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Sediment and Nutrient Yield from Great Lakes Tributary Drainage, Canada

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Abstract

The role of tributary drainage, as one primary source of sediment and nutrient loads to the Great Lakes, is outlined within the context both of historic cultural impact on land drainage and of relative importance of contemporary point and diffuse sources. Regional trends and patterns of sediment, nutrient and chloride yields to the four Canadian Great Lakes are created from Ontario Ministry of the Environment period-of-record water quality surveillance data files collected at or near the mouths of 102 rivers and creeks. Limitations both of raw data and analyses employed herein are briefly explored. Denudational equivalents should be used with caution.

Résumé

Le rôle des affluents en tant que source principale d'apport aux Grands Lacs en sédiments et substances nutritives est discuté dans le double contexte de l'impact culturel historique sur le bassin versant et de l'importance relative des sources contemporaines ponctuelles et diffuses. Les changements et la distribution par région des charges en sédiments, substances nutritives et chlorures aux quatre Grands Lacs Canadiens sont établis à partir de données recueillies à proximité de l'embouchure de 102 rivières et ruisseaux par le Ministère Ontarien de l'Environnement dans le cadre d'un programme de surveillance de la qualité des eaux. Les limites dues aux donneés brutes et aux méthodes d'analyses utiliseés sont brièvement étudiées. Les *équivalents «dénudationaux» doivent* être utilisés avec prudence.

Introduction

The understanding of water quality of the Great Lakes must take into account a variety of inputs: - tributary drainage, flow from connecting waterways, industrial and municipal effluent discharged directly into the lacustrine environment, and biochemical cycling in the water column and lake sediments. This paper deals with the role of tributary drainage as one primary source of sediment and nutrient loads to the Great Lakes.

Since colonial deforestation, loadings of sediment and nutrient have increased many fold - an observation which is well documented in the Great Lakes literature (Lewis and McNeely, 1957; Basset and Terasmae, 1962; Upchurch, 1972; Kemp *et al.*, 1974, 1976). Although Southern Ontario may be regarded as a low energy environment relative to other geomorphic environments, deforestation is accompanied by significant changes in runoff regimes wherein storm and melt runoff produce shorter runoff events with greater discharge peaks than under forested conditions. Hence, in agricultural southern Ontario where deforestation is virtually complete, significantly greater energy is available during runoff events than in precolonial times. This increased energy is particularly important in mobilizing clastic sediments. Although agricultural disturbance of land surfaces is undoubtedly the primary provenance of most clastic load, an unanswered research question is the degree to which bank failure and floodplain modification act as sediment sources following channel geometry changes in response to deforested hydrologic regimes. In terms of sedimentation into Lakes basins, post-settlement increases by factors of three and four were found by Kemp *et al.*, (1974). Nevertheless, such estimates must err on the low side as the coarse fraction of the fluvial load remains in the littoral zone. While total particulate loads supplied to the Great Lakes are dominated by shore bluff erosion (Kemp *et al.*, 1976), fluvially transported particulates are of interest in studies of water quality because of the capacity of the finer fraction to transport significant quantities of adsorbed phosphorus and nitrogen. Because suspended sediment is discharge-dependent the systematic monitoring of sediment loads presents large sampling problems. As will be noted below, our understanding of total suspended sediment loads into the Great Lakes is far from adequate.

The temporal change in solute loadings has received extensive study, particularly in a comprehensive report to the International Joint Commission (1969). In addition to discharge from connecting waterways, solute loadings of point or diffuse source origin are routed into the Great Lakes both by tributary rivers and direct discharge from municipal and industrial sources located on Great Lakes shores. The relative importance of these two routes is difficult to assess. The International Joint Commission (1969) calculated that nine per cent of total phosphorus and five per cent of total nitrogen loadings to Lake Erie were attributable to direct discharge - most of which originated on the U.S. side. Comparable values have not been calculated for Lake Ontario, where the densely populated Canadian side is serviced primarily by municipal sewerage systems discharging directly into the Lake. The relative importance of land drainage vis-a-vis direct flow to lake may, therefore, be less for Lake Ontario than for the rest of the Canadian Great Lakes.

As can be seen from the above comments, the study of land drainage to the Great Lakes is not intended to convey a holistic picture of land-based activity. It represents only those land use activities which contribute to fluvial water quality. River mouth data, therefore, reflect diffuse sources which may be both natural and anthropogenic, and such direct sources which are input directly into fluvial systems. In general, therefore agricultural impact, such as it is , is documented by river data. In large watersheds with significant urban and/or industrial concentrations, river water quality may be significantly affected and therefore monitorable some distance downstream.

Recognizing the necessity of understanding the relationships between tributary drainage and Great Lakes' water quality, the 'Pollution From Land Use Activities Reference Group' (PLUARG) was established by the International Joint Commission in 1973. As part of the PLUARG activities, an assessment was to be made of all available water quality and discharge records for Great Lakes' tributary drainage. The first phase of this assessment has been completed for Canadian data and is the subject of this report. It must be emphasized at the outset that the data presented represent a 'first look' at regional trends. As will be noted below, the currently available data files are subject to a number of systematic biases which are under examination through ongoing PLUARG studies.

Data Base

The data base consists of two data files. *The first includes all (reasonably)* continuously monitored discharge records collected across the Province of Ontario by the Water Survey of Canada. These data are in the form of daily mean and monthly mean discharge in cubic feet per second (cfs). The records used here are generally near but not at the mouth of larger tributary rivers and creeks. The second data file contains routinely monitored concentrations for the following water quality parameters:

- total solids
- suspended solids
- total phosphorus as P (TP)
- soluble reactive phosphorus as P (SRP)
- ammonia as nitrogen (NH_3-N)
- total kjeldahl (TK)
- nitrate as nitrogen (NO_3-N)
- nitrite as nitrogen (NO_2-N)
- chloride

Dissolved solids may be obtained by subtracting suspended from total solids. Occasionally available are:

- hardness as $CaCO_3$
- total iron
- alkalinity as $CaCO_3$

These data, collected and made available by the Ontario Ministry of the Environment for the entire (Canadian) Great Lakes, average one to two samples per month taken at or very near the mouth of most tributary watercourses. The numbers of watersheds for which data are available are enumerated in Table I. Routine monitoring was begun in 1964 in most of the Lower Lakes' and Southern Huron tributary watersheds. The Upper Lakes are generally represented by only a few sample years. Lake Superior was not fully monitored until 1973. In a report to the International Joint Commission (Ongley, 1974) the data are processed by individual watershed for period of record to 1972. Using the same period the data are now aggregated by Great *Lake for the purpose of inter-lake* comparison. It should be noted that inputs via connecting waterways are excluded from this study.

Although it is not possible to make a unique distinction between watersheds draining agricultural Southern Ontario and forested Precambrian Northern Ontario, the Trent-Severn system provides a convenient separation (Fig. 1). Lake Huron data have been divided into Southern Huron (agricultural) and Northern Huron (forested). It should be noted that most of the tributary systems to Lake Ontario, from the Trent eastwards, cover a proportion of Shield terrain.

Table I
Number of Basins[1] (to 1972)

	Ontario	Erie	Huron (south)	Huron (north)	Superior
Water Quality	50	19	17	8[3]	8
Discharge[2]	26	13	11	9	18

Footnotes
[1]excludes basins tributary to connecting waterways
[2]reasonably complete records
[3]includes both the Moon and Muskoka River outlets of the Muskoka watershed

Limitation and Methods of Data Analysis

The limitations of the data set and consequent methods of analysis have been reported previously (Ongley, 1974; 1976) and it was noted that data limitations impose certain restrictions on analysis which may well prove to be substantially in error.

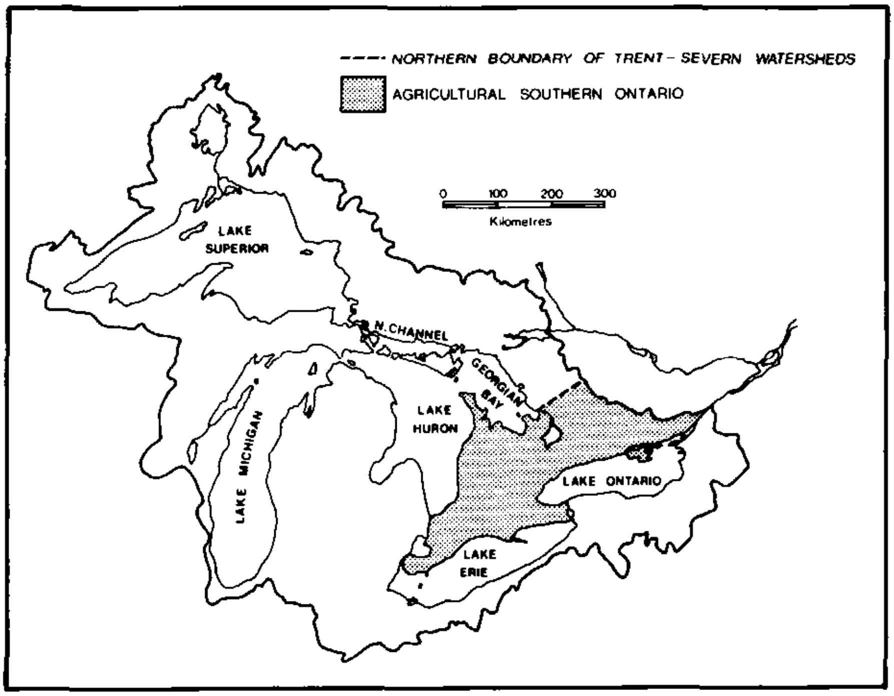

Figure 1
Great Lakes Watershed illustrating division of Canadian Tributary Drainage into agricultural, carbonate Southern Ontario and Precambrian Northern Ontario.

1)Water quality data are generally available for only one or two days per month. Moreover, collection of samples has been predicted by sampling convenience rather than an attempt to sample over ranges of stage or range of antecedent conditions. Inevitably then, sampling is biased towards low flow. In view of the limited sample size and bias towards low flow it has not been possible to compute the mathematical relationships between parameter concentration and discharge. Hence, monthly mean values of concentraion and flow were employed to yield monthly loadings in the full knowledge that products of means will not provide the accuracy of more complete experimental data sets. An assessment of this procedure is currently underway through ongoing PLUARG studies. monthly mean values of concentration and flow were employed to yield monthly mean annual loadings. This procedure was adopted for the simple reason that no other data exist for a more accurate determination of tributary loadings.
2) In most tributary watersheds the gauge site is sufficiently upstream from the water quality monitoring site that a natural increase in flow is very likely. Because discharge is closely linked, statistically, to basin area (Ongley, 1973, 1974) in the Great Lakes, discharge records were pro-rated on a unit area basis when more than 10 per cent of the basin area fell between the gauge and quality monitoring sites.
3) As will be noted in Table I, many basins, usually small ones, for which concentration data are available are ungauged. Loadings were calculated by annual mean concentrations and mean annual flow calculated from other flow-area data for that particular region (Ongley, 1974).
4) Water quality determinations are generally obtained from a single grab sample taken at less than a metre depth. Although turbulent mixing ensures reasonable values for solutes, suspended sediment data are highly underestimated owing to their depth-dependent nature. Although theoretically the wash load which carries adsorbed nutrient is probably well mixed throughout the water column, the degree to which nutrient-bearing particulates are transported as larger aggregates is not known.
5) The bias in quality sampling towards low flow produces average concentration values which are too high in the case of solute load and too low for clastic load. It follows that solute loadings of nutrients, particularly nitrogen and phosphorus may well be overestimated while those same nutrients transported in an adsorbed mode on particulates are too low. There is no reason to believe the two errors cancel out over the long term.

Regional Loadings and Denudational Equivalents

Loadings in metric tons are enumerated for the routinely available water quality parameters in Table II. The numbers of apparently significant digits reflect computer tabulations rather than accuracy of results. The values represent monitored loads; the lower values for a number of the Upper Lakes parameters reflect paucity of monitoring stations rather than reduction of loadings. In the case of Lake Superior, the loadings are biased by a preponderance of stations in the Thunder Bay area in the period prior to 1973. Generally, suspended loads are about 10 per cent of total loads. A cursory examination of limited Sediment Survey of Canada records in Southern Ontario suggest that these values for suspended sediment are approximately

Table II
Sediment and nutrient loads (mean annual values; exluding connecting waterways)

	Lake Ontario		**Lake Erie**		**Lake Huron (South #91-115)**		**Lake Huron (North #116-131)**		**Lake Superior**	
Parameter	Metric Tons	Tons/km²	Metric Tons	Tons/km²	Metric Tons	Tons/km²	Metric Tons	Tons/km²	Metric Tons	Tons/km²
Total Solids	*1913302*	*149*	*1359881*	*142*	*2334008*	*144*	*1586733*	30	762079	90
Suspended Solids	194790	18	155424	21	177007	11	138229	2	73055	12
Dissolved Solids	1723510	134	1204448	121	2174903	133	1448501	28	689094	77
TP	1442	.2	1550	.1	400	.05**	635	.01**	1126	.3
SRP	689	.1	1084	.05**	149	.02**	166	.003**	275	.1
NH_3-N	2097	.3	882	.1	616	.05**	11090	.1	1058	.4
TK	8047	.6	3526	.5	4493	.3	21557	.3	5201	1.0
NO_2-N	135	.01**	100	.01**	103	.01**	131	.002**	113	.01**
NO_3-N	2932	.3	3928	.5	5838	.5	2677	.1	1316	.1
Chloride	164746	18	86255	9.4	160780	7	108390	1.9	40641	4.9
Organic Nitrogen	5950	.3	2644	.4	3877	.25	10467	.2	4143	.6
Total Nitrogen	11114	.9	7554	1.0	10434	.8	24365	.4	6630	1.0

Footnotes
*Data highly biased by urban runoff in Thunder Bay area.
**Not to be regarded as a significant digit.

one-third their real values for reasons noted above. Total (monitored) dissolved loadings are close to two million metric tons per year in Lakes Ontario and Southern Huron, and in excess of one million for Northern Huron and Erie. The value of 689,000 tons for Superior reflects lack of records rather than significantly lower loadings.

A better appreciation of relative contributions to water quality by tributary drainage is obtained by pro-rating the loadings by spatial unit - here, square kilometers. Only the areas tributary to monitoring stations are used. Although this spatially averaged value of parameter production is misleading in the sense that point sources are ignored, it does provide some measure of interbasin variability. In general, the most consistent pattern is the marked reduction in loadings per square kilometre in non-agricultural Northern Ontario. The Northern Huron data is most representative of that environment because of the aforementioned bias of Superior data by the Thunder Bay data subset. The least variable component is organic nitrogen. The chloride loadings are of interest in that Hem's (1970) review of the subject indicates the necessity for a source other than cyclic salt. In a paper in preparation, Ongley (1976) has noted evidence for chloride storage in Lake Erie drainage systems - this in spite of the conservative nature of chloride. It suggests that like suspended sediment - area relationships, large basins output smaller amounts of chloride per unit area than small basins. Alternatively, proximity of major roads (on which are applied deicing compounds) to monitoring stations may be a significant factor.

Until such time as the data limitations and biases are more thoroughly explored the tabulated values are offered (Table II) without further comment. They represent the most complete understanding of regional loadings yet available but should be regarded with due caution.

From a geomorphological point of view, loadings are frequently represented in terms of uniform reduction of a landsurface. Such values are highly misleading for two reasons. Firstly, mobilization of suspended sediment is generally highly localized and only by using evidence, representative of periods of geological time, can one reasonably infer widespread if not uniform reduction of land surfaces. Secondly, solute loadings can infrequently be segregated into natural versus anthropogenic components, a problem studied by Meade (1969). Although the former may be regarded as acting more or less uniformly across the landscape via groundwater and soil water transfers, the latter certainly cannot. As a matter of comparison, denudation equivalents as recorded in the Great Lakes area by other writers are listed in Table III against the present findings. It is not known how other data were collected, hence no interpretation in terms of sampling procedure can be made. The size of basin for which data are obtained is an important consideration. In contrast to small basin data, large basin data such as those provided by Slaymaker and McPherson (1973) tend to depress both suspended total and solute sediment values and to suppress fluctuations arising from local land-use activities. The present data incorporates both size categories. The present data are averaged for the Lower Lakes and Southern Huron to provide a value representative of predominantly agricultural conditions. Municipal and industrial effects are included where large drainage systems receive significant point sources of effluent.

Table III
Mean annual denudation (mm per year)

	Agricultural				Shield
	Ontario	**Erie**	**Huron (south)**	**Huron (north)**	**Superior**
Suspended	.007	.008	.004	.0008	.005
Dissolved	.051	.046	.050	.010	.029
Total	.056	.054	.055	.011	.034
Average Suspended		.006		.0008	
Average Dissolved		.049		.010	
Average Total		.055		.011	

Published Values for Great Lakes Basin[1]	
Suspended	.0026-.005
Dissolved	.011 -.02
Total	.011 -.02
Suspended[2]	0.0 -.0034
Suspended[3]	.007 -.033

Footnotes
[1]as synthesized by Slaymaker and McPherson (large basin data)
[2]Fournier, 1960 (small basin data)
[3]Stichling, 1973 (variety of basin sizes)

Northern Lake Huron is used to typify Shield conditions for, as noted above, Superior data are highly biased by a concentration of stations in the Thunder Bay area.

In general, suspended sediment values for the Lower Lakes are substantially in excess of other values with the exception of detailed sediment data provided by Stichling (1973) for selected Lower Lakes drainage systems. By contrast, typical Shield suspended denudation is far lower than other published data. Dissolved load denudation in the Lower Lakes is greater by a factor of two to three than other data which corresponds closely with Shield values.

Summary

A first look at regional patterns of suspended nutrient and total loadings and their denudation equivalents for Canadian drainage (excluding connecting waterways) is presented by Great Lake. Although the results are suspect owing to inadequacies inherent in available data files, the values, drawn from large provincial and federal monitoring files, represent the most complete set of Lake loadings available. Detailed interpretation of the data either by time or space must await the more thorough assessment of data limitations currently underway.

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