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A Simple Method for Estimating Change in Sediment Transport Trends in Watercourses

Key Words: *Sediment transport, urbanization, erosion*

Abstract

Anticipation and mitigation of changes in sediment transport trends, such as due to urbanization of a catchment and resulting changes in runoff flow trends, is an important factor in nonstructural solutions in floodplain management because changes in sediment transport can result in changes in the flood carrying capacity of a watercourse. Almost all sediment transport relationships found in the literature equate sediment transport capacity or sediment load, in a flow of storm runoff, to flow rate, by use of the well-known power law mathematical model involving two parameters; namely, a coefficient and an exponent. Some equations relate sediment load to flow velocity by use of the power law equation. Other equations relate sediment load to flow rate, or a flow rate in excess of a threshold flow rate. For most conditions, where changes in erosion or deposition is primarily due to changes in flowrate (such as due to urbanization and/or diversion effects), the changes in sediment transport trends can be readily related to the changes in catchment runoff trends (or flow rate trends) by examining the cumulative changes in the ratio of each storm's sediment transport load for a time history of storm events. Different power law relationships can be used for wash load analysis or for bed load transport.

Using this approach, the sediment transport parameter needs, for a soil species, are reduced to a single parameter, the exponent, greatly simplifying the uncertainty in sediment transport estimates. By equating the computed cumulative change in sediment transport to the observed effects in the watercourse (i.e., observed or computed total erosion or deposition), the proportion of the observed effects caused by the particular changes in the catchment can be estimated. Such an approach is convenient to apply in large scale watershed studies involving the identification of possible locations in watercourses where further analysis may be needed in order to quantify erosion and deposition effects, and changes due to anticipated urbanization.

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Introduction

Almost all sediment transport relationships found in the literature equate sediment transport capacity or sediment load, in a flow of storm runoff (and where there is ample sediment supply), to flow rate, by use of the well-known power law mathematical model involving two parameters; namely, a coefficient and an exponent. The literature contains numerous references that list sets of load estimation equations, all of which are formulated in terms of a power law relationship (see references). Some equations relate sediment load to flow velocity or flow rate by use of the power law equation. Other equations relate sediment load to flow velocity or flow rate in excess of threshold values. Different power law relationships can be used depending on whether wash load or bed load is of interest. For many situations of interest, where changes in erosion or deposition are primarily due to changes in flowrate (such as due to urbanization and/or diversion effects), and where there is ample sediment supply, the changes in sediment transport trends can be related to the changes in catchment runoff by examining the cumulative changes in the ratio of each storm's sediment transport load for a time history of storm events. Such an approach results in ratios of runoff, for the "before" and "after" conditions, that is a function of only one variable: the power law exponent.

Sediment Transport Relationships

Sediment transport capacity or sediment load, at a fixed point along a watercourse, given ample sediment supply, is typically modeled by a power law equation that relates sediment load (e.g., mass of sediment per unit flow rate) to flow rate or flow velocity, in the form of one of the equations:

$$L = \begin{cases} \alpha_1 Q^{\beta_1} & \text{(1a)} \\ \alpha_2 V^{\beta_2} & \text{(1b)} \\ \alpha_3 (Q-Q_t)^{\beta_3} & \text{(1c)} \\ \alpha_4 (V-V_t)^{\beta_4} & \text{(1d)} \end{cases}$$

where L is the sediment load; the α_i and β_i parameters are held fixed for a particular soil species; Q is flow rate; V is the flow velocity; and Q_t and V_t are a threshold flow rate and flow velocity, respectively, such that load is zero unless the threshold value is exceeded. (These equations can be applied depending on whether wash load or bed load is the focus of the study). Numerous researchers and authors (see reference list) have developed equations to predict values for the above α_i and β_i, resulting in dozens of parameter predictor equations, but the use of the well-known power law, as in the set of equations in Eq. (1), is common to all of these load equations. In general, β values lie in the range of between 1 and 5, with values frequently falling between 2 and 3.

In general, for a fixed point along the watercourse, and with ample sediment supply, and for a particular range of flow rates, a logarithmic stage-discharge relationship can be developed that can be used to transform Eqs. (1b) and (1d) into the form of Eqs. (1a) and (1c), respectively. Therefore, only Eqs. (1a) and (1c) will be carried forward. The use of Eqs. (1a) and (1c) is widespread among practitioners and has found use in numerous standard computer programs and governmental agency policy guidelines (e.g., Los Angeles County Hydrology and Sedimentation Manual, p. 3.10, 1991).

Catchment Runoff Trend Changes

The effects of catchment urbanization include increased impervious areas, changes in stream flow velocities, and flow diversions, among other factors. These alterations generally change flow rates for a given storm, and also change the sediment delivery to the watercourse such as in a reduction in wash load due to the development of land sediment wash load sources.

At a particular point along a watercourse, the parameters used in Eqs. (1a) or (1c) generally remain the same for both the pre- and post-development conditions, for a subject type of soil unless there exist significant differences in channel soil properties with depth. Consequently, the sediment load for both conditions remains predicted by Eqs. (1a) or (1c) under the mild conditions that, for example, erosion (at the subject point) is not limited by sediment supply at that point (in which case a factor may be multiplied to the power law to represent a reduced sediment load) and that sediment supply, such as from wash load, does not alter the load equation parameters (for example, if wash load is reduced, the subject point may be subject to even more erosion than as represented by only considering an increase in flow rates in the equations).

Change in Sediment Transport Load for a Single Event

From the above discussion, a single storm event, can be modeled as a set of unit period flows, over time, such as estimated by a runoff hydrograph procedure, denoted as q_i, i=1,2,...,n, where n is the number of unit periods. Then, for q_i^2 and q_i^1 being the unit period i flow rate for conditions 2 and 1, respectively, of the catchment

$$\frac{L_i^2}{L_i^1} = \frac{\alpha_1 (q_i^2)^{\beta_1}}{\alpha_1 (q_i^1)^{\beta_1}} = \left(\frac{q_i^2}{q_i^1}\right)^{\beta_1} \tag{2}$$

where L_i^2 and L_i^1 are the load estimates from Eq. (1a). A similar equation results from using Eq. (1c) in Eq. (2).

For the total storm event, k, composed of n_k intervals of unit flow rates,

$$\left(\frac{L^2}{L^1}\right)_k = \sum_{i=1}^{n_k} \left(\frac{q_i^2}{q_i^1}\right)_k^{\beta_1} t \tag{3}$$

where L^2 and L^1 are the total loads for the subject single storm event; t is the unit period duration; and the considerations of sediment supply are as discussed previously.

Change in Sediment Transport Load for a Storm History

For m storm events in a storm history, the total ratio of sediment load, for the load estimator of Eq. (1a), is given by

$$\frac{L_t^2}{L_t^1} = \sum_{k=1}^{m} \left(\frac{L^2}{L^1}\right)_k = \sum_{k=1}^{m} \sum_{i=1}^{n_k} \left(\frac{q_i^2}{q_i^1}\right)_k^{\beta_1} \tag{4}$$

where L_t^1 is the total sediment load involved over the storm history, for condition 1, and Eq. (3) applies for each storm event, k. Note that in Eq. (4), a $\beta_1 = 1$ results in the ratio L_t^2/L_t^1 being the ratio of total storm runoff, over the storm history, between the two catchment conditions. It is also noted that a catchment history of changing conditions can be considered in Eq. (4) by simply using the appropriate runoff values. A similar equation to Eq. (4), results in the use of Eq. (1c).

Estimating the Proportion of the Change in Sediment Transport caused by a Particular Change in Catchment Conditions

Equation (4) can be used to estimate the proportion of, for example, observed erosion at a particular location, caused by a change in the catchment (that primarily only causes a change in runoff trends, i.e., the change in runoff trends is the primary factor that explains the change in sediment transport trends).

For example, if the erosion observed at a particular site is depth D_O, occurring over T_O years, and for the total storm history of T_O years Eq. (4) results in

$$\frac{L_t^2}{L_t^1} = r \tag{5}$$

where, for example, condition 1 represents natural unurbanized conditions and condition 2 is the evolving urbanization occurring over the T_O years, then an estimate of the proportion, P, of observed erosion D_O, caused by the changing catchment conditions is

$$P \left\{ k \begin{array}{l} \qquad 0\ ;\ r \quad 1 \text{ (i.e., little change in erosion trends is estimated)} \\ (r - 1)\ ;\ r > 1 \end{array} \right. \tag{6}$$

For example, if $r = 3$ in Eq. (5), then $P = 2.0$, or an increase in erosion rate of 200%, over condition 1, is estimated, and hence about 2/3 of the observed erosion is estimated to have been caused by changing catchment conditions, by use of the above equations and assumptions. Naturally, other factors enter into the above analysis, such as a change in threshold flow rate or flow velocity values, and changes in sediment supply. For example, if wash load is decreased by urbanization, then sediment supply is reduced, and Eq. (6) underestimates the impact of urbanization in increased erosion.

Design Storm Considerations

Many flood control regulatory agencies prescribe use of particular design storm situations as a standard for estimating flood control impacts and criteria for design purposes. The above simple method can be readily applied to the resulting design storm runoff hydrograph as an indicator of locations in watercourses where further study may be needed

Conclusions

With an increased interest in watershed planning and with a focus on use of natural watercourses in an urbanizing watershed, methods are needed for use in identifying possible locations in watercourses where changes in sediment transport may occur. In this paper, a simple method is presented that can be used to help identify watercourse locations where changes in sediment transport might occur due to changes in watershed runoff production. The method is easy to apply, and can be used on design storm hydrology results as a planning tool.

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