Regional patterns of sediment yield in the Laurentian Great Lakes basin

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Abstract A Water Survey of Canada data base is used to investigate regional patterns of fluvial sediment yield from 92 Canadian basins tributary to the Great Lakes. Multiquadric interpolation is used to generate a map representing 20-year mean annual sediment yields for the study area. Average sediment yields for the lake basins range from 21.7 to 87.3 t km^{-2} year^{-1} but the maximum value exceeds 500 t km^{-2} year^{-1}. Areas of highest yield coincide with agricultural and industrial land use activities in basins with fine-grained glaciolacustrine parent materials.

INTRODUCTION

With an increasing number of river monitoring programs worldwide, measurements of material transport by rivers are being used to provide global-scale assessments of river loads (Milliman & Meade, 1983) and sediment yields (Fournier, 1960; Strakhov, 1967). These contributions have improved knowledge of global erosion, but considerable work is required to refine these estimates at varying spatial and temporal scales in response to controlling factors such as relief, geology, climate and land use change (Walling & Webb, 1987).

River monitoring activities of the Water Survey of Canada during the past 30 years have produced detailed records of suspended sediment transport for several Canadian rivers tributary to the Laurentian Great Lakes. Previous studies have used these data to estimate specific suspended sediment yields for several southern Ontario basins (Ongley, 1972; Dickinson *et al.*, 1975; Wall *et al.*, 1982) and to document the impact of agricultural land use on sediment delivery to the Great Lakes. However, these studies are based on a short period of record (<5 years) and represent local rather than regional patterns of sediment yield in southern Ontario. Furthermore, their analyses did not address the issue of fine-grained (<0.063 mm) sediment yield which is important in the context of contaminant transport.

In this paper, we use a 20 year sediment and hydrometric data base to examine regional patterns of mean annual sediment yield from 92 Canadian basins tributary to the Great Lakes. A multiquadric interpolation method is used to generate a sediment yield surface for the study area and to identify areas of regional variation. Regional variability in yields for lake basins are discussed in the context of drainage basin area, erodibility of surface materials, sediment availability, land use practice and hydrological regimes of the rivers.

SEDIMENT DATA

This study is based on records of suspended sediment transport collected by the Water Survey of Canada during the period 1972 to 1991. In total, 92 Canadian rivers tributary to the Great Lakes were investigated; 13 for Lake Erie, 34 for Lake Ontario, 5 for Lake St Clair, 24 for Lake Huron and 16 for Lake Superior. These rivers represent a range of small (10^2 km^2) to intermediate sized (10^4 km^2) basin areas (Walling & Webb, 1987).

Sediment yield data were used to generate a multiquadric surface of yields for the sample space between longitudes 76.90°W and 89.60°W and between latitudes 42.10°N and 49.20°N. Before computation, the average yield for each station for the 20 year period of record was rounded off to the nearest tonne as additional precision was considered illusionary at this scale. In cases where a drainage basin had several stations, the yields from those stations were aggregated and an average calculated for the basin. Other catchments had only one station. As a result of this spatial aggregation, 37 of the original 92 stations were used as a basis for surface generation. Longitudes and latitudes provided cartesian coordinates for each sample location and yields provided the scalar quantity to be mapped.

MULTIQUADRIC INTERPOLATION

The multiquadric (MQ) method was discovered and introduced by Hardy (1971) for the generation of surfaces where $z = f(x,y)$, z being the scalar dependent variable and x, y the locational coordinates of z. The MQ method is known as an exact method because the surface goes through the original sample points, in contrast to statistical methods that involve smoothing of the original point data. Fluvial applications include MQ mappings of fluid scalars (Saunderson, 1992) and of fluid vectors (Saunderson & Brooks, 1994). The software used in those applications (Saunderson, 1994) has been used in the present study.

Multiquadric interpolation requires, as a first step, the solution of a system of simultaneous linear equations:

$$\sum_{j=1}^{n} c_j\left[(x_i - x_j)^2 + (y_i - y_j)^2 + R^2\right]^{0.5} = z_i \tag{1}$$

where the $[x,y]_{ij}$ coordinates are known for each sample point and z_i is the sampled value of sediment yield at each location. The basis function in this form is that of a circular hyperboloid, but with $R = 0$ as used in this application it reduces to that of a right circular cone. The only unknown in this system of equations is the column vector c_j which was found using singular value decomposition (Press *et al.*, 1988). Using the solution for the c_js from equation (1) it is possible to interpolate the z_p value at any intermediate point x_p,y_p in the sample space using:

$$\sum_{j=1}^{n} c_j\left[(x_p - x_j)^2 + (y_p - y_j)^2 + R^2\right]^{0.5} = z_p \tag{2}$$

Interpolating to a dense spacing of points produces a continuous surface from these discrete points. In the present application, the interpolated values at 208 * 10^3 points were used to generate a multiquadric surface.

RESULTS AND DISCUSSION

Mean annual sediment yields for the five lake basins range from 21.7 to 87.3 t km^{-2} year^{-1}. Yields are significantly different (ANOVA, $\alpha = 0.05$) within and between lake basins (Table 1). These data reflect the range and variability of yields observed in Canadian rivers tributary to the Great Lakes. Maximum yields ranged from 200 to 650 t km^{-2} year^{-1}, two orders of magnitude less than the global maximum of 53 500 t km^{-2} year^{-1} cited by Walling & Webb (1987). With the exception of Big Otter Creek most of the higher sediment yield rivers listed in Table 1 traverse clay plains. While much of the upper Great Lakes drainage area is characterized by low flow variability (Richards, 1990), the largest area of consistent high flow variability is in the western and central Lake Erie Basin. The high flow variability is attributed to a combination of heavy soils (clays) and intensive row crop agriculture (Richards, 1990). For the southern Ontario agricultural basins, it is estimated that 70-100% of the suspended sediment load is delivered by sheet and rill erosion (Wall *et al.*, 1982).

To investigate the relationship between sediment yield and drainage area, sediment data for the 92 rivers were categorized according to river basin area (Table 2) and plotted with other yield data reported in the literature (Fig. 1). No clear relationship between sediment yield and drainage area is apparent for the Great Lakes basin. When grouped according to basin area, variability in mean annual sediment yield, expressed as the Standard Error of the Mean (SEM) was low, generally about 10% (Table 2).

For small river basins, the particle size characteristics of suspended sediment generally reflect the textural composition of the eroded parent materials and will often be enriched in the silt-clay fractions (Walling & Moorehead, 1989). This is evident in Table 2, where a significant proportion (75-100%) of the suspended sediment load consists of silt-clay sized materials (Stone & Saunderson, 1992). Fine-grained materials in fluvial systems represent an important vector for contaminant transport (Stone & Droppo,

Table 1 Mean annual suspended sediment yield.

Lake basin	High yield rivers	Drainage area (km^2)	Mean	Maximum	Minimum	Standard deviation
Erie		12 200	71.94	381.7	6.3	65.6
	Big Otter Creek	676	216.8	381.7	51.9	83.9
	Sturgeon	14.2	115.9	369.5	18.2	71.6
Ontario		28 200	53.38	652.6	0.9	70.5
	Welland	230	191.1	323.4	54.8	77.6
	Highland	88	184.1	652.6	41.8	154.3
	Don	316	132.8	527.7	41.3	98.5
St Clair		9 780	87.25	341.4	8.8	61.2
	MacGregor	202	171.7	341.4	30.5	82.1
	Thames	4300	80.1	123.1	39.8	20.8
Huron		89 900	26.23	193.9	0.8	26.8
	French	13 900	97.7	193.9	20.4	38.5
	Ausable	865	59.7	108.2	18.4	24.2
Superior		83 900	21.7	185.1	0.2	29.7
	Pic/Marathon	4270	98.2	185.1	19.1	44.1

Table 2 Mean annual sediment yield by drainage area.

Lake	Basin area (km^2)	Number of basins	Mean annual suspended sediment load ($t\ year^{-1}$)	Standard error of mean (%)	Silt-clay load (%)	Mean annual sediment yield ($t\ km^{-2}\ year^{-1}$)	Standard error of mean
Erie	0-100	3	2 412	8.6	78	76	9.3
	100-1000	9	29 916	7.5	78	76	6.9
	1000-10 000	1	114 308	10.9	80	22	10.9
	>10 000	0					
Ontario	0-100	14	4540	8.2	72	62	7.4
	100-1000	18	16 904	7.8	89	52	6.7
	1000-10 000	1	3885	15.4	100	2	16
	>10 000	1	39 062	22.6	100	3	22
St Clair	0-100	0					
	100-1000	3	24 319	8.7	96	100	9.6
	1000-10 000	2	205 911	11.9	94	68	5.4
	>10 000	0					
Huron	0-100	2	11 600	5.8	99	28	6.4
	100-1000	12	22 899	12.5	99	38	8.9
	1000-10 000	9	22 754	13.7	100	20	6.9
	>10 000	1	1 357 434	8.8	100	98	8.8
Superior	0-100	2	37 523	11.2	100	23	8.9
	100-1000	5	2958	10.2	97	5	11.5
	1000-10 000	9	61 780	16.3	84	31	7.8
	>10 000	0					

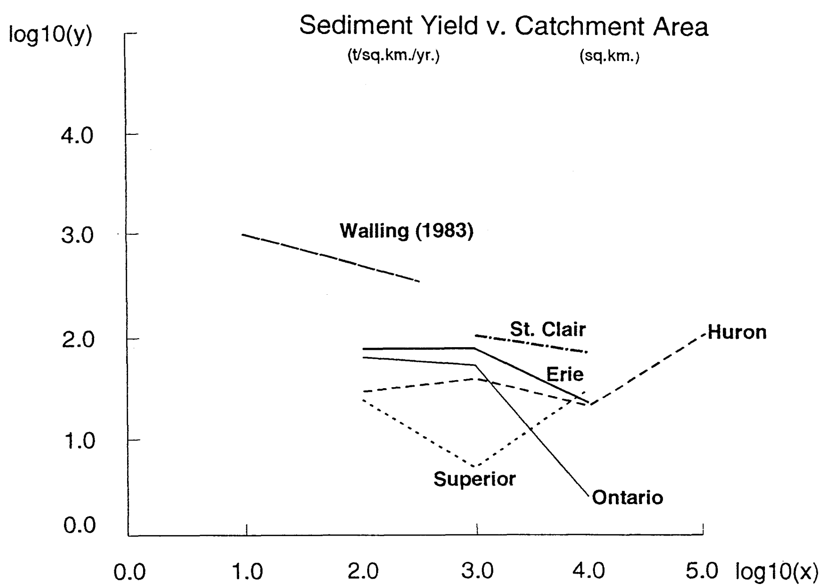

Fig. 1 Relationships between sediment yield and basin area for the Great Lakes basin compared with that provided for other areas of the world by Walling (1983).

1994). The high silt-clay yields in tributaries traversing industrial areas and agricultural land pose a special concern for sediment-associated contaminant transport to the Great Lakes. Management activities should be directed to target these high yield basins.

MQ RESULTS FOR SEDIMENT YIELDS

Interpolation using the sediment yield data generated a map showing the spatial distribution of yields grouped by class (Fig. 2). Class boundaries were defined from the sediment yield values at 10% class intervals based on the maximum yield of 126.50 t km^{-2} year^{-1}, giving a contour interval of 12.65 t km^{-2} year^{-1}. This maximum yield does not correspond with maximum yields reported in Table 1 because average yield data for the 20 year period of record were used to generate the sediment yield map.

The largest yields are associated with rivers flowing into Lake St Clair in southwest Ontario and a secondary high occurs in the Niagara Peninsula between lakes Ontario and Erie. The largest yield class for the St Clair tributaries is 113.85-126.50 t km^{-2} year^{-1}

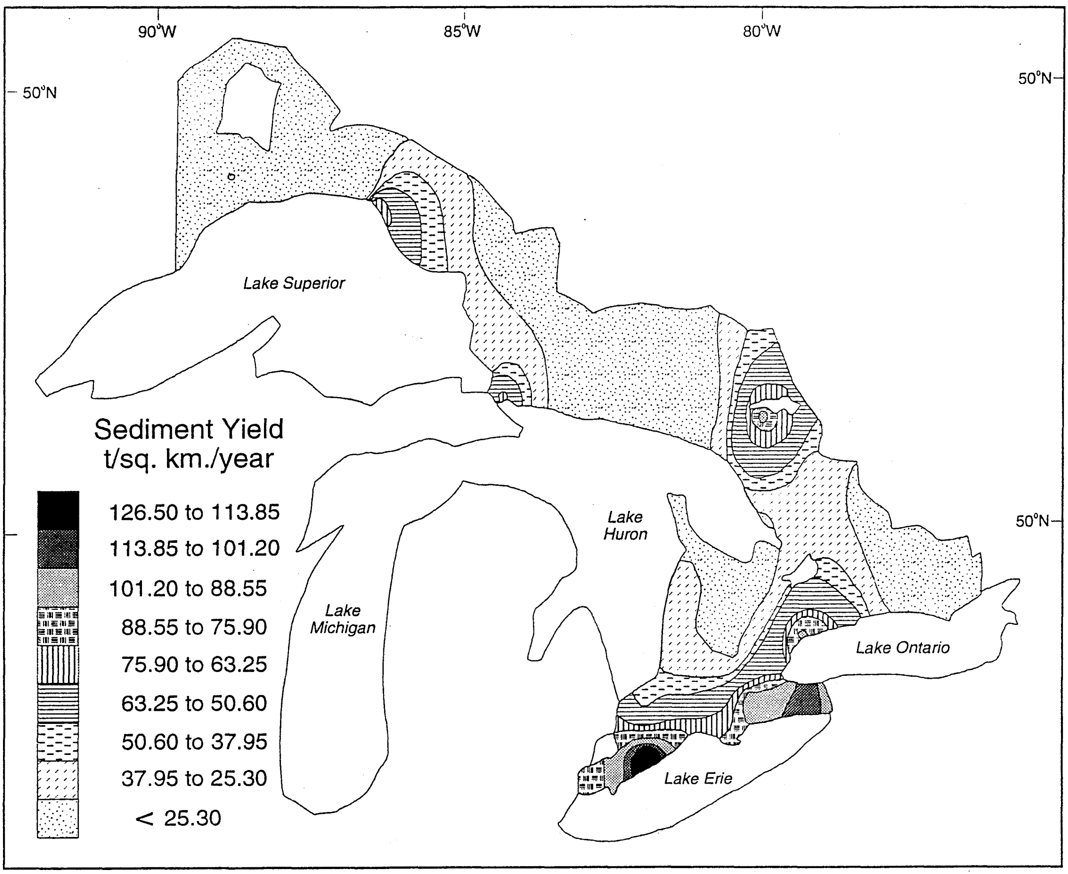

Fig. 2 Mean annual sediment yields in the Great Lakes basin.

and for the Niagara Peninsula it is 101.20-113.85 t km^{-2} $year^{-1}$. The exact location of maximum yield is slightly to the east of Lake St Clair, upstream from the mouths of the rivers flowing into the lake. Most of the total yield is contributed by rivers in southern and south-central Ontario, to the north and east of which there are distinctive gradients down to lower values.

The smallest sediment yields (<25 t km^{-2} $year^{-1}$) are from rivers draining the Precambrian Shield in the eastern, northern and northwestern parts of the mapped area. Small yields also occur for rivers draining the Bruce Peninsula and the exposed part of the Niagara Escarpment to the south of it. Within the broad band of low yields from the shield, and standing out in stark contrast to this area, are several pockets of moderate to high yields to the north and east of lakes Superior and Huron.

Possible explanations for the spatial variation in the sediment yield surface (Fig. 2) may be sought in the hydraulic and hydrological regimes of the rivers, the erodibility of geological materials, sediment availability and land use practice. The largest values of sediment yield and a concentration of the largest yields occur in that part of Ontario having a veneer of Quaternary glaciogenic deposits (Chapman & Putnam, 1984). The largest yields are from stations that are well upstream of their river mouths at Lake St Clair. These stations include Thamesville on the Thames River and Chatham on MacGregor Creek; also Strathroy on the Sydenham River and Petrolia on Bear Creek. The upstream location of these stations shows that the highest yields have been attained along short reaches of river. The Sydenham and Thames catchments have been classified as having variable flows whereas other catchments in Ontario had event, stable and super-stable flows (Richards, 1990). One might deduce from this classification that the high yields of the Sydenham and Thames catchments are the result of this flow variability. However, in the Welland catchment on the Niagara peninsula, high sediment yields are associated with flows classified as super-stable. Clearly, flow variability cannot be used as an explanation that is common to the Lake St Clair and Niagara Peninsula areas. What is common to both is a surficial swath of Quaternary glaciolacustrine sediments (Stone & Saunderson, 1992) that sweeps around the margins of the tills and glaciofluvial deposits of south-central Ontario. Both areas are the focus of intensive agricultural practice. The large yields in these areas relate to the compounding effect of available, easily erodible fine-grained deposits and high flow variability. Still to be determined, but potentially as important, are the effects of land use practice on soil textures, including the "effective" drainage density produced by extensive tile drainage and the effects of irrigation practices in promoting the delivery of fine-grained sediments to river channels from irrigation ditches.

The outliers of moderate sediment yields delivered to the Superior and Huron lake basins include, from west to east, the Pic and Black Rivers near Marathon, the Root River at Sault Ste Marie and the French River at Lake Nipissing. These yields seem anomalous for short rivers draining part of the Canadian Shield, but the presence of glaciolacustrine deposits raised above modern lake levels (Prest *et al.*, 1967) shows these yields to correlate strongly with the occurrence of Quaternary glaciogenic materials. The Lake Nipissing area especially has been well documented as a late-glacial connection between the upper Great Lakes, the Ottawa valley and the St Lawrence River (Prest, 1970).

CONCLUSIONS

This paper presents the first large-scale map of sediment yields in the Great Lakes basin. Multiquadric mapping shows clearly the spatial distribution of yields and these yields correlate strongly with variables other than basin area. The marked correlation between high to moderate yields and Quaternary deposits and between low yields and Precambrian Shield rocks leads to the conclusion that the availability of soft, easily erodible materials is very important in explaining sediment yields. A corollary is that estimates of denudation rates need to take into account the thickness and extent of soft materials and the time interval after which rates based on these materials are likely to change suddenly. Extrapolation beyond such a time-stratigraphic boundary will lead to serious errors in denudation estimates.

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REFERENCES

Chapman, L. J. & Putnam, D. F. (1984) *The Physiography of Southern Ontario* (3rd edn). Government of Ontario.

Dickinson, W. T., Scott, A. & Wall, G. (1975) Fluvial sedimentation in southern Ontario. *Can. J. Earth Sci.* **12**(11), 1813-1819.

Fournier, F. (1960) *Climat et Erosion*. Presses Universitaires de France, Paris.

Hardy, R. L. (1971) Multiquadric equations of topography and other irregular surfaces. *J. Geophys. Res.* **76**(8), 1905-1915.

Milliman, J. D. & Meade, R. H. (1983) World-wide delivery of river sediment to the oceans. *J. Geol.* **91**, 1-21.

Ongley, E. D. (1972) Sediment discharge from Canadian basins into Lake Ontario. *Can. J. Earth Sci.* **10**, 146-156.

Press, W. H., Flannery, B. P., Teukolsky, S. A. & Vetterling, W. (1988) *Numerical Recipes in C: The Art of Scientific Computing*. Cambridge University Press, Cambridge.

Prest, V. K. (1970) Quaternary Geology of Canada. In: *Geology and Economic Minerals of Canada*, 676-764. Geological Survey of Canada.

Prest, V. K., Grant, D. R. & Rampton, V. N. (1967) *Glacial Map of Canada*. Map 1253A, 1:5 000 000. Geological Survey of Canada, Ottawa.

Richards, R. P. (1990) Measures of flow variability and a new flow-based classification of Great Lakes tributaries. *J. Great Lakes Res.* **16**(1), 53-70.

Saunderson, H. C. (1992) Multiquadric interpolation of fluid speeds in a natural river channel: In: *Advances in the Theory and Applications of Radial Basis Functions* (ed by E. Kansa). *Computers & Math. Applic.* **24**(12), 187-193.

Saunderson, H. C. (1994) Multiquadric surfaces in C. *Computers & GeoSciences* **20**(7/8), 1103-1122.

Saunderson, H. C. & Brooks, G. R. (1994) Multiquadric sections from a fluid vector field. *J. Appl. Sci. & Computat.* **1**(2), 208-226.

Stone, M. & Saunderson, H. (1992) Particle size characteristics of suspended sediment in southern Ontario rivers tributary to the Great Lakes. *Hydrol. Processes* **6**, 189-198.

Stone, M. & Droppo, I. (1994) In-channel surficial fine-grained sediment laminae: Chemical characteristics and implications for contaminant transport in fluvial systems. *Hydrol. Processes* **8**(2), 113-124.

Strakhov, N. M. (1967) *Principles of Lithogenesis*. Oliver & Boyd, Edinburgh.

Wall, G. J., Dickinson, W. T. & Van Liet, L. J. P. (1982) Agriculture and water quality in the Great Lakes basin: II. Fluvial sediments. *J. Environ. Qual.* **11**, 482-486.

Walling, D. E. (1983) The sediment delivery problem. *J. Hydrol.* **65**, 209-237.

Walling, D. E. & Moorehead, P. W. (1989) The particle size characteristics of fluvial suspended sediment: an overview. *Hydrobiologia* **176/177**, 125-149.

Walling, D. E. & Webb, B. W. (1987) Material transport by the world's rivers: evolving perspectives. In: *Water for the Future: Hydrology in Perspective* (ed. by J. C. Rodda & N. C. Matalas) (Proc. Rome Symp., April 1987), 313-329. IAHS Publ. no. 164.