Hillslope and channel sediment delivery and impacts of soil erosion on water resources

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ABSTRACT Total soil erosion is less important than the amount of sediment which is retained in stream channels, from a water quality perspective. Estimating the latter is problematic. A physical model is proposed for estimating channel delivery ratios. If an estimate of a drainage basin delivery ratio is available, the model allows a direct estimation of the impact of soil erosion on surface waters.

INTRODUCTION

Sediment derived from soil erosion is a critical pollutant in surface waters. In addition to the adverse water quality impacts of sediment itself, other important contaminants (including some nutrients and pesticides and most heavy metals) are adsorbed to sediment particles, and their delivery to streams depends on soil erosion and sediment transport processes. It is increasingly recognized that the off-site impacts of soil erosion on water resources are often more costly and severe than the on-site impacts on land resources.

Due to the complexity of fluvial sediment systems, reducing the water resource impacts of soil erosion is not a simple matter of reducing upland soil loss. Achieving erosion reduction goals on land may not result in achieving water quality goals. Among other considerations in integrated soil and water management are the following: (1) Not all eroded soil reaches waterways; (2) Tolerable soil losses in terms of upland soil productivity may still exceed assimilative or transport capacities of streams; and (3) Measurements or estimates of upland soil erosion or stream sediment yields may not provide an accurate picture of sources, storage, and sinks of sediment (see Trimble 1977; Meade 1982; Phillips 1986).

The ideal analytical tool for management of soil erosion and sediment pollution is the sediment budget, which allows for an accounting of the sources and fates of eroded material (Phillips 1986). However, detailed sediment budgets are difficult to construct. From a water resource perspective, the most important consideration is how much eroded soil is entering waterways. If erosion surveys or estimates are available, the water resource manager needs to know what proportion of the soil lost from hillslopes is entering waterways within a given time.
frame (usually one year). If sediment yield data are available, the manager needs to know what proportion of the sediment supplied to the stream is being exported. If both erosion and yield are known the water resource manager needs to know what proportion of the eroded soil is being stored as colluvium (where it has no immediate impact on water) and how much is stored as alluvium.

The purpose of this paper is to explore a means for determining a rudimentary sediment budget using relatively easily-obtained data. The goal is to be able to determine what portion of eroded upland soils are delivered to the channel-floodplain system, and what portion of the latter is exported from the drainage basin.

SEDIMENT DELIVERY RATIOS

The sediment delivery ratio (SDR) for a drainage basin (Db) is defined as sediment yield at the basin mouth divided by total upland erosion. It can be expressed as

\[ D_b = \left( \frac{D_s E A D_c}{EA} \right) = D_s D_c \]  

(1)

where E is mean soil loss per unit area in the basin, and A is basin area. Ds is the hillslope SDR, defined as soil loss to streams (including floodplains and other alluvial storage) divided by total slope erosion. Dc is the channel SDR, which is the ratio of sediment yield to total sediment supplied to the channel/floodplain system. If Db and either Dc or Ds are known, eroded sediment can be allocated to upland storage, alluvial storage, and yield, allowing an assessment of impacts of soil erosion on water resources.

There are three basic approaches for determining the basin SDR. One is to measure or estimate both erosion and yield (for reviews of methods and techniques see Mitchell and Bubenzer 1980; Onstad 1984; USDA 1975). A second is to use a nomograph or empirical relationship to estimate the SDR from morphometric and/or hydrologic data (for a review see Walling 1983). This approach is typically used in nonpoint source pollution and erosion-sedimentation assessment handbooks (for example Robillard et al. 1982; McElroy et al. 1976). A third approach is simulation modelling (for reviews see Novotny 1986; DeCoursey 1985; Foster 1982). Presuming the availability of an estimate of the basin SDR, the problem is to estimate Dc or Ds. In the next section a theoretical approach to estimating the channel delivery ratio is presented.

CHANNEL DELIVERY RATIOS

Given a mass of sediment supplied to the stream network, the channel SDR is a function of the stream's ability to transport the imposed sediment load. This transport ability is determined by the energy of the flowing water,
which can be described by Bagnold's (1966; 1977) stream power concept. Stream power is the energy expenditure or work of water flowing downslope. Sediment transport capacity has been shown to be a function of stream power, with transport occurring when a critical threshold is exceeded (Gilley et al. 1985; Govers and Rauws 1986; Bagnold 1966; 1977).

The channel-floodplain system is conceptualized as one where all alluvium is moved and emplaced by streamflow. This assumes that the proportion of sediment delivered directly to floodplains from hillslopes is negligible—consistent with the idea that floodplains are constructed almost entirely by lateral accretion channel deposits and overbank deposition during floods. Thus, if colluvial spillover onto floodplains is ignored, all channel and floodplain material can be viewed as resulting from stream sediment transport and deposition. Then, with the additional assumption of a transport-limited system (or a system where transport and deposition are directly proportional to transport capacity), we can consider the channel SDR as the ratio of sediment transport capacity at the basin mouth to total transport capacity of the upstream network.

Since transport is a function of stream power, power provides an index of sediment transport capacity. The channel SDR can then be described as the ratio of stream power at the basin mouth to total stream power of the upstream drainage network. This assumes that stream power at some index condition is proportional to stream power over a range of flow conditions. This is least likely to be true during very low flows (when lower-order channels may be dry or discontinuous), but significant transport is also unlikely during these low flows.

Using Bagnold's expressions for total stream power of a reach (defined over a whole network; subscript T) and for cross-sectional stream power at a station (the basin mouth; subscript cx), we obtain

\[
D_c = \frac{(wyVs)_{cx}}{(wyVs)_{T}} = \frac{(Qs)_{cx}}{(QsLs)_{T}}
\]

where \( w \) is channel width, \( y \) is depth of flow, \( V \) is mean velocity, \( s \) is energy slope, and \( Ls \) is total stream length.

Use of eq. (2) will yield unrealistically low channel SDRs, because it is appropriate for instantaneous rather than long term conditions. Consider the following generalized relationship:

\[
D_c = hLs
\]

From equation (2), \( h = (wyVs)_{cx}/(wyVs)_{T} \). Equation (2) would also suggest that \( r = 1 \). While this is sufficient for instantaneous conditions, \( r = 1 \) is not realistic for longer time periods. Since deposition thresholds of stream power are smaller than entrainment thresholds,
sediment mobilized within the network has a greater chance of being exported than eq. (2) would suggest—i.e., $r < 1$.

Assuming flow which can be described by the Manning equation (uniform, turbulent, kinematic, steady-state flow), stream power per unit weight of water is a function of the 0.4 power of discharge. Moore and Burch (1986) derived this using Yang's stream power concept (time rate of energy expenditure of flowing water) rather than Bagnold's, but since both Yang and Bagnold's expressions for unit stream power reduce to $Pu = Vs$, Moore and Burch's derivation is valid for Bagnold's stream power. Note also that velocity, which strongly influences stream power, varies as the 0.4 power of discharge. From the Manning equation,

$$V = q s n$$

where $n$ is the Manning roughness coefficient.

A choice of $r = 0.4$ implies a linear increase in discharge with total channel length. This is a reasonable assumption for humid perennial streams. This assumption is also consistent with the idea of the constant of channel maintenance—a given runoff-producing area required to generate flow to create and maintain each linear unit of channel (Schumm 1977).

The expression for the channel SDR is now

$$D_c = (wyVs)_{cx}/(wyVs)_T L_s$$

with a suggested value for $r$ of 0.4.

**UPPER TAR RIVER, NORTH CAROLINA**

The Upper Tar River basin in the lower Piedmont of North Carolina, U.S.A., provides an example of the role of hillslope and channel sediment delivery in water quality management, and an opportunity for preliminary testing of the models above. Previous studies constructed a sediment budget for the 1120 km² basin, examined the implications of the sediment budget on sediment pollution control, and analyzed the stability of the fluvial sediment system (Phillips 1985; 1986; 1987).

The estimated long-term annual average of 53,000 metric tons of sediment per year exported from the basin is believed to represent the sediment transport capacity of the Tar River on an average-annual basis (Phillips 1985; 1986). Total erosion in the basin is estimated at about 690,000 t/yr, with an estimated 198,000 tons delivered to the Tar and its tributaries (i.e., $D_s = 0.29$; USDA 1982; Phillips 1985; 1986). An analysis of several proposed soil erosion control plans showed that any of the plans would still result in more sediment being delivered to the river than the river is able to transport. This suggests a need for point-of-delivery
Hillslope and channel sediment delivery in addition to erosion reduction if water quality goals are to be achieved (Phillips 1986). More generally, the Upper Tar basin studies illustrate the importance of considering slope and channel sediment delivery as well as total soil loss and/or sediment yield in sediment pollution assessment and control.

The estimated sediment budget allows determination of the basin SDR (0.076), and the hillslope SDR was estimated from field data in the earlier studies (Ds = 0.29). Then, from eq. (1), we can determine the channel SDR, which is 0.276. With 198,000 t/yr delivered to streams, the channel SDR implies that an average of 143,353 t/yr is remaining in the channel-floodplain system—about 237 t/yr per km of stream channel. This sediment is causing problems with siltation of fish spawning habitats, disruption of riffle-pool sequences which are critical for some aquatic species, navigation problems due to channel sedimentation, turbidity, and concentration of adsorbed pollutants in benthic sediments.

The Upper Tar may be used for qualitative testing of the channel SDR model. Evaluation of the model proposed above is incomplete. Numerous tests in a variety of watersheds are impractical, as they would require long-term, detailed measurements of hillslope, channel, and basin-scale sediment delivery. Accordingly, tests are at this point qualitative—the model is applied to watersheds where sediment erosion and transport patterns are relatively well known. Results cannot be tested quantitatively, but can be evaluated in terms of their reasonableness in light of what is known about the basin.

Given that Dc is already known for the Upper Tar basin, eq. (3) (with r = 0.4) can be solved for h, the ratio of cross-sectional stream power at the basin mouth to mean cross-sectional power of the entire drainage network. This implies a value of h = 3.58. This value appears to be reasonable. Consider an extreme case of a single channel with a monotonic downstream increase in stream power (a reasonable assumption for humid-region perennial streams such as the Tar River; but not for all rivers). In this case the mean cross-sectional stream power for the whole channel would be roughly half the value at the mouth. Thus h = 2 establishes a theoretical lower limit. Considering a network rather than a single channel, there will be lower-order tributary channels with lower cross-sectional stream power. There is no theoretical upper limit for h, but a value of 3 to 5 for most humid, perennial, alluvial streams seems likely, given the ratios of stream numbers, lengths and drainage areas for different stream orders which have typically been found (Knighton 1984). Thus the 3.58 value found above is in the expected range.

DISCUSSION

The stream power-based method for determining the channel
SDR described here is still under development, and needs further, more detailed field tests. There is also a need for operational refinements, such as developing sampling schemes to determine the mean bankfull hydraulic geometry for the drainage network.

The model depends on a number of assumptions, summarized in Table 1. These are believed to be reasonable in the aggregate for humid perennial streams. However, like any simplifying assumptions, those in Table 1 will be occasionally (or frequently) violated at particular points in space and time. Further examination of the assumptions is therefore prudent, to determine the extent of their applicability and the implications or their violation.

While the model described here cannot yet be offered as the solution to the problem of estimating hillslope and channel sediment delivery within a basin, it does suggest that such a solution exists. The optimal solution is a detailed sediment budget. But a sediment budget is often impractical for widespread application in land and water resource management. The model suggested here requires two basic components: (1) Estimation of a sediment delivery ratio for the entire basin, via field

<table>
<thead>
<tr>
<th>Table 1. Assumptions and Presumptions of the Channel Delivery Ratio Model (see text for further discussion)</th>
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<tr>
<td>1. A basin SDR is known or has been estimated.</td>
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<td>2. Sediment transport capacity is a function of stream power.</td>
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<td>3. The fluvial system being modeled is transport (as opposed to supply) limited, or actual sediment transport is directly proportional to transport capacity.</td>
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<td>4. All channel and floodplain alluvium is emplaced by streamflow (i.e., colluvial spillover into channels and floodplains is negligible).</td>
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<td>5. Stream power over a range of sediment-transporting flow conditions is directly proportional to stream power at bankfull flow (or at some other reference flow).</td>
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<td>6. Flow is uniform, turbulent, kinematic, and steady-state.</td>
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<td>7. Total stream power averaged over time (as opposed to an instantaneous measurement) varies as the 0.4 power of discharge.</td>
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<td>8. Within a particular river system, there is a linear increase in discharge with greater total stream channel length.</td>
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measurements or estimates, empirical equations or nomographs, or simulation modeling; and (2) measurements or estimates of a reference discharge or associated hydraulic geometry at the basin mouth and at a number of locations upstream. These data will generally be more practical for resource managers to obtain than the types of soil, stratigraphic, and chronological data or more detailed field surveys needed to develop a conventional sediment budget (see Dietrich, et al. 1982).

Whether the model proposed here survives future tests or not, there is a clear need for a method of determining hillslope and channel sediment delivery which has reasonable (for resource managers) data requirements. The impact of soil erosion on water resources cannot be fully understood or managed unless there is some understanding of how much eroded soil is reaching waterways, and how much is being stored as alluvium.

REFERENCES


Moore, I.D. & Burch, G.J. (1986) Modeling erosion and deposition: Topographic effects. Trans. ASAE 29,


