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G. J. Wall

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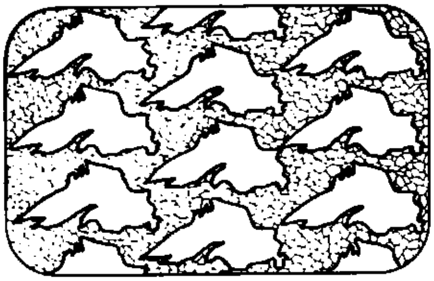

Temporal Pattern of Erosion and Fluvial Sedimentation in the Great Lakes Basin

W. T. Dickinson
School of Engineering
University of Guelph
Guelph, Ontario

G. J. Wall
Agriculture Canada
University of Guelph
Guelph, Ontario

Abstract

The flow system of the Great Lakes Basin is considered to be composed of a land basin and a lake basin. Land runoff contributes significantly to the total water budget of the Great Lakes. The per cent of total lake outflow resulting from land runoff ranges from >50 per cent in the upper Great Lakes to <15 per cent in the lower lakes of Ontario and Erie. Fluvial sediment inputs to the Great Lakes are the resultant of complex upland erosion and sedimentation processes. These processes are not synonomous, as the magnitude and temporal distribution of field erosion losses are significantly different from fluvial sediment yields and their temporal patterns. Fluvial sediment inputs to the Great Lakes have been reported to range from 5250 to 175,000 kg/year/km^2 for the different climatic, physiographic and land use regions. While these values express average annual loading rates, the role of single low probability floods (e.g., 100 yr. storm) is important in an assessment of the magnitude of erosional losses and fluvial sediment inputs to the Great Lakes. Current knowledge of the processes, magnitudes, and sources of terrestrial erosion and fluvial sediment loading rates in the Great Lakes Basin is limited. The dynamic contributing area approach is presented as a watershed reponse concept which shows considerable promise for the description of upland erosion processes.

Résumé

Un bassin terrestre ainsi qu'un réservoir d'eau composent le réseau fluvial de la région des Grands Lacs. L'érosion terrestre contribue largement au volume d'eau des Grands Lacs ainsi donc le débit d'eau provenant de l'érosion terrestre varie >50 pour-cent dans la région des Lacs Supérieur et Michigan à <15 pour-cent dans la région des Lacs Ontario et Erié. Les sédiments fluviaux allant aux Grands Lacs proviennent des hautes terres qui sont «érodées» pour ainsi déposer les sédiments dans les Grands Lacs. Ces procédés ne sont pas synonymes puisque la quantité en perte d'érosion terrestre est totalement différente du mantant accumulé par les sédiments fluviaux. L'accumulation des sédiments fluviaux dans la région des Grands Lacs ont une variance de 5250 à 175,000 kg/année/km^2. Cette variance est due à la topographie, à la physiographie, à l'utilisation des terres et aussi à une différence du climat de cette région. Ces données indiquent une moyenne annuelle mais la probabilité qu'une seule inondation se présente est d'une importance pour évaluer la quantité en perte d'érosion terrestre et de l'accumulation des sédiments dans la région des Grands Lacs. Les connaissances actuelles de ces procédés, de la quantité et les causes de l'érosion terrestre et de l'accumulation des sédiments fluviaux dans la région des Grands Lacs ne sont pas trop familier. Les éléments mentionnés ci-haut sont d'un dynamisme contribuant à ce réseau fluvial et qui décrivent avec certitude le processus de l'érosion des hautes terres.

The Great Lakes System

The watershed of the Great Lakes may be considered as a massive land-lake system. The drainage basin upstream of the outlet from Lake Ontario to the St. Lawrence River is approximately 777,000 km^2 in extent with the land comprising two thirds of the area and the lakes one third. In terms of the land and lake areas involved and their interrelationships, the system is unique.

A clear picture of the natural water flow system in the joint land-lake system is fundamental to understanding and management of the lakes themselves. Detailed descriptions of the various components of the hydrology of the Great Lakes System are not yet available. However, the relative importance of various input and output fluxes can be considered with regard to a set of land-lake equations.

For the land basin of the Great Lakes, the hydrologic continuity expression is:

$$P_L - E_L - R_L = \Delta S_L$$

where P_L is precipitation on the land area,
E_L is evaporation from the land area,
R_L is runoff from the land area, and
ΔS_L is the change in moisture storage on the land.

For the lake areas, the hydrologic equation can be written:

$$I + P - E + R_L - O = \Delta S$$

where I is inflow from an upstream lake,
P is precipitation on the lake surface,
E is evaporation from the lake surface,
R_L is runoff from the land
O is outflow to an outlet river of a downstream lake, and
ΔS is change in water stored in the lake.

From the above equations, it is evident that land runoff (R_L) is the only flux term common to both the land and lake systems. The relative importance of land runoff to local hydrology depends upon the particular lake system considered. Witherspoon (1971) has reported that land runoff contributes 50 to 60 per cent of the average water supply to the upper lakes (i.e., Lakes Superior, Huron and Michigan), while only 14 per cent to the lower lakes (i.e., Lakes Erie and Ontario). In the case of the two lower lakes, inflow from the upstream lake accounts for 86 per cent of the water supply.

In the land-lake system, the role of land runoff may also be significant when considered as a transport medium for the movement of water-borne materials. For soil particles, land runoff is the prime mechanism for transporting materials originating from upland sheet, gulley, and streambank erosion. Another source of soil material, lakeshore erosion, will not be discussed in this paper since it is more specifically dependent on lake processes.

Discussion in this paper will focus on the flux of sediment from the land to the lake system that is dependent on the land runoff (R_L) component of the hydrologic equations. More specifically, the objectives are: 1) to examine the temporal patterns of sediment flux from the land to lake system with regard to both seasonal and long term variation, and 2) to assess the implications of the temporal patterns of sediment flux upon the conventional methodologies employed to study sediment loading rates.

Estimation of Sediment Loading Rates

The sediment yield of a land basin may be determined in two basic manners: 1) sediment load measurements, and 2) sediment load prediction models. The state of the art of each approach is briefly considered below as it relates to the Great Lakes System.

Suspended sediment load measurements afford the most reliable method of estimating sediment yield from large watersheds. It is unfortunate, however, that relatively few streams draining into the Great Lakes have stations where suspended load has been measured regularly. Mildner (1974) reports that of 1329 flow gauging stations in the U.S. portion of the Great Lakes basin, only 60 have sediment data. Of these, 48 have a record of over five years but only 12 have a record of over 10 years. The Water Survey of Canada (1973) reports nine sediment stations, of which one has more than five years of record. Until very recently, data collected by the Ontario Ministry of the Environment have been of limited value for estimating sediment yield.

This lack of comprehensive suspended sediment load measurement for the Great Lakes Basin makes it difficult to obtain precise quantitative estimates of the sediment yield from the land basin to the lakes. However, data do provide initial information regarding the nature of temporal variations in sediment loadings.

The second approach to estimating the sediment yield of the land basin involves the use of mathematical prediction equations. It is desirable that such equations be based on fundamental hydrologic, hydraulic, and physical laws, and employ input information regarding climatic and watershed variables. Although some steps have been taken in this regard (Kling and Olson, 1974; Foster *et al.*, 1973) such an approach proves to be difficult and is developing slowly. The slow development is due not so much to a lack of understanding of the basic laws and processes as to our inability to describe adequately the spatial and temporal boundary conditions for the problem.

The stage of development of predictive models for sediment yield from land basins does not allow accurate quantitative estimates to be made at this time. Considerably more work is yet required on the description of various component parts of the models.

The state of the art in sediment studies as they relate to the Great Lakes Basin reveals that we are at an early stage of development, both in the collection of data and in our ability to predict. At such a stage there would appear to be a need to carefully examine the available records in order: 1) to confirm that the data being collected is of the most useful type, and 2) to develop concepts for the improvement of our predictive capability. Temporal variations in erosion and sedimentation processes are examined below with regard to the implications to our data collection system and our approach to sediment modelling.

Temporal Pattern of Land Erosion

The erosion of upland land surfaces by sheet and rill erosion processes is a prime source of sediment to fluvial systems. However, it is important to note that the total on-site sheet and rill erosion is not delivered to streams since considerable deposition during transport may occur. The factors affecting sheet and rill erosion processes are well documented (Musgrave, 1947; Wischmeier and Smith, 1965) and generally include land use, rainfall, slope, soil moisture, and soil erodibility parameters. But the relative significance of these parameters and the variable interrelationships that may occur between them are not clearly understood.

Measurement of land erosion rates is difficult because of the number of variables involved and the cyclic nature of the process. Currently there is no single method for measuring land erosion rates that is universally accepted. In the USA a soil loss prediction equation has been developed and used extensively by the Soil Conservation Service (Wischmeier and Smith, 1965). This soil prediction equation takes the form of $A=RKLSCP$, where A is soil loss, R is the rainfall factor, K is the soil erodibility factor, L is slope length, S is slope per cent, C is the cropping - management factor, and P is the erosion control practice factor. It is worthwhile to consider the soil loss equation as a tool to assist in demonstrating the temporal variability of the land erosion process.

Figure 1 illustrates the average annual land erosion rates as computed with the soil loss equation for a small agricultural watershed (40 km^2) in central Ontario. Current erosion losses are greatest (8.3 metric tons/ha.) in the 22 per cent of the basin occupied by corn crops; while lowest erosion losses (0.3 metric tons/ha.) occur on the 18 per cent of the basin in pasture and woodlands. Integration of the area beneath the curve on Figure 1 reveals the current average annual land erosion rate in the watershed to be about 3.5 metric tons/ha.

One can speculate about pre-cultural erosion rates by extrapolation of current erosion losses from woodland areas to larger regions. When the erosion rates from the woodland area of the watershed (Fig. 1) are extrapolated to the entire basin, current gross land erosion losses are about 10 times larger than precultural levels.

In a similar manner one can speculate about future erosion losses. Current agricultural trends are to increased acreages of row crops such as corn, soybeans (highest erosion hazard, Fig. 1) at the expense of forage and pasture crops (lowest erosion hazard, Fig. 1).

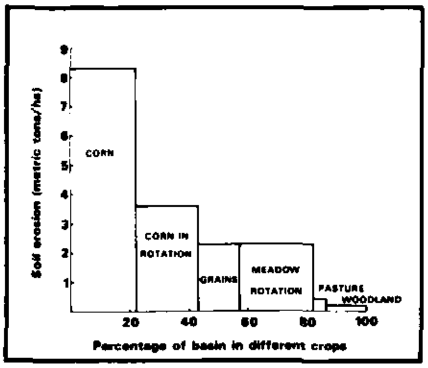

Figure 1
Average annual potential erosion losses for a watershed in Central Ontario.

The replacement of forages, pastures, and grain crops in grass rotations with row crops such as corn, in the watershed studied, would result in a doubling of current land erosion losses.

If only those variables of the soil loss prediction equation that change over the course of a year are considered, several observations may be made with respect to the temporal nature of land erosion. Figure 2 illustrates the seasonal variability of the rainfall and cropping parameters of the soil loss equation. The summer period (June-August) of most intense rainfall is often considered to be the critical time period for land erosion (Ketcheson *et al.*, 1973). However, land erosion in the spring and fall periods should not be underestimated because of the lack of high intensity rainfall events. The high cropping ratio values that occur in the spring and fall combined with high antecedant moisture conditions and low evapotranspiration values can result in a considerable erosion hazard.

Table I is used to illustrate the effect of a single low probability high intensity storm on spring vs. summer land erosion losses. The product of the rainfall factor (R) and the cropping ratio values (C) is used as an erosion index. The single 50 year 15 minute duration storm yields 48 to 237 times the average erosion for time periods in the summer and spring, respectively. Soil erosion losses from similar infrequent events (particularly in the spring when ground cover is minimal) can result in land erosion levels that make average annual projections relatively insignificant in the total erosional process.

Although the values obtained by the soil loss equation may not be absolute estimates of erosional soil losses, they do serve to indicate that:- 1) current gross land erosion losses are about 10 times greater than precultural levels, 2) continued intensification of agricultural practices could double current land erosion losses, 3) there is a seasonal variability in land erosion losses, and 4) average annual values for land erosion may be small compared to land erosion losses that occur in single low probability rainfall events.

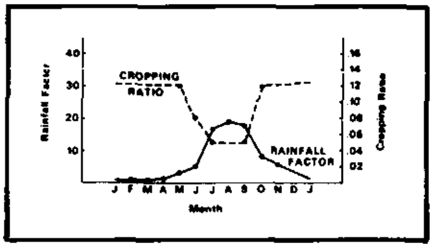

Figure 2
Seasonal distribution of rainfall factor (R) and cropping ratio (C) for a corn crop in Southern Ontario.

Table I
Effect of a low probability storm (50 yr/15 min) on land erosion.

Season	Rainfall Factor R	Cropping Ratio C	Erosion Index (EI) RXC	Ratio 50 yr EI/Ave EI
Spring				
Average[1]	4	.12	.48	114/.48=237
50 yr. storm[2]	950	.12	114	
Summer				
Average[1]	20	.05	1.0	48/1=48
50 yr. storm	950	.05	48	

Footnotes
[1] Average conditions as portrayed in Figure 2 for a corn crop in Ontario.
[2] Rainfall factor (R) computed for 50 yr/15 min duration storm.

Streambank Erosion

Although the mechanisms involved in bank erosion have been well documented and various methods of bank stabilization have been developed and effectively implemented, the significance of streambank erosion as a contributor to fluvial sedimentation has not been well established. Silberberger (1958) determined that 53 per cent of the sediment entering Buffalo Creek and the Buffalo Harbor portion of Lake Erie originated from streambank erosion. Mildner (1974) estimated that less than five per cent of the suspended load of the Maumee River came from streambank erosion, while 10 to 40 per cent of the Genessee River suspended sediment load might have originated from banks. Carson *et al.*, (1973) reported that suspended sediment originated primarily from scour of the banks in the dominantly forest-covered Eaton Basin. While the literature suggests that the variability of the physiography and land use in the Great Lakes Basin results in a wide range of absolute and relative contributions by streambank erosion, parameters have not yet been identified which may be used to quantitatively estimate such erosion in selected landscapes.

A detailed examination has been conducted of the streambanks in sixteen small upland watersheds (1.3 to 54.6 km²) representing various climatic, physiographic, hydrologic, and agricultural regions of Southern Ontario. A preliminary summary of the results reveals the following observations. Fifty-five per cent of the total bank area shows stabilized conditions or no active erosion. The most common form of active erosion is rotational slumping, which occurs on 25 per cent of the total bank area. Undercut slumping, rilling, and gullying each account for a small percentage of the erosion. About 15 per cent of the bank area is exposed and about 25 per cent is covered with small vegetation comprised of grass and/or reeds.

One of the prime mechanisms for the removal of material from the banks appears to include the generation of numerous small rotational slumps followed by a periodic flushing action of the stream. The flood flows involved in such flushing generally occur not more frequently than once a year and more likely only once in several years. Streambank erosion, therefore, primarily contributes to fluvial sedimentation in discrete events, such events coinciding with flood flows.

Temporal Patterns in Fluvial Sedimentation

An intermediate integrating variable reflecting the contribution of upland surface and streambank erosion to sediment levels in the Great Lakes is the suspended sediment load transported in the tributary river systems. The variable includes the delivery ratio effect on the gross land erosion to the point in the river system considered. It may not include the effects of all downstream inputs and/or deposition opportunities unless the sampled point is at the mouth of the tributary river.

Temporal patterns in suspended sediment load have been examined with regard to seasonal trends and long term variations. Daily suspended sediment loads estimated by the Water Resources Branch of Environment Canada and by the U.S. Geological Survey were considered for six rivers, for which the basin areas and years of record analyzed are presented in Table II.

The seasonal pattern for these lower Great Lakes Basins is illustrated in Figure 3. It is evident that more than 55 per cent of the annual load occurs during the months of March and April, while only a small percentage is transported during the summer months. This seasonal pattern does not vary *significantly from river to river for the six* rivers considered, and closely parallels the seasonal distribution of flood occurrences in Southern Ontario (Dickinson, 1972).

Long term variations in suspended sediment load are reflected in a duration curve analysis of the data (Fig. 4). In order that the curves for the various rivers might be compared, the magnitude axis of the graph has been scaled in a dimensionless fashion. The duration curves yield relationships between the percentage of suspended sediment contributed by suspended loads greater than or equal to selected values, and the percentage time that these selected values are equalled or exceeded.

A number of points are reflected in this set of curves. Suspended sediment loads have a highly skewed frequency distribution. In fact, the distributions are so skewed that the movement of suspended load might be considered to be a discrete process dependent on extreme events. Fifty per cent of the suspended material is transported in less than five per cent of the time; 80 per cent is moved downstream in less than 10 per cent of the time.

Additionally it was observed that severe storms flushed as much as, or more material in a few days than moved through the system during an average year. A similar observation was made by

Table II
Data base for sediment sampling stations in southwestern Ontario.

Sediment Sampling Station	**Basin Area (km²)**	**Years of Record Analysed**
Big Creek near Walsingham	591	1967-1971
Big Otter Creek near Vienna	697	1967-1971
Canagagigue Creek near Elmira	109	1968-1971
Humber River at Elder Mills	303	1967-1971
Humber River at Weston	800	1968-1971
Thames River near Ingersoll	518	1967-1971
Maitland River near Donnybrook	1760	1970-1971

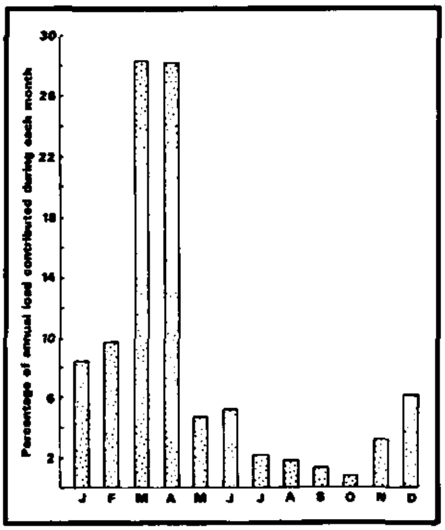

Figure 3
Percentage of annual suspended sediment load contributed during each month of the year.

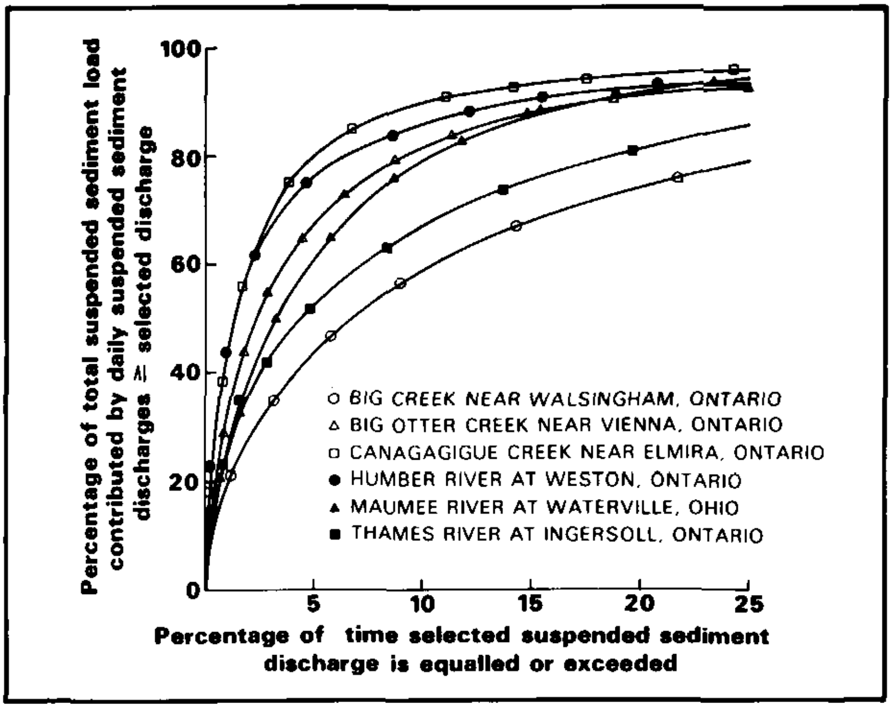

Figure 4
Comparative dimensionless duration curves for suspended sediment loads carried by streams tributary to the Great Lakes.

Archer (1960) on Ohio streams. Wolman and Miller (1960) did not find such an extreme variability for the large rivers which they considered, but noted that as river flow variability increased a larger percentage of the total load was carried by less frequent loads. Piest (1965) noted that sediment yield caused by storms with a return period greater than two years could vary from three to 46 per cent of the total suspended sediment yield.

Streamline duration curves, which add information to this consideration of temporal variability in fluvial sedimentation, have been developed for the basins under study and are presented in Figure 5. Comparison of Figures 4 and 5 reveals that the sediment load variable is more highly skewed than the streamflow variable itself. It has been noted by Johnson and Moldenhauer (1970) that suspended loads increase more rapidly than their discharge. Deterministic ratings between sediment load and discharge do not reveal a specific relationship. However, the analysis in the frequency domain clearly reveals that suspended sediment loads are more extremal oriented than streamflow itself.

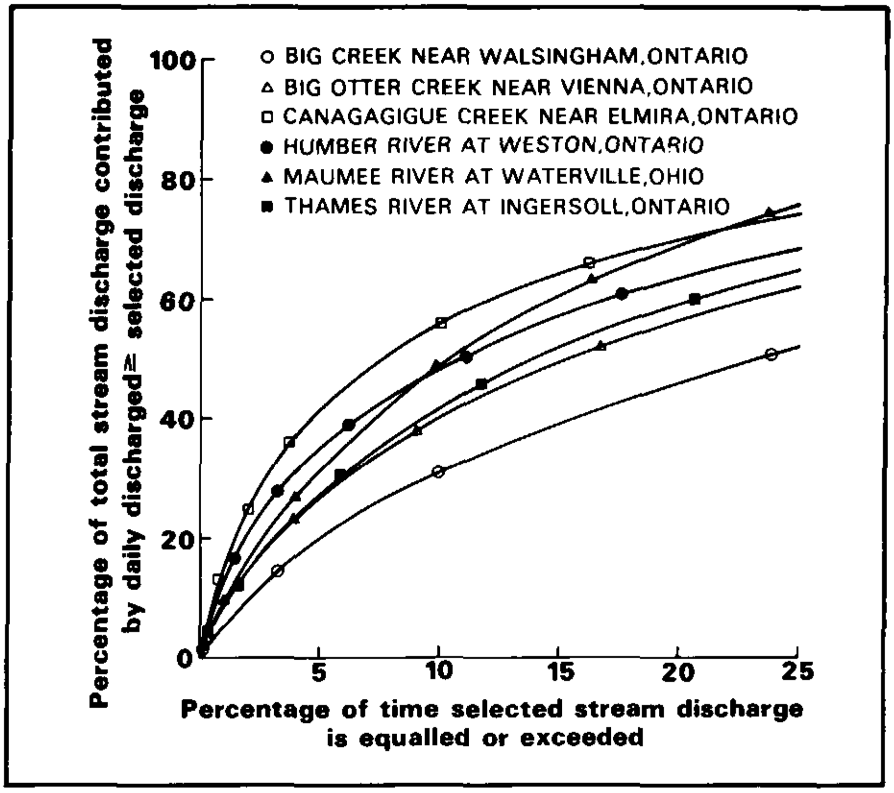

Figure 5
Comparative dimensionless duration curves for stream discharges carried by streams tributary to the Great Lakes.

Implications of Temporal Patterns

The seasonal and long term variations exhibited by surface land erosion, streambank erosion, and fluvial sedimentation reveal facts important to the understanding of the land-lake system.

1) Upland erosion and fluvial sedimentation exhibit a strong seasonal pattern. The major erosion and transport activity occurs during a relatively short period of time during spring runoff. *Therefore, the sediment yield leaving the* land basin and entering the lake system occurs in essentially a discrete manner.

2) The variability of suspended sediment loads carried by streams tributary to the lower Great Lakes is very great and considerably larger than the variability of the associated streamflows. As a result, infrequent severe runoff events contribute significant sediment yields. Therefore, over a term of several years, *basin sediment yield may appear to be* quite discrete with relatively infrequent loads contributing the only major inputs to the lake system.

The implications of these observations can be considered with regard to the two approaches to estimating sediment yield outlined earlier, i.e., suspended sediment measurements, and suspended sediment prediction models. A few of these implications are noted below.

1) Due to the variability of suspended sediment flows, the time sampling program must be strongly event-oriented in order to obtain accurate *estimates of suspended sediment loads.* Dickinson (1967) has shown that, for a variable with a seasonal pattern such as that exhibited by suspended sediment loads in the Great Lakes system, the accuracy of annual estimates can be improved substantially by increased frequency of sampling during major event periods and reduction of sampling during long intervals of low flow.

2) Determination of the significance of *extreme events for an extreme event-*oriented variable requires a statistical extreme value analysis. Experience in hydrology (Chow, 1964) suggests that a considerable period of record is required for such an approach. Reliable estimates of the significance of individual sediment yield events by this means must await the availability of at least 10 to 15 years of suspended sediment measurement data from a variety of tributaries in the Great Lakes basin.

3) The concepts incorporated into mathematical prediction models for sediment yield must be sufficiently *nonlinear in form to allow the generation* of major sediment loads for large runoff events while producing minor loads during an extensive range of lesser events. The so-called dynamic contributing area concept for modelling surface or direct runoff is one approach which produces such results.

4) The state of the art in model development demands (i) the creation of model frameworks which embody concepts that allow the generation of temporally correct patterns, and (ii) the verification of such models on a watershed basis to permit extrapolation to other areas of the basin.

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