	262	31	306	0	668
Whitemud River	578	207	200	90	395
Other drainages	862	299	264	121	525
Groundwater	228	228	228	228	228
Narrows**	468	440	580	501	0
Precipitation direct to lake surface	1510	1540	1170	1660	1180
Total Inflow	3910	2750	2750	2600	3000
Outflow					
Narrows**	1074	580	502	257	1620
Residual Term*	2830	2170	2250	2340	1380
NORTH BASIN					
Inflow					
Narrows**	1074	580	502	257	1620
Waterhen River	2620	3430	3030	2240	3530
Other drainages	219	77	118	53	235
Groundwater	362	362	362	362	362
Precipitation direct to lake surface	947	969	732	990	740
Total Inflow	5220	5420	4740	3900	6490
Outflow					
Narrows**	468	440	580	501	0
Dauphin (Fairford) River	2760	3400	2610	1720	5420
Total Outflow	3230	3840	3190	2220	5420
Residual Term*	1990	1580	1550	1680	1070

* Residual term distributed from whole lake budget representing evaporation, storage, and errors in measured and estimated values.

** Gross value based on monthly exchanges; net value of transfer for year equals the difference in terms.

Note: Annual water balance is approximate only. Groundwater flows added subsequently to balance affect net inter-basin exchanges by 2-10% over period.

Table A-48. Annual water budgets for Lake Winnipeg, 1969-1974.

	1969	1970	1971	1972	1973	1974
	(m^3 year^{-1} x 10^6)					
SOUTH BASIN						
Inflow						
Winnipeg River	42,700	44,500	39,400	33,400	25,800	48,300
Other Precambrian Shield drainages	2,130	2,220	1,970	1,660	1,290	2,410
Red River	9,990	10,300	5,830	7,090	2,890	12,200
Other sedimentary drainages	364	374	208	260	104	437
Precipitation direct to lake surface	1,210	1,300	1,280	995	1,810	1,170
Total Inflow	56,390	58,690	48,690	43,410	31,890	64,520
Outflow						
Narrows*	55,000	57,300	47,300	42,020	30,500	63,130
Evaporation*	1,390	1,390	1,390	1,390	1,390	1,390
NORTH BASIN & NARROWS						
Inflow						
Poplar River	2,490	782	1,080	1,140	835	1,080
Berens and Pigeon Rivers	7,930	3,760	4,720	3,610	3,630	5,690
Manigotogan River	326	332	235	196	290	470
Other Precambrian Shield drainages	4,040	2,080	2,260	1,950	1,990	3,010
Saskatchewan River	20,000	19,900	20,300	23,100	18,000	29,400
Dauphin River	1,950	2,740	3,400	2,610	1,710	5,420
Fisher River	57.9	66.7	24.0	39.8	24.3	184
Other sedimentary drainages	3,230	3,290	2,450	2,990	2,390	6,940
Narrows	55,000	57,300	47,300	42,020	30,500	63,130
Precipitation direct to lake surface	10,430	9,950	9,940	8 540	14,590	10,310
Total Inflow	105,500	100,200	91,700	86,200	74,000	125,600
Outflow						
Nelson River	91,600	96,200	87,600	84,000	62,350	98,900
Evaporation and Storage+	13,900	4,000	4,100	2,200	11,650	26,700

* Outflow *via* the Narrows was computed by subtracting evaporation from the total inflow to the South Basin; evaporation was estimated to be 0.5 meters year^{-1}.

+ Computed by subtracting the outflow *via* the Nelson River from the total inflow to the Narrows and North Basin.

Water Renewal Times

Water renewal times for the Lake Manitoba and Lake Winnipeg basins are reported in Tables A-49 and A-50 , respectively. Of the four lake basins considered here, the South Basin of Lake Manitoba has the smallest ratio of terrestrial drainage area (A_d) to lake surface area (A_o) - approximately 5:1. It also has the longest residence time (approximately 20 years). Conversely, the ratio A_d to A_o for the South Basin of Lake Winnipeg is 155:1 and the water renewal time in that basin is approximately 0.5 years. Residence times for the North Basins of Lake Manitoba and Lake Winnipeg were computed, on an average to be about 1. and 2.5 years, respectively.

Loading Rates, 1969-1974

Ranges of estimated total annual inputs of SS, Ca, Mg, Na, K, Cl, SO_4, HCO_3, TN and TP to the South Basin and North Basin of Lake Manitoba and the South Basin and Narrows/North Basin of Lake Winnipeg from 1970-74 and 1969-74, respectively, are reported in Table A-51 . Total annual loads of these parameters to the Lake Manitoba and Lake Winnipeg basins are clearly largely related directly to total annual inflow. With few exceptions, minimum inputs corresponded with low flow years and maximum inputs corresponded with high flow years. Highest total annual inflows to the Lake Manitoba and Lake Winnipeg basins ranged from about 1.5 to 3 times minimum annual inflows (Tables A-47 and A-48); maximum total annual loads of major ions and nutrients ranged from about 1.5 to 3 times higher than minimum total annual loads (Table A-51). There were order of magnitude differences between minimum and maximum annual inputs of suspended sediment to the south basins of Lakes Manitoba and Winnipeg (Table A-51).

Annual loads of Ca, Mg, Na, K, SO_4, Cl and HCO_3 from the Precambrian Shield accounted for less than 30 percent of the total terrestrial loads of these elements to Lake Winnipeg. On an average, 30-50 percent of the total annual terrestrial loads of TN and TP to Lake Winnipeg came from the Precambrian Shield. When the South Basin of Lake Winnipeg was considered by itself, the Precambrian Shield was found to contribute 30-50 percent of the total annual terrestrial loads of K and up to 60-75 percent of the total annual terrestrial loads of Ca, HCO_3, TN and TP (recall that annual discharge of the Winnipeg River was 4-9 times that of the Red River). Contributions of Mg, Na, SO_4 and Cl from the Precambrian Shield to the South Basin of Lake Winnipeg were generally less than 30 percent of the annual total. Relatively large rates of transport (in relation to drainage area) of constituents such as TN and TP from the Precambrain Shield (only 25 percent of the total drainage area and only 40 percent of the drainage area of the South Basin) are certainly due in part to the much higher runoff of water in comparison to sedimentary drainages. Other likely factors which, in conjunction with differences related to climate, result in different transport rates (kg km^{-2} $year^{-1}$) between sedimentary drainages and Precambrian Shield drainages, are bedrock geology

Table A-49. Estimated residence times (water renewal times) of the South Basin and the North Basin of Lake Manitoba, 1970-1974.

	Residence time (years)				
	1970	1971	1972	1973	1974
South Basin*	13.6	25.2	29.1	56.8	19.0
North Basin+	1.7	1.5	1.8	2.5	1.0

$$* \text{ Residence time} = \frac{\text{Volume of South Basin}}{\text{Annual outflow } \underline{\text{via}} \text{ the Narrows}}$$

$$+ \text{ Residence time} = \frac{\text{Volume of North Basin}}{\text{Annual outflow } \underline{\text{via}} \text{ the Narrows and Dauphin River}}$$

Table A-50. Estimated residence times (water renewal times) of the South Basin and the Narrows and North Basin of Lake Winnipeg, 1969-74.

	Residence time (years)					
	1969	1970	1971	1972	1973	1974
South Basin*	0.5	0.5	0.6	0.6	0.9	0.4
Narrows and North Basin+	2.8	2.7	2.9	3.1	4.1	2.6

$$* \text{ Residence time} = \frac{\text{Volume of South Basin}}{\text{Outflow } \underline{\text{via}} \text{ the Narrows}}$$

$$+ \text{ Residence time} = \frac{\text{Volume of Narrows and North Basin}}{\text{Outflow } \underline{\text{via}} \text{ Nelson River}}$$

Table A-51 Estimated Ranges of Constituents Transported Annually to Lake Manitoba from 1970-1974 and to Lake Winnipeg from 1969-1974.

		Total annual input (metric tons X 10^3)									
		Suspended Solids	Ca	Mg	Na	K	Cl	SO_4	HCO_3	Total N	Total P
LAKE MANITOBA											
South Basin	Minimum	16.7(73)	81.2(73)*	52.4(73)	123.4(74)	19.0(74)	113.1(74)	266.1(73)	231.5(73)	2.22(73)	0.105(73)
	Maximum	342 (74)	189.4(70)	70.4(70)	269.1(72)	30.6(70)	360.0(72)	382.1(70)	543.6(70)	4.78(70)	0.428(74)
North Basin	Minimum	31.8(70)	176.6(73)	99.8(73)	745.9(73)	39.7(73)	1149 (73)	359.0(73)	625.1(73)	3.80(73)	0.081(73)
	Maximum	76.6(74)	353.6(74)	230.9(74)	1426 (74)	83.6(74)	2131 (74)	769.8(74)	1259 (74)	7.16(74)	0.169(70)
LAKE WINNIPEG											
South Basin	Minimum	386 (73)	562.0(73)	150.9(73)	194.1(73)	43.6(73)	160.4(73)	490.7(73)	2028 (73)	25.4 (73)	2.30 (73)
	Maximum	4033 (69)	1411 (74)	421.2(74)	542.7(74)	130.2(74)	439.8(74)	1516 (74)	5189 (74)	69.6 (74)	9.46 (70)
Narrows/North basin	Minimum	+	1622 (73)	525.1(73)	922.3(73)	122.7(73)	988.1(73)	1546 (73)	6199 (73)	48.9 (73)	3.19 (73)
	Maximum	+	3606 (74)	1346 (74)	2423 (74)	317.4(74)	2762 (74)	4046 (74)	15050 (74)	83.8 (74)	6.48 (74)

* Bracketted ( ) figures indicate the year in which a minimum or maximum rate of transport was observed.

+ Data not available.