Organic Carbon, Nitrogen and Phosphorous Fluxes in Rivers Flowing into and out of Lake Winnipeg

With an analysis of discharges and nutrient fluxes between the North and South Basins

Final Report
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Introduction

This report documents results of a contract with the Canada Department of Fisheries and Oceans to calculate major nutrient fluxes into and out of Lake Winnipeg, and includes a description of input data and computations leading to the results, and an analysis of precision of the results.

Objectives

The contract requirements are to:

1. Calculate monthly fluxes of total, dissolved and particulate organic carbon (OC) nitrogen (N) and phosphorous (P) via major rivers into and out of Lake Winnipeg, and through the Lake Winnipeg Narrows, for months for which OC, N, and P data are archived in the Canada Department of Fisheries and Oceans (DFO) LWATDAT (i.e. data up to 1993) database or are otherwise made available by DFO.

2. Retrieve nutrient data that has been recorded since 1993 from federal, provincial and City of Winnipeg agencies and add it to the LWATDAT to bring the database up to date. Calculate monthly fluxes as described above, for the post-1993 period of available records.

Products

1. Tabulated and plotted monthly C, N and P fluxes into and out of Lake Winnipeg for major rivers and the Narrows for periods for which sufficient chemistry data are available.

2. Annual lake basin budgets of C, N and P such as to identify sources and sinks of these nutrient elements for periods for which sufficient chemistry data are available.

3. Documentation of data sources and methods of flux calculation, with software (Excel spreadsheets or other programs as required, on CD) necessary to extend the monthly C, N, and P flux data set beyond 1999 (i.e. post-LWATDAT database) when appropriate data are assembled.

Data

Data files

Daily discharge data used in this report are archived on the accompanying CD in the Microsoft Excel file “L Wpg in&out flow 1960-2001.xls”. These records include some estimated daily values (see section “River flow and lake level” below) when necessary to create continuous daily data. Daily lake level data are archived in the files “L Wpg S Basin level 1960-2001.xls” and “L Wpg N Basin level 1960-2001.xls”.

The most current version of the LWATDAT database is stored on the accompanying CD as the Microsoft Access file “LWATDAT v3-5.mdb”. Measurements of OC, N and P have been extracted and are stored on the CD as the Excel file “LW nutrients - raw data (LWATDAT3-5).xls”.

Reorganized data used in this report for calculation of fluxes are stored in the Excel file “LW nutrients - organized as OC,N,P (LWATDAT3-5).xls”. In this file, in the worksheets “allData1” and “alldata2”, data are reorganized from observations listed by individual agency methods into observations by the summary categories TOC, DOC, POC, TN, DN, PN, TP, DP and PP (see section “Regrouped nutrient parameters” below) . N and P data collected by Gregg Brunskill of the Canada Department of Fisheries and Oceans (not archived in LWATDAT) has been added to the worksheet “allData2”. The worksheet “dailyData” is a record of data reduced to one observation per day created by averaging “allData2” by agency-station-time, effectively cross-tabulating the 9 nutrient parameters, and either removing duplicate records or averaging multiple daily observations. This latter daily data set was used in all subsequent calculations of fluxes.

Data and calculations stored in “LW nutrients - organized as OC,N,P (LWATDAT3-5).xls” can be used to trace each individual daily concentration value back to the agency methods code. Detailed description of the field and analytical methods are not stored in the database. The 1994 report, “LWATDAT. Lake Winnipeg and Tributaries Water Quality Database” (Agassiz North, 1994) identifies persons at each of the supplying agencies who may be contacted for further information. A copy of the Agassiz North report is archived as the Word file “LWATDAT.doc” on the accompanying CD.

Concentration data and time series concentration plots (Appendix D) for each river are stored on the accompanying CD in the Excel files “LW nutrients - <*river name*>.xls”. Monthly flux plots (Appendix F) for each river are stored in the Excel files “LW nutrient flux - <*river name, agency*>.xls”.

River flow and lake level

Locations of major tributary rivers are identified on Figure 1, along with various places mentioned in this report. River mean daily discharge and lake level flow for the stations listed below up to 1995 have been retrieved from the Environment Canada, Water Survey of Canada HYDAT 1995 CD. More recent data have been purchased Water Survey of Canada to build the period of record for this study up to December, 1999. 1999 data for the Saskatchewan River and upper Nelson River stations was supplied by Manitoba Hydro.

Station #	Station Name	Drainage Area (km^2)
105KL001	Saskatchewan R at Grand Rapids	364000
105LM006	Dauphin R at Dauphin R. community	82400
105LM001	Fairford River (Dauphin R) at Fairford	
105OJ010	Red River at Lockport	278000
105OC001	Red River at Emerson	
105MJ001	Assiniboine R at Headingley	
105PF069	Winnipeg River at Pine Falls	134050
105PF063	Winnipeg River at Slave Falls	
105RA001	Manigotagan R	1830
105UB008	Nelson R at Sea R Falls	980000
105UB009	Nelson R at Jenpeg Dam	980000
105UD004	Nelson R at Bladder Rapids	

Nutrient flux calculations used in this study require continuous daily records. For periods when discharge was not measured at the stations nearest to Lake Winnipeg, daily discharges were estimated by regression on upstream stations (downstream in the case of the Nelson River). Further details are provided in Appendix A. Continuous daily records used in the flux calculations are recorded in the Excel file "L Wpg in&out flow 1960-2001.xls" archived on the accompanying CD.

Daily level data for Lake Winnipeg stations was abstracted from the Water Survey of Canada HYDAT CD (1995) for the stations listed below. Additional level data has been acquired from Water Survey of Canada for these stations to build the period of record for this study up to December, 1999.

Station #	Location
05RD005	Berens River
05RE003	George Island
05SB006	Gimli
05SD002	Matheson Island Landing
05SG001	Mission Point
05RF001	Montreal Point
05SD001	Pine Dock
05SA003	Victoria Beach
05SB001	Winnipeg Beach

The wind records used in this study were recorded by Environment Canada, Atmospheric Environment Service at their meteorological station at George Island.

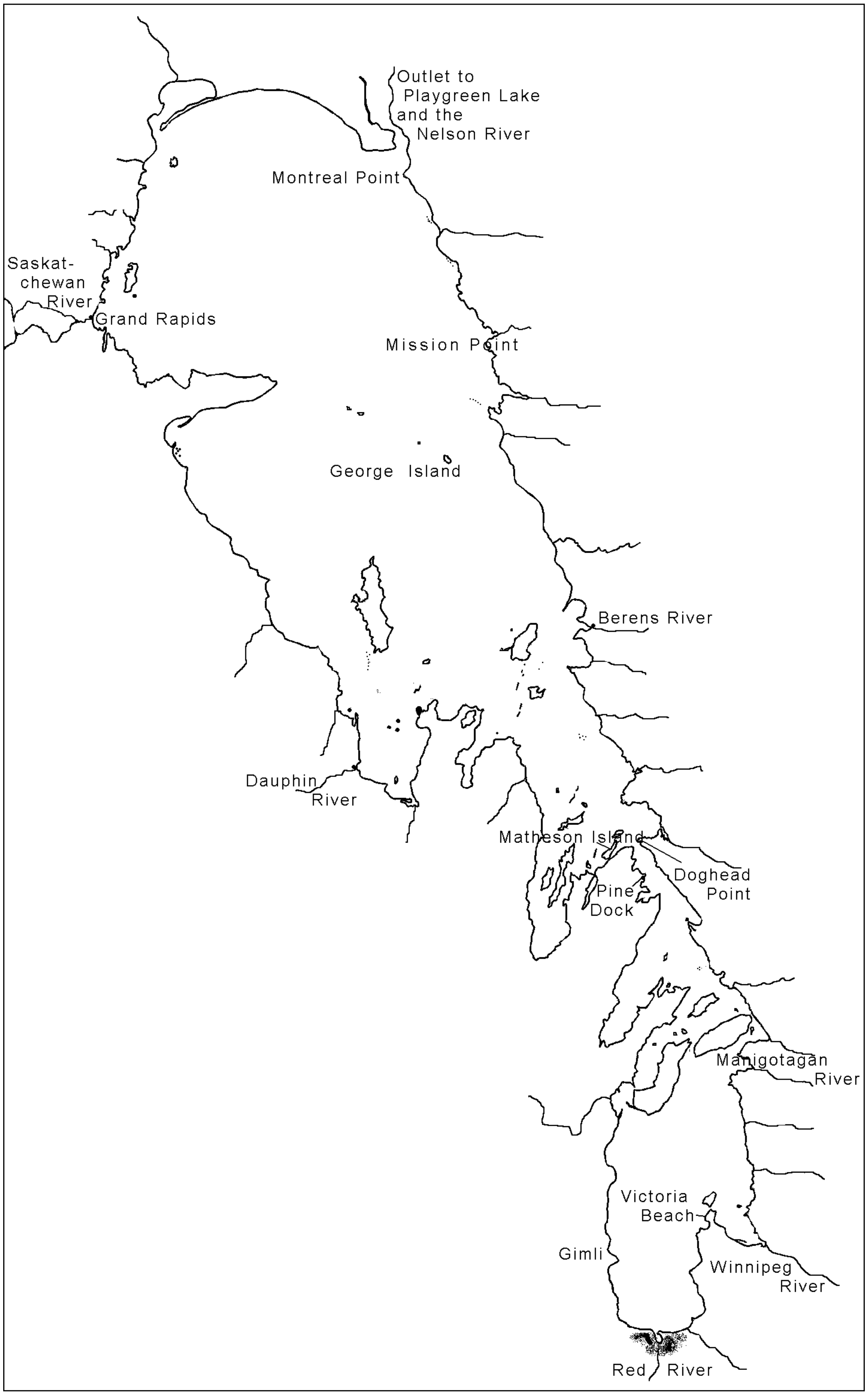

Figure 1. Major tributary rivers and water level and climate stations mentioned in this study.

Water quality parameters

Acronyms for water quality parameters drawn from the LWATDAT database for use in this study are identified below.

Acronym	Parameter description
TOC	Total organic carbon as C
DOC	Dissolved organic carbon as C
POC	Particulate organic carbon as C
TN	Total nitrogen as N
TKN	Total Kjeldahl nitrogen as N
DN	Dissolved nitrogen as N
DKN	Dissolved Kjeldahl nitrogen as N
DNO3NO2	Dissolved NO3+NO2 as N
PN	Particulate nitrogen as N
NH3	Ammonia
TP	Total phosphorous as P
DP	Dissolved phosphorous as P (lab. filtered)
DPfield	Dissolved phosphorous as P (field filtered)
PP	Particulate phosphorous as P

Water Quality Stations

The LWATDAT database contains nutrient (and other) chemistry for the Saskatchewan, Dauphin, Red, Winnipeg, and Manigotagan Rivers upstream of Lake Winnipeg, the Nelson River and its East and West Channels at the Lake Winnipeg outlet, and for Lake Winnipeg itself. Geographical descriptions and coordinates for each station are listed in Table 1. The agency responsible for data collection at each station, together with the period of record, are listed in the same table. Descriptive statistics for the nutrient data archived in the LWATDAT database for these stations are reported by river and by agency/station in Appendix C.

For the Saskatchewan River, all water quality stations are downstream of Grand Rapids. Dauphin River stations are all downstream of Lake St. Martin. Red River stations are all downstream of the City of Winnipeg. For the Winnipeg River, the most extensive water quality record is at Point du Bois, about 120 km upstream of the mouth. Concentration data at stations nearer to the mouth is available only intermittently up until 1984. The water quality station on the Manigotagan River is near its mouth, along the east shore of Lake Winnipeg. Water quality stations on the Nelson River, the outlet of Lake Winnipeg, have been at various times located at Warrens Landing (prior to 1972, the sole outlet channel), along the East Channel at Norway House and at Sea River Falls, and along the West Channel at Jenpeg Dam.

Table 1. Water quality station identifiers, location information, sample period (y) of record and number of samples (n) for river stations in the LWATDAT v. 3.5 database. “Env Can”=Environment Canada; “Man Env”=Manitoba Environment; “Cty Wpg”=City of Winnipeg, Waterworks, Waste and Disposal Department. Stations identified as “DFO Can” (Canada Department of Fisheries and Oceans) are Gregg Brunskill’s 1968-1971 stations.

River	Agency	Station	Station Name	Lat	Long	1st Obs’n	Last Obs’n	Period	n
Assiniboine	DFO Can	0A	Red River at S Perimeter Bridge	49.78	97.13	68 Nov 05	71 Mar 15	2.4	52
Dauphin	Env Can	MA05LM0004	Dauphin River 8 km upstream of Anama Bay	51.95	98.15	69 Jul 23	90 Mar 27	20.7	90
Dauphin	Env Can	MA05LM0005	Dauphin River near Dauphin River	52.00	98.32	90 Apr 17	97 Jan 15	6.8	79
Dauphin	Man Env	WQ0404	Dauphin River upstream of Anama Bay	52.00	98.32	78 Apr 24	88 Jul 04	10.2	99
Manigotagan	Env Can	MA05RA0004	Manigotagan River at Hwy 304	51.10	96.28	69 Jul 24	97 May 06	27.8	258
Manigotagan	Env Can	MA05RB0001	Manigotagan River at Hwy 304	51.10	96.28	91 May 30	00 Nov 10	9.5	34
Manigotagan	Man Env	WQ0867	Manigotagan River at Hwy 304			93 Jul 12	97 Oct 23	4.3	3
Nelson	Env Can	MA05UB0002	Nelson River at Warren Landing	53.70	97.87	69 Jul 22	77 May 24	7.8	47
Nelson	Env Can	MA05UB0006	Nelson River, East Channel below Sea River Falls	54.24	97.59	87 Jan 30	89 Sep 13	2.6	23
Nelson	Env Can	MA05UB0015	Nelson River at Jenpeg	54.50	98.05	90 Jan 17	96 Jul 25	6.5	23
Nelson	Man Env	WQ0049	Nelson River, East Channel at Norway House	54.00	97.83	75 Jan 23	00 Aug 01	25.5	116
Red	DFO Can	0	Red River at Selkirk	50.16	96.87	68 Oct 27	71 Mar 15	2.4	55
Red	DFO Can	0B	Assiniboine River at W Perimeter Bridge	49.87	97.33	68 Nov 05	71 Mar 15	2.4	52
Red	Env Can	MA05OJ0001	Red River at Selkirk	52.00	98.32	60 May 14	00 Dec 09	40.6	358
Red	Cty Wpg	REDR_LCKPRT	Red River at Lockport			90 Jan 27	00 Nov 28	10.8	202
Red	Cty Wpg	REDR_NPERIM	Red River at N Perimeter Bridge	49.97	97.07	90 Feb 14	97 Nov 04	7.7	160
Red	Man Env	WQ0142	Red River at Selkirk	50.14	96.87	67 Jan 13	01 Jan 03	34.0	371
Saskatchewan	DFO Can	29	Saskatchewan River at Reservoir	53.15	99.29	69 Mar 20	69 Oct 29	0.6	7
Saskatchewan	Env Can	MA05SH0001	Saskatchewan River below Grand Rapids	53.16	99.29	69 Jul 23	97 Jan 15	27.5	153
Saskatchewan	Man Env	WQ0163	Saskatchewan River below Grand Rapids	53.16	99.29	73 Jul 10	00 Oct 25	27.3	92
Winnipeg	Env Can	MA05PF0002	Winnipeg River below Pine Falls Power Plant	50.57	96.18	60 Jun 12	74 Aug 08	14.2	80
Winnipeg	Env Can	MA05PF0022	Winnipeg River at Pointe du Bois	50.30	95.56	72 Jul 05	01 Feb 20	28.7	282
Winnipeg	Man Env	WQ0213	Winnipeg River at PR313 bridge near Lac du Bonnet	50.28	96.00	72 Jul 11	84 Feb 23	11.6	95
Winnipeg	Man Env	WQ0216	Winnipeg River at Fort Alexander	50.62	96.30	71 Mar 03	77 Jan 13	5.9	14

Period of record

Nutrient chemistry archived in LWATDAT v. 3.5 extends from May, 1960 to February, 2001, although it is not necessarily complete for all agencies/stations to 2001. Periods of record for individual stations are listed in Table 1. For a more detailed illustration of the data record for each station, see Appendix D, Figures D-1 to D-19, which show nutrient concentration time series.

Agencies

Water quality data archived in LWATDAT were contributed by three agencies:

> Environment Canada, Water Quality Branch (Env Can)
> Manitoba Environment, Water Quality Management Section (Man Env)
> City of Winnipeg, Waterworks, Waste, and Disposal Department (Cty Wpg)

Water quality data have been acquired from these agencies to build the LWATDAT database to cover the period 1993 to 2001. The most current version, archived on the accompanying CD, is LWATDAT v. 3.5. Additional water quality for in-lake stations have been provided by the Canada Department of Fisheries and Oceans. These DFO data are archived on the accompanying CD, but have not been incorporated into LWATDAT v. 3.5.

Methods

Regrouped nutrient parameters

Fluxes were calculated for river-borne organic carbon (OC), nitrogen (N) and phosphorous (P) both as total flux, and also separately as dissolved and particulate (suspended) fluxes. To this end, parameters retrieved from LWATDAT have been regrouped as shown below. (e.g. For total organic carbon, if TOC was not independently determined then, if separate dissolved and particulate determinations were done, TOC is calculated as the sum of DOC+POC). The order of alternatives implies precedence. (e.g. if DN was not independently determined, then if TN and PN were determined, DN=TN-PN, if not then if DKN and DNO3NO2 were determined, DN=DKN+ DNO3NO2).

	Acronym	Derivation
Organic Carbon	TOC	= TOC or DOC+POC
	DOC	= DOC
	POC	= POC or TOC-DOC
Nitrogen	TN	= TN or TKN+DNO3DNO2
	DN	= DN or TN-PN or DKN+DNO3NO2
	PN	= PN or TN-DN
Phosphorous	TP	= TP or DPall+PP
	DP	= DPfield or DP or TP-PP
	PP	= PP or TP-DP

Note that depending on the data available for each given station-date, TN may refer either to the result of analysis for total nitrogen or to the sum of Kjeldahl nitrogen plus dissolved nitrate and nitrite (as N). DN likewise may refer to either total dissolved nitrogen, or Kjeldahl nitrogen plus nitrate and nitrite. All Man Env TN and DN concentrations used in this study were derived from Kjeldahl nitrogen plus nitrate and nitrite values. The City of Winnipeg measured TN directly. 73% of Env Can TN concentrations, and 98% of DN concentrations, were by direct measurement of TN and DN respectively. The remainder were derived from Kjeldahl nitrogen plus nitrate and nitrite values. In the Env Can record, TN was measured directly since 1979; Kjeldahl-derived TN and DN dates from the period 1960-78. Directly measured DN dates mostly from 1978, although a few DN measurements were made in the early 1970s. The method used to determine individual values can be traced in the Excel file “LW nutrients - organized as OC,N,P (LWATDAT3-5).xls” (worksheet “reduced1”) archived on the accompanying CD.

Where dissolved or suspended fractions have been estimated as differences (e.g. POC=TOC-DOC) if the difference is negative (as happened in a very few cases, all for the suspended fraction) the result is reported as $0\ \mathrm{mg \cdot L^{-1}}$.

In some cases, agencies have identified dissolved phosphorous data as being from water samples filtered in the laboratory (DP) or filtered in the field (DPfield). For those station-dates for which both were available, DPfield is used in preference to DP.

Nutrient concentrations outside analytical detection limits

In the LWATDAT database, all negative values other than -9999 indicate a measurement that was below the analytical limit of detection, with the absolute value of the negative number indicating the limit of analytical detection. Measurements exceeding the upper limit of detection are indicated as the sum of the upper limit plus 90,000.

Values below detection limit were replaced with a value equal half of the detection limit.. Out of a total of 22328 analyses for nutrient parameters [OC, N, P and components] in river water samples in the LWATDAT database, 1091 values (4.9%) were below detection limits. This is probably a conservative estimate of any bias that may have been introduced by the use of half-detection values.

All observations for which results exceeded the analytical detection limit are listed below. Because they are rare, all of these high values were excluded from the analysis.

Location	Date
Red R at Selkirk Bridge	89 Sep 07
Sask. R downstream of d Grand Rapids Dam	87 Aug 06
Dauphin R upstream of Anama Bay	87 Jun 03
Dauphin R upstream of Anama Bay	87 Jul 08
Dauphin R upstream of Anama Bay	87 Dec 09
Dauphin R upstream of Anama Bay	88 May 04

* All are Man_Env data.

Nutrient fluxes in major tributary rivers and the outflow

Daily fluxes were calculated within the DOS program “DailyCNP.exe”. The program reads an ASCII file of daily discharges and a second ASCII file of occasional TOC, DOC, POC, TN, DN, PN, TP, DP and PP concentrations. It calculates an interpolated concentration for each date in the discharge file, and then multiplies daily concentration times daily water discharge to estimate daily flux. Linear interpolation was not performed between observations >120 d apart.

Executable code is stored as “DailyCNP.exe” and source code in Pascal as “DailyCNP.pas” on the accompanying CD, together with example input and output files. A more detailed description of the functioning and use of DailyCNP is presented in Appendix E.

ASCII output files from the Pascal program were read into Excel spreadsheets, in which the monthly and annual fluxes were calculated. Monthly fluxes were calculated by summing daily fluxes, and were determined for only those months for which no daily fluxes were missing. Likewise, annual fluxes were calculated by summing monthly fluxes, for only those years for which all monthly fluxes had been calculated.

Nutrient budget

A rudimentary budget of fluvial TOC, TN and TP in and outputs was constructed for comparison with the annual fluxes calculated for the Nelson River downstream of Lake Winnipeg. This was done by summing the products of calculated river yields multiplied by appropriate sub-areas of the Lake Winnipeg drainage. Annual yields of TOC, TN and TP used were the means for the 1990s; values are shown in Table 2. Note that the actual number of years averaged varies among the rivers studied, ranging from 1990-95 up to 1990-99. The monitored watershed area of monitored rivers is 860 280 km^2, or 91% of the total terrestrial drainage area of Lake Winnipeg, 942 745 km^2. More detailed regarding the budget calculation is recorded in Appendix G.

Interbasin fluxes

Interbasin water discharge

Flow through the Narrows was estimated by multiplying the difference between daily mean South Basin levels (current day minus previous day) times the basin area. For days with sufficient data to characterize the mean level of both the South and North Basins, a second estimate of interbasin flow can actually be calculated. Comparison of same-day interflows by the two methods was used to investigate the precision of the interbasin flow calculation.

Daily mean basin water levels were calculated as described below:

For the South Basin, mean daily level was calculated as the average of levels at Pine Dock and one of (in order of preference)

1) the average of levels measured at Victoria Beach and Gimli, if both recorded,
2) else average of levels measured at Victoria Beach and Winnipeg Beach, if both recorded.

For the North Basin, mean daily level was calculated as the average of all that were available among the following three values:

1) the average of levels measured at Montreal Point and Matheson Island, if both recorded,
2) else the average of levels measured at Mission Point and Berens River, if both recorded,
3) else the level at George Island.

Note that for the South Basin, the mean level was calculated only if both a northern and southern pair of level measurements were available. For the North Basin, the mean was calculated only if at least one northern and southern pair of stations could be averaged, or if the centre-basin level at George Island was available.

Interbasin nutrient fluxes

Daily TN and TP concentrations were estimated for the northern South Basin and the southern North Basin by interpolation between occasional measurements made by Gregg Brunskill over the period November 1968 to November 1969. Interbasin N and P fluxes were then calculated by multiplying the daily flow by the appropriate source water TN and TP concentrations. For further information, see the section "Results / *Interbasin fluxes / Nutrient fluxes through the Narrows*".

Results

Nutrient fluxes in major tributary rivers and the outflow

Table 2 shows annual yields of total, dissolved and particulate OC, N and P via major rivers into and out of Lake Winnipeg. Annual yields shown were calculated from the Environment Canada (Env Can) database if the observation gaps were <=120 days, or alternately from the Manitoba Environment (Man Env) database if it met the same criterion. In a few cases, annual yields shown in Table 2 were calculated from combined federal and provincial data sets. Source agency is identified beside each annual value. Also shown, for the years 1969-74, are yields calculated by Brunskill (1980). Monthly and annual yields are archived in the file "LW CNP flux - monthly, annual.xls". The CD archive lists monthly and annual transport (as fluxes in $t \cdot y^{-1}$, and as yields in $kg \cdot km^{2} \cdot y^{-1}$) that could be calculated from each of the three source agency's data sets, given the <=120 day gap requirement.

Time series plots of monthly fluxes are shown in Appendix F. These plots, together with underlying data, are archived on the accompanying CD in the file Excel files "LW CNP flux - <*river name*>.xls". The time series plots of monthly fluxes also show instantaneous concentration data, where concentration data is in most cases grouped by agency. For concentration data discriminated by both agency and station, time series plots showing concentration observations only are shown in Appendix D. These plots are archived in the files "LW CNP - <*river name*>.xls".

Comparability of the different source agencies' concentration data is discussed at length in the "Interstation/interagency comparison…" sections below. Note that through the period of record averaged, there are unresolved breaks in the Env Can DN and TN concentration record. The problem, a distinct drop in concentrations in all rivers (except possibly in the Red River) in 1991 followed by a sharp rise in 1993, seems to affect input data for all rivers in the study, and needs to be resolved and corrected before the long term record of DN and TN fluxes can be meaningfully interpreted. Until this is done, DN or TN fluxes based on Env Can data for the late 1990s cannot confidently be compared with pre-1991 fluxes.

It is apparent from Figure 2 that yields of TOC have been much higher in Precambrian Shield drainage than from the Plains. Yields of TN have also been higher from the Shield than from the Saskatchewan and Dauphin Rivers, but yields of TN from the Red River are less clearly associated with either; although for TN yield in some periods the Red has grouped with the Saskatchewan and Dauphin Rivers (e.g. 1971-73, 1988-92) at other times yields from the Red have fallen between Shield and other Plains TN yields, or even as high as Shield TN yields (e.g. 1979, 1986-87, 1997-1998). The Red River watershed has frequently produced dramatically higher yields of TP than other Lake Winnipeg tributaries but at least as frequently Red River and Shield TP yields have been of similar magnitude (e.g. 1971-74, 1980-81, 1987-1994). The Saskatchewan and

Dauphin Rivers have consistently yielded less TP than other tributaries to Lake Winnipeg.

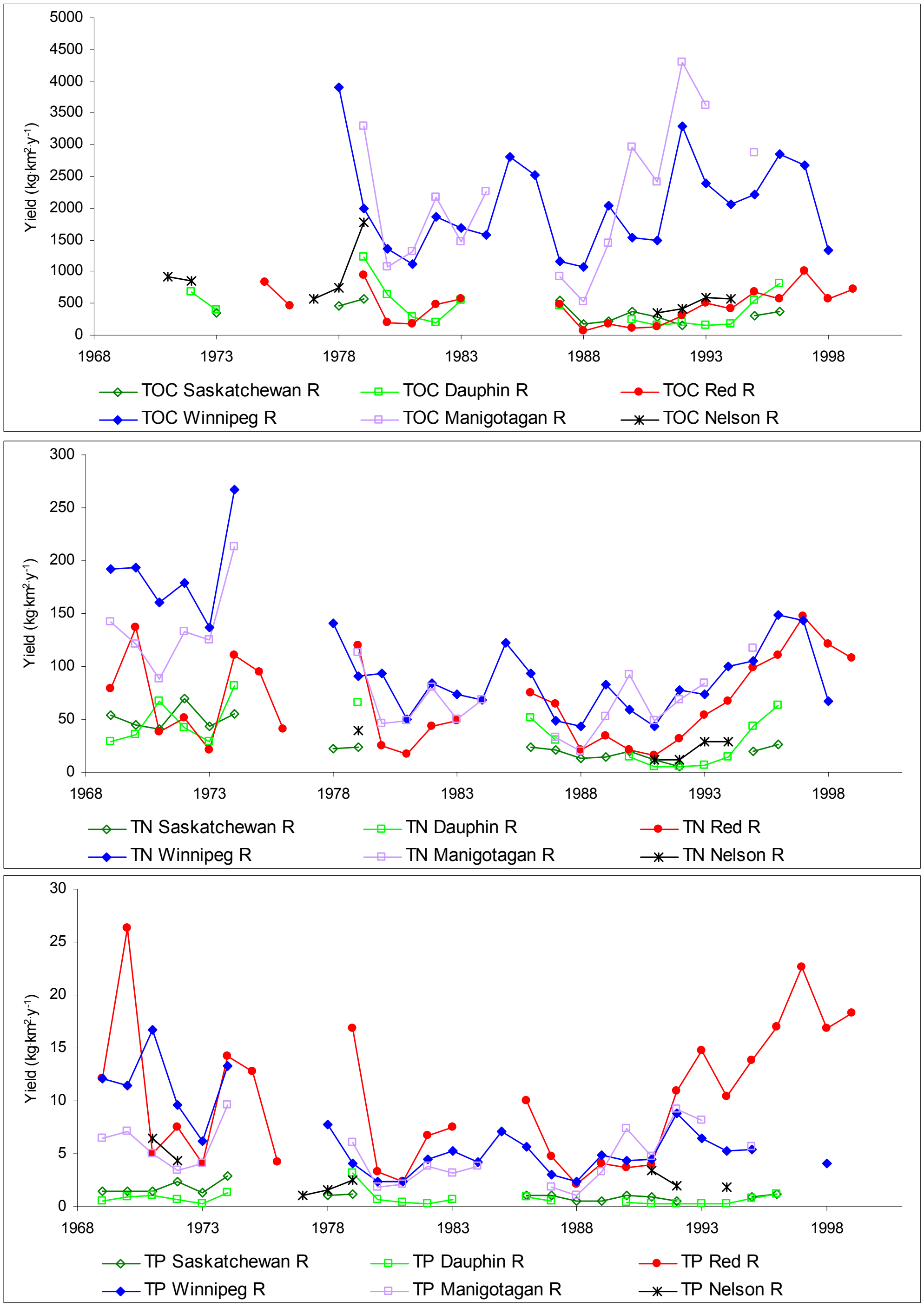

Figure 2. Annual yields of TOC, TN and TP for selected rivers flowing into and out of Lake Winnipeg.

Table 2. Annual yields of OC, N and P for selected rivers flowing into and out of Lake Winnipeg. Source data: EC=Environment Canada; F=Canada Department of Fisheries and Oceans (Brunskill, 1980); ME=Manitoba Environment; *combined federal-provincial data Units: $kg \cdot km^{-2} \cdot y^{-1}$.

Saskatchewan River

	TOC		DOC		POC		TN		DN		PN		TP		DP		PP	
1969							53	F					1.5	F				
1970							44	F					1.4	F				
1971							41	F					1.4	F				
1972							69	F					2.3	F				
1973	344	EC					43	F					1.3	F				
1974							56	F					2.9	F				
1978	459	*					22	*					1.0	*				
1979	565	ME					24	ME					1.1	ME				
1986							24	ME					1.1	ME				
1987	547	ME					21	ME	21	ME	1.6	ME	1.0	ME	0.50	ME	0.44	ME
1988	175	ME					13	ME					0.54	ME				
1989	229	*					15	*					0.59	*				
1990	375	EC	350	EC	25	EC	20	EC	16	EC	3.6	EC	1.1	EC	0.56	EC	0.58	EC
1991	276	EC	255	EC	21	EC	12	EC	9.2	EC	2.9	EC	0.94	EC	0.52	EC	0.45	EC
1992	160	EC	149	EC	11	EC	5.2	EC	3.4	EC	1.8	EC	0.51	EC	0.27	EC	0.24	EC
1995	304	EC	285	EC	20	EC	19	EC	16	EC	3.1	EC	0.91	EC	0.58	EC	0.33	EC
1996	374	EC	356	EC	18	EC	26	EC	23	EC	3.1	EC	1.2	EC	0.74	EC	0.51	EC

Dauphin River

	TOC		DOC		POC		TN		DN		PN		TP		DP		PP	
1969							29	F					0.59	F				
1970							35	F					0.90	F				
1971	918	EC	753	EC	165	EC							0.86	EC				
1971							67	F					1.02	F				
1972	672	EC					42	F					0.65	F				
1973	386	EC					29	F					0.28	F				
1974							82	F					1.30	F				
1979	1221	ME					66	ME					3.18	ME				
1980	640	ME											0.60	ME				
1981	274	ME											0.37	ME				
1982	190	ME											0.22	ME				
1983	538	ME											0.60	ME				
1986							52	ME					0.87	ME				
1987	458	ME					30	ME	27.9	ME	2.2	ME	0.56	ME	0.24	ME	0.33	ME
1990	249	EC	226	EC	23	EC	15	EC	12.6	EC	2.5	EC	0.38	EC	0.20	EC	0.19	EC
1991	153	EC	141	EC	13	EC	5.7	EC	4.3	EC	1.4	EC	0.23	EC	0.12	EC	0.11	EC
1992	188	EC	169	EC	19	EC	5.7	EC	3.6	EC	2.1	EC	0.28	EC	0.13	EC	0.14	EC
1993	143	EC	127	EC	16	EC	6.2	EC	4.4	EC	1.7	EC	0.30	EC	0.14	EC	0.16	EC
1994	182	EC	163	EC	19	EC	14	EC	11.9	EC	2.0	EC	0.30	EC	0.15	EC	0.15	EC
1995	546	EC	491	EC	55	EC	44	EC	37.6	EC	5.9	EC	0.80	EC	0.45	EC	0.34	EC
1996	801	EC	750	EC	51	EC	64	EC	57.8	EC	5.7	EC	1.22	EC	0.77	EC	0.45	EC

Table 2 (continued). Annual yields of OC, N and P for selected rivers flowing into and out of Lake Winnipeg.

Red River

	TOC		DOC		POC		TN		DN		PN		TP		DP		PP	
1964													2.4	EC				
1969							78	F					12	F				
1970							137	F					26	F				
1971													5.1	ME				
1971							39	F					5.0	F				
1972													7.3	ME				
1972							51	F					7.4	F				
1973													3.1	ME				
1973							20	F					4.0	F				
1974													11	ME				
1974							110	F					14	F				
1975	839	ME					95	ME					13	ME				
1976	463	ME					41	ME					4.2	ME				
1979	952	ME					119	ME					17	ME				
1980	194	ME					25	ME					3.3	ME				
1981	167	ME					17	ME					2.3	ME				
1982	484	ME					43	ME					6.8	ME				
1983	577	ME					48	ME					7.6	ME				
1986							75	ME					10	ME				
1987	476	ME					64	ME	58	ME	6	ME	4.7	ME	2.9	ME	1.8	ME
1988	69	ME					21	ME	18	ME	4	ME	2.2	ME	1.1	ME	1.0	ME
1989	169	ME	157	ME	15	ME	35	ME	31	ME	3	ME	4.0	ME	2.5	ME	1.6	ME
1990	105	EC	83	EC	22	EC	21	EC	18	EC	3	EC	3.6	EC	2.3	EC	1.4	EC
1991	130	EC	107	EC	23	EC	16	EC	13	EC	3	EC	3.9	EC	2.7	EC	1.3	EC
1992	311	EC	190	EC	121	EC	32	EC	19	EC	12	EC	11	EC	5.8	EC	5.0	EC
1993	507	EC	377	EC	132	EC	54	EC	38	EC	15	EC	15	EC	9.7	EC	5.1	EC
1994	419	EC	354	EC	65	EC	68	EC	56	EC	11	EC	10	EC	7.0	EC	3.4	EC
1995	686	ME	355	ME	331	ME	98	EC	83	EC	15	EC	14	EC	9.0	EC	4.9	EC
1996	567	ME					110	EC	88	EC	22	EC	17	EC	11.2	EC	5.8	EC
1997	1001	EC	705	EC	295	EC	147	EC	112	EC	35	EC	23	EC	16.5	EC	6.1	EC
1998	573	EC	442	EC	131	EC	121	EC	106	EC	15	EC	17	EC	10.8	EC	6.0	EC
1999	715	EC	490	EC	225	EC	108	EC	88	EC	24	EC	18	EC	11.1	EC	6.1	EC

Table 2 (continued). Annual yields of OC, N and P for selected rivers flowing into and out of Lake Winnipeg.

Winnipeg River

	TOC		DOC		POC		TN		DN		PN		TP		DP		PP	
1969							192	F					12	F				
1970							193	F					11	F				
1971	2933	EC	2588	EC	345	EC							11	EC				
1971							161	F					17	F				
1972	2602	EC											9.3	EC				
1972							179	F					9.6	F				
1973	2168	EC					119	EC					5.5	EC				
1973							136	F					6.2	F				
1974							268	F					13	F				
1978	3900	ME					140	ME					7.7	ME				
1979	2003	EC	1924	EC	79	EC	90	EC	77	EC	13	EC	4.1	EC	2.3	EC	1.8	EC
1980	1358	EC	1309	EC	49	EC	93	EC	83	EC	10	EC	2.3	EC	1.4	EC	0.9	EC
1981	1121	EC	1071	EC	50	EC	50	EC	41	EC	8.4	EC	2.4	EC	1.2	EC	1.2	EC
1982	1873	EC	1779	EC	90	EC	84	EC	71	EC	12	EC	4.5	EC	2.9	EC	1.8	EC
1983	1699	EC	1632	EC	66	EC	74	EC	66	EC	7.5	EC	5.3	EC	2.0	EC	3.3	EC
1984	1576	EC	1508	EC	62	EC	69	EC	58	EC	10	EC	4.3	EC	2.6	EC	1.8	EC
1985	2818	EC	2693	EC	125	EC	122	EC	101	EC	20	EC	7.2	EC	4.0	EC	3.3	EC
1986	2516	EC	2441	EC	75	EC	93	EC	81	EC	10	EC	5.6	EC	2.9	EC	2.8	EC
1987	1171	EC	1138	EC	33	EC	49	EC	44	EC	4.5	EC	3.1	EC	2.0	EC	1.1	EC
1988	1071	EC	1040	EC	31	EC	43	EC	38	EC	4.6	EC	2.3	EC	1.4	EC	1.0	EC
1989	2046	EC	1973	EC	73	EC	83	EC	72	EC	11	EC	4.9	EC	2.6	EC	2.4	EC
1990	1536	EC	1486	EC	49	EC	60	EC	52	EC	7.6	EC	4.4	EC	2.7	EC	1.8	EC
1991	1498	EC	1455	EC	43	EC	43	EC	36	EC	6.5	EC	4.5	EC	2.9	EC	1.6	EC
1992	3291	EC	3183	EC	107	EC	78	EC	60	EC	18	EC	8.8	EC	5.8	EC	3.0	EC
1993	2395	EC	2329	EC	65	EC	73	EC	63	EC	10	EC	6.5	EC	4.2	EC	2.2	EC
1994	2071	EC	2010	EC	61	EC	100	EC	90	EC	10	EC	5.3	EC	3.6	EC	1.8	EC
1995	2215	EC	2151	EC	65	EC	105	EC	95	EC	10	EC	5.4	EC	3.5	EC	2.1	EC
1996	2851	EC	2754	EC	97	EC	148	EC	133	EC	15	EC			5.3	EC		
1997	2670	EC	2572	EC	98	EC	144	EC	128	EC	16	EC			5.3	EC		
1998	1330	EC	1287	EC	42	EC	67	EC	60	EC	6.3	EC	4.0	EC	2.6	EC	1.4	EC

Table 2 (continued). Annual yields of OC, N and P for selected rivers flowing into and out of Lake Winnipeg.

Manigotagan River

Y	TOC		DOC		POC		TN		DN		PN		TP		DP		PP	
1969							142	F					6.5	F				
1970							121	F					7.1	F				
1971							89	F					5.0	F				
1972	1942	EC											3.0	EC				
1972							133	F					3.4	F				
1973	2593	EC					126	EC					3.9	EC				
1973							126	F					4.0	F				
1974							213	F					9.6	F				
1979	3296	EC	3191	EC	105	EC	113	EC	96	EC	17	EC	6.1	EC	3.0	EC	3.0	EC
1980	1078	EC	1135	EC	38	EC	46	EC	38	EC	7.9	EC	1.9	EC	1.2	EC	0.7	EC
1981	1305	EC	1268	EC	38	EC	48	EC	42	EC	5.7	EC	2.1	EC	1.1	EC	1.0	EC
1982	2163	EC	2089	EC	73	EC	80	EC	67	EC	11	EC	3.8	EC	2.3	EC	1.5	EC
1983	1472	EC	1437	EC	35	EC	50	EC	46	EC	4.1	EC	3.2	EC	1.5	EC	1.7	EC
1984	2249	EC	2189	EC	60	EC	68	EC	61	EC	8.3	EC	3.8	EC	2.7	EC	1.4	EC
1987	927	EC	901	EC	27	EC	33	EC	30	EC	2.8	EC	1.9	EC	1.1	EC	0.7	EC
1988	527	EC	513	EC	14	EC	20	EC	18	EC	1.7	EC	1.0	EC	0.6	EC	0.4	EC
1989	1445	EC	1463	EC	48	EC	53	EC	47	EC	6.1	EC	3.3	EC	2.1	EC	1.3	EC
1990	2968	EC	2863	EC	105	EC	92	EC	80	EC	12	EC	7.4	EC	4.2	EC	3.2	EC
1991	2418	EC	2343	EC	74	EC	49	EC	39	EC	9.4	EC	4.7	EC	3.1	EC	1.6	EC
1992	4297	EC	4138	EC	159	EC	69	EC	49	EC	20	EC	9.3	EC	5.9	EC	3.4	EC
1993	3628	EC	3521	EC	107	EC	85	EC	71	EC	14	EC	8.2	EC	5.1	EC	3.0	EC
1995	2877	EC	2781	EC	91	EC	117	EC	106	EC	12	EC	5.6	EC	3.8	EC	1.8	EC

Nelson River

	TOC		DOC		POC		TN		DN		PN		TP		DP		PP	
1971	924	EC	683	EC	241	EC							6.4	EC				
1972	850	EC											4.3	EC				
1977	564	*											1.1	*				
1978	737	ME											1.6	ME				
1979	1781	ME					40	ME					2.5	ME				
1991	341	EC	323	EC	18	EC	12	EC	9.2	EC	2.5	EC	3.4	EC	1.3	EC	2.1	EC
1992	426	EC	403	EC	23	EC	12	EC	8.3	EC	3.7	EC	2.0	EC	1.1	EC	1.0	EC
1993	585	*	565	*	87	*	29	*	19	*	5.5	*						
1994	570	*	517	*	122	*	29	*	23	*	5.5	*	1.8	*	0.9	*	0.9	*

Intermittent >120 d gaps in the observational record of concentrations created numerous gaps in the record of annual yields. The period 1990-95 is the longest contiguous period for which annual data could be calculated for most of these rivers simultaneously. Quantitative among-river comparisons made in the next few paragraphs are based on the mean yields for this early-1990s period. Note (from inspection of time series in Figure 2) however, that relative yields have varied among rivers over the longer post-1968 period. In particular, yields of all nutrients from the Red River in the early 1990s were near minimum for the record; this segment of the record probably produced conservative estimates of nutrient yields of the Red River relative to other Lake Winnipeg tributary rivers.

From 1990-95, yields for all nutrients were lowest from the Saskatchewan and Dauphin Rivers. Both drain Plains watersheds, but both pass through large lakes and/or reservoirs just upstream of Lake Winnipeg. Yields of all nutrients, whether total, dissolved (except DOC) or particulate were higher in the Red River. The difference is least for TOC, which was less than 50% greater in the Red than in either the Saskatchewan or Dauphin River. The TN yield of the Red River was 3X higher than the other Plains rivers; the TP yield was 15X higher.

Yields of all nutrients are also higher for the two Shield rivers, the Winnipeg and the Manigotagan, than for the Saskatchewan and Dauphin Rivers. TOC and TP yields are ~10X higher, and TN is ~5X higher. Most of these differences are due to higher yields in the dissolved fractions. Although particulate yields are generally higher in Shield than in Plains rivers (though not generally by as high a factor as for the dissolved fraction) particulates comprise a smaller part of the total yield for each nutrient in Shield rivers. The two Shield Rivers yielded 6-9X more TOC than the Red River. All of this difference is due to the dissolved load. Differences in TN and TP yield were smaller. Shield rivers yielded about 60-70% more TN and 30-40% less TP than the Red.

Yields calculated for the outflow of Lake Winnipeg are somewhat higher than for the Saskatchewan and Dauphin Rivers but much lower than for the other rivers studied. Presumably outflow yields were more like the Saskatchewan and Dauphin Rivers because all of the three stations are downstream of large lakes which may act as traps or sinks for nutrients. In fact, in the case of Lake Winnipeg at least, the sums of fluvially-borne nutrient influxes exceed the flux at the outlet for all three nutrients discussed in this report (Table 5).

Based on average values for 1990-95 (Table 3) over 90% of the TOC yield of Lake Winnipeg tributary rivers is carried as dissolved load, except in the Red River in which DOC accounts for only 60-70% of the yield. About 80-85% of the nitrogen yield is as DN. The apparently smaller fraction reported for the outflow may be a spurious result of using multi-agency/multi-station data sets; DN+PN accounts for only 94% of the total N flux. The dissolved fraction is generally lower in the phosphorous yield than for yields of other nutrients in all tributary rivers. DP accounts for ~65% of TP in the Red, Winnipeg and Manigotagan Rivers, ~55% in the Saskatchewan and Dauphin Rivers, and only 45% in the outflow.

Table 3. Dissolved and particulate fractions as percents of total yield of Lake Winnipeg tributary rivers. Values are based on the average of non-missing annual values in Table 2 for the period 1990-95. Note that for the Nelson River, totals for OC and N do not equal 100%; this may be the result of using mixed data sets (two agencies, three stations) for the yield calculation.

		DOC	POC	DN	PN	DP	PP
Dauphin River	90-95	90	10	83	17	53	47
Saskatchewan River	90-95	93	7	80	20	56	46
Red River	90-95	68	32	79	21	63	37
Winnipeg River	90-95	97	3	86	13	65	36
Manigotagan River	90-95	97	3	84	16	63	37
Nelson River	91-94	94	13	73	21	45	55

Temporal patterns of nutrient yields shown in Figure 2 tend to follow patterns in the hydrographs of annual discharge, shown in Figure 3. This is particularly true for some nutrients in some rivers (e.g. TOC in the Manigotagan River, or TP in the Red) and perhaps less apparent for others (e.g. TN in the Winnipeg River). In fact, annual nutrient yields tend to be well-correlated with annual discharge in Lake Winnipeg tributary rivers (Table 4). Correlation is strongest for organic carbon. For DOC yield in the Red, Winnipeg and Manigotagan Rivers, r=0.98 in each case. (r is not shown where fewer than 10 annual nutrient yields were available to test for correlation.) For TOC, r>0.90 for all but the Saskatchewan River (where r=0.58). Correlation with discharge ranges lowest for TN and DN yields in the Shield rivers , down to r=0.68, although it is fairly high in the Dauphin and Red (0.93<r<0.96). However, the weaker correlations of TN and DN yields with discharge are not necessarily environmental, as they are subject to unresolved concerns about Env Can TN and DN methods changes through time, discussed below. Correlation of phosphorous yields with discharge range through r=0.81 to r=0.97. Where correlation of both DP and PP with discharge were determined, correlation is slightly higher for dissolved than particulate yields.

Mean 1990-95 terrestrial nutrient influxes into the north and south basins of Lake Winnipeg are shown in Table 5. Table 6 shows the fraction of the total annual terrestrial influx delivered by each of the major rivers. Note that problems with the Env Can DN and TN concentration record seems to affect input data for all rivers in the study, and thus should affect both influx and outflux TN proportionately. Hence while the absolute TN values in Table 5 are provisional, the fractions in Table 6 are less likely to be affected.

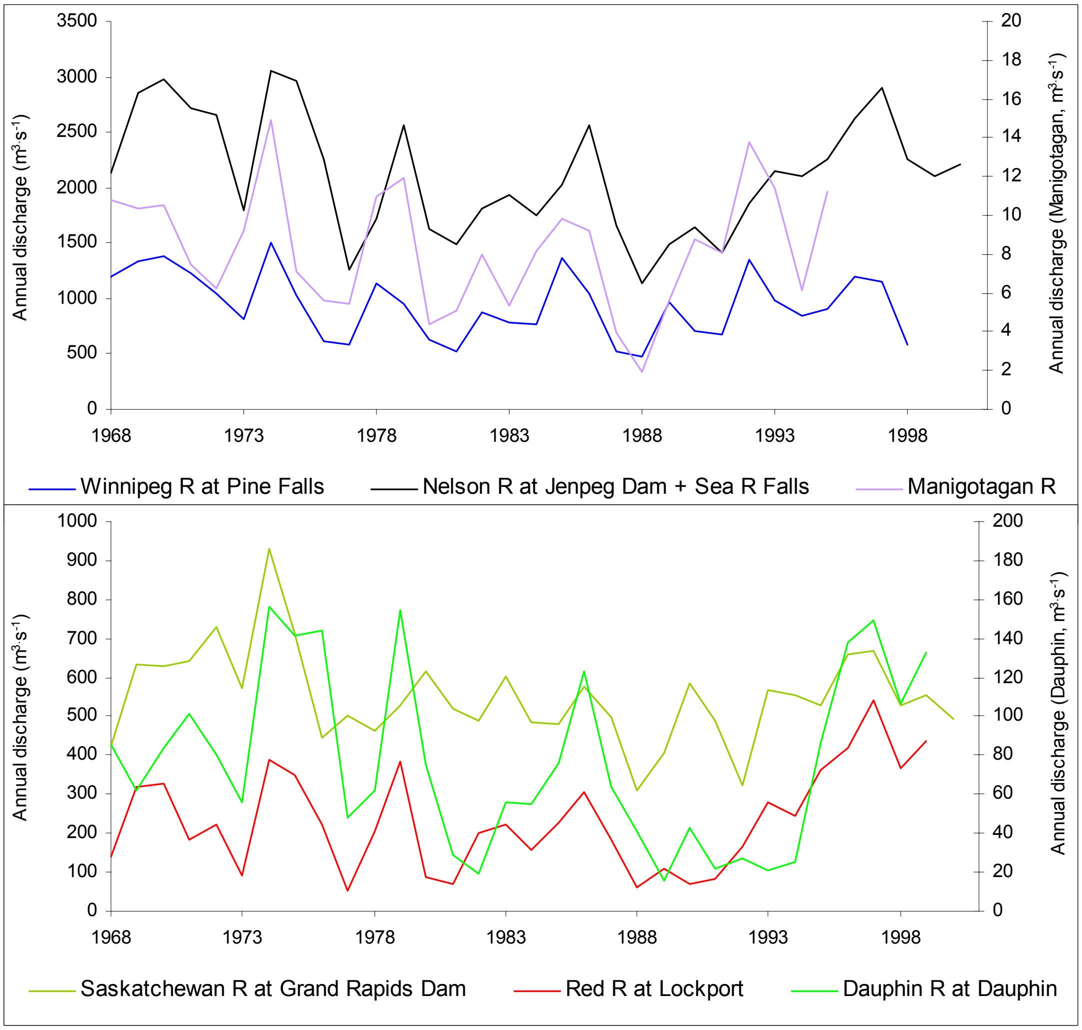

Figure 3. Mean annual discharges of Lake Winnipeg tributary rivers and the Nelson River at Jenpeg Dam + Sea River Falls. Note that Manigotagan and Dauphin River data are plotted against relatively expanded scales marked on the right hand axis.

Table 4. Coefficients of correlation between mean annual river discharge and mean annual nutrient yields. *sample n<10.

	TOC	DOC	POC	TN	DN	PN	TP	DP	PP
Saskatchewan R	0.58	*	*	0.81	*	*	0.94	*	*
Dauphin R	0.96	*	*	0.96	*	*	0.81	*	*
Red River	0.93	0.98	0.87	0.94	0.93	0.95	0.88	0.97	0.89
Winnipeg River	0.91	0.98	0.95	0.79	0.68	0.93	0.83	0.84	0.83
Manigotagan R	0.98	0.98	0.96	0.73	0.74	0.95	0.93	0.92	0.89
Nelson River	*	*	*	*	*	*	*	*	*

Table 5 Annual terrestrial fluxes of TOC, TN and TP into/out of Lake Winnipeg. Influx estimates are based average annual 1990s yields (Table 2) of the major tributary extrapolated as described in the text. Flux out is based on annual yields of the Nelson River calculated for the Jenpeg and Sea River Falls stations. The interbasin boundary is at the Narrows between Whiteway and Dog Head Point. Units: $10^3 t\cdot y^{-1}$.

	TOC	TN	TP
North Basin influxes			
Shield and islands	134	4.0	0.32
Plains	126	6.6	0.35
Total	260	11	0.67
South Basin influxes			
Shield and islands	315	11	0.83
Plains	103	14	2.76
Total	418	25	3.59
Total Lake Winnipeg terrestrial influx	679	35	4.26
Nelson R at Jenpeg and Sea R Falls	464	20	2.32

Table 6. Annual terrestrial influx of nutrients into Lake Winnipeg via each major tributary river as percents of terrestrial influx to the whole lake.

	TOC	TN	TP
Saskatchewan R	15	15	7
Dauphin R	3	4	0.7
Red R	15	38	62
Winnipeg R	43	29	18
Manigotagan R	0.9	0.4	0.3

Most of the nutrients flowing into Lake Winnipeg are delivered into the South Basin, in the flow of the Red and Winnipeg Rivers. 62% of TOC, 70% of TN and 84% of TP from Lake Winnipeg tributary watersheds enters via the South Basin.

Plains watersheds contribute about 34% of TOC, 58% of TN and 73% of TP delivered by rivers to Lake Winnipeg. The Red River alone contributes 62% of all P carried by rivers into Lake Winnipeg. It contributes 24%, 54% and 74% of all TOC, TN and TP flowing into the South Basin. The Winnipeg River carries most of the rest flowing into the South Basin, i.e. 69%, 41% and 22% of TOC, TN and TP respectively. It contributes fully 43% of all OC flowing into the whole lake.

Total annual terrestrial influxes are larger than the measured flux out of Lake Winnipeg in the Nelson River. Losses of about 30% of inflowing TOC and 45% of inflowing TN may be accounted for by sedimentation and/or by net losses to the atmosphere. Unlike TOC and TN, TP cannot escape in gaseous phase into the atmosphere; the loss of over 45% of the 4260 $t\cdot y^{-1}$ of TP flowing into Lake Winnipeg must therefore be explained by sedimentation.

Interbasin fluxes

Water discharge through the Narrows

Summaries of interbasin flow for the period 1960-1998 are presented graphically in Figure 4. Data summarized in the upper row are daily mean rates of flow. The middle and lower panel show data grouped by events, where events are defined as periods of flow continuously in one direction. (i.e. Because flow is determined from lake level change, the period of a given northward event lasts as many days as the level of the South Basin drops continuously.) Events are plotted by the month in which they end. Scattergrams on the left show data by month; histograms on the right show distributions by scale and direction of flows and flow events for three seasons: Jan.-Mar. (ice-cover), May (spring runoff) and Jul.-Oct. (summer-autumn). Note that category widths on all histograms double both downwards and upwards from zero. Note also that since every change of flow direction marks a new event, there are by definition equal numbers of northward and southward flow events in any given period.

The largest daily mean discharges through the Narrows during the period were 35893 $m^3 \cdot s^{-1}$ northward, and 28095 $m^3 \cdot s^{-1}$ southward; both occurred in October. For comparison, the highest measured daily mean discharge recorded for the Red River was 4320 $m^3 \cdot s^{-1}$ (4-6 May, 1997) and on the Winnipeg River was 2990 $m^3 \cdot s^{-1}$. Kenney (1979) measured current velocity through the Narrows at 10.5m and 5.5 m above the bottom from 14 May-15 Oct 1976 and then computed discharges through the Narrows based on these velocity data. His measurements are 10 min and 20 min means. Considering that the estimates from this study are daily mean discharges, they accord well with Kenney's measured maximum discharge of 50000 $m^3 \cdot s^{-1}$. Kenney observed flows in excess of 14000 $m^3 \cdot s^{-1}$ 25% of the time. Over the period 1960-2001, mean daily fluxes during the open water season (May-Oct inclusive) were found in this study to be over 6245 $m^3 \cdot s^{-1}$ 25% of the time, and 4392 $m^3 \cdot s^{-1}$ for 25% of the full year daily data. The difference may be due to the difference in integration periods. Since the seiche period on the North Basin is about 13 h (and the South Basin and Narrow considerably less) the daily means reported in this study may frequently integrate through periods incorporating at least one flow reversal. Hence, while reasonable as estimates of daily mean discharge, the daily values reported in this study are conservative indicators of typical interbasin transfers by shorter term seiche motions.

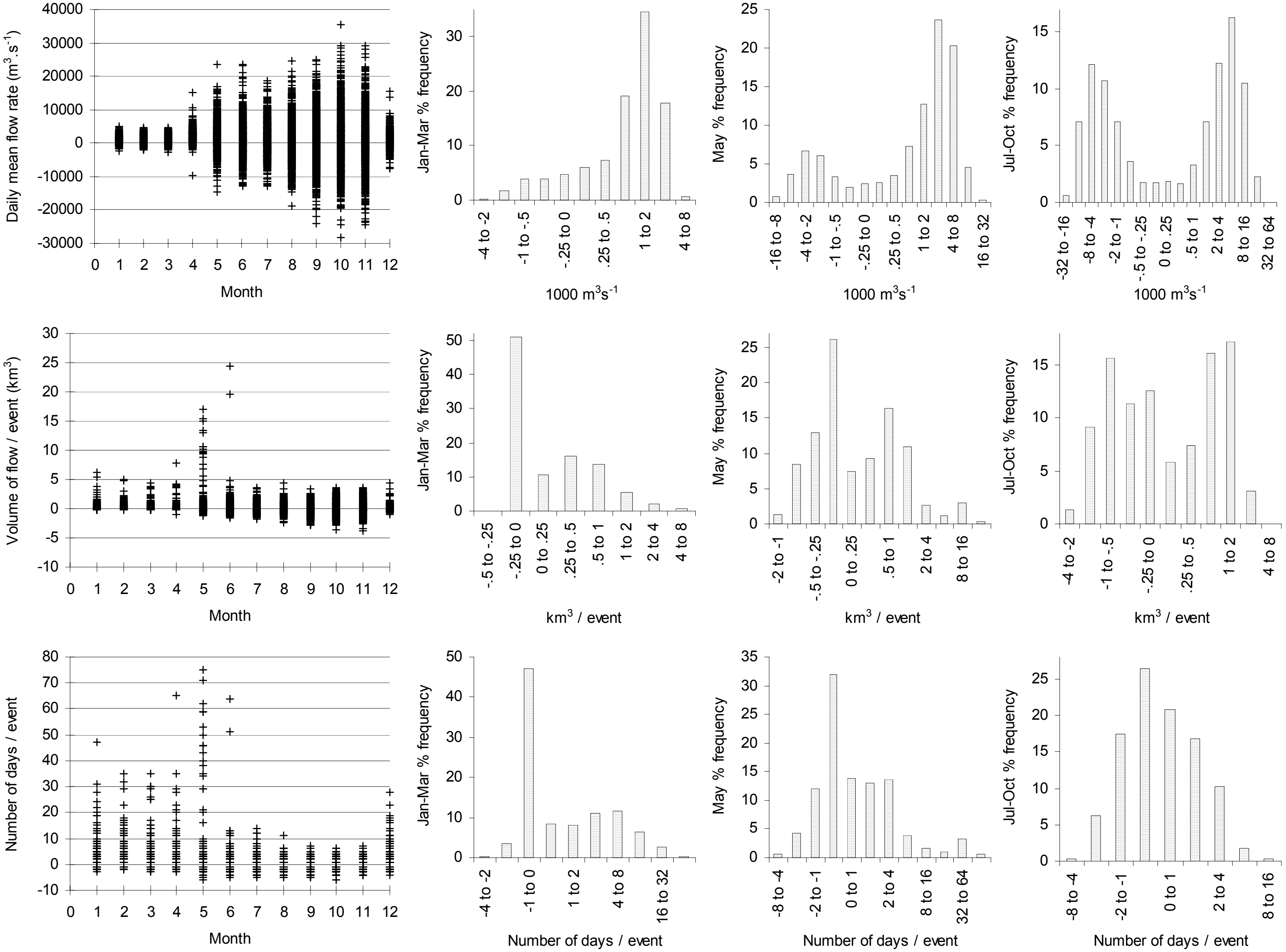

Figure 4. Distributions of flow rates and flow events through the Lake Winnipeg Narrows by month (left) and season (right, histograms for Jan.-Mar., May, Jul.-Oct.) through the period 1960-98. Top: daily mean rate of flow. Middle: Volume of flow / event. Bottom: Number of days / event. . +ve=northward flow. Events are defined as periods of flow continuously in one direction as determined by the record of daily mean levels of the South Basin. See text for further information and discussion.

Under-ice interbasin discharge rates are relatively low and predominantly northward (mostly 500 to 4000 $m^3 \cdot s^{-1}$ northward). During the period of ice-cover, periods of southward flow, though frequent, were mostly brief (1 day) and transferred only small volumes of water (<250 km^3) with each event. Thus under-ice southward interbasin transfers were generally smaller than the error estimated for the method, 320 km^3 per event (see section "Precision of interbasin discharge estimates" below) though it might be argued that mean basin level is more precisely known for the relatively tranquil ice-covered water surface. Northward flow events were generally longer and larger than southward. That is, winter flow through the Narrows is mostly governed by flow from the watershed through the basin; forces that may push water back into the South Basin (mainly differential atmospheric pressure, differential snowfall) are relatively weak.

May (and to some extent April – histograms not plotted) interbasin flow is also frequently dominated by flow from the watershed through the basin, though larger southward events occur than in winter, because the surface of at least the South Basin is frequently first exposed to wind energy between late April to mid-May. Nonetheless, southward flow events are brief, and effect water exchanges only as great as 2 km^3 per event, whereas northward events are frequently from several days to several weeks in length, each responsible for the transfer of several times as much water as southward events. Not surprisingly in view of the relative magnitude of spring runoff in the watershed, the largest periods of continuous northward flow for the year occur in May and twice have stretched through May into June. The largest continuous flow event in the record transferred 24.3 km^3 of water through the Narrows over the period 16 April to 6 June, 1997; i.e. a period of 51 days during the 1997 Red River flood. For comparison, the volume of the South Basin, south of Black Island, is 27 km^3 (Brunskill, 1980, Table 1).

Although net interbasin transfer of water is determined by the water balance of the South Basin, oscillating interbasin flows are largely attributable to setup and seiche following periods of strong northerly or southerly winds. Monthly mean rates of interbasin flow (mean of directionless magnitudes) typically increase regularly from ~3000 $m^3 \cdot s^{-1}$ in June and July to peak at 6000-7000 $m^3 \cdot s^{-1}$ in October (see upper left plot in Figure 4). A similar seasonal pattern is evident in the wind record. The monthly mean wind speed at George Island (1988-98 record) increases over the open water season from an average of 17 $km \cdot h^{-1}$ in June and July to 23 $km \cdot h^{-1}$ in September and October.

Figure 5 shows stronger northerly winds over the North Basin to be associated with stronger southerly currents through the Narrows, and stronger southerly winds to be associated with stronger northerly interbasin flow. Wind data are from the George Island station, 1985-98 open water season. Each value is the mean speed for the two days previous to the flow record. Data is shown only for days when the mean 2-day antecedent wind direction was between 330^o-30^o azimuth (northerly, left plot) or 150^o-210^o (southerly, right plot) and the standard deviation for the same period was <=30^o. Two-day antecedent northerly winds explain 53% of the variability in southward interbasin flow (r^2=0.52, P=0.000, n=35); southerly winds account for 27% of the variability in northward flow (r^2=0.27, P=0.000, n=54). It may be that another expression of the antecedent wind would be a better predictor. Seiche motions subsequent to direct setup by a strong wind event make it unlikely that there are much stronger direct correlations between the wind and interbasin flow records. It is beyond the scope of this study to more than demonstrate that interbasin flux magnitudes during the open water season are largely a function of wind energy. In any case, seiche and setup in Lake Winnipeg have been modeled as functions of wind energy and basin geometry by Einarsson and Lowe (1968) and Hamblin (1976).

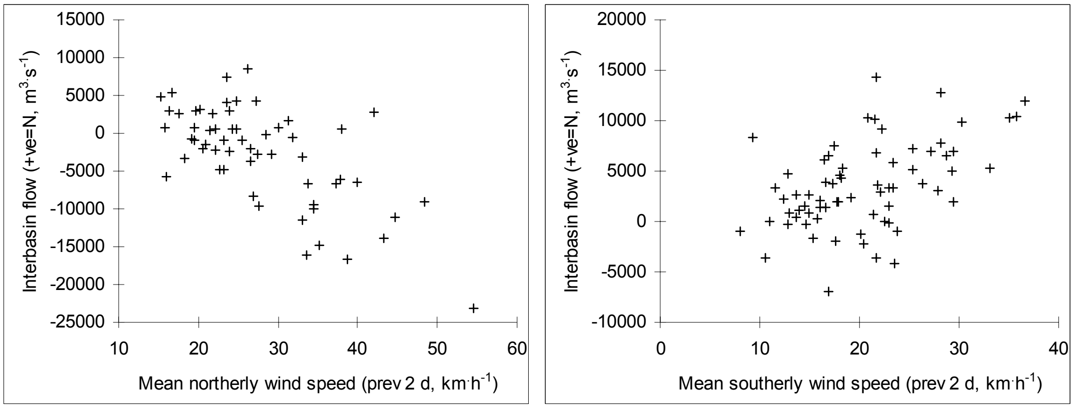

Figure 5. Northerly and southerly antecedent wind speeds plotted against rates of interbasin flow. Wind data are from the George Island station, 1985-98 open water season. Each value is the mean speed for the two days previous to the flow record. Data is shown only days when the mean 2-day antecedent wind was between 330^{o}-30^{o} (northerly, left plot) or 150^{o}-210^{o} (southerly, right plot) with a standard deviation of <=30^{o}.

Nutrient fluxes through the Narrows

Figure 6 shows seasonal patterns of TN and TP for 6 latitudinally-defined regions in Lake Winnipeg. The data were recorded on a series of cruises during the open water season of 1969. The concentrations plotted were calculated by averaging all observations within each region sampled within periods each not greater than 7 days. Neither DOC nor POC were recorded in 1969, so that TOC could not be computed.

Concentrations of all nutrients were highest and most variable in the South Basin. Sub-monthly variability exceeded and masked seasonal patterns. In contrast, everywhere north of Hecla Island, TN rose gradually through the summer and then dropped off in autumn; and TP was either nearly constant through the season, or rose gradually at least through to the last observations in late October. Higher concentrations in the South Basin were maintained throughout the open water season. Indeed, through the 5 regions north of the South Basin as well, a smaller concentration gradient, decreasing northward, was also maintained throughout the period

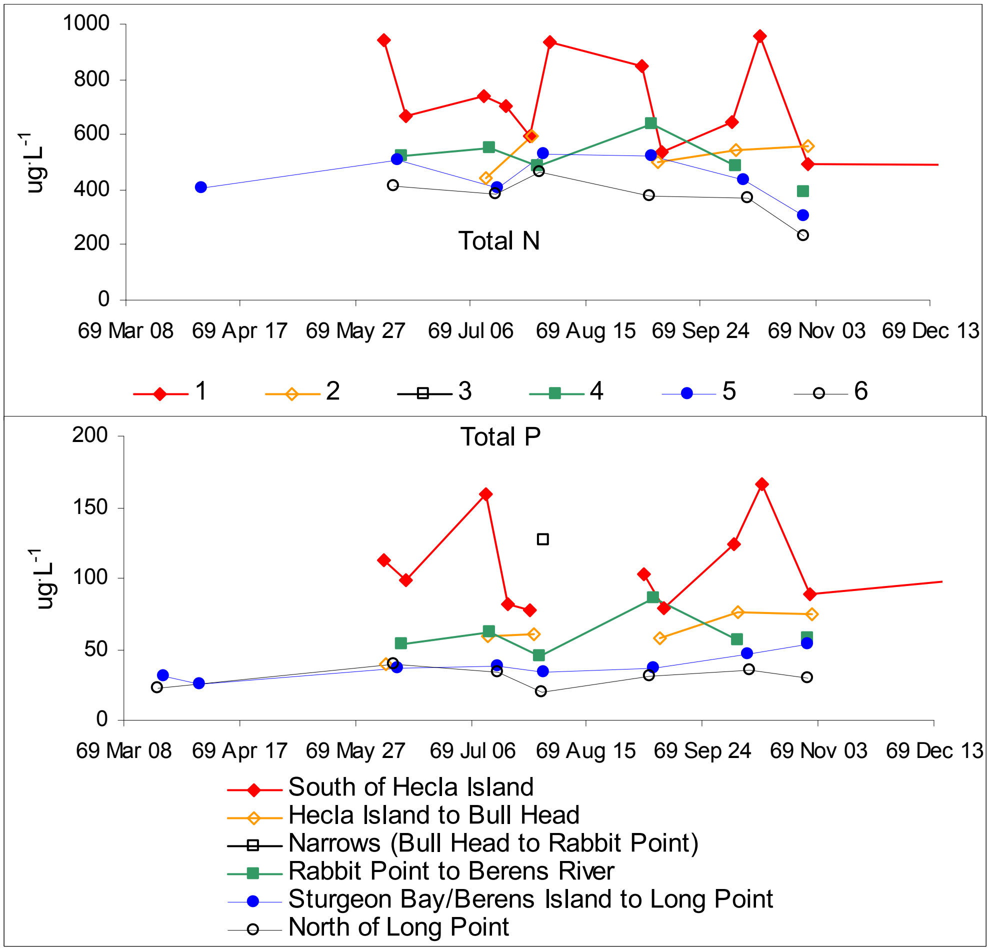

Figure 6. Seasonal series of PC, TN and TP concentration in Lake Winnipeg, 1969. Data are averages for regions from the South Basin to the northern part of the North Basin.

For the purpose of interbasin nutrient flux calculation, daily TN and TP concentrations were estimated for regions near the Narrows in the North and South Basins by interpolation between observations made by Brunskill in 1968-69. Daily mean flow through the Narrows was calculated as described in the section "Water discharge through the Narrows". Each daily flux of nutrients was then calculated as the product of daily interbasin flow multiplied by the daily nutrient concentration south of the Narrows if flow were northward, and by the concentration north of the Narrows if southward. Observational data used to interpolate daily nutrient concentrations is shown in Table 7. Each value is the mean of up to 4 observations made on or about that day near the Narrows. TN and TP data for the South Basin on 31 July were considered anomalously high and were not used in the interpolation routine. Daily fluxes are plotted in Figure 7. Cumulative northward flux over the open water season is plotted in Figure 8.

Table 7. TN and TP sample data used to estimate daily concentrations in the North and South Basins. Data were supplied by DFO (sampled by Brunskill). Values shown are mean for observations south of Berens River in the North Basin and north of Hecla Island in the South Basin.

North Basin			South Basin		
Sample date	TN (ug·L^{-1})	TP (ug·L^{-1})	TN (ug·L^{-1})	TN (ug·L^{-1})	TP (ug·L^{-1})
68 Oct 28	493	53	68 Oct 28	401	70
69 Apr 02	757	53	69 Apr 02		
69 Jun 11	549	53	69 Jun 06	643	70
69 Jul 13	463	53	69 Jul 10	529	51
69 Jul 27	565	56	69 Jul 26	553	48
69 Jul 31	639	30	69 Jul 31	4115	217
69 Sep 08	527	50	69 Sep 08	507	63
69 Oct 05	515	65	69 Oct 04	548	96
69 Oct 12	510	68	69 Oct 12		
69 Oct 28	301	60	69 Oct 27	316	92
69 Oct 31	515	52	69 Oct 31	542	82

The mean of daily interbasin fluxes (absolute values) over the Oct 1969-Oct 1969 period was 163 t of N and 20 t of P. (For comparison, the mean flux of N in the Winnipeg River in the 1990s was 33 t·d^{-1}, and in the Red River, 60 t·d^{-1}. The flux of P in the Winnipeg River was 2 t·d^{-1}, and in the Red River, 10 t·d^{-1}.) Over the 1969 open water season, the average daily interbasin fluxes were somewhat larger: 217 t and 25 t of N and P respectively. The largest daily N flux was 1127 t, northward on 14 August. This was carried in a daily mean discharge of 24460 m^{3}·s^{-1}, about 50% smaller than the largest interbasin flux determined from South Basin level fluctuations. The largest daily P flux was 152 t on 7 October, carried in a mean daily discharge of 18318 m^{3}·s^{-1}.

Over the 1969 open water season (5 Mar – 31 Oct) a net 22000 t of N and 3000 t of P were transferred from the South to the North Basin. During the same period, the influx via the Red River was a similar 22000 and 3300 t of N and P respectively. Also during the same period, the influx via the Winnipeg River was 17000 and 900 t of N and P respectively.

If under-ice concentrations were roughly the mean of the last autumn and first spring values, then a substantial 11000 t of N and 1700 t of P would have been transferred from the South Basin to the North between 1 Nov 1968 and 1 Apr 1969. These are of similar magnitude to typical terrestrial influxes for the same winter period, 8000 and 1500 t of N and P respectively. The implication that there was no storage (sedimentation) through the winter is unexpected; it must be emphasized that it is based on very little under-ice information.

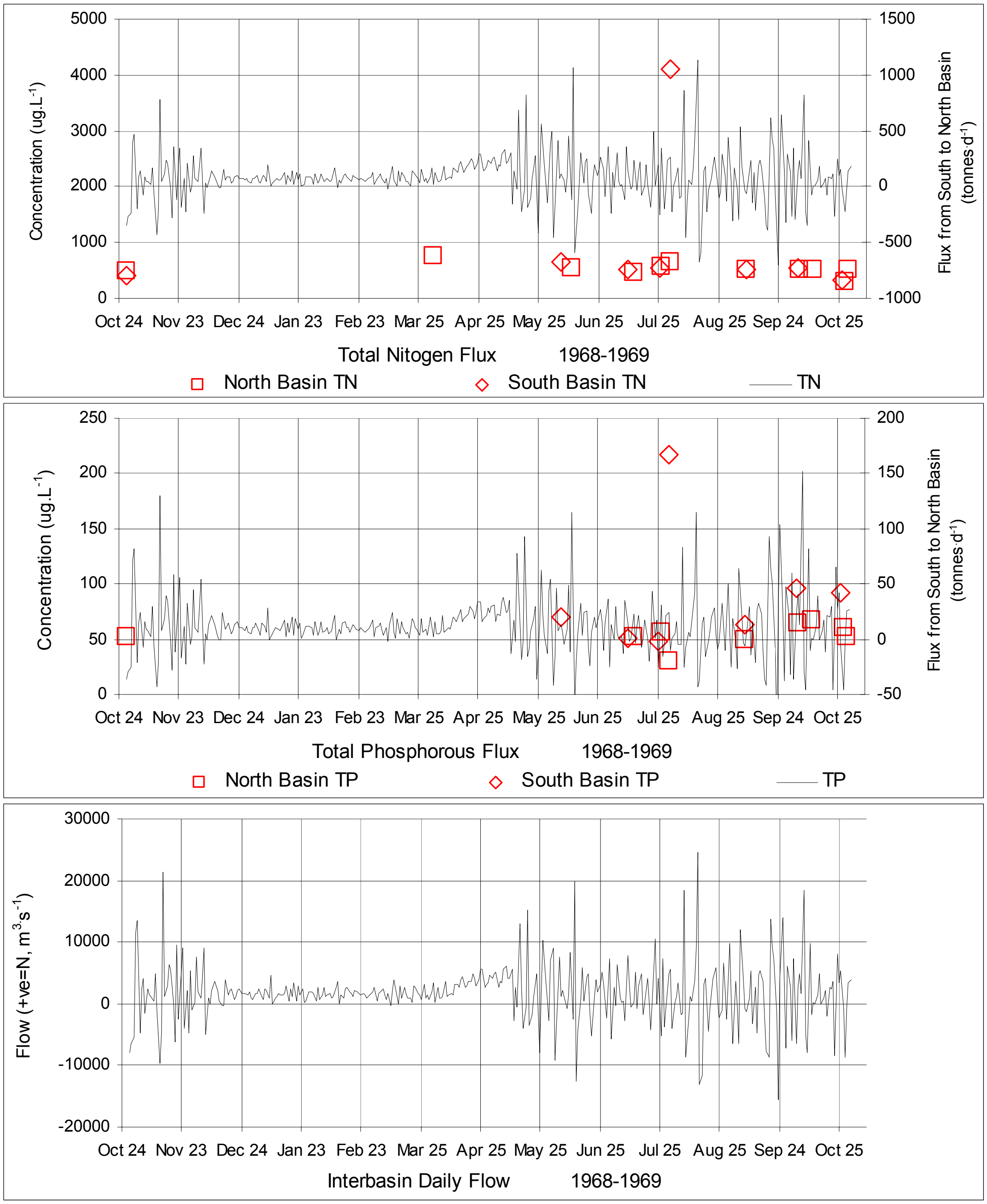

Figure 7. Upper two panels: daily interbasin fluxes of TN and TP, and concentrations of TN and TP sampled near the Narrows. Anomalously high TN and TP concentrations recorded for 31 July were excluded from the interpolation procedure used to calculate daily fluxes. Third panel shows daily flows. +ve=north for both fluxes and flow.

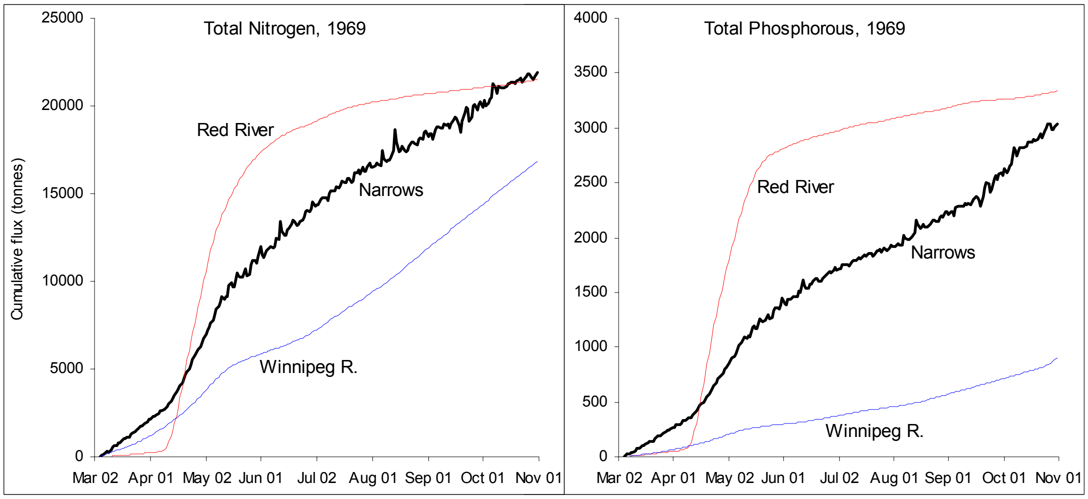

Figure 8. Cumulative fluxes of TN (left) and TP (right) through the Narrows, open water season, 1969, with cumulative influxes from the Red and Winnipeg Rivers for comparison. Anomalously high TN and TP concentrations on 31 July (Figure 7) were excluded from the interpolation procedure used to calculate daily fluxes.

Very few under-ice nutrient concentrations are reported in the 1968-69 data set, and none from the vicinity of the Narrows. For four observations reported from the South Basin during late March, 1970, TN averaged 488 ug·L^{-1}, within the range of open-water season values (Table 7). In the same sample, the mean TP was 115 ug·L^{-1}, somewhat higher than the open-water season values. No under-ice nitrogen data are reported for the North Basin. However, 3 observations are recorded for TP in the North Basin east of Grand Rapids, for March, 1969. They average 26 ug·L^{-1}, or somewhat less than half typical open-water season concentrations. The available under-ice data for the South Basin supports the simplification used in estimating winter 1968-69 nutrient fluxes, i.e. estimating daily under ice concentrations by interpolating between late autumn and early spring values. While the same approximation overestimates North Basin under-ice concentrations compared to available data, and hence would overestimate southward fluxes, this is of less concern because under-ice southward fluxes are small in comparison to northward fluxes.

After summing open-water and under-ice in- and outfluxes, and correcting terrestrial influxes for unmetered watershed area, these figures imply annual sedimentation in the South Basin of about 30% of N delivered from the watershed, and 20% of P. Most of this occurs in the open-water season, which may be explained as sedimentation of relatively coarse sediments carried by the inflowing rivers, particularly the Red, in their periods of flood. On the other hand, the results must be regarded as very uncertain, given the infrequency of observations, and particularly given the lack of good under-ice data.

Discussion

Methods change effect on the Environment Canada TN and DN record

A change was made in analytical method for DN by Env Can in 1993 and for PN in 1986 (Appendix B). While the change had no apparent affect on PN, there is a sharp and large increase in the autumn of 1993 in DN and TN reported by Env Can. Although the shift is most clearly defined in the Winnipeg and Manigotagan Rivers records (Appendix D, Figures D-12, 15) it is also apparent in the record of the Saskatchewan, Dauphin and Nelson Rivers (Appendix D, Figures D-2, 5, 18). Although Env Can does not report any earlier change in analytical methods for TN or DN, there is also apparent in the same figures a sudden reduction in concentrations of both in the spring of 1991. At least for the Winnipeg and Manigotagan Rivers, there are clear seasonal patterns in the DN record until late 1993; in the post-1993 record any seasonal pattern is obscured by more random scatter.

TN and DN concentration data for the three periods pre-January 1991, July 1991 to August 1993 and post-October 1993 are compared in Table 8. Compared to pre-January 1991 concentrations, TN was 35-42% lower in the period July 1991 to August 1993. DN was 30-52% lower. The differences are less consistent between the post-October 1993 and pre-January 1991 periods, though for all rivers except the Red, both TN and DN were higher (by 20-57% and by 25-67% respectively) in the later period. On the other hand, in the Red River both TN and DN dropped from the earlier to the later period. It is possible that local environmental factors affecting the Red River basin outweigh any effect of methods changes. In any case, this possible negative shift in Red River TN and DN data is small relative to the scatter in the data; note the relatively high standard deviations for Red River TN and DN reported in Table 8.

This difference between the Red and the other rivers in the study may be environmental. When Env Can concentration data for the Red River is compared with same-day concentrations measured by both Man Env and the City of Winnipeg, the mean difference is lower in the July 1991 to August 1993 period relative to both other agencies than it is before or after (Table 9). Unfortunately, again because of the large scatter in the Red River data, this difference is not significant, but merely suggestive. In any case, there is in this between-agency comparison no indication of an increase between pre-1991 and post-1993 comparable to that apparent in other rivers.

Table 8. Comparison of TN and DN for Env Can stations with records in the three periods pre-January 1991 (beginning no earlier than January 1984), July 1991 to August 1993 and post-October 1993. "% diff." = % difference is for the 2nd and 3rd period compared to the first. "Norm. % diff." = % difference divided by the average standard deviation for the two periods compared. A value <1 indicates that the difference is small relative to the scatter in the data. Units: $mg \cdot L^{-1}$.

			TN					DN				
	River	STATION	mean	s.d.	n	% diff.	Norm. % diff.	mean	s.d.	n	% diff.	Norm. % diff.
Pre-January 1991	Dauphin	MA05LM0005	0.91	0.22	9			0.75	0.21	9		
	Manig.	MA05RA0004	0.52	0.10	70			0.47	0.09	70		
	Red	MA05OJ0001	3.14	1.38	22			2.73	1.47	22		
	Sask	MA05SH0001	0.35	0.14	21			0.28	0.12	21		
	Winnipeg	MA05PF0022	0.38	0.05	82			0.33	0.05	83		
July 1991-August 1993	Dauphin	MA05LM0005	0.59	0.22	26	-35	1.6	0.40	0.19	26	-46	2.3
	Manig.	MA05RA0004	0.31	0.04	25	-41	6.3	0.24	0.04	25	-49	7.5
	Red	MA05OJ0001	1.78	0.88	35	-43	0.4	1.41	0.70	35	-48	0.4
	Sask	MA05SH0001	0.20	0.07	24	-42	4.1	0.13	0.05	24	-52	6.0
	Winnipeg	MA05PF0022	0.25	0.06	26	-35	6.7	0.20	0.06	26	-39	6.6
Post-October 1993	Dauphin	MA05LM0005	1.43	0.33	35	57	2.1	1.26	0.35	35	67	2.4
	Manig.	MA05RA0004	0.71	0.09	13	35	3.8	0.64	0.08	14	36	4.2
	Red	MA05OJ0001	2.23	0.97	122	-29	0.2	1.80	0.94	125	-34	0.3
	Sask	MA05SH0001	0.42	0.06	34	20	2.1	0.35	0.08	34	25	2.4
	Winnipeg	MA05PF0022	0.49	0.05	75	30	6.3	0.44	0.08	76	34	5.2

Table 9. Differences between concentrations for same-day observations determined by Env Can and Man Env / City of Winnipeg, expressed as % differences [e.g. 100(Can-Man)/Man]. Canada and Manitoba data are for the Red River at Selkirk. City of Winnipeg data is for the Red River at Lockport. Mean and standard deviations describe subsets of same-day observations in the LWATDAT database. The three groups are for periods separated by shifts in Env Can TN and DN record, as discussed in the text above.

	Env. Can. compared to Man. Env.		Env. Can. compared to City of Wpg (Lockport)
	TN	DN	TN
1989-January 1991			
mean	-19	-21	-13
s.d.	12	11	0
n	18	18	1
July 1991-August 1993			
mean	-29	-31	-35
s.d.	16	19	12
n	4	4	5
Post-October 1993			
mean	-21	-25	-14
s.d.	21	34	15
n	5	4	6

Time series concentration data

Several general differences among subsets of the concentration data are apparent in time series plots (Appendix D). TOC are higher and more scattered (viewed river-by-river) in the Man Env data than in post-1978 Env Can data. The differences are small in the Winnipeg River data set, but are large in time series for the prairie rivers data. Also for TOC, there is much greater scatter in earlier (1969-78) compared with later (1978-2000) Env Can data, with the greatest variability showing up in the very earliest (1969-72) data. This latter change in the Env Can data applies to DOC and POC as well. Both the Man Env versus Env Can difference, and the change in variability in the Env Can data are of concern in time series analysis because data from each group must be used if the length of the series is to be maximized.

Both the Man Env versus Env Can differences and the larger scatter in the earlier Env Can record also appear in the nitrogen time series, though they are less consistent and partially masked by additional shifts in the DN and TN series. The higher scatter and higher concentrations of Man Env compared to Env Can data appear in all except the Red River record. In the Red River, variability is relatively high in every data set for all components of OC, N and P. However, it is only for the TOC record that Man Env concentrations appear to be generally high compared to both the Env Can and the Wpg record. The additional shifts of concern are in the Env Can record for DN (and hence TN which is mostly in the dissolved phase). In the time series for every river, DN drops by about one-third in the spring of 1991, and then increases sharply in late 1993 to greater than pre-1991 concentrations. Only the latter shift has been associated with a known change in analytical methods by Env Can (see previous section). As with other shifts in the time series record, breaks in the Red River record are less apparent, or sometimes different from these general patterns.

The time series for phosphorous appears to be the least problematic of the three. Man Env reports P to a lower precision than Env Can, but the concentration range appears about the same as for the Env Can record. Except for the Winnipeg River record, early (1970s) data shows the same variability as later P data.

Effect of observation frequency on calculated flux

For most of the period January, 1990-December 2000, the City of Winnipeg measured TOC, TN and TP on the Red River at Lockport at biweekly intervals. This is the most frequent concentration record of such length among the archives investigated. It makes possible a rudimentary investigation of the accuracy of the fluxes calculated using the longer observation interval generally available for Lake Winnipeg tributary rivers.

For comparative analysis, monthly TOC, TN and TP fluxes were calculated based on the original biweekly record and on longer interval subsets. Records with lower sampling frequency were prepared by resampling the City of Winnipeg data set as follows: The chronologically-ordered record was split by removing every 2nd observation into a 2nd set, creating two subsets, each with observations at approximately monthly intervals. These subsets were further split in the same manner, creating four subsets with data at bi-monthly intervals. Subsets at a 3-4 month interval were created by removing every 7th value in the original set to separate subsets. The resulting ranges of observation intervals for each set were: biweekly (1-20 d, mean=14 d, s.d.=3 d), monthly (21-40 d), bimonthly (41-60 d) and 3-4 (83-120 d) month sampling interval.

Monthly fluxes calculated from these data sets are listed in full in Appendix H. Summary results are shown in Table 10. Note that because the monthly data are not independent, variance estimates are potentially underestimated. Standard deviations of the monthly differences increase regularly with decreasing observation frequency, indicating that individual monthly fluxes can only be very loosely approximated from less than monthly sampling. However, TOC, TN and TP fluxes calculated from longer interval concentration data typically differ from biweekly data by only 0-5% (except for TOC, 3-4 month sampling=9%) i.e. close to insignificant given the larger standard deviations. This suggests that fluxes integrated over longer periods may be estimated from concentration measurements at up to 60 d intervals with somewhat greater confidence than monthly fluxes, if temporal trends in concentration can be ruled out.

Table 10 Averaged differences between TOC, TN and TP monthly fluxes calculated from monthly, bimonthly and 3-4 month interval concentration data compared to fluxes calculated from biweekly data. For example, on average, monthly fluxes calculated from TOC resampled at a monthly (26-40 d) intervals are 0.2% larger than TOC fluxes calculated from biweekly concentration data (s.d. of the difference=8%, n=33 months).

	TOC			TN			TP		
Observation interval (d)	26-40	41-60	84-120	21-40	41-60	83-120	21-40	41-60	83-120
mean % difference	0.2	-0.3	9	0.7	2	6	1	4	5
s.d. % difference	8	17	29	11	18	25	13	26	32
number of months	33	64	50	52	102	115	67	96	93

Table 11 shows results of a test for the effect of observation frequency on estimates of fluxes for successive 12-month periods. Because there are numerous gaps in the records of monthly fluxes calculated from each these data sets, few complete January-December fluxes could be calculated. To increase the sample size, pseudo-annual data were created. For each group (monthly, bimonthly and 3-4 month observation intervals) non-missing monthly flux percent differences were chronologically ordered, and subtotaled at 12 month intervals.

Table 11. Averaged differences between TOC, TN and TP pseudo-annual fluxes calculated from monthly, bimonthly and 3-4 month interval concentration data compared to fluxes calculated from biweekly data. *=mean difference significantly non-zero at 95% confidence; **=non-zero at 99% confidence (2-tailed t-Test, unequal variances).

	TOC			TN			TP		
Observation interval (d)	26-40	41-60	84-120	21-40	41-60	83-120	21-40	41-60	83-120
mean % difference	0.4	0.5	9**	-0.4	2	7**	1	6*	5
s.d. % difference	6	9	13	4	6	11	1	10	12
number of 12-month periods in sample	3	6	4	4	9	10	5	8	8

Although standard deviations of the annual differences still increase regularly with decreasing observation frequency, uncertainty is reduced by about half from results for monthly differences. The positive bias (mean differences) remains, indicating that using longer sampling intervals in excess of 2 months probably overestimates annual fluxes.

Although for calculation of annual fluxes reported in this study, gaps up to 120 d between observations were allowed, most fluxes are in fact based on monthly to bimonthly data. For TOC and TN, the multi-year average fluxes are probably very similar to averages that could have been calculated from biweekly concentration data. For TP, multi-year average fluxes may in some cases be of the order of 5% high. However, individual annual fluxes are only estimated within +/-10 to +/-20% (with 95% confidence, i.e. 2X s.d.) of fluxes that would have been calculated from biweekly data. At best, long term change in total fluxes cannot be detected with confidence from this data unless it exceeds this uncertainty.

It is important to recall that these deductions are specific to the parameters and the sampling station studied, i.e. the Red River below Winnipeg. The statistics are likely dependent on at least such factors as the inherent variability in the particular parameter, and the relationship between each parameter and river discharge. In particular, particulate concentrations tend to be more variable than concentrations of dissolved elements.

Interstation/Interagency comparison using Red River data

a) Interstation comparison (Lockport, N Perimeter Bridge)

The City of Winnipeg has sampled the Red River at both Selkirk and the North Perimeter Bridge for TOC, TN and TP. For the most part, the two stations were sampled approximately biweekly on the same dates. Over the period 1989-1997, the mean difference between same-day concentrations is only 1-2%, and is not statistically significant for any parameter (Table 12). The standard deviation of the difference is higher, about 20% for TOC and TN and 35% for TP.

Table 12. Differences between concentrations for same-day observations determined by City of Winnipeg for Red River stations at the North Perimeter bridge and at Lockport, expressed as % differences [100(Prmtr-Lkprt)/Lkprt]. T-Test statistic is for the null hypothesis that the mean % difference is zero (2-tailed t-Test, unequal variances).

	TOC	TN	TP
1989-1997			
mean	1	2	2
s.d.	20	23	35
Prob(T<t)	0.628	0.368	0.482
n	106	147	145

b) Interagency comparison

Means and standard deviations of percent differences between agencies for same-day concentrations are shown in Table 13 (Env Can vs. Man Env) and Table 14 (Env Can vs. City of Winnipeg). Except for TN and DN, statistics are for the period 1989-1997. TN and DN interagency differences are summarized for a smaller, pre-1991 subset to avoid spurious variability due to methods changes discussed above. To exclude very high percent differences due to very low denominators (very low concentrations) observations were removed from the calculation if the concentration was less than the minimum concentration plus 20% of the standard deviation in the original sample.

Table 13. Differences between concentrations for same-day observations determined by Env Can and Man Env expressed as % differences [100(Can-Man)/Man]. Both data sets are for the Red River at Selkirk. Mean and standard deviations describe all same-day observations in the LWATDAT database for the station. Data are from the period 1989-1997 (plus one in 1971) except for TN and DN, which are from only 1989-1991. T-Test statistic is for the null hypothesis that the mean % difference is zero (2-tailed t-Test, unequal variances).

	TOC	DOC	POC	TN	DN	PN	TP	DP	PP
mean	4	0	-15	-19	-21	19	16	14	65
s.d.	33	29	39	12	11	77	45	29	231
Prob(T<t)	0.488	0.996	0.102	0.000	0.000	0.152	0.051	0.003	0.124
n	35	33	19	18	18	34	35	40	32

Table 14. Differences between TOC and TP concentrations for same-day observations determined by Env Can (Selkirk station) and City of Winnipeg (Red River at Lockport station) expressed as % differences [100(Can-Wpg)/Wpg]. Mean and standard deviations describe all same-day observations in the LWATDAT database for the station. Data are for the period 1989-1997. T-Test statistic is for the null hypothesis that the mean % difference is zero (2-tailed t-Test, unequal variances).

	TOC	TP
mean	18	12
s.d.	45	22
Prob(T<t)	0.247	0.037
n	10	17

Mean differences between Env Can and Man Env same-day concentrations are not significantly different for TOC, DOC, POC, PN, TP and PP (see P(T<t) in Table 13). Env Can TN and DN, at least through the period 1989-91, are about 20% lower (99.9% conf.) than Man Env data. The scatter in the difference is fairly small (s.d.~12%) and the differences are significant The mean difference for PN (1989-97 data) is in the opposite direction, but is not statistically significant.

Env Can concentrations appear to be higher than Man Env concentrations for all phosphorous data although, due to wide scatter in the data, the differences are not conclusively proven. The difference is statistically significant only for DP, for which Env Can concentrations are 14% higher (99% conf.). PP is on average 65% higher for Env Can data, but this large difference is rendered non-significant by the very large scatter in the differences. Removal of a single outlier (1113%) reduces the mean difference to 31% but the variability in the between-agency difference remains high (s.d.=131, n=31). TP is likewise on average higher in the Env Can record, but again, not significantly.

Compared to City of Winnipeg same-day concentrations, Env Can TOC is not significantly different (Table 14). TP reported by Env Can is 12% higher (95% conf.) than City of Winnipeg same-day concentrations. Insufficient pre-1991 same-day pairs of TN data exist to test for comparability.

In summary, using data subsets comprised of same-day, different-agency concentration observations from the lower Red River, there is no apparent interagency difference in any of the organic carbon fractions investigated. Env Can TN and DN are about 20% low compared to Man Env and would be even lower if only the 1991-1993 period were tested. Although Env Can may report TP and/or DP 10-15% high relative to Man Env and the City of Winnipeg, the evidence in Red River data for this difference is very weak. Stronger, and different, inferences can be made based on Winnipeg River data (albeit for a different period, 1974-83). Winnipeg River data is discussed below.

Table 15 shows annual fluxes of TOC, TN and TP calculated from the 4 data sets for the Red River downstream of Winnipeg. Note that annual fluxes are calculated only for years without >120 d gaps in the concentration records.

Note that for the City of Winnipeg data, average differences in fluxes does not show the same patterns as average differences in concentration. For instance, average same-day TP concentration did not differ significantly between City of Winnipeg data at the North Perimeter Bridge and Lockport (Table 12). Nonetheless, average TP annual fluxes are 9% lower by data at the North Perimeter Bridge (Table 15). A closer look at the distribution of TP concentrations explains this apparent discrepancy. TP concentration was lower at the North Perimeter Bridge in 17 of the 20 highest flow months from 1990-1997. These 20 high flow months accounted for ~90% of total TP flux in the period. Hence the 9% overall lower flux at North Perimeter Bridge, even though average concentrations were indistinguishable between the two stations.

It is not obvious why this particular distribution of % differences between City of Winnipeg stations occurred. However, the important lesson is that even with relatively frequent sampling (15-22 observations per year), with collection and analysis of all observations by a single agency, and using identical flow records, differences as great as 10 to 15% in annual fluxes seem unexceptional.
The range in interagency differences in annual fluxes is up to 46%. The two largest values, -44% and –46% appear to be related to the anomalously low Env Can TN and DN values for the 1991-1993 period. However, even without counting these values, the range in interagency differences is much higher than the City of Winnipeg interstation range.

Table 15. Comparison of annual fluxes of TOC, TN and TP calculated from 4 data sets for the Red River downstream of Winnipeg (EC=Environment Canada at Selkirk; ME=Manitoba Environment at Selkirk; Wlk=City of Winnipeg at Lockport; Wpm=City of Winnipeg at the North Perimeter Bridge). Values shown in the second group (under the heading "% differences" are for EC compared to ME data and for each of EC, ME and Wpm compared to Wlk. (e.g. EC-ME=100(EC-ME)/ME) Over the period, the City of Winnipeg sampling frequency at Lockport was 15-22 observations per year for all parameters.

	TOC				TN				TP			
Annual yield $(kg \cdot km^{2} \cdot y^{-1})$												
	EC	ME	Wlk	Wpm	EC	ME	Wlk	Wpm	EC	ME	Wlk	Wpm
1990	105	124			21	25			3.6	3.0		
1991	130		126	157	16		30	29	3.9		2.9	2.9
1992	311		220	206	32		56	58	10.9		9.1	8.2
1993	507				54		73	66	14.8		13.2	11.9
1994	419	497			68	77	98	85	10.4	9.3	10.6	9.5
1995		686			98	125	126	119	13.8	15.3	20.1	17.7
1996		567			110	118	80	83	17.0	15.2	11.7	10.7
1997	1001	665			147				22.6	29.1		
1998	573	510			121				16.9	14.6		
1999	715	649			108				18.2	17.5		

% difference

	EC-ME	EC-Wlk	ME-Wlk	Wpm-Wlk	EC-ME	EC-Wlk	ME-Wlk	Wpm-Wlk	EC-ME	EC-Wlk	ME-Wlk	Wpm-Wlk
1990	-15				-15				21			
1991		3		25		-46		-3		35		-1
1992		41		-6		-44		3		20		-10
1993						-27		-10		12		-10
1994	-16				-11	-31	-22	-14	12	-2	-13	-11
1995					-21	-22	-1	-5	-9	-31	-24	-12
1996					-6	38	47	3	12	45	30	-9
1997	50								-22			
1998	12								15			
1999	10								4			
mean	8	22		9	-14	-22	8	-4	5	13	-2	-9
s.d.	27	27		22	6	31	35	7	15	27	28	4

In general for fluxes derived from Env Can data compared with fluxes from both Man Env and City of Winnipeg data, the pattern is similar to that for concentrations. As with TOC and TP concentrations, average TOC and TP fluxes calculated from Env Can data are higher, but the difference are not statistically significant in either case. As is the case for TN concentrations, TN fluxes calculated from Env Can data are lower. The difference is barely significant [$P(t<T)=0.044$, $n=10$] for the values in Table 15, though it is very highly significant [$P(t<T)=0.001$, $n=8$] if 1996 values are excluded. As was discussed above, Env Can TN concentrations shifted dramatically at the end of 1993 due to a change in analytical methods, so that a shift in the similarity of the annual fluxes is not unexpected .

Only very few same-year fluxes could be calculated Man Env and City of Winnipeg data. In those small samples scatter in the % differences is too high to quantify differences between annual fluxes derived from the two agencies' records.

Interstation/Interagency comparison using Winnipeg River data

a) Interstation comparison (Point du Bois to Fort Alexander)

In Tables 16 and 17, nutrient concentrations from upstream stations on the Winnipeg River are compared with concentrations from stations near the outlet in Lake Winnipeg. Although there appears to be a slight reduction in both TOC and TN in Env Can data between Pointe du Bois and Pine Falls, the difference between same-day concentrations is not statistically significant for either nutrient. In the Man Env data, TOC is indistinguishable between Lac du Bonnet upstream and Fort Alexander at the mouth. There are no comparable records for TN in the Man Env database.

Table 16. Differences between concentrations for same-day observations determined by Man Env at Lac du Bonnet and at Fort Alexander, expressed as % differences [100(LduB-FtAlex)/FtAlex]. Data are for the period 1972-77.

	TOC	TP
mean	-1	16
s.d.	13	60
Prob(T<t)	0.386	0.210
n	9	10

Table 17. Differences between concentrations for same-day observations determined by Env Can at Pointe du Bois and at Pine Falls expressed as % differences [100(PduB-PineF)/PineF]. Data are for the period 1972-74.

	TOC	TN	TP
mean	-8	-22	-31
s.d.	13	28	26
Prob(T<t)	0.105	0.107	0.049
n	5	4	4

The case TP is inconclusive. Comparison of same-day observations indicate that TP is about 30% lower at Pointe du Bois than near the river mouth, but the sample is very small and the difference is barely significant at 95% confidence. In a slightly larger sample, TP at Lac du Bonnet may be slightly higher than downstream at Fort Alexander, but because of greater variance the difference is not statistically significant. The two analyses taken together suggest that for the purposes of this study, along-stream differences in TP concentration, as for both TOC and TN, are effectively random.

It is unlikely that the travel time between upstream and downstream stations seriously affects these conclusions. In the Env Can database differences between observations taken 2 to 7 days apart were insignificant for each of TOC, TN and TP [mean differences=0 to 8%, n=13 to 19, P(t<T)=0.125 to 0.987].

The available evidence suggests that influx of at least the totals for OC, N and P are reasonably well estimated using stations as far upstream as Pointe du Bois from the mouth of the Winnipeg River. Nonetheless, given the paucity of good comparative data,

a) collection and comparative analysis of more up/downstream paired data would improve confidence in this conclusion, and
b) in any case, future Lake Winnipeg loading studies would be better served by sampling at Pine Falls.

b) *Interagency comparison*

Percent differences between observations taken within one day of each other by Env Can (at Pointe du Bois) and Man Env (at Lac du Bonnet) are summarized in Table 18. All of these approximately paired observations were recorded in the period 1974-83. Annual flux data calculated from each agency's data for the years 1979-1983 is compared in Table 19.

TOC, TN and TP concentrations reported by Env Can are on average significantly lower, 32%, 17% and 36% respectively, than those reported by Man Env. All differences are statistically significant (non-zero) by two-tailed t-Test (unequal variances). These interagency average concentration differences carry over into the annual fluxes. TOC, TN and TP fluxes based on data reported by Env Can are on average 35%, 7% and 24% lower than those based on Man Env data. For annual fluxes, only the TOC difference is statistically significant, but the samples (n=5) are very small.

That interagency differences in average concentrations differ from interagency differences in average flux much more in the Red River than in the Winnipeg River is likely related to the much higher seasonal variability of Red River discharge. Over the period 1970-1999, the ratio of the highest to lowest monthly discharge in each calendar year has averaged 22X for the Red River; it has averaged only 3X for the Winnipeg River. Hence, small concentration differences in a few observations at high discharge easily dominate annual fluxes of dissolved and suspended materials in the Red; this unequal weighting by discharge has less effect on Winnipeg River flux calculations.

Interagency TN differences are similar for Winnipeg River and Red River data. On the Red River for the pre-1991, period Env Can TN is 19% lower than same-day Man Env TN (and 13% lower than same-day City of Winnipeg TN). On the other hand, for TOC and TP, these results are not supported by interagency comparisons of Red River stations. The two agencies report similar TOC for same-day observations on the Red River, although scatter in the differences is higher there. Env Can TP on the Red River is, if anything, slightly higher than Man Env TP for same-day stations, the opposite result to comparison of Winnipeg River same-day observations. As with TOC, scatter in the differences is much higher for the Red River data, making conclusion drawn from that data set weaker than conclusions from Winnipeg River data.

Table 18. Differences between concentrations for same-day or next-day observations determined by Env Can at Pointe du Bois and Man Env at Lac du Bonnet expressed as % differences [100(Can-Man)/Man]. Test statistic is for the null hypothesis that the mean % difference is zero (2-tailed t-Test, unequal variances). Data are for the period 1974-83.

	TOC	TN	TP
Mean	-32	-17	-36
s.d.	20	30	15
Prob(T<t)	0.000	0.027	0.000
N	17	15	17

Table 19. Comparison of annual fluxes of TOC, TN and TP calculated from 3 data sets for the lower Winnipeg River (Env Can=Environment Canada, Man Env=Man Env). Values shown in the second group are % differences (i.e. 100(Env. Can.-Man. Env.)/ Man. Env.).

Annual yield (kg.km2.y-1)

	TOC		TN		TP	
	Env Can	Man Env	Env Can	Man Env	Env Can	Man Env
1979	2003	3629	90	113	4.1	5.7
1980	1358	2149	93	76	2.3	3.9
1981	1119	1812	50	50	2.4	3.6
1982	1878	2799	84	98	4.5	6.5
1983	1696	2189	74	98	5.3	4.7

Env Can – Man Env (% difference)

	TOC	TN	TP
1979	-45	-20	-28
1980	-37	23	-41
1981	-38	-1	-33
1982	-33	-14	-31
1983	-22	-25	13
mean	-35	-7	-24
s.d.	8	19	21

Precision of interbasin discharge estimates

Net interbasin flow computed by daily level differences compares well over the long term with measured river discharge into the South Basin. Over the period 1985-1998, mean net northward flow computed from the South Basin level record was 1235 $m^3 \cdot s^{-1}$, about 1% more than the mean terrestrial inflow, 1218 $m^3 \cdot s^{-1}$, into the South Basin over the same period (flows of Red, Winnipeg and Manigotagan Rivers prorated to total South Basin drainage area). The small difference may be attributed to net precipitation on to the lake surface minus evaporation, plus error in the method.

However, there is considerable variation between same day flows calculated independently from North and South Basin level records (Figure 9). Recent data (1990-99) indicate the expected 1:1 relationship (approximately) with broad scatter. For 1969, the only year for which there is nearly bi-monthly whole lake nutrient data, there is similar scatter, but poor correlation between the two interflow calculations. (1969 is of particular concern because it is the only year for which nutrient data exist with which to estimate nutrient fluxes over a whole open water season. It is argued below that most of the variation between the two estimates is due to imprecision in the North Basin level record; hence interbasin fluxes derived for 1969 from solely South Basin level data are given considered to be of greater precision than the comparison for 1969 data at first suggests.)

Interbasin flow calculated by level changes in either basin should be the same. In fact, for the period 1990-99, the average difference between same-day South and North Basin-derived interbasin flows is only 5 m^3·s^{-1}. However, the standard deviation of the difference is 3924 m^3·s^{-1} (n=3573. For reference, the daily mean computed interbasin flow for the 1990s, ignoring direction, was 3363 m^3·s^{-1}.) Basin areas being constant in the flow calculation, the variability of the differences must be largely due to imprecision in the calculation of daily level changes. The area of Lake Winnipeg north of the Narrows is almost 5X greater than south of the Narrows (19768 km^2 vs. 3981 km^2). Hence, equal level errors in the two basins would propagate into 5X larger errors in interbasin flow based on North Basin data.

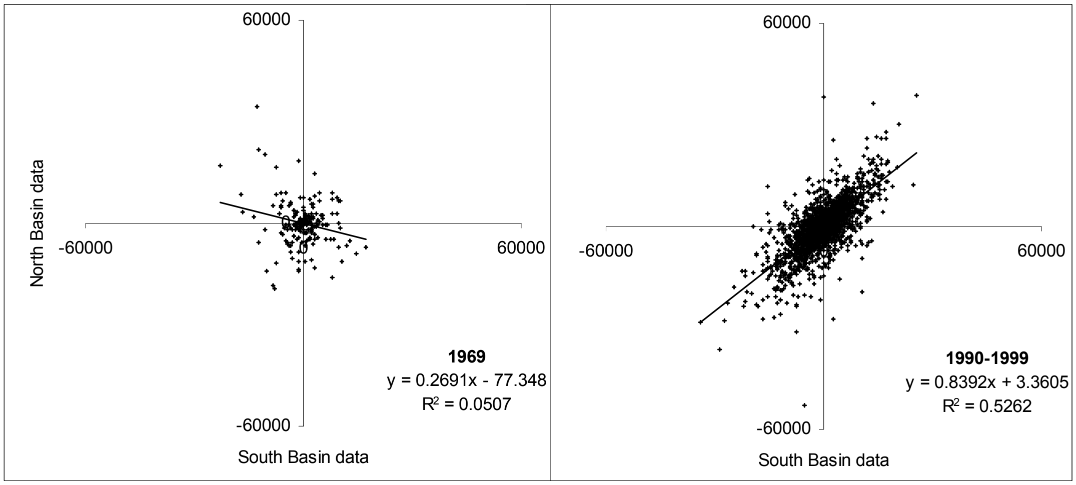

Figure 9. Daily flow through the Narrows calculated from level changes in the North Basin plotted versus same-day flows calculated from level changes in South Basin. Left: 1969 data. Right: 1990-1999 data. Units: m^3·s^{-1}.

In fact, the very large area of the North Basin makes the instantaneous level record quite imprecise. George Island being near the centre of the North Basin, it is least responsive of the level stations to setup at either end of the basin, and as such the best single estimator of the average level of the basin at any moment. Montreal Point and Matheson Island, and Mission Point and Berens River are paired because they are at opposite ends of the basin, and most nearly equidistant from the centre. For the period 1990-99, the standard deviation of the difference between the average of end-basin levels and the level at George Island was 0.029 m (mean=0.009, -0.222<diff.<0.122, n=3266). Translated into daily discharge, that uncertainty is nearly an order of magnitude larger standard deviation of the differences between same-day flows calculated from the two basin level records, and seems therefore to exaggerate the uncertainty in the method.

Between-station differences in mean daily levels are slightly smaller in the South Basin, as one might expect given the smaller fetches. The standard deviation of the difference between Gimli and Victoria Beach data for a period of overlapping record (1988-95) was 0.020 m (-0.337<diff.<0.103, n=2594). Given the basin area of 3981 km^2, 95% confidence in derived flow is estimated from the standard deviation of level differences to be 3700 $m^3 \cdot s^{-1}$ (i.e. 2 * 2 obs. * 0.02 m * 3981 km^2 / 86400 sec.) or slightly larger than the daily mean interbasin flow, and only 1/7th the corresponding uncertainty based on North Basin level data. Hence, interbasin flows and derived nutrient fluxes discussed in this report are based on South Basin level data only, and +/-3700 $m^3 \cdot s^{-1}$ serves as a conservative 95% confidence interval, about the magnitude of daily mean computed interbasin flow, 3363 $m^3 \cdot s^{-1}$. Expressed as volume, 0.02 m uncertainty in level is equivalent to a 95% confidence interval of +/-320 km^3 of water transferred between basins.

Recall that for 1969 the scattergram shows negligible correlation between interflow calculated using South and North Basin data respectively. This may be because prior to the installation of the level recorder at George Island in 1983, the mean North Basin level was calculated from only the opposite-end paired stations, and frequently only on one pair. More recent North Basin mean levels are based on data from 3 or 5 stations (George Island plus 1 or 2 opposite-end paired stations). However, for most of the 1969 record, the South Basin mean level is calculated from 3 station records, the same as are available for most of the 1990s record: Pine Dock, near the Narrows, and the mean of Victoria Beach and Gimli, near to the south end of the lake. Thus the error estimate based on 1990s level data should apply as well to the 1969 values used in this report.

Conclusions and Recommendations

Based on early 1990s data, yields (annual flux per unit watershed area) of all nutrients by Lake Winnipeg tributary watersheds are lowest from the two Plains rivers which pass through large lakes and/or reservoirs just upstream of the lake, that is, the Saskatchewan and Dauphin Rivers. The Shield Rivers, the Winnipeg and Manigotagan, yield 10X as much OC and P, and 5X as much N. In the same period, OC and N yields calculated for Red River were intermediate to these two pairs of rivers. The Shield rivers yield 6-9X more OC and 60-70% more N than the Red River. However, the Red River delivers more P per unit area than other major tributaries to Lake Winnipeg, 40-70% more than the yields of the Shield rivers and 15X the yields of the Saskatchewan and Dauphin Rivers.

Annual watershed yields of all nutrients are correlated with annual water discharge, most strongly for OC ($r>0.9$ except the Saskatchewan River for which $r=0.58$) but almost as well for N ($r>0.7$) and P ($r>0.8$). As a result, annual fluxes show no simple linear trend through time, but rather follow the pattern of discharge. As with discharge, fluxes of all nutrients tended to be low from the late 1970s through to the early 1990s and then to rise towards the end of the period of record. This pattern is clearest in the N and P flux record for all tributary rivers, although it is weaker in the Shield rivers because the difference in annual discharges was less pronounced in the Shield drainage. Apparently higher yields in the 1968-74 period are partly associated with higher discharge, but are also partly a product of the larger scatter in concentration data from this earlier period.

62% of OC, 70% of N and 84% of P carried from tributary watersheds into Lake Winnipeg are delivered into the South Basin. Almost three-quarters of the OC flowing into the South Basin comes from Shield watersheds. Three-quarters of the P from the South Basin watershed and just under two-thirds of N is delivered by the Red River. The Saskatchewan and Dauphin Rivers together contribute less than 20% of OC and N to the whole of Lake Winnipeg, and less than 10% of P. Most of all nutrients flowing into the North Basin are carried by the net northward flux from the South Basin through the Narrows. Total annual terrestrial influxes are larger than the measured flux out of Lake Winnipeg in the Nelson River. Losses of about 30% of inflowing TOC and 45% of inflowing TN may be accounted for by sedimentation and/or by net losses to the atmosphere. 45% of TP flowing into Lake Winnipeg is lost to sedimentation.

Typical open water season daily fluxes through the Narrows are 220 $t \cdot d^{-1}$ of N and 25 $t \cdot d^{-1}$ of P, i.e. several times larger than daily mean fluxes (averaged over the 1990s) in the Winnipeg and Red Rivers. Under-ice daily fluxes are typically smaller, and the range of daily fluxes typically increases through the open water season to peak in the windier autumn months. It is useful to consider interbasin flow in terms of events, i.e. periods through which net daily flow through the Narrows has been continuously in one direction. The largest and longest events (in terms of volume of water transported and nutrients transported, and in terms of the persistence of unidirectional flow) are northward in May and June, and are in response to the spring peak of watershed discharge. Individual events in these months have in the past effected the transfer of volumes of water approaching the total volume of the South Basin. Irregular transfer of nutrients northward through the Narrows tends to smooth the highly episodic, spring-flood dominated delivery of nutrients by the Red River to the South Basin, to a gradual year-long delivery of nutrients into the North Basin. As a result, a south-to-north declining nutrient concentration gradient is maintained over the whole length of Lake Winnipeg through at least the open water season.

In the open water season of 1969, daily fluxes of N and P ranged up to 1127 t and 152 t respectively. However, these interbasin fluxes are carried in oscillatory currents. The net flux northward from autumn, 1968 to autumn 1969 transferred to the North Basin only 70% of N and 80% of P flux from the watershed of the South Basin.

Several cautions should be observed in interpreting temporal series of both concentration in the LWATDAT database, and derived flux data:

1) Even with relatively frequent sampling (15-22 observations per year), with collection and analysis of all observations by a single agency, and using identical flow records, differences as great as 10 to 15% in annual fluxes seem unexceptional. However, such large uncertainty may be associated more with rivers like the Red, in which flood peak discharges are many times larger than daily discharges through extended low flow periods. It is likely to be an overly conservative estimate of uncertainty in annual flux determinations for rivers like the Winnipeg, in which the annual range of discharges is less extreme.
2) Due to large, sudden concentration shifts in DN in early 1991 and late 1993, at least partly associated with analytical methods changes, Env Can TN and DN data are unsuitable for temporal analysis through these dates.
3) In all but the Red River record, TOC and TN tend to be higher and more scattered in the Man Env record compared to the 1988-2000 Env Can record. Within the Env Can record, 1969-78 TOC and TN exhibit more scatter than 1978-2000 data.
4) In the Red River, variability is relatively high in every data set for all components of OC, N and P. However, it is only for the TOC record that Man Env concentrations appear to be generally high compared to both the Env Can and the Wpg record. Interagency analysis of concentrations and fluxes showed Env Can TOC concentrations and fluxes to be about 30% lower than Man Env values in same-day Winnipeg River observations, although they produced similar values on the Red River. Env Can TN was about 20% lower than Man Env for both Winnipeg River and Red River observations.
5) Man Env reports TP to a lower precision than Env Can, but the concentration range appears about the same as for the Env Can record. Except for the Winnipeg River record, early (1970s) P data in the Env Can data set shows the same variability as later P data. Interagency analysis of concentrations and fluxes with regard to P was less conclusive than for OC and N: for same-day observations Env Can TP concentrations were higher on the Red River, and but 36% lower on the Winnipeg River than Man Env TP. However, the positive difference in Red River data was highly significant only for the dissolved fraction (and not significant for TP) whereas the negative difference in the Winnipeg River data was very highly significant for TP.
6) Use of TP observations at Pointe du Bois rather than near the Winnipeg River mouth may have resulted in an underestimate of as much as 30% in the

determination of TP yields from the watershed into Lake Winnipeg, although the sample supporting this conclusion is very small (n=4). A slightly larger sample does not show any significant difference between sampling at Lac du Bonnet and near the river mouth. No significant differences due to distance of observations upstream are shown for either TOC or TN.

Recommendations

1) Discrepancies in the Env Can DN record that may be due to methods changes or otherwise should be resolved and some form of date-dependent correction applied to make pre-early 1991, early-1991 to late 1993, and post-late 1993 TN and DN concentrations fully comparable. This can only be adequately investigated with the cooperation and support of Env Can laboratory and/or field sampling staff with knowledge of methods and procedures used historically.
2) An interagency comparison of OC, N and P concentrations and variance should be undertaken. This report takes interagency comparison as far as it can be done using same-day observations in the LWATDAT v. 3.5 database, with results too inconclusive to develop with confidence corrections which would allow us to combine data sets for a more complete historic flux record. It may be possible to determine such corrections by reviewing historic inter-lab calibration data. It must be emphasized that an interagency comparison study using only current data cannot provide adequate correction to historic data, given, in particular, the shifts in the Env Can record.
3) Because most of the historic record for nutrient concentrations in the Winnipeg River is from the Pointe du Bois station, far upstream of Lake Winnipeg, longitudinal changes in OC, N and P concentrations (all fractions) should be determined for the reach from Pointe du Bois to Lake Winnipeg.
4) Given the high correlation between OC, N and P annual yield and annual mean discharge, where nutrient concentration data can be shown to be temporally invariant, data gaps which limit the continuity of annual flux records can reasonably be filled in by regression of nutrient yield on annual discharge. Manitoba Environment has reviewed their own data in this regard (Dwight Williamson, personal communication) and such an study could readily be done with the Env Can and City of Winnipeg data archived in LWATDAT v. 3.5. Clearly, the Env Can historic N concentration record does not, in its current state, support such a technique.
5) More precise determination of interbasin OC, N and P fluxes, and through them, of South Basin nutrient budgets, can only be achieved with greater frequency of observations in the regions north and south of the Narrows. A minimum frequency for more precise interbasin flux estimation would be biweekly. If such a program were envisioned, future interbasin discharge estimates would be better calculated either a) using hourly lake level data (events being defined by local minima and maxima in the South Basin level record) or b) through development of a hydrodynamic model.

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