Morphometry, Hydrology, and Watershed Data Pertinent to the Limnology of Lake Winnipeg

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MORPHOMETRY, HYDROLOGY, AND WATERSHED DATA PERTINENT TO THE LIMNOLOGY OF LAKE WINNIPEG

by

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Morphometric, hydrologic, and climatic data for Lake Winnipeg and its watershed are given. Over half the annual water supply to the lake comes from eastern Precambrian Shield rivers, which drain only 18% of the total lake watershed. Prairie rivers (which drain sedimentary watersheds), have lower discharges of water, but carry high concentrations of nutrients, salts, and sediments. Theoretical water renewal time for the lake varied from 2.9 to 4.3 years for 1969-1974, depending upon seasonal variations in river discharge. Theoretical water renewal time for the south basin of Lake Winnipeg was computed to be 0.4 to 0.8 years, but interbasin water fluxes due to wind-driven currents are much larger than river discharge into this small basin. With large fetch, abundant wind energy, and shallow water depths, the lake is well mixed vertically. Large horizontal gradients for most limnological parameters were related to the orientation, magnitude, dissolved salt and suspended sediment load of river discharge into the three major basins of the lake.

Annual sediment transport (=drainage area erosion rate) for the muddy prairie rivers (Red, Saskatchewan) was 1 to 20 tonnes km^{-2} watershed yr^{-1}, which was in the lower part of the range of other North American prairie rivers. Dissolved salt and nutrient transport rates were computed, and were found to be relatively low, compared to other agricultural watersheds. The highest chemical erosion rates were from the Precambrian Shield watershed of the Winnipeg River, which has 5 to 10 times more water runoff than the prairie watersheds. Very low nutrient transport rates were computed for the Saskatchewan River.

We tabulated the annual cultural and/or technological supply of N and P to the Lake Winnipeg watershed, using historical and statistical records of human and livestock populations, fertilizer and detergent consumption. Historical trends of human and livestock populations, and land area under cultivation indicate moderate growth, but fertilizer application rates are increasing exponentially. We estimate that 0.5-3.5% of P, and 0.4-0.8% of the N mobilized by agriculture and populations of humans and livestock reaches Lake Winnipeg via rivers. A tentative estimate of chlorinated hydrocarbons and mercury supply rates to Lake Winnipeg was also made.

Key words: erosion rates; nutrient supply; agricultural runoff; livestock wastes; fertilizers.

RESUME

Brunskill, G. J., S. E. M. Elliott, and P. Campbell. 1980. Morphometry, hydrology, and watershed data pertinent to the limnology of Lake Winnipeg. Can. MS Rep. Fish. Aquat. Sci. 1556: v + 23 p.

Les auteurs ont recueilli des données morphométriques, hydrologiques et climatiques sur le lac Winnipeg et son bassin. Plus de la moitié des apports d'eau au lac provient des cours d'eau de l'est du bouclier précambrien, même s'ils ne drainent que 18% du bassin. Les cours d'eau de prairie (qui drainent les bassins sédimentaires) ont un faible débit, mais transportent beaucoup d'éléments nutritifs, de sels et de sédiments. Selon les variations saisonnières du débit des cours d'eau, de 1969 à 1974, on estime qu'il a fallu de 2.9 à 4.3 années pour que les eaux du lac se renouvellent. Théoriquement, on évalue que le renouvellement des eaux du bassin sud du lac Winnipeg a pris de 0.4 à 0.8 année, mais, à cet endroit, la circulation d'eau entre les bassins, due aux courants engendrés par le vent, est beaucoup plus importante que l'apport d'eau dans ce petit bassin. L'importance du fetch, l'énergie éolienne et la faible profondeur assurent un bon brassage vertical des eaux du lac. Quant aux forts gradients horizontaux observés pour la plupart des paramètres limnologiques, ils s'expliquent par la teneur en sels dissous et en matières en suspension des cours d'eau, par l'orientation et l'importance du débit dans les trois grands bassins du lac.

Dans les rivières boueuses de prairie (la Red, la Saskatchewan), le transport annuel de MES (égale à la vitesse d'érosion dans leur bassin hydrographique) a été de 1 à 20 tonnes km^{-2} de bassin, ce qui était assez faible par rapport à ce que l'on observe dans les autres cours d'eau de prairie d'Amérique du Nord. L'apport de sels dissous et de sels nutritifs s'est révélé relativement faible, comparativement à ce qui se passe avec d'autres bassins de terres agricoles. C'est dans le bassin du bouclier précambrien de la Winnipeg River que l'érosion a été la plus marquée, du fait que le ruissellement est de 5 à 10 fois supérieur à ce qu'on trouve dans les autres bassins de prairie. Dans la Saskatchewan, le transport de sels nutritifs a été très faible.

A l'aide de données rétrospectives et statistiques sur la population humaines et le cheptel, sur l'utilisation de détergents et d'engrais, les auteurs ont déterminé l'apport annuel de N et de P, dans le bassin du lac Winnipeg. D'après les tendances du nombre d'habitants, le cheptel et la superficie des terres cultivées augmentent de façon modérée tandis que le rythme d'épandage d'engrais s'accroît de façon exponentielle. D'après les calculs, de 0.5 à 3.5% de P et de 0.4 a 0.8% de N utilisés se retrouvent dans le lac Winnipeg. Les auteurs ont aussi tenté d'estimer les apports de mercure et d'hydrocarbures chlorés au lac Winnipeg.

Mots-clés: vitesses d'érosion; apport en éléments nutritifs; ruissellement des terres agricoles; déjections du bétail; engrais.

INTRODUCTION

Limnologists have come to recognize that many properties of lakes are often largely dependent upon their terrestrial watersheds. This paper is essentially about the paralimnology (Hutchinson 1937) of Lake Winnipeg. The eastern watersheds of Lake Winnipeg are of igneous bedrock of Precambrian Shield (Fig. 1), overlain with variable thicknesses of glacial Lake Agassiz-derived soils, muskegs, and boreal forests. The southern, western, and northwestern watersheds of Lake Winnipeg are of sedimentary (Palaeozoic and Mesozoic shales, limestones, dolomites, and sandstones) strata overlain with considerable thicknesses of glacial Lake Agassiz sediments, well developed chernozemic soils, originally prairie grasses in the south, and mixed decidious and coniferous forests to the west and northwest (National Atlas of Canada; Elson 1967; Davies et al. 1962). The prairie watersheds now support agricultural activities and a number of cities, whereas the Precambrian Shield supports mining and forest industries, little agriculture, and few large communities. The rivers draining these markedly different watersheds have very different chemical and biological characteristics, and they have very different effects upon the limnology of Lake Winnipeg (Bajkov 1930, 1934; Brunskill, Schindler, Elliott et al. 1979; Brunskill, Schindler, Holmgren et al. 1980; Brunskill, Campbell, and Elliott 1979; Brunskill and Graham 1979).

METHODS

Hydrological data for rivers flowing into Lake Winnipeg were obtained from the Winnipeg office of Water Survey of Canada. Bathymetric and morphometric data were generated from Canadian Hydrographic Service charts (6240, 6241, 6267 and 6251) and our own 20-200 KC/sec sonar transects on the lake in 1969. Since these charts have several different datum levels, we adjusted them to a common datum of 218 meters above sea level to estimate the volume of the lake. Surface area, area of each contour, and volume were obtained by planimetry. Morphometric parameters were calculated according to Hutchinson (1957).

Measurements of Ca, Mg, Na, K, HCO_3, SO_4, Cl, dissolved Si, total nitrogen (TN) and total phosphorus (TP) were done on seasonal samples of rivers tributary to Lake Winnipeg. Methods and the data are reported in Brunskill, Schindler, Holmgren et al. (1979); Brunskill, Campbell, and Elliott (1979); and Stainton et al. (1974). Brunskill and Graham (1979) give data on the rate of supply of these elements in the particulate fraction to the south basin of Lake Winnipeg via the Red River. Average monthly concentrations of the above elements were multiplied by total monthly discharge and summed for the yearly transport of each element from each watershed. Some chemical data was taken from Water Quality NAQUADAT computer print-out for these computations in 1971-74. W. Carroll of the City of Winnipeg Water Works and Waste Disposal Division provided us with nutrient chemistry and discharge of sewage plant effluents. Suspended sediment data came from Environment Canada (1978).

Annual total land area that is within the Lake Winnipeg watershed that is under cultivation in Manitoba, Saskatchewan and Alberta was determined by summing the number of hectares seeded in all major field crops, plus summer fallow, for the three provinces (Statistics Canada 1975).

Proportions of North Dakota and Minnesota within the Lake Winnipeg drainage basin were determined from maps by planimetry. These fractions were then applied to the annual state areas under cultivation for major crops (Taylor et al. 1962; Minnesota Dep. Agric. 1971; U.S. Dep. Agric. 1963-1974). Cultivated land area for the three Canadian prairie provinces and the two U.S. states were then summed to yield estimates of cultivated land area in the Lake Winnipeg watershed for the years 1960 to 1974.

The identical approach was used to determine total human population for the years 1900 to 1970 (Statistics Canada 1961, 1974; U.S. Bureau of Census 1960, 1974; Voelker and Ostenson 1968), total annual populations of cattle, hogs and sheep for 1960 to 1973 (Minnesota Dep. Agric. 1971; Statistics Canada, Handbook of Agricultural Statistics 1974; North Dakota State Univ. of Agriculture and Applied Science 1962, 1971; U.S. Dep. Agric. 1973a, b, and c), and total fertilizer applied to the land for 1945 to 1969 (Statistics Canada 1946 to 1970; U.S. Dep. Agric. 1966, 1971).

Amounts of nitrogen and phosphorus contained in fertilizers were reported (Statistics Canada 1946 to 1970; U.S. Dep. Agric. 1966 to 1971). Estimates of N and P from human excrement were obtained by applying the annual per capita excretion rates of 4.4 kg N and 0.54 kg P (Vollenweider 1968) to the total human population in the drainage basin for each year. Similarily, annual per capita excretion rates of 675 kg N and 9 kg P for cattle; 187 kg N and 5.6 kg P for pigs; and 94 kg N and 1.5 kg P for sheep (Vollenweider 1968) were used to estimate nitrogen and phosphorus production from the excrement of livestock.

Phosphorus supplied from washing detergents was calculated by applying the rate of 1.1 kg P per capita-year (Vallentyne 1974) to the annual human population figures for the period 1950-1970.

Linear regressions of land area cultivated, numbers of humans or livestock, and tonnes of total fertilizer or nitrogen and phosphorus from each source versus time were performed for each set of data. The data were left untransformed or the natural logarithim was taken, whichever gave the most significant straight line fit. The equations thus determined were used to extrapolate the data to the year 2000, to determine rates of increase, and to calculate doubling times.

RESULTS

HYDROLOGICAL, CHEMICAL AND RIVER SEDIMENT DATA

Morphometric data for Lake Winnipeg are given in Tables 1 and 2, and Figs. 2 and 3. Table 3 indicates that most of the water in the lake originates from the Winnipeg, Saskatchewan, and Red Rivers, in order of annual discharge. The land area of the watershed of Lake Winnipeg is presented in Table 4, according to the geological nature of the drainage basin. The hydrological and morphometric data allow an estimate of theoretical water renewal time (τ = volume ÷ annual outflow, or inflow minus evaporation) to be made (Table 5), which indicates that South Basin water of Lake Winnipeg was renewed once in 0.4 to 0.8 years, whereas the whole lake was flushed once in 2.9-4.3 years, over 1969-1974. Long term average and 1969 precipitation and mean monthly temperature data are given in Table 6.

Using the annual mass of major and nutrient elements transported to Lake Winnipeg in river water (Brunskill, Campbell, and Elliott 1979; Brunskill, Schindler, Holmgren et al. 1980) and the land area of drainage in Table 4, we have computed the annual transport rate per unit watershed area for each element in selected tributary rivers (Tables 7 and 8). Since these data are the product of discharge and element concentration, and are then divided by the watershed area, they present a very different aspect of the rivers. The Winnipeg River has relatively low concentrations of most elements (Brunskill, Campbell, and Elliott 1979), but its rate of transport of Ca, K, HCO_3 and Si, per unit watershed area per year, is equal or greater than that of the Red River, which has much higher concentrations of these elements. This is caused by the much greater discharge of water from the Winnipeg River basin (see the runoff data in Table 4). Highest major element transport rates occurred in the Dauphin and Fisher River watersheds, and lowest transport rates were found in the granitic watersheds of the smaller eastern tributaries (Poplar and Manigotagan Rivers). The large flux of Na and Cl from the Dauphin River is at least partly due to the discharge of saline groundwater in the Lake Winnipegosis and Lake Manitoba drainage area. The flux of nutrient elements N and P from the land to Lake Winnipeg was greatest in the watershed of the Winnipeg and Red Rivers (Table 8, 370 moles P km^{-2} yr^{-1} and 500 to 13,400 moles N km^{-2} yr^{-1}). Low P and N transport rates were found in the watersheds of the Saskatchewan and Dauphin Rivers, which may be due to the presence of large lakes and man-made reservoirs in their watersheds (cf. Schreiber and Rausch 1979).

The annual transport of river-borne sediments from the Lake Winnipeg watershed by the Red, Winnipeg, and Saskatchewan Rivers is given in Table 9. Much of the large sediment load carried by the Saskatchewan River (shown in Table 9) is deposited in Cedar Lake (the Saskatchewan River delta) and the man-made reservoir at Grand Rapids, downstream from The Pas. Suspended sediment measurements on samples taken below the hydroelectric dam at Grand Rapids (near #13 on Fig. 2) indicated that <1% of The Pas sediment load of the Saskatchewan River reached Lake Winnipeg (Brunskill, Schindler, Elliott et al. 1979). The variations in annual sediment load for each river are largely related to variations in discharge of water from the drainage basin (Fig. 4). During low water years (1973), the Red and Winnipeg Rivers carry about the same annual sediment load to Lake Winnipeg but during moderate to high water years (1974), the Red River carries an order of magnitude more sediment. The rate of mechanical erosion (sediment yield) from the largely prairie watersheds of the Red and Saskatchewan Rivers is similar (Table 10) at present, but the presence of many hydroelectric reservoirs on the Saskatchewan River in Alberta, Saskatchewan, and Manitoba greatly impedes sediment transport to Lake Winnipeg. Sediment transport rates of the Saskatchewan River basin, before the construction of hydroelectric dams, were likely much higher than the Red River transport rates shown in Table 10. The drainage area of the Saskatchewan River reaches the eastern flank of the Rocky Mountains in Alberta, where erosion rates (50-150 tonnes km^{-2} watershed yr^{-1}) are much greater than in the prairies (0.3-20 tonnes km^{-2} yr^{-1}) (Table 11). We speculate that the supply of river-borne sediment to the north basin of Lake Winnipeg was considerably greater before 1900, compared to recent times. Erosion rates of the Red River basin in southern Manitoba, North Dakota and Minnesota are more than twice the erosion rate of the Assiniboine River drainage in western Manitoba and southern Saskatchewan (Table 11). Erosion rates are lower and less variable in the watershed of the Winnipeg River (Table 10). Table 12 gives a chemical characterization of the major river waters as they flow into Lake Winnipeg.

POPULATIONS OF HUMANS AND LIVESTOCK, AND AGRICULTURAL DATA PERTINENT TO NUTRIENT SUPPLY TO LAKE WINNIPEG

We will now present data on agricultural activities and populations of humans and livestock, for the purpose of estimating the amount of nutrients potentially available for transport in runoff to Lake Winnipeg. Table 13 shows the number and density of humans and livestock for the major drainage basins tributary to Lake Winnipeg. The Saskatchewan and Red River drainages have the largest population and population density of people and livestock, due to the rich agricultural soils in these areas. The Winnipeg River and Precambrian Shield drainages have much lower populations of people and livestock, and the terrain there is less suitable for agricultural activities. The population density data (numbers per km^{-2} drainage area) shown in Table 13 should be taken with the realization that over one third of the human population of the Red River basin is concentrated in the City of Winnipeg on the banks of the Red and Assiniboine Rivers (Fig. 1), just 60 km upstream from Lake Winnipeg. Other population centers in this drainage area are situated on the Red River in North Dakota and Minnesota, and on the Assiniboine River in western Manitoba and North Dakota. In contrast, the major human populations of the Saskatchewan drainage are 500 to 1000 km upstream from Lake Winnipeg, and there are several major hydroelectric dams on this river. Much of the small human population of the Winnipeg River is in western Ontario mining, lumbering, and tourist communities. Livestock are likely more evenly distributed over the prairie drainage areas, but there is a trend toward increased feedlot and livestock confinement operations near larger cities. Since the Precambrian Shield drainages to the east of Lake Winnipeg, including the Winnipeg River, have small livestock populations and little agricultural activity, we have not considered these areas in the following treatment of the data.

In Table 14 and Fig. 5 we show that human and livestock populations in the sedimentary watersheds of Lake Winnipeg have grown slowly over the years of available census data. Change in land area under cultivation is very small over the short period of record, but use and application rate of agricultural fertilizers has increased exponentially since 1945 (Table 14, Fig. 5). Annual household detergent use appears small, compared to the fertilizer data, but it must be remembered that phosphorus in detergents can be readily transported through municipal sewage systems to tributary rivers. Regression analyses of the data in Fig. 5 allows an estimate of rates of increase and doubling time for these parameters (Table 15), which indicates that fertilizer use is the most rapidly growing nutrient source in the Lake Winnipeg watershed. We directly extrapolated these regression lines to the year 2000, in order to consider future rates of nutrient transport to Lake Winnipeg (Fig. 5, Table 14).

The annual amounts of N and P contributed to the Lake Winnipeg watershed by the agricultural and population activities given in Table 14 were estimated from census, statistical, and physiological data for humans, cattle, hogs, poultry, and horses (Table 16, Figs. 6 and 7). Some of the N and P in livestock and human excretory wastes will have come from fertilizer N and P applied to crop lands in the previous few years, and this will result in double-counting of some N and P. We have not tried to correct this unknown error. The rate of increase and doubling time for N and P from annual fertilizer applications dominates the array of nutrient sources presented here. The data in Table 16, Figs. 6 and 7 are estimates of the annual amounts of N and P added to Lake Winnipeg drainage area soils and water bodies. Not all of this reaches Lake Winnipeg. Table 17 indicates that, of the average N and P supply to the watershed by fertilizer, livestock, and human populations, 1.4% of the N and 7.7% of the P is transported by the Red River to Lake Winnipeg. In contrast, the Saskatchewan River transports to the lake only 0.4% of the N and P added to the watershed in 1970. These are clearly overestimates because we do not know the rate of natural soil leaching and particulate erosion of N and P in the drainage area.

Another source of nutrient elements to the lake might be the increased transport of soluble and particulate nutrients after forest fires. We noted increased concentrations of nutrients (NO_3, molybdate reactive phosphorus) and chlorophyll pigments along the east shore of the north basin of Lake Winnipeg (see Brunskill, Schindler, Holmgren et al. 1980), where the tributary rivers (Bélanger, Mukutawa, Poplar, and Berens Rivers) drained supposedly nutrient-poor Precambrian Shield watersheds. Maps of the history and distribution of forest fires in this region were constructed from unpublished records of the Canadian Wildlife Service over 1929 to the present. Insignificant areas of this region were burned during 1969, the year of our work on Lake Winnipeg, but large areas of the Mukutawa River drainage were burned in 1960 and 1962. The Berens, Pigeon, and Poplar River drainage areas are of Precambrian Shield covered with boreal forest and very low population density, but their P flux is similar to to that of the Red River Valley (Table 8).

DISCUSSION

LIMNOLOGICAL CONSEQUENCES OF THE MORPHOMETRIC AND HYDROLOGIC PARAMETERS OF LAKE WINNIPEG

Among lakes of large surface area, Lake Winnipeg is unusual in being so shallow. Lakes Chad, Erie, and Balkhash are of similar dimensions (Hutchinson 1957, p. 169). The length and breadth of the Lake Winnipeg basins (Table 1) allows the prairie wind to drive the water in surface currents of 20-90 cm/sec (Kenney 1979), and to cause water levels to increase by 1-2 m at downwind shore locations (Einarsson and Lowe 1968). Constrictions in the 436 km length of the basin (Figs. 2 and 3) cause great variations in wind-driven current velocities, and a dampening of lake level oscillations (Einarsson and Lowe 1968; Hamblin 1976; Lehn et al. 1976; Kenney 1979). A disproportionate fraction of the lake's shoreline is found in the Narrows (Fig. 3, Table 1), whereas the North and South Basins of Lake Winnipeg have relatively smooth outlines (D_L = 1.6-1.9).

With large fetch, abundant wind energy, and shallow water depths, Lake Winnipeg water masses are usually well mixed vertically. Turbulent mixing occurs to all depths of the water column with moderate winds, and because of this, little or no stratification of temperature, oxygen, or dissolved elements occurs in the lake (Brunskill, Elliott, and Campbell 1979; Brunskill, Schindler, Holmgren et al. 1980). Due to the energy of currents, waves, and turbulent mixing, surface sediments are frequently resuspended and redistributed throughout the lake. Despite abundant energy for mixing, horizontal gradients of many chemical parameters, nutrient elements, light extinction coefficients, suspended sediments, algal, zooplankton, and benthic biomass occur in the lake, especially in the South Basin and Narrows (Brunskill, Elliott, and Campbell 1979; Brunskill, Schindler, Holmgren et al. 1980; Brunskill, Schindler, Elliott et al. 1979; Patalas, in press; Flannagan, Saether, and Delorme, unpublished). These horizontal gradients are partly caused by lake morphometry, the orientation of major river inflows, the effect of wind in controlling the path of these river plumes, the character of the geological substrate and soils, and technological development in the watershed of the rivers.

The South Basin of Lake Winnipeg has a theoretical water residence time of about 6 months (Table 5), according to the simplistic calculations used. Kenney (1979) studied the northward and southward flowing currents in the Narrows off Little Doghead Point, and found that interbasin fluxes of water greatly exceeded the flux of water from river discharge into the lake. He estimated a water residence time of 0.17 years for the South Basin, based upon a simplified model of differential mass transport of water in the Narrows. Kenney (1979, and personal communication) proposed that wind-driven, northward flowing water in the Narrows enters the North Basin as a turbulent jet. When flow reverses, due to lake level oscillations, water is entrained from shallow water zones on either side of the northward jet, and this Narrows water mass is injected into the South Basin. This is an important hypothesis that has pertinence to chemical mass balance studies and to the distribution of phyto- and zooplankton.

Records of Lake Winnipeg water level are available from 1927 to the present (Lakes Winnipeg and Manitoba Board 1958; Crippen and Associates 1964). In this time period, Lake Winnipeg level varied from 216.2 to 218.5 m above sea level, with minimal lake levels in 1932, 1940, 1949, and maximal levels in 1927, 1935, 1943-47, and 1950. This 8-10 year oscillation in lake level could be related to sunspot cycles. At minimum recorded lake level, lake volume would be 17% less, and surface area would be 5% less than the data in Table 1. Depending upon the magnitude of annual discharge of tributary rivers, lake flushing time could vary by at least 20% from the estimates in Table 5. Manitoba Hydro now controls Lake Winnipeg outflow discharge, and they hope to dampen the magnitude of the annual lake level variations as well as maximizing discharge during the times of peak power demand (Lehn et al. 1976; Crippen and Associates 1964; Mudry 1973; Province of Manitoba 1972). Hunt and Jones (1972) discuss the effect of decreased water level fluctuations on littoral fauna.

Over half of the water in Lake Winnipeg comes from Precambrian Shield rivers, which drain only 18% of the watershed of Lake Winnipeg (Tables 3 and 4). Runoff from Precambrian Shield watersheds is 5 to 10 times higher than from sedimentary drainages (Table 4). This is probably due to greater precipitation, lower evaporation, and low soil storage capacity for water in Precambrian Shield watersheds (Table 6). Low runoff from prairie rivers is due to low precipitation and high evaporation. Some areas of the Red River (Assiniboine) drainage are usually closed basins, and have no runoff. Some studies on groundwater movements in the Red River Valley (Charron 1974; Johnston 1934) indicate that subsurface discharge of water to Lake Winnipeg is a small percentage of surface river flow, but that salt transport via groundwater could be significant for some elements.

Annual discharge is probably the major parameter controlling the magnitude of the annual sediment load carried by each river (Fig. 4), but the annual sediment erosion rate is modified by watershed geology, vegetation and the presence of reservoirs. Before the clearing of the land, ploughing the prairie sod, improved drainage and channelization of agricultural areas, soil erosion rates were likely lower than shown for the Red River in Fig. 4. The earliest data we found was that of Ward (1926), who estimated that an average of 1.7×10^6 tonnes yr^{-1} of suspended sediment was carried by the Red River over 1916-1926. This is equivalent to an erosion rate of 6 tonnes km^{-2} yr^{-1}, which is well within the range of values shown in Table 10 and Fig. 4. The Cedar Lake delta of the Saskatchewan River, and more recent reservoirs retain much of the sediment carried by this river. For a given increase in water discharge, the prairie rivers pick up more sediment than does the Winnipeg River (Fig. 4) which drains the shallow soils of the Precambrian Shield. Despite the turbid and muddy appearance of the Red and upstream Saskatchewan Rivers, the sediment transport rates (erosion rates) for these watersheds are among the lower values of North American watersheds in temperate prairie climatic zones (Table 18). Much higher erosion rates occur where great relief or high human populations occur (Asian rivers, Western Arctic) (Table 18). Brunskill and Graham (1979) give data on the chemistry of suspended sediments of the Red River.

In spite of the low solubilities of soil and bedrock in the watershed of the Winnipeg River, the average annual chemical erosion rate of major elements (per unit watershed area) is not greatly different from that of the prairie watersheds (Tables 7 and 19). Calcium, HCO_3, and Si are transported in solution more rapidly from the Winnipeg River watershed than from the prairie river watersheds, whereas fluxes of Na, Cl, and SO_4 are greater from the prairie watersheds. In general, the Red River fluxes of major elements are greater than the Assiniboine River (Table 19). These salt fluxes are mixed in Lake Winnipeg to flow to Hudson Bay via the Nelson River. Some additional sources of Na, Cl, and Mg are required to yield the computed fluxes for these elements in the Nelson River (Table 19): perhaps groundwater flow into Lake Winnipeg from western evaporite beds could supply some of this (Johnston 1934; Charron 1974). The tributaries to Lake Winnipeg are carrying salts at a moderate to low rate, compared to other large river systems (Table 19).

The rate of transport of nutrient elements N and P from watersheds of tributaries to Lake Winnipeg varies greatly, roughly in proportion to variations in annual discharge for each river (Tables 3 and 8; Figs. 8 and 9). In spite of great differences in geology, landform, vegetation, human and livestock densities (see Table 13), the Precambrian Shield drainages have nutrient transport rates similar to the prairie river drainages (Table 20). Although individual cultivated fields have very high nutrient loss rates, large rivers draining these agricultural areas have nutrient transport rates similar to native prairie and small experimental watersheds on Precambrian Shield in boreal forest (Table 20). The very high nutrient fluxes for croplands in southern Ontario and the midwest of U.S.A. shown in Table 20 occur in regions where annual precipitation is higher than in the Red and Saskatchewan drainages. The very low P transport rate for the Saskatchewan River is likely caused by P retention in numerous reservoirs and the Cedar Lake delta, upstream of Lake Winnipeg (Schreiber and Rausch 1979).

The lack of great differences in dissolved major element and nutrient transport rates from the greatly different drainage areas of the Prairie and Precambrian Shield is a little surprising. We propose that the following factors tend to balance the annual nutrient flux from the less erodible and nutrient-poor crystalline bedrock watersheds (Winnipeg River) and the easily erodible and nutrient-rich prairie watersheds (Red River). Firstly, annual precipitation is 30-50% greater in the Shield watersheds (Table 6), and runoff is 5 to 10 times greater from Shield watersheds, compared to prairie watersheds (Table 4). Furthermore, the discharge of water from Shield watersheds is more evenly spread over the spring and summer months, whereas the major discharge of prairie rivers occurs in one or two months in spring (Water Survey of Canada discharge records, 1906-1965, unpublished). A patch of soil on the Shield will then have more water flushed through it, for a longer period of time in the warm season, than will a similar patch of prairie soil. Secondly, the relatively thin, acid soils of the Shield carry P in more soluble and mobile forms (Baker 1977; Maftoun and Krause 1977), compared to the deep, silt and clay-rich prairie soils.

The Red and Winnipeg Rivers deliver their respective sediment, salt, and nutrient supplies to Lake Winnipeg in very different ways. The Red

River presents most of its nutrient load to the lake as a smaller volume of water with high concentrations of nutrients over a few months in spring. The Winnipeg River contributes a large volume of water with low to moderate concentrations of nutrients over 4-6 months of discharge. This results in very sharp gradients of suspended sediments, turbidity, salt and nutrient concentrations near the mouth of the Red River, and a great dilution of these concentrations by the Winnipeg River plume (see Brunskill, Schindler, Elliott et al. 1979; Brunskill, Campbell, and Elliott 1979; Brunskill, Schindler, Holmgren et al. 1980). The sum of all river annual nutrient supply is divided by lake area in Table 21, which indicates that the whole lake is receiving P at rates comparable to Lakes Michigan and Ontario. Most of the annual discharge of water and nutrients (Tables 3 and 8) comes from the Winnipeg and Red Rivers, which flow into the smaller south basin of the lake (Fig. 3, Table 1). Annual nutrient supply (per unit lake surface area) to the south basin of Lake Winnipeg is very high, compared to the St. Lawrence Great Lakes (Table 21). South basin water residence time (τ) is probably lower than indicated in Table 21 (see Kenney 1979), and is likely in the range of 0.1 to 0.5 years. Further discussion of the biological response of the lake to these nutrient supplies is given in Brunskill, Schindler, Holmgren et al. (1980), Patalas and Salki (in prep.), Flannagan (in prep.), and Saether (in prep.).

LIMNOLOGICAL CONSEQUENCES OF TECHNOLOGICAL ACTIVITIES IN THE LAKE WINNIPEG WATERSHEDS

The human-influenced sources for this large supply of nutrients to the south basin of Lake Winnipeg are largely in the Red River watershed. In addition to the natural rate of leaching, erosion, and transport of ΣN and ΣP from these rich soils, man's activities utilize huge amounts of N and P (see Table 16, Figs. 6 and 7). The annual magnitude of these agricultural and population sources of nutrients represent 10 to 100 times the mass of nutrients added to Lake Winnipeg by rivers in a year (Tables 22 and 23). A large fraction of the nutrients used in agriculture is exported out of the watershed as grain or livestock products (Hedlin and Cho 1974), but some will remain in the watershed in the form of livestock, people, and their food and waste products. In Tables 22 and 23 we compare the annual mass of N and P available from fertilizer use, livestock and human populations, to the annual mass of nutrients delivered to Lake Winnipeg by its tributary rivers. Since most agricultural activities and population centers are in the sedimentary part of the lake's watershed, we have computed the annual runoff of N and P to Lake Winnipeg from its sedimentary watershed as a percentage of the annual "above-ground available N and P" from fertilizer use, livestock, and human populations (Tables 22 and 23). This calculation reveals that, at a maximum, 0.5-3.5% of the P, and 0.4-0.8% of the N available from agriculture and populations of livestock and humans reached Lake Winnipeg via rivers.

This is an overestimate, since some unknown fraction of Lake Winnipeg's nutrient supply was derived from natural erosion and leaching of prairie and forest soils, before the appearance of the plow and Lord Selkirk's settlers in 1820. Since much of the land in the lake's sedimentary watershed is in agricultural use, it seems likely that agricultural, municipal, industrial, and water management practices now dominate the factors controlling the rate of release of nutrients from the watershed to the lake. If this speculation is tentatively accepted, then we propose that the above computed, river-transported fractions of "above-ground available N and P" (Tables 22 and 23) will continue to reach Lake Winnipeg (largely the south basin), and can be applied to any predicted, future fertilizer and population data (Table 14). This allows a computation of estimates of future rates of nutrient supply to the lake, based upon the assumption (Table 23) that 1.6% of "above-ground available ΣP" in 1980, 1990, and 2000 will reach Lake Winnipeg. These estimates are given in Table 24, which indicates a tripling of ΣP supply to the lake by 1990, and a 6-fold increase in P supply by the year 2000.

The above hypothesis and speculative calculations are not clearly supported by our own observations. Comparisons of 1969 abundance and species of phytoplankton, zooplankton, and benthic organisms of Lake Winnipeg with data from Bajkov (1930, 1934) indicate no major changes over a period of order of magnitude increase in fertilization rate (Brunskill, Schindler, Holmgren et al. 1980; Patalas, in prep.; Flannagan and Cobb, in prep.). Annual nutrient supply to the lake appears to vary in proportion to annual river discharge (Figs. 8 and 9) rather than the incremental increases in "above-ground N and P" (Tables 14 and 15). It would probably require 10-20 years of nutrient budget measurements to filter out the relative effects of discharge and the annual magnitude of "above-ground N and P." It may be that both agricultural crop production and nutrient flux from the land are a function of annual precipitation in these semi-arid prairie watersheds. The measured nutrient fluxes from the Lake Winnipeg agricultural watersheds are more similar to nutrient fluxes from native prairie than to intensively cultivated and fertilized cropland (Table 20). On the other hand, experimental studies on fertilized crop land by Burwell et al. (1977) and Nicholaichuk and Read (1978) indicated that 10-16% of fertilizer N and 1.4-10% of fertilizer P was lost in runoff. These values are equal or much greater than the values given in Tables 22 and 23, and lends some support to our above speculations about the proportion of applied fertilizer that is lost in runoff.

Economic restraints and changes in agricultural technology will likely alter our predicted data for fertilizer use and livestock populations. Availability of natural gas (used in manufacturing nitrogen fertilizers) may limit the use of nitrogen fertilizers (Wittwer 1975; Chancellor and Goss 1976). Genetic or physiological manipulation of food crops and livestock (such as the development of nitrogen-fixing spring wheat (Anonymous 1976)) may increase agricultural yields without increases in fertilizer use. The application of 100 tonnes P km^{-2} yr^{-1} on prairie agricultural land in the year 2000 seems preposterous by today's standards and farming techniques. On the other hand, it appears that agricultural regions of the Lake Winnipeg watershed are receiving much less fertilizer than maximum crop production requires. Manitoba fertilizer use was generally less than the recommended 2.4 tonnes P km^{-2} yr^{-1} in 1971, whereas up to 19.4 tonnes km^{-2} yr^{-1} were used in German wheat fields (Hedlin and Cho 1974), and fertilization rates of 29-44 tonnes km^{-2} yr^{-1} occur in Japan and Taiwan (Gavan and Dixon 1975) where water supply is more abundant. With these figures in mind, it may be conceivable to expect fertilizer application rates of ≈20 tonnes km^{-2} yr^{-1} for some irrigated agricultural regions of the Lake Winnipeg watershed in 1985 (see Table 14). Predictions from the fertilizer industry on future sales and consumption trends of N and P fertilizers are similar to ours (Table 14, Figs. 6 and 7), and they note that fertilizer P application is 160-270% in excess of crop P removal rates (Beaton 1974; Blair 1975; Nielsen 1975), whereas N application rates are less than crop N removal rates in the Canadian prairie region. Other agricultural and water management techniques (tile drainage, large scale irrigation, feed lot drainage lagoons, river diversions and dams) will likely alter the flux of nutrients from the land to rivers.

We devised an alternate scenario to the one shown in Table 24, which could be viewed as a "best case" situation for N and P supply rates. We now assume that nutrients are more efficiently transported to Lake Winnipeg from large populations of people and livestock near rivers or adjacent to the lake, compared to nutrient transport from areas remote from the lake. We calculated the amount of N and P (477 mol N ca^{-1} yr^{-1} and 38 mol P ca^{-1} yr^{-1}, for 560,000 people in 1975) added directly to the Red River by the sewage treatment plants of the City of Winnipeg, and applied these per capita rates to sewered communities of the Red River watershed in Manitoba, North Dakota, and Minnesota. For the most distant communities of Saskatchewan and Alberta within the Lake Winnipeg drainage area, we used a per capita nutrient production rate of 50% of those for the City of Winnipeg, because reservoirs and natural sedimentation along these rivers likely trap nutrients from these western sources. We allowed our projected fertilizer application rate (Figs. 6 and 7) to increase only to the current maximum recommended fertilization rate (11.6 tonnes N km^{-2} yr^{-1} and 2.54 tonnes P km^{-2} yr^{-1}) for present estimates of arable (Class 1-4) land area in the sedimentary drainage of Lake Winnipeg. Our model then allowed 0.5% of fertilizer N, 1% of fertilizer P, and the modified nutrient flux from humans and livestock to reach Lake Winnipeg. The total nutrient flux to Lake Winnipeg in the year 2000 estimated in this way amounted to an increase of 195% for P and 62% for N, compared to the original 1969 data. It appears from these computations that nutrient supply to Lake Winnipeg will at least double in the next 20 years.

Trends in farm management, livestock husbandry, and livestock waste handling in the St. Lawrence Great Lakes watersheds were described by Bangay (1976). He found that there was a reduction in farm land area (18-40% decrease over 1931-1971), an increase in annual production of livestock products, a great increase in the cost of operation, use of advanced technology, chemical fertilizers, high-gain feed, and feedlot-style meat production. Bangay also shows that the increasing geographical separation of the components of a beef, hog, or poultry operation (grain production, feeder calf production, feedlot fattening) results in depletion of crop nutrients in the grain field, and an accumulation of nutrients in animal wastes at the feedlot. This causes an increase in chemical fertilization rates on the grain fields, and a costly disposal problem at the feedlot, despite the generally beneficial effect of manure on soil condition, erosion, and crop growth (Young and Holt 1977). Some of these trends may occur in the Lake Winnipeg watershed, but agricultural land area appears to be still increasing here (Fig. 5, Table 14).

Similar watershed budgets, sources, and annual use and transport rates of metals, pesticides, radioactive elements, or any deleterious substances could be measured or computed for the Lake Winnipeg system. Wauchope (1978) estimates that ≈0.5% of applied commercial pesticides are lost to runoff from agricultural areas. Gummer (1979) and Allan (1979) give some data on 2,4-D concentrations in Red and Saskatchewan River waters. Murphy and Carleo (1978) indicate that urban runoff and sewage carried about 1 kg of chlorinated hydrocarbons km^{-2} city area yr^{-1} (= 0.24 g ca^{-1} yr^{-1}), which suggests that the City of Winnipeg alone may contribute about 144 kg of chlorinated hydrocarbons to Lake Winnipeg each year.

Murphy and Carleo (1978) also estimate that urban runoff and sewage carries about 17 mol Hg km^{-2} yr^{-1} (= 3.7 mmol Hg ca^{-1} yr^{-1}), which gives an order of magnitude estimate for the City of Winnipeg flux to Lake Winnipeg as over 2200 mol Hg yr^{-1}. Approximately 7500 mol Hg km^{-2} yr^{-1} is applied to golf courses and public lawns in Manitoba (Derksen 1978a), and more than 0.3 mol Hg km^{-2} yr^{-1} is added to Manitoba agricultural land as treated seed (Derksen 1978b). If this latter figure is applied to the cultivated land area of the Lake Winnipeg drainage basin, it would amount to 113,000 mol Hg yr^{-1}. This allows a probably low estimate of ≈115,000 mol Hg yr^{-1} being available for transport (primarily by soil erosion) to Lake Winnipeg. If this amount were transported annually to the lake by rivers, it would appear as a sedimentation rate of 4.8 μmol Hg m^{-2} yr, which is about half the Hg sedimentation rate estimated by Brunskill and Graham (1979), based on Red River water and suspended sediment data of Derksen (1973), and 1969-70 Hg transport from the Winnipeg River (Armstrong and Hamilton 1973). Lake Winnipeg fish contained between 5 and 20 mol Hg in 1969-70 (G. McGregor, pers. comm.), a tiny fraction of the annual supply to the lake. Fish can take up Hg from sediments (Kudo and Mortimer 1979).

It should be emphasized that total annual technological and agricultural Hg consumption rates are likely higher than given above, that Hg applied to the soil is not 100% mobile, and that Hg discharge from the Winnipeg River has decreased since 1969 (J. W. M. Rudd and G. McGregor, Freshwater Institute, pers. comm.). Derksen (1978a), for example, found little evidence of Hg contamination of Clear and Falcon Lake sediments in western Manitoba, which are adjacent to golf courses with surface soil Hg concentrations of 0.06-1.0 μmol Hg/g. Natural Hg concentrations in surface soil of the Red River Valley are likely in the range 0.3 to 0.8 nmol Hg/g (Mills and Zwarich 1975; Derksen 1978b; Jonasson 1970), which is also the range of Hg concentrations in south basin Lake Winnipeg sediments (see Table 24 in Brunskill and Graham 1979).

It will be difficult to control the acceleration of the rate of supply of nutrients, metals, and other deleterious substances to Lake Winnipeg, because of the diffuse source of many of these substances. Part of the Red River drainage area is in the U.S.A. Large cities are increasing in population, while the rural population of the Red River Valley is decreasing (Framingham 1975). This latter trend will create more human and industrial waste on the banks of the Red and Assiniboine Rivers, which will be directly transported to Lake Winnipeg. Intelligent planning and management of agricultural activities can restrain runoff of deleterious substances, with special emphasis on soil erosion control (Karr and Schlosser 1978). As stressed by Chapra and Robertson (1977), however, control of point-source pollutants will have to be matched by attempts to control diffuse, agricultural sources of pollutants, in order that water quality and aquatic biological resource criteria are maintained.

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Table 1. Morphometric data for Lake Winnipeg.*

Parameter	North Basin	Narrows‡	South Basin†	Whole Lake
Surface Area (A_0, km^2)	17,520	3,450	2,780	23,750
Volume (V, km^3)	232.4	24.6	27.0	284
Mean Depth ($\bar{Z}$, m)	13.3	7.2	9.7	12.0
Maximum Depth (Z_m, m)	19	36§	14	36§
Maximum Length (l, km)	232	143	93	436
Maximum Breadth (b, km)	111	30	46	111
Shoreline (L, km)	761	640	349	1,750
Shoreline ÷ Area (km km^{-2})	0.043	0.19	0.13	0.074
Development of Shoreline ($D_L = \frac{L}{2\sqrt{\pi A_0}}$)	1.6	3.1	1.9	3.2
Development of Volume ($D_V = 3\bar{Z}/Z_m$)	2.1	0.6	2.1	1.0
$\bar{Z}/Z_m$	0.70	0.20	0.69	0.33
Relative Depth $Z_r = 50\, Z_m \sqrt{\pi}\, (\sqrt{A_0})^{-1}$	0.013	0.054	0.024	0.021

* Computations of morphometric parameters were done according to the methods of Hutchinson (1957). Mean annual lake level varied between 217.7 and 218.3 meters above sea level during the period 1969-74. Over the period 1913 to 1975, the minimum lake level was 216.5 m, and the maximum was 218.4; this variation results in a maximum variation in volume of the lake of about 17%. Data given here refer to a lake level of 218.1 m.

† The northern boundary of the South Basin of Lake Winnipeg is designated as a line drawn across Grassy Narrows to Hecla Island, from the Gull Harbour navigation light directly east to Black Island, from the Red Cliff on Black Island to Clements Point navigation light (northwest of the mouth of the Manigatogan River). See Canadian Hydrographic Service Chart No. 6251.

‡ The northern boundary of the Narrows of Lake Winnipeg is designated as a line drawn from the first point of land west of Wicked Point to the western-most point of land on Commissioner Island, to the map triangle on the south shore of Berens Island, and from the map triangle on the north shore of Berens Island to the southern-most point of land at Disbrowe Point (Sandy Bar). See Canadian Hydrographic Service Chart No. 6267.

§ This deep hole is a V-shaped channel of <1 km length between Drumming Point (NE shore of Black Island) and the east shore of Lake Winnipeg. The area and volume of water in this deep hole are insignificant in relation to the rest of the lake.

Table 2. Areas and volumes of the South Basin, Narrows, and North Basin of Lake Winnipeg, at 2 meter depth intervals. This data was derived from hydrographic charts of different datum reference (see footnotes), and consequently the volume totals do not agree with Table 1.

	South Basin[1]		Narrows[2]		North Basin[3]	
Contour (m)	Area ($m^2 \times 10^8$)	Volume ($m^3 \times 10^8$)	Area ($m^2 \times 10^8$)	Volume ($m^3 \times 10^8$)	Area ($m^2 \times 10^8$)	Volume ($m^3 \times 10^8$)
0	27.78		34.45		175.22	
		53.36		62.86		346.23
2	25.57		28.51		171.02	
		49.48		49.51		327.72
4	23.90		21.09		156.81	
		45.19		37.24		305.99
6	21.29		16.25		149.21	
		38.61		28.39		289.59
8	17.37		12.23		140.42	
		27.87		16.56		270.40
10	10.74		4.88		130.05	
		9.36		6.11		251.13
12	0.65		1.54		121.13	
		0.04		2.12		225.63
14			0.64		104.70	
				1.58		178.92
16			0.22		75.04	
				0.28		69.53
18			0.07		6.64	
				0.41		0.64

[1] South Basin datum is 216 m above sea level.
[2] Narrows datum is 217 m above sea level.
[3] North Basin datum is 218 m above sea level.

Table 3. Annual water budgets for Lake Winnipeg, 1969-1974, based on data from Water Survey of Canada and Atmospheric Environment Service.

	(m^3 year^{-1} x 10^9)					
	1969	1970	1971	1972	1973	1974
INFLOW						
South Basin						
Winnipeg River	42.70	44.50	39.40	33.40	25.80	48.30
Other Precambrian Shield drainages	2.13	2.22	1.97	1.66	1.29	2.41
Red River	9.99	10.30	5.83	7.09	2.89	12.20
Other sedimentary drainages	0.36	0.37	0.21	0.26	0.10	0.44
Precipitation direct to lake surface	1.21	1.30	1.28	1.00	1.81	1.17
Total to South Basin	56.39	58.69	48.69	43.41	31.89	64.52
Narrows and North Basin						
Poplar River	2.49	0.78	1.08	1.14	0.84	1.08
Berens and Pigeon Rivers	7.93	3.76	4.72	3.61	3.63	5.69
Manigotagan River	0.326	0.33	0.24	0.20	0.29	0.47
Other Precambrian Shield drainages	4.04	2.08	2.26	1.95	1.99	3.01
Saskatchewan River	20.00	19.90	20.30	23.10	18.00	29.40
Dauphin River	1.95	2.74	3.40	2.61	1.71	5.42
Fisher River	0.058	0.067	0.024	0.04	0.024	0.18
Other sedimentary drainages	3.23	3.290	2.45	2.99	2.390	6.94
Precipitation direct to lake surface	10.43	9.95	9.94	8.54	14.59	10.31
Total inflow to Lake Winnipeg	107.00	102.00	93.10	87.60	75.30	127.00
OUTFLOW						
Nelson River	91.60	96.20	87.60	84.00	62.35	98.90
EVAPORATION AND STORAGE*	15.40	5.80	5.50	3.60	13.00	28.10

* Computed by subtracting the outflow via the Nelson River from the total inflow to Lake Winnipeg.

Table 4. Terrestrial drainage areas of rivers tributary to Lake Winnipeg, and annual runoff for the watersheds.

	Drainage Area (km^2)	Runoff* (cm)
SOUTH BASIN		
East side - Precambrian Shield		
Winnipeg River	126,400	31
Other	6,300	-
West and South sides - approx. 85% sedimentary		
Red River	287,500	2.8
Other	10,400	-
	430,600	
NORTH BASIN AND NARROWS		
East side - Precambrian Shield		
Poplar River	6,790	18
Berens and Pigeon Rivers	19,700	25
Manigotagan River	1,800	17
Other	12,760	-
West side - approx. 98% sedimentary		
Saskatchewan River	340,400	6.4
Dauphin River (including Lakes Manitoba and Winnipegosis)	80,000	3.7
Fisher River	1,360	4.8
Other	59,840	-
TOTAL TERRESTRIAL DRAINAGE AREA	953,250	

* Runoff = annual river discharge ÷ drainage area, averaged over 1969-1974.

Table 5. Estimated water renewal time of the South Basin and the entire Lake Winnipeg basin, 1969-1974, based on data in Table 1 and hydrological data from Water Survey of Canada (see Table 3).

	1969	1970	1971	1972	1973	1974
South Basin*	0.49	0.47	0.56	0.62	0.83	0.43
Entire Lake Winnipeg Basin+	3.1	2.9	3.2	3.3	4.3	2.9

* Renewal time = $\frac{\text{Volume of South Basin}}{\text{Annual inflow - annual evaporation}}$,

where annual evaporation was assumed to be 0.5 meters/year

\+ Renewal time = $\frac{\text{Volume of entire lake}}{\text{Outflow via Nelson River}}$

Table 6. Mean annual precipitation and mean monthly air temperature for the Lake Winnipeg watershed.

Location	Mean Monthly Air Temperature In °C (1931-1960) Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Precipitation in mm 1969	Mean Annual (1931-1960)
Kenora, Ontario	-17.1*	-14.4	-7.3	2.4	10.6	16.1	19.6	18.2	12.2	5.7	-4.9	-13.6	733§	614*
Winnipeg, Manitoba	-17.7†	-15.5	-7.9	3.3	11.3	16.5	20.2	18.9	12.8	6.2	-4.8	-12.9	548§	517†
Edmonton, Alberta	-14.1†	-11.6	-5.5	4.2	11.2	14.3	17.3	15.6	10.8	5.1	-4.2	-10.4	479§	473†
Medicine Hat, Alberta	-11.1†	- 9.5	-3.2	6.2	12.6	16.2	20.6	18.9	13.4	7.5	-1.5	- 6.7	218§	363†
Fargo, North Dakota	-13.8‡	-11.8	-3.7	5.6	12.8	18.1	21.8	20.6	14.9	7.8	-2.4	-10.6	474‖	476‡

* From: Canada Department of Transport. Meteorological Branch. Temperature and precipitation tables for Ontario. Volume IV. Toronto, Ontario. 1967. 44 p.

† From: Canada Department of Transport. Meteorological Branch. Temperature and precipitation tables for Prairie Provinces. Vol. III. Toronto, Ontario. 1967. 56 p.

‡ From: U.S. Department of Commerce. Weather Bureau. Climatography of the United States No. 60-32. Climates of the States. North Dakota. Washington. 1959. 16 p.

§ From: Canada Department of Transport. Meteorological Branch. Monthly record of meteorological observations. Jan.-Dec. 1969. Toronto, Ontario. 1971.

‖ From: U.S. Department of Commerce Environ. Science Services Admin. Weather Bureau. Washington. Annual Reports.

Table 7. Rates of transport of dissolved major elements per unit watershed area per year for selected tributary rivers to Lake Winnipeg over 1969-1974. These data are in units of 10^3 mol km^{-2} land area yr^{-1}. A_d = watershed area.

River	Year	Ca	Mg	Na	K	SO_4	Cl	HCO_3	Si
Red River (A_d = 287,500 km^2)	1969	45.0	37.9	47.8	6.88	33.0	33.4	119.0	7.01
	1970	54.5	40.9	48.9	5.91	44.5	22.3	139.0	7.23
	1971	29.9	14.0	37.4	6.73	24.6	20.5	76.6	3.62
	1972	36.0	24.4	36.3	4.32	24.5	16.2	91.2	4.20
	1973	15.9	11.9	21.4	1.86	11.1	11.6	43.2	1.79
	1974	59.5	42.3	66.2	7.60	43.5	34.7	154.0	7.07
	$\bar{x}$	40.1	28.6	43.0	5.55	30.2	23.1	103.8	5.15
Winnipeg River (A_d = 126,400 km^2)	1969	130.0	25.3	21.0	6.79	31.4	16.8	273.0	13.1
	1970	129.6	12.0	19.4	7.43	17.2	10.2	248.8	11.9
	1971	119.0	16.0	21.2	6.70	14.9	13.7	239.5	12.0
	1972	91.7	24.4	19.1	5.19	14.3	6.98	194.1	9.21
	1973	70.0	20.1	15.5	4.24	13.6	8.00	153.6	6.30
	1974	131.6	35.5	28.9	8.04	21.2	15.5	294.9	12.4
	$\bar{x}$	112.0	22.2	20.9	6.40	18.8	11.9	234.0	10.8
Dauphin River (A_d = 80,000 km^2)	1969	43.5	43.7	295.1	10.8	43.9	309.5	121.3	3.34
	1970	48.6	57.4	373.8	12.4	51.4	375.5	143.1	3.52
	1971	82.2	58.8	492.4	17.1	64.0	509.5	201.3	5.76
	1972	54.9	51.0	367.4	12.2	48.3	364.3	126.3	4.00
	1973	35.0	20.8	239.1	7.87	33.7	232.0	77.7	2.43
	1974	100.3	100.4	706.7	22.4	115.3	705.6	243.5	8.37
	$\bar{x}$	60.8	57.0	412.4	13.8	59.4	416.1	152.2	4.57
Fisher River (A_d = 1,360 km^2)	1969	61.7	75.2	21.1	4.61	19.5	3.82	286.1	3.47
	1970	71.3	75.9	21.7	4.93	24.4	4.28	323.5	5.09
	1971	24.0	27.2	8.07	1.69	8.16	1.56	127.0	1.97
	1972	37.8	42.5	11.7	2.73	13.4	2.45	187.2	3.37
	1973	32.4	30.9	9.66	2.24	8.54	1.70	118.3	2.98
	1974	197.8	200.6	62.7	14.0	67.8	11.3	835.0	16.8
	$\bar{x}$	70.8	75.4	22.5	5.03	23.6	4.19	312.9	5.61
Manigotagan River (A_d = 1,800 km^2)	1969	42.7	16.0	8.14	4.22	7.16	5.33	134.8	5.80
	1970	43.8	14.9	8.25	4.29	7.32	5.64	147.4	5.60
	1971	30.4	10.3	6.02	2.92	4.85	4.04	59.9	4.35
	1972	24.0	8.84	4.64	2.63	7.16	2.98	51.5	3.80
	1973	40.3	13.4	7.68	4.50	5.04	5.28	85.9	5.06
	1974	60.4	19.8	12.3	5.63	10.0	8.34	164.3	8.64
	$\bar{x}$	40.3	13.9	7.84	4.03	6.92	5.27	107.3	5.54
Pigeon and Berens Rivers (A_d = 19,700 km^2)	1969	82.4	28.7	18.0	7.21	8.98	16.2	143.5	17.1
	1970	40.7	12.9	8.63	3.32	4.41	6.72	69.0	7.78
	1971	50.0	12.8	10.2	4.10	5.50	7.25	89.9	9.50
	1972	36.8	10.5	7.65	2.95	4.09	3.47	72.1	7.05
	1973	38.6	11.2	8.93	3.22	4.40	5.78	73.1	6.80
	1974	58.1	16.8	13.1	5.08	6.64	11.4	112.0	11.1
	$\bar{x}$	51.1	15.5	11.1	4.31	5.67	8.47	93.3	9.89
Poplar River (A_d = 6,790 km^2)	1969	35.4	17.7	19.5	7.36	9.65	8.00	67.3	18.6
	1970	12.7	5.31	6.16	2.25	3.15	2.68	20.5	5.82
	1971	17.9	7.61	8.31	3.01	3.82	4.11	30.2	7.90
	1972	17.5	6.86	8.05	3.05	3.70	4.16	31.4	8.34
	1973	14.8	5.86	6.66	2.21	3.16	2.94	23.8	5.82
	1974	17.6	7.06	8.15	2.90	3.77	4.07	31.0	7.59
	$\bar{x}$	19.3	8.40	9.47	3.46	4.54	4.33	34.0	9.01
Saskatchewan River (A_d = 340,000 km^2)	1969	70.4	36.9	40.5	3.62	27.4	17.4	196.1	2.83
	1970	70.4	37.1	40.2	3.44	27.3	17.4	194.8	2.73
	1971	69.9	34.6	43.6	3.93	27.6	19.8	182.2	2.34
	1972	76.9	40.5	48.5	4.53	30.6	20.6	200.2	3.31
	1973	60.2	31.2	33.8	3.31	22.4	13.2	154.0	1.62
	1974	95.8	50.3	61.2	5.73	37.3	23.5	256.0	2.82
	$\bar{x}$	73.9	38.4	44.6	4.09	28.8	18.7	197.2	2.61

Table 8. Rates of transport of total phosphorus (TP) and total nitrogen (TN) per unit watershed area per year for selected tributary rivers flowing to Lake Winnipeg over 1969-1974. The data are in units of 10^3 mol km^{-2} land area yr^{-1}. N and P data for 1971-1974 are from Inland Waters (Water Quality) NAQUADAT, and discharge data was taken from Water Survey of Canada records.

River	Year	ΣN	ΣP
Red River (A_d = 287,500 km^2)	1969	5.59	0.39
	1970	9.76	0.85
	1971	2.76	0.16
	1972	3.64	0.24
	1973	1.46	0.13
	1974	7.85	0.46
	$\bar{x}$	5.18	0.37
Winnipeg River (A_d = 126,400 km^2)	1969	13.7	0.39
	1970	13.8	0.37
	1971	11.5	0.54
	1972	12.8	0.31
	1973	9.73	0.20
	1974	19.1	0.43
	$\bar{x}$	13.4	0.37
Dauphin River (A_d = 80,000 km^2)	1969	2.10	0.019
	1970	2.53	0.029
	1971	4.79	0.033
	1972	3.00	0.021
	1973	2.04	0.009
	1974	5.86	0.042
	$\bar{x}$	3.39	0.026
Fisher River (A_d = 1,360 km^2)	1969	3.02	0.13
	1970	3.80	0.19
	1971	0.82	0.034
	1972	1.76	0.031
	1973	1.12	0.014
	1974	8.42	0.29
	$\bar{x}$	3.16	0.11
Manigotagan River (A_d = 1,800 km^2)	1969	10.1	0.21
	1970	8.64	0.23
	1971	6.33	0.16
	1972	9.52	0.11
	1973	8.96	0.13
	1974	15.2	0.31
	$\bar{x}$	9.79	0.19
Pigeon and Berens Rivers (A_d = 19,700 km^2)	1969	21.0	0.44
	1970	9.89	0.26
	1971	10.1	0.29
	1972	8.49	0.24
	1973	8.85	0.22
	1974	14.0	0.40
	$\bar{x}$	12.2	0.31
Poplar River (A_d = 6,790 km^2)	1969	22.1	0.82
	1970	6.82	0.22
	1971	7.70	0.27
	1972	6.82	0.20
	1973	6.67	0.21
	1974	7.62	0.31
	$\bar{x}$	9.62	0.34
Saskatchewan River (A_d = 340,000 km^2)	1969	3.81	0.048
	1970	3.17	0.045
	1971	2.91	0.045
	1972	4.94	0.075
	1973	3.10	0.041
	1974	3.97	0.093
	$\bar{x}$	3.65	0.058

Table 9. Annual suspended sediment transport from the Lake Winnipeg watersheds of the Red, Winnipeg, and Saskatchewan Rivers. Data for the Red and Saskatchewan Rivers are from Environment Canada (1978). Data for the Winnipeg River was estimated and extrapolated from our own suspended sediment measurements and discharge data from Water Survey of Canada.

Year	Red River at Lockport, Manitoba	Winnipeg River near the mouth	Saskatchewan River at the Pas
		tonnes yr^{-1}	
1969	3,427,135	348,000	2,853,705*
1970	3,126,000	389,000	2,137,295
1971	1,911,810	300,000	2,027,100
1972	1,437,600	248,000	2,743,460
1973	256,210	191,000	1,879,670
1974	3,376,630	730,000	6,239,125

* As discussed in the text, most of this sediment load does not reach Lake Winnipeg, but is retained in the Saskatchewan River Delta (Moose and Cedar Lakes) and in the Grand Rapids reservoir.

Table 10. Rates of transport of suspended sediment from watersheds tributary to Lake Winnipeg. Suspended sediment data is from Table 9.

Year	Red River at Lockport, Manitoba	Winnipeg River	Saskatchewan River at the Pas
		(tonnes km^{-2} watershed area yr^{-1})	
1969	11.9	2.75	8.81*
1970	10.9	3.08	6.60
1971	6.65	2.37	6.26
1972	5.00	1.96	8.47
1973	0.89	1.51	5.81
1974	11.7	5.78	19.3
Mean	7.85	2.91	9.20

* As discussed in the text, most of this sediment does not reach Lake Winnipeg, but is deposited in the Saskatchewan River Delta (Moose and Cedar Lakes) and in the Grand Rapids reservoir.

Table 11. Rates of transport of suspended sediment in prairie and mountainous drainages tributary to Lake Winnipeg. Data is from Environment Canada (1978).

Year	Red River at St. Agathe, Manitoba south of City of Winnipeg and upstream from Assiniboine River	Assiniboine River at Portage la Prairie, Manitoba, tributary to Red River
	tonnes km^{-2} yr^{-1}	
Prairie Watersheds		
1969	14.7	7.81
1970	13.9	3.27
1971	19.6	1.86
1972	8.31	1.86
1973	5.47	0.39
1974	17.4	6.21
Mean	13.2	3.57

Mountainous Watersheds

	South Saskatchewan River at Highway 41, Alberta	North Saskatchewan River at Whirlpool Point, Alberta	Red Deer River at Red Deer, Alberta
1969	69.0	-	-
1970	40.8	-	-
1971	35.5	-	-
1972	71.5	-	43.6
1973	10.9	144	19.1
1974	62.1	134	-
1975	113.0	130	-
Mean	57.5	136	31.4

Table 12. Physical and chemical characteristics of the major rivers flowing into Lake Winnipeg. The data are mid-summer values (July 9-31, 1969), and the samples were taken at or near the mouths of the rivers. Annual discharges of these rivers are given in Table 3. Station locations and seasonal variation of these parameters is given in Brunskill, Campbell, and Elliott (1979) and Brunskill, Schindler, Holmgren et al. (1979). River locations are shown in Figs. 2 and 3.

River (Station)	Secchi Visibility (m)	Conductivity µmhos/cm 25°C	mol m^{-3}							pH	mmol m^{-3}					
			Ca	Mg	Na	K	SO_4	Cl	HCO_3		TDP	PP	TDN	PN	dSi	PC
Winnipeg (07)	0.80	100	0.32	0.16	0.074	0.023	0.083	0.034	0.88	7.65	0.13	0.87	32.8	12.1	11.4	55.0
Saskatchewan (29)	1.5-2.0	380	1.0	0.64	0.62	0.059	-	-	2.76	8.38	0.45	0.55	27.8	5.28	8.15	57.5
Red (01)	0.35	675	1.40	1.28	1.57	0.20	1.16	0.78	4.08	8.30	0.16	3.68	7.14	16.7	62.6	168.0
Dauphin (66C)	2	1720	0.92	2.10	9.91	0.42	1.36	10.83	3.28	8.80	0.10	0.84	61.4	19.8	48.4	298.0
Berens (51)	0.90	48	0.35	0.11	0.052	0.015	0.63	0.034	0.30	7.23	2.10	1.36	29.3	5.44	28.5	58.3

Table 13. Estimations of populations of humans, livestock and poultry in major Lake Winnipeg drainage basins during 1970. See Methods Section for sources of data.

	DRAINAGE BASIN									
	Saskatchewan River		Red River		Other Sedimentary Drainages		Winnipeg River		Other Shield Drainages	
	Total Number	Number km^{-2}	Total Number	Number km^{-2}	Total Number	Number km^{-2}	Total Number	Number km^{-2}	Total Number	Number km^{-2}
Humans	1,721,000	5.1	1,815,000	6.3	140,000	0.9	183,000	1.4	Data Unavailable Probably Insignificant	Data Unavailable Probably Insignificant
Cattle	4,491,000	13.2	3,115,000	10.8	426,000	2.8	92,000	0.7		
Swine	2,013,000	5.9	1,500,000	5.2	273,000	1.8	22,000	0.2		
Sheep	281,000	0.8	333,000	1.2	18,000	0.1	14,000	0.1		
Chickens	8,852,000	26.0	9,569,000	33.3	994,000	6.6	408,000	3.2		

Saskatchewan River watershed = 340,000 km^2
Red River watershed = 287,500 km^2
Other sedimentary drainages = 151,600 km^2
Winnipeg River watershed = 126,400 km^2
Other Shield drainages = 47,350 km^2

Table 14. Estimates of human and livestock populations, annual agricultural fertilizer use, areas of cultivated land, and detergent consumption for the Lake Winnipeg watershed. The values per unit area ($\#/km^2$) are computed excluding the eastern Precambrian Shield drainages, because this area supports little agriculture and a small human population. Sedimentary land drainage to Lake Winnipeg is 779,500 km^2.

	1945*		1960*		1970*		1985†		2000†	
Year	$\Sigma\#\times10^6$	$\#/km^2$	$\Sigma\#\times10^6$	$\#/km^2$	$\Sigma\#\times10^6$	$\#/km^2$	$\Sigma\#\times10^6$	$\#/km^2$	$\Sigma\#\times10^6$	$\#/km^2$
Human population	3.6	4.6	4.5	5.8	5.0	6.4	5.7	7.4	6.5	8.3
Livestock population	11.6	14.9	13.3	17	14.8	19	18.0	23	23.3	30
Area of cultivated land, in km^2	0.305	0.39	0.344	0.44	0.377	0.48	0.405	0.52	0.442	0.57
Fertilizer use, in tonnes/yr	0.051	0.17‡	0.333	0.97‡	1.15	3.1‡	8.35	21‡	52.5	119‡
Household detergent use, in tonnes/yr	-	-	0.0049	-	0.0054	-	-	-	-	-

* Statistical data from references given in Methods.

† Predicted values, based upon linear regression equations derived from historical data, see Methods.

‡ Annual fertilizer use divided by the area of cultivated land in the Lake Winnipeg watershed, in tonnes km^{-2} yr^{-1}.

Table 15. Estimates of doubling time and annual rates of increase for annual agricultural fertilizer use, human and livestock populations, and the area of cultivated land in the sedimentary portion of the Lake Winnipeg watershed. These estimates are based on statistical data in references cited in Methods, and linear regression equations derived from this data. Rates of increase given in % indicate exponential growth, whereas arithmetic rates indicate linear increases.

	Fertilizer Use (tonnes)	Livestock (Head)	Humans (Head)	Land Under Cultivation km^2
Rate of increase per year, for 1950-1980	13%	1.7%	48,672	2,406
Doubling time from 1975	6 years	40 years	108 years	159 years

Table 16. Estimates of the total annual mass, rates of increase, and doubling time of nitrogen (N) and phosphorus (P) from human, livestock, and fertilizer sources in the sedimentary portion of the Lake Winnipeg watershed. N and P from human and livestock sources are based on physiological data for excreted wastes. The percentage of N and P in the total mass of fertilizer used annually (see Table 14) was obtained from references cited in Methods. Percentage rates of increase indicate exponential growth, whereas arithmetic rates indicate linear growth.

Year	Fertilizer		Livestock		Humans		Total	
	N and P in tonnes x 10^3							
	N	P	N	P	N	P	N	P
1950*	10.5	21.1	6,138	88	16.3	2.04	6,165	111
1960*	44.4	42.0	6,680	100	19.7	2.46	6,744	145
1970*	279	136	7,505	114	21.8	2.72	7,806	253
1980†	1,609	406	8,471	128	23.7	3.00	10,104	537
1990†	9,279	1,218	9,431	145	25.8	3.27	18,736	1,366
2000†	53,505	3,652	10,501	163	28.0	3.54	64,034	3,818
Annual Rate of Increase	19.1%	11.6%	1.1%	1.2%	0.213 tonnes	0.027 tonnes		
Doubling Time from 1975	4 years	6 years	64 years	57 years	106 years	108 years		

* Statistical data from references given in Methods.

† Predicted values, based upon linear regression equations derived from historical data, see Methods.

Table 17. Comparison of the measured rate or transport of N and P from sedimentary watersheds of Lake Winnipeg (from Table 8) with the annual amounts of N and P added to the watershed of Lake Winnipeg by livestock, humans, and fertilizer (from Table 16). Both data sets are for 1970.

Red River		Saskatchewan River		N and P from Livestock, Humans, and Fertilizer	
N	P	N	P	N	P
10 mol km^{-2} watershed area yr^{-1}					
9.8	0.85	3.2	0.045	715	11

Table 18. Comparison of annual suspended sediment transport rates (ROT(SS), erosion rates) for North American rivers, and some other large rivers of the world. Q_a = average annual discharge; A_d = drainage area.

River	Q_a (km^3)	A_d (10^3 km^2)	ROT(SS) (tonnes km^{-2} yr^{-1})	Reference
Mackenzie	313	1690	68	Brunskill, 1975
Yukon	173	855	103	Mathews, 1973
Yenisei	548	2470	4.21	Holeman, 1968
Ob	394	2447	5.96	Holeman, 1968
Red	10	288	7.9	This report
Saskatchewan	22	340	9.2	This report
Winnipeg	40	126	2.9	This report
Mississippi	563	3220	64-97	Gibbs, 1967; Holeman, 1968
Missouri	61.9	1370	159	Holeman, 1968
Columbia	25	88.1	12.6	Water Survey of Canada
Peace	16.1	293	164	Water Survey of Canada
Amazon	5500	6300	79	Gibbs, 1967
Niger	100	1110	9.0	Grove, 1972
Zaire	1250	4010	8.9	Gibbs, 1967
Ganges	445	1060	1400	Holeman, 1968
Yellow	47.3	715	2640	Holeman, 1968
Ching	1.79	57.0	7180	Holeman, 1968

Table 19. Comparison of dissolved major element transport rates (per unit area of watershed) for the Lake Winnipeg drainage and other areas of the world.

River	Ca	Mg	Na	K	HCO_3	SO_4	Cl	Si	Reference
				(10 mol km^{-2} yr^{-1})					
Red	40	29	43	5.6	104	30	23	5.2	A
Assiniboine	21	23	39	4.7	67	27	16	3.2	A
Saskatchewan	74	38	45	4.1	197	29	19	2.6	A
Winnipeg	112	22	21	6.4	234	19	12	11	A
Nelson	53	45	93	6.7	207	31	76	3.1	B
Churchill	49	25	13	3.6	149	0.6	6.3	3.2	B
Mackenzie	148	77	51	4.6	357	69	41	32	C
Yukon	237	75	28	7.3	567	47	4.0	45	D
Mississippi	149	54	84	14	290	75	73	17	B
St. Lawrence	207	74	108	8.7	427	65	139	8.7	B
Colorado	45	24	104	0.002	58	58	61	4.4	B
Columbia	162	74	198	-	502	57	40	62	B
Amazon	142	36	117	22	323	28	98	164	E
Mekong	252	90	113	36	675	28	211	105	F
Ganges	234	123	178	33	798	43	90	63	F
Brahmaputra	529	148	135	61	1475	-	146	-	F

A. This work, see Table 8 and Brunskill, Campbell, and Elliott 1979.

B. Durum et al. 1960; and UNESCO 1969.

C. Brunskill et al. 1973; Campbell et al. 1975.

D. Matthews 1973; Durum et al. 1960.

E. Gibbs 1972.

F. Meybeck and Carbonnel 1975.

Table 20. Comparison of rates of transport (per unit land area) of the nutrients total nitrogen (ΣN) and total phosphorus (ΣP) from the watersheds of Lake Winnipeg tributaries and other areas of the world.

Watershed	ΣN	ΣP	Reference
	(10^3 mol km^{-2} yr^{-1})		
Precambrian Shield or Crystalline Rock Watersheds			
Experimental Lakes Area, Ontario	6.7	0.16	Schindler et al. 1976
Southern Ontario watersheds	-	0.08-0.25	Dillon & Kirchner 1975
Clear Lake, Ontario	9.0*	0.284	Schindler & Highswander 1970
Hubbard Brook W-6, N.H.	28.6	0.067	Hobbie & Likens 1973; Likens et al. 1970, 1977
Fernow Experimental Forest WS4, W. Virginia	12.1*	0.13	Aubertin & Patric 1974
Winnipeg River	9.7-19.1	0.2-0.5	This report, see Table 8
Pigeon & Berens Rivers	12.2	0.31	This report, see Table 8
Manigotagan River	9.8	0.19	This report, see Table 8
Poplar River	9.6	0.34	This report, see Table 8
Prairie or Agricultural Watersheds			
Grain, cotton and grazed watersheds, Oklahama†	1.1-94	0.065-35	Menzel et al. 1978
Corn fields near Treynor, Iowa†	172-310	1.4-2.7	Burwell et al. 1977
Corn fields, Minnesota	200-560	27-60	Young & Holt 1977
Mississippi River	7-10‡	0.3-0.8	Alberts 1970; Cook 1975
Swiss forest and pasture†	60-180	0.13-2.4	Gachter & Furrer 1972
Southern Ontario watersheds	-	0.66-1.2	Dillon & Kirchner 1975
Wheat fields and fallow, Saskatchewan†	<0.7-55	<0.3-18	Nickolaichuk & Reed 1978
Native prairie, W. Minnesota	0.8-12	<0.03-0.81	Timmons & Holt 1977
Red River	1.5-9.8	0.13-0.85	This report, see Table 8
Fisher River	0.8-8.4	0.01-0.29	This report, see Table 8
Saskatchewan River	2.9-4.9	0.04-0.09	This report, see Table 8

* Inorganic N only, not ΣN.

† Some of these agricultural watersheds were fertilized with commercial inorganic N and P and/or manure.

‡ NO_3-N only, not ΣN.

Table 21. Annual rates of supply of the nutrients N and P, per unit lake surface area, for Lake Winnipeg, the south basin of Lake Winnipeg, and the St. Lawrence Great Lakes. Also given for comparison is mean depth ($\bar{Z}$) and estimated lake water residence time (τ).

Year	Basin	N	P	$\bar{Z}$	τ	A_0
		$g\ m^{-2}\ yr^{-1}$	$g\ m^{-2}\ yr^{-1}$	m	yr	km^2
1969	Lake Winnipeg	4.2	0.29	12.0	3.1	23,750
1970		4.5	0.47	"	2.9	
1971		3.2	0.25	"	3.2	
1972		3.8	0.22	"	3.3	
1973		2.5	0.15	"	4.3	
1974		5.1	0.37	"	2.9	
1969	South Basin of Lake Winnipeg	21	1.9	9.7	0.49‡	2,780
1970		24	3.4	"	0.47	
1971		12	1.4	"	0.56	
1972		15	1.3	"	0.62	
1973		9.1	0.75	"	0.83	
1974		25	2.2	"	0.43	
	Superior		0.03*	148*	185*	82,410†
	Michigan		0.14	84	113	58,020
	Huron		0.13	61	21	59,600
	Erie		1.06	18	2.6	25,720
	Ontario		0.65	84	7.9	19,480

* P, $\bar{Z}$, and τ data for St. Lawrence Great Lakes are from Vollenweider (1976).

† A_0 for St. Lawrence Great Lakes are from Beeton and Chandler (1963).

‡ See page 3 for criticism of these values of τ.

Table 22. Annual rates of supply of ΣN to Lake Winnipeg via rivers (excluding direct rainfall on the lake surface), and an estimate of annual above-ground available ΣN from fertilizer use, livestock, and human populations on the sedimentary portion of the Lake Winnipeg watershed.

	1969	Range for 1969-1974
Annual ΣN supply to Lake Winnipeg via rivers	83,090 tonnes	47,020-108,260
% of total supply delivered to South Basin	59%	52-71%
% of total supply from Red River	27%	13-42%
% of total supply from sedimentary watershed	56%	51-67%
Annual above-ground N on Lake Winnipeg sedimentary watershed (humans, livestock, fertilizer)*	7,783,000 tonnes	7,783,000-8,528,000 tonnes
Annual ΣN supply to Lake Winnipeg from its sedimentary watershed as a % of annual above-ground N* on the watershed	0.6%	0.4-0.8% ($\bar{X}$ = 0.57%)

* Data estimated from statistical records and predicted from regression equations, as described in Methods. See Tables 13-16.

Table 23. Annual rates of supply of ΣP to Lake Winnipeg via rivers (excluding direct rainfall on the lake surface), and an estimate of annual above-ground available ΣP from fertilizer use, livestock and human populations on the sedimentary portion of the Lake Winnipeg watershed.

	1969	Range for 1969-1974
Annual ΣP supply to Lake Winnipeg via rivers	6,620 tonnes	2,980-10,570 tonnes
% of total supply of P delivered to South Basin	78%	68-89%
% of total supply of P from Red River	52%	30-72%
% of total supply of P from sedimentary watershed	66%	45-83%
Annual above-ground P on Lake Winnipeg sedimentary watershed (humans, livestock, fertilizer)*	236,260 tonnes	236,260-332,270
Annual ΣP supply to Lake Winnipeg from sedimentary watershed as % of above-ground P on watershed	1.9%	0.5-3.5% ($\bar{X}$ = 1.6%)

* Data estimated from statistical records and predicted from regression equations as described in Methods. See Tables 13-16.

Table 24. Estimates of the increase in rate of supply of P and N to Lake Winnipeg. The calculation is based upon 1) the assumption that 1.6% and 0.6% of the "above-ground available P and N" will reach Lake Winnipeg, and 2) the predicted values for future fertilizer use, livestock, and human populations.

Year	Above-Ground Available (on Sedimentary Watershed) ΣP (tonnes)	Runoff from Sedimentary Watershed to Lake Winnipeg (tonnes)	Runoff from Shield Watershed & Precipitation to Lake Winnipeg (tonnes)	Total Runoff to Lake Winnipeg (tonnes)	% Increase over 1969 ΣP Supply to Lake Winnipeg
1969	236,260*	4,390†	4,640†	9,030†	0
1980	537,000‡	8,590	4,640	13,230	47
1990	1,366,000‡	21,860	4,640	26,500	193
2000	3,818,000‡	61,090	4,640	65,730	628

Year	Above-Ground Available (on Sedimentary Watershed) ΣN (tonnes)	Runoff from Sedimentary Watershed to Lake Winnipeg (tonnes)	Runoff from Shield Watershed & Precipitation to Lake Winnipeg (tonnes)	Total Runoff to Lake Winnipeg (tonnes)	% Increase over 1969 ΣN Supply to Lake Winnipeg
1969	7,192,000*	46,378†	54,162†	100,540†	0
1980	10,081,000‡	57,462	54,162	111,624	11
1990	18,711,000‡	106,653	54,162	160,815	60
2000	64,010,000‡	364,857	54,162	419,019	317

* Estimated from census and physiological data, see Tables 13-16, 22 and 23.
† Based on chemical and hydrological measurements, see Table 8.
‡ Predicted from regression analysis of historical census data, see Figs. 5-7.

Fig. 1. Map of the major tributaries to Lake Winnipeg, the extent of glacial Lake Agassiz, and a delineation of the Precambrian Shield and sedimentary regions of the watershed.

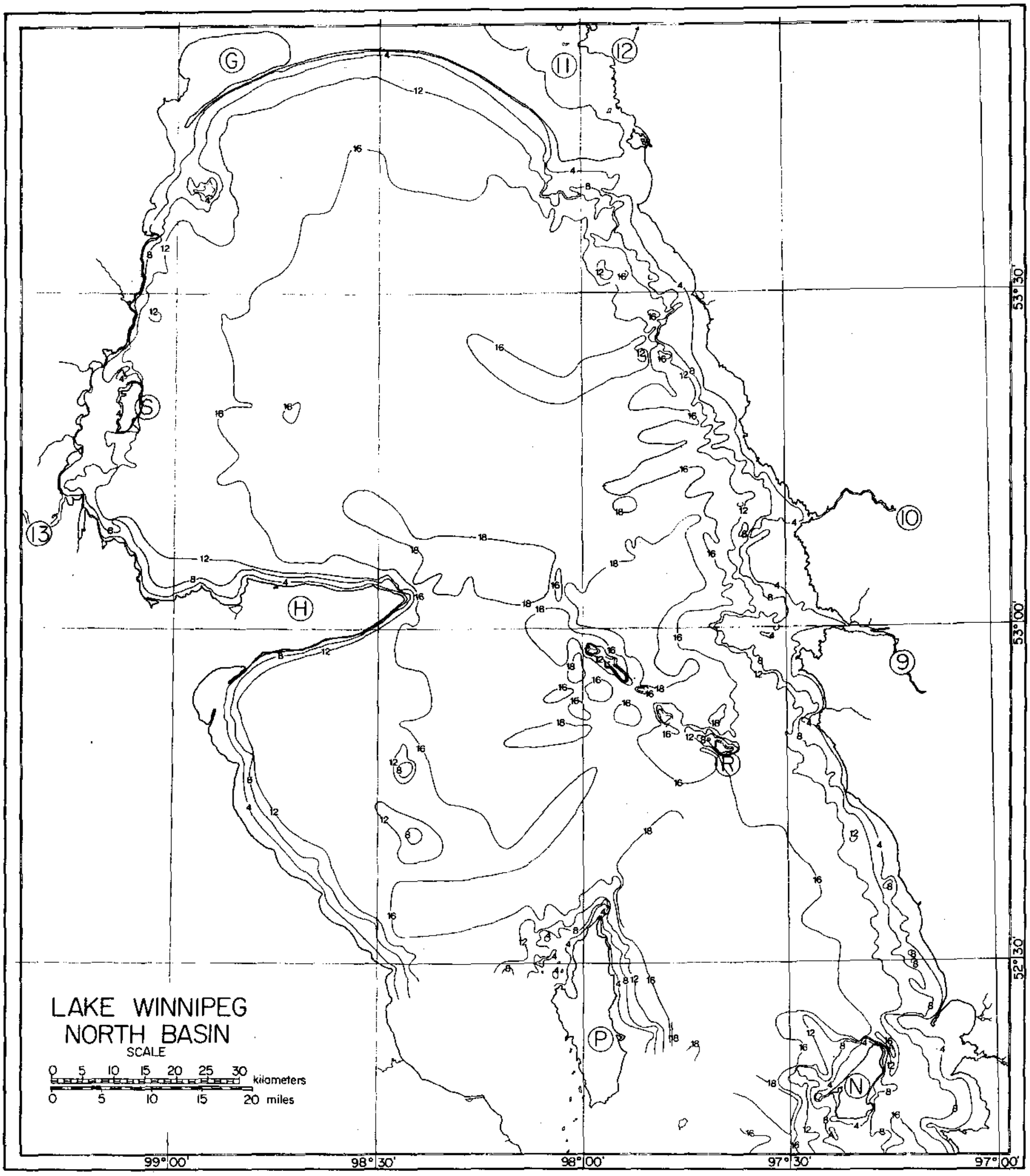

Fig. 2. Bathymetric map of the North Basin of Lake Winnipeg. Depth contour interval is 4 meters.

sedimentary regions of the watershed.

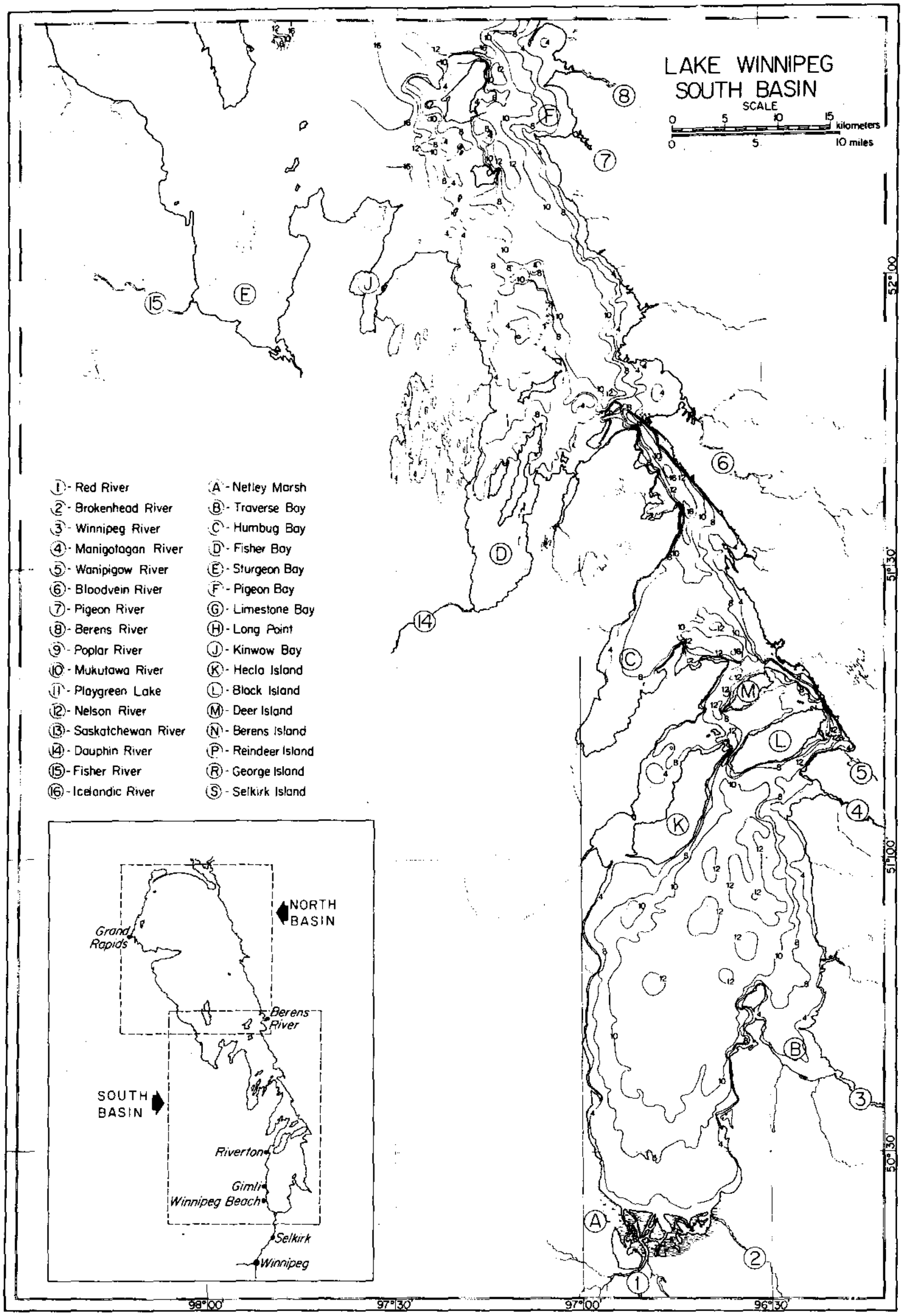

Fig. 3. Bathymetric map of the South Basin and Narrows of Lake Winnipeg. Depth contour interval is 4 meters.

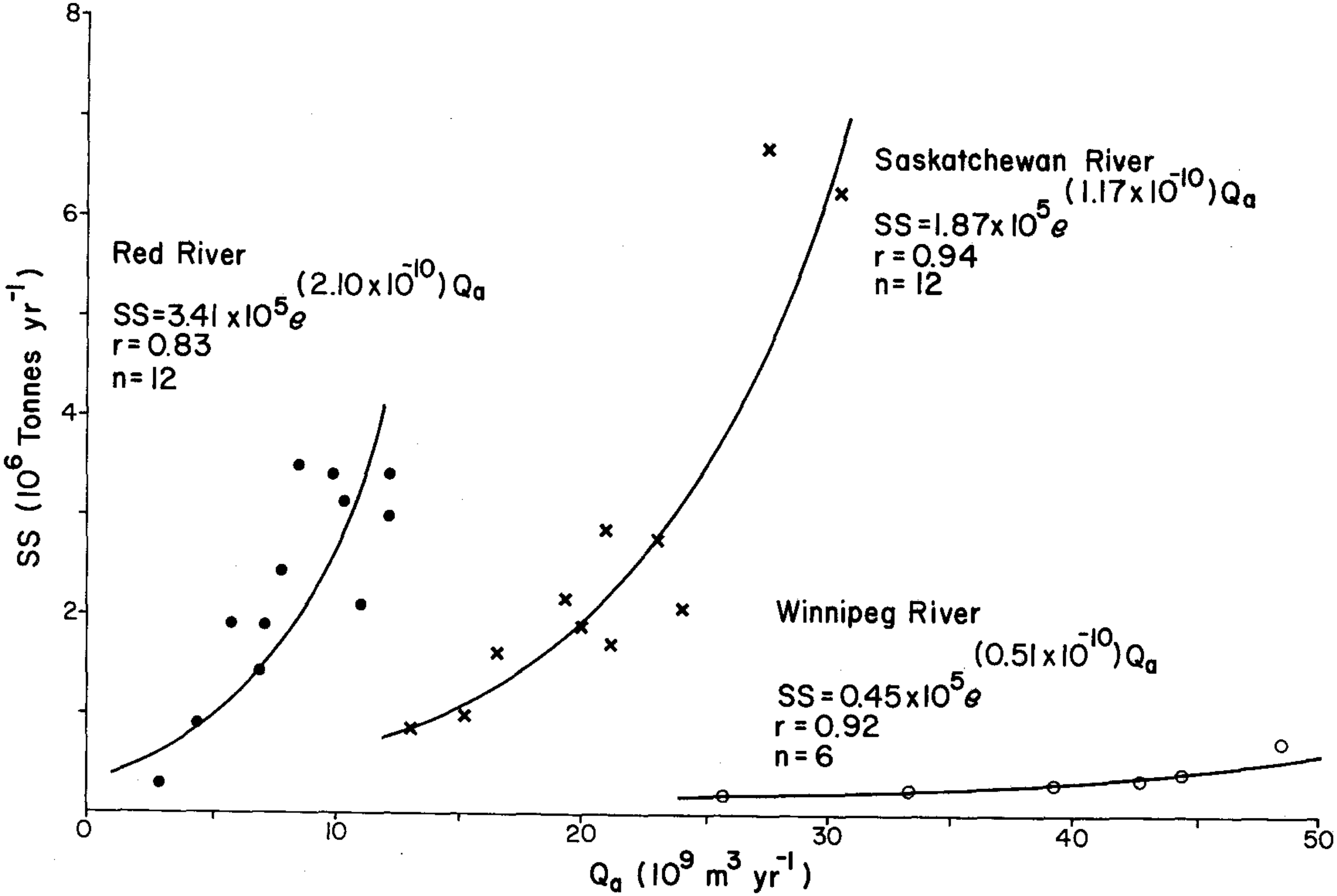

Fig. 4. The relationship between annual river discharge (Q_a) and annual suspended sediment transport (SS) for the Red, Winnipeg, and Saskatchewan Rivers over 1965 to 1976.

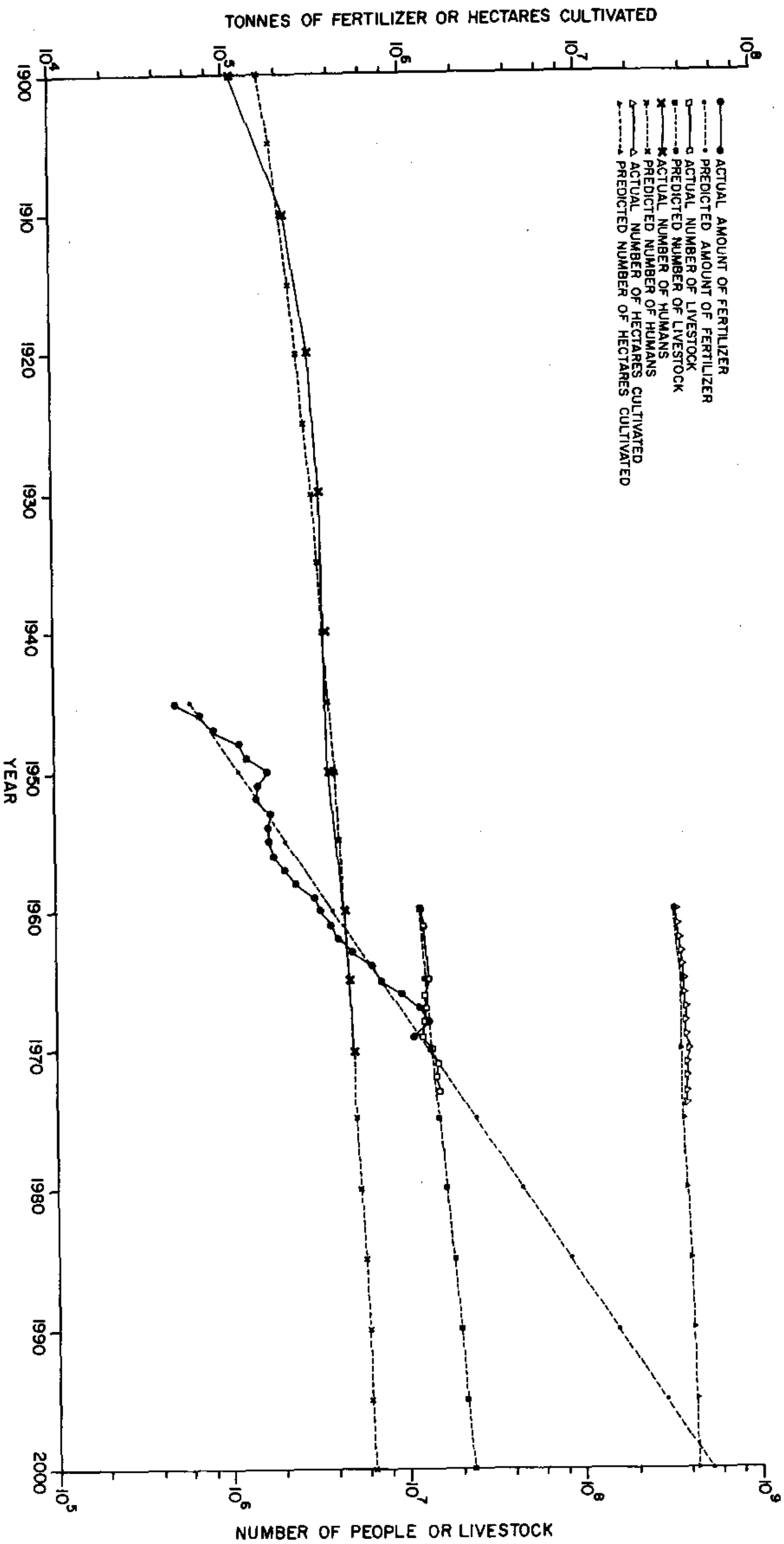

Fig. 5. Historical and extrapolated trends in fertilizer use, human and livestock populations, and area of cultivated land. These data apply to the sedimentary portion of the Lake Winnipeg drainage area.

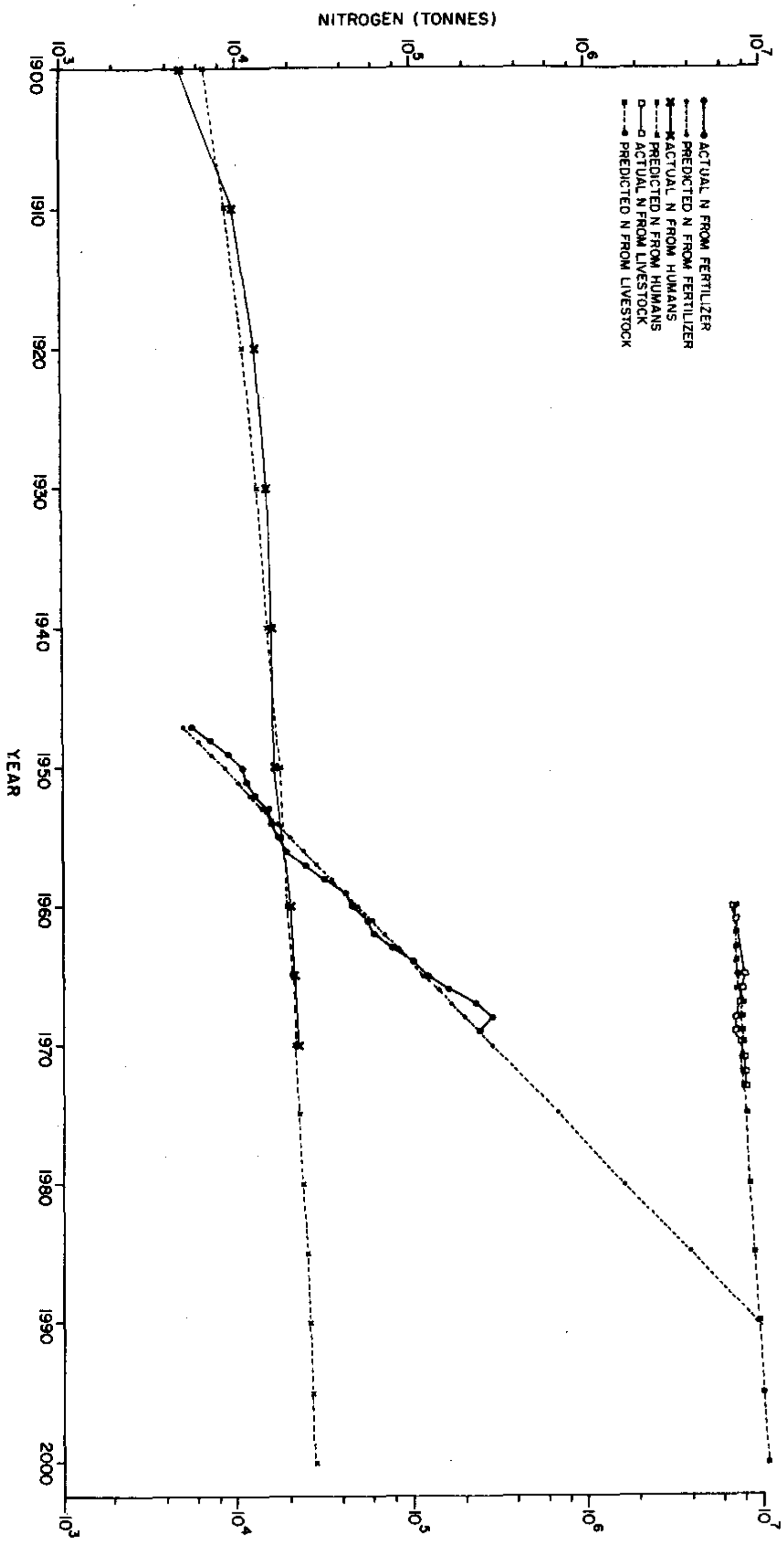

Fig. 6. Historical and extrapolated trends in the annual release of nitrogen to the land and water of the Lake Winnipeg sedimentary drainage area.

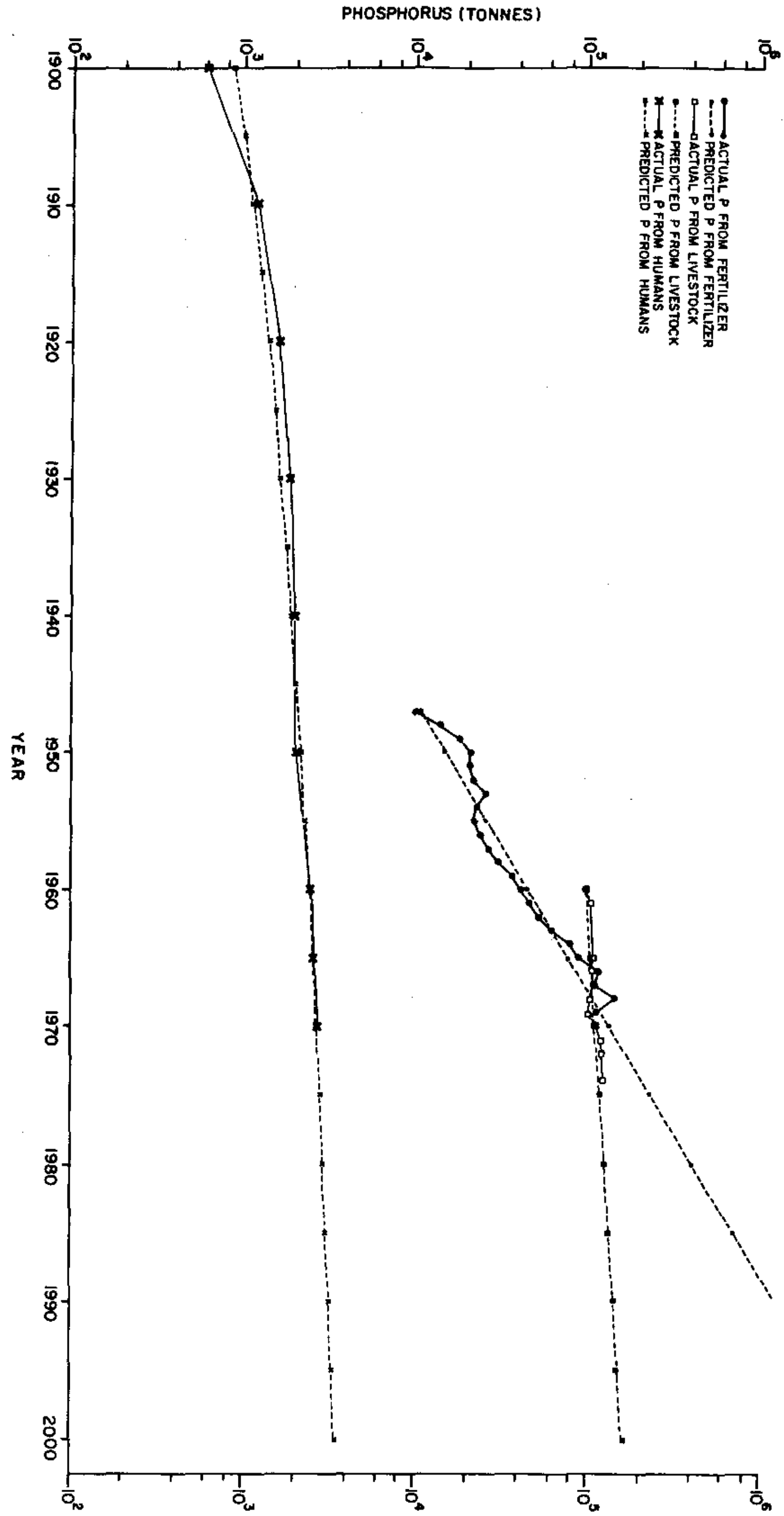

Fig. 7. Historical and extrapolated trends in the annual release of phosphorus to the land and water of the Lake Winnipeg sedimentary drainage area.

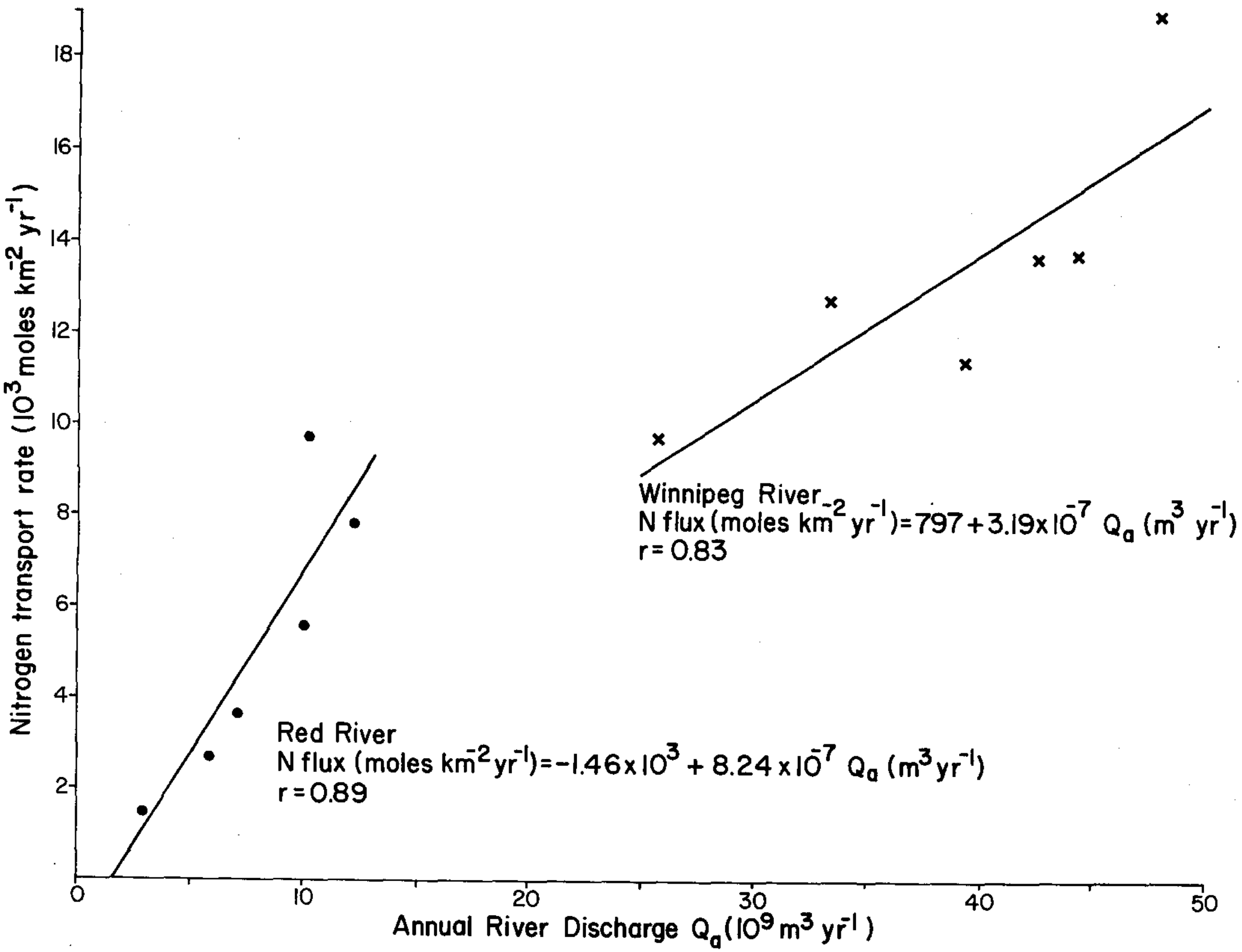

Fig. 8. The relationship between annual river discharge and annual nitrogen transport rate to Lake Winnipeg.

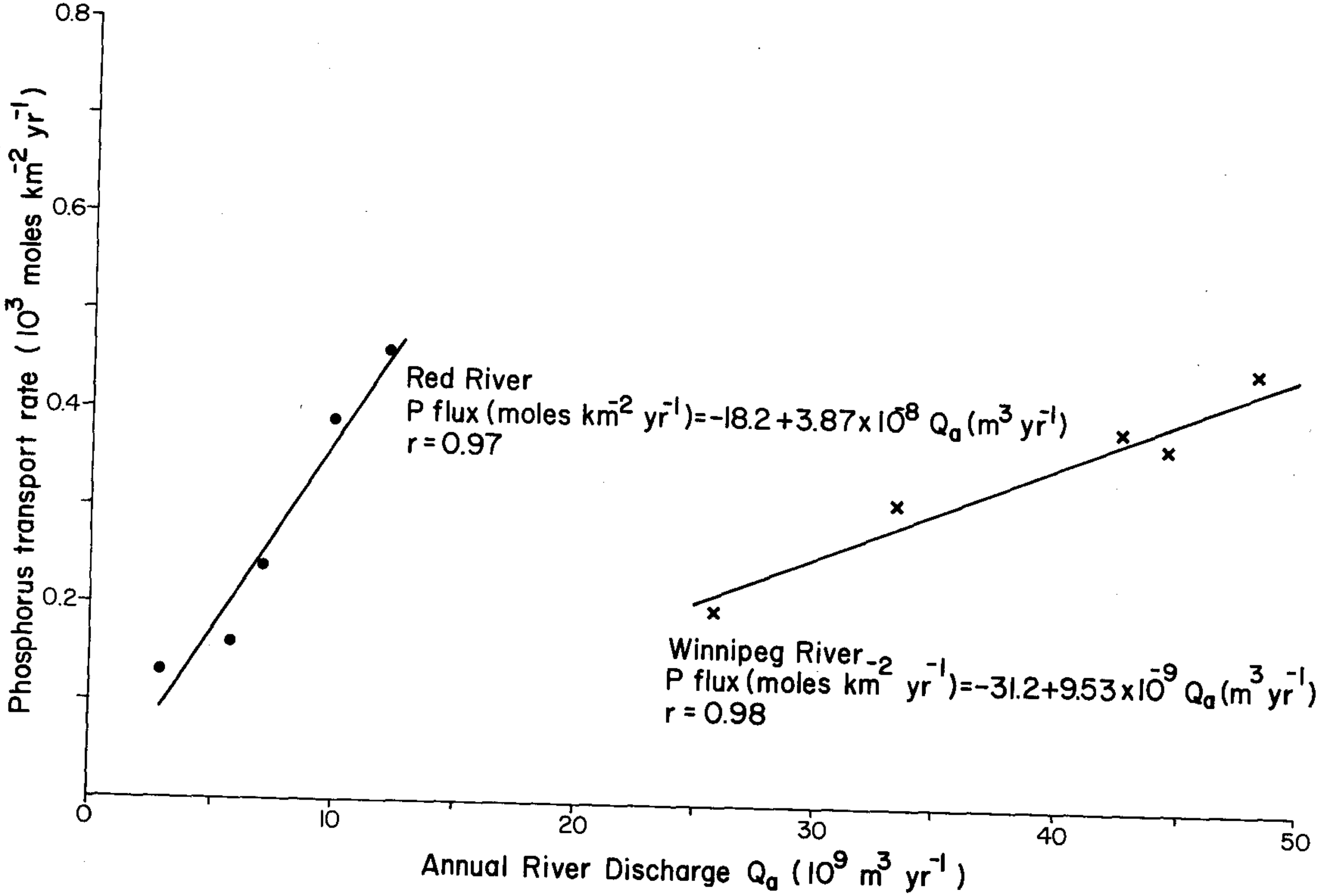

Fig. 9. The relationship between annual river discharge and annual phosphorus transport rate to Lake Winnipeg.