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 (icluding 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

$$D_b = (D_s EAD_c)/(EA) = D_s D_c \qquad (1)$$

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 occuring 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 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 discontinous), 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

$$D_c = (wyVs)_{cx} / (wyVsL_s)_T = (Qs)_{cx} / (QsL_s)_T \qquad (2)$$

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:

$$D_c = hL_s^{-r} \qquad (3)$$

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 < l.

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,

$$V = q^{0.4} s^{0.3} n^{-0.6} \tag{4}$$

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

$$D_c = (wyVs)_{cx}/(wyVs)_T \ L_s^{-r} \tag{5}$$

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., Ds = 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

sediment control 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 (D_s =
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 D_c 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 1. Assumptions and Presumptions of the Channel
Delivery Ratio Model (see text for further discussion)

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1. A basin SDR is known or has been estimated.

2. Sediment transport capacity is a function of stream
power.

3. The fluvial system being modeled is transport (as
opposed to supply) limited, or actual sediment transport
is directly proportional to transport capacity.

4. All channel and floodplain alluvium is emplaced by
streamflow (i.e., colluvial spillover into channels and
floodplains is negligible).

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).

6. Flow is uniform, turbulent, kinematic, and steady-
state.

7. Total stream power averaged over time (as opposed to
an instantaneous measurement) varies as the 0.4 power of
discharge.

8. Within a particular river system, there is a linear
increase in discharge with greater total stream channel
length.

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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

Bagnold, R.A. (1977) Bedload transport by natural
     rivers. Wat. Resour. Res. 13, 303-312.
Bagnold, R.A. (1966) An approach to the sediment
     transport problem from general physics. USGS Prof.
     Pap. 422-J.
DeCoursey, D.G. (1985) Mathematical models for nonpoint
     water pollution control. J. Soil Wat. Cons. 40, 408-
     413.
Dietrich, W.E., Dunne, T., Humphrey, N.F. & Reid, L.M.
     (1982). Construction of sediment budgets for
     drainage basins. In: Sediment Budgets and Routing in
     Forested Drainage Basins. U.S. For. Ser. PNW-
     141, Portland, OR, 5-23.
Foster, G.R. (1982) Modeling the erosion process. In:
     Hydrologic Modeling of Small Watersheds (C.T. Haan,
     ed.). Amer. Soc. Ag. Eng. Monog. 5, 295-380.
Gilley, J.E., Woolhiser, D.A. & McWhorter, D.B. (1985)
     Interrill soil erosion. Trans. ASAE 28, 147-159.
Govers, G. & Rauws, G. (1986) Transporting capacity of
     overland flow on plane and irregular beds. Earth
     Surf. Proc. Landf. 11, 515-524.
Knighton, A.D. (1984). Fluvial Forms and Processes.
     Edward Arnold, London.
McElroy, A.D. Chiu, S.Y., Nebgen, J.W., Letti, A. &
     Bennett, F.W. (1976) Loading Functions for
     Assessment of Water Pollution From Nonpoint Sources.
     U.S. Environ. Prot. Agen. EPA-600/2-76-151,
     Washington, D.C.
Meade, R.H. (1982) Sources, sinks, and storage of river
     sediment in the Atlantic drainage of the United
     States. J. Geol. 90, 235-252.
Mitchell, J.K. & Bubenzer, G.D. (1980) Soil loss
     estimation. In: Soil Erosion (M.J. Kirkby, R.P.C.
     Morgan, eds.) John Wiley, New York, 17-62.
Moore, I.D. & Burch, G.J. (1986) Modeling erosion and
     deposition: Topographic effects. Trans. ASAE 29,

1624-1631.
Novotny, V. (1986) A review of hydrologic and water quality models used for simulation of agricultural pollution. In: Agricultural Nonpoint Source Pollution: Model Selection and Application (A. Giorgini, F. Zingales, eds.). Elsevier, New York, 9-36.
Onstad, C.A. (1984) Sediment yield modelling. In: Erosion and Sediment Yield: Some Methods of Measurement and Modelling (R.F. Hadley, D.E. Walling, eds.). GeoBooks, Norwich, U.K., 71-90.
Phillips, J.D. (1985) Soil Conservation, Sediment Control, and the Fluvial Sediment Budget: Analysis and Policy Implications for the Upper Tar River, North Carolina. Pamlico-Tar River Found. Res. Pap. no. 5, Washington, N.C.
Phillips, J.D. (1986) The utility of the sediment budget concept in sediment pollution control. Prof. Geog. 38, 246-252.
Phillips, J.D. (1987) Sediment budget stability in the Tar River basin, North Carolina. Am. J. Sci. 287, 780-794.
Robillard, P.D., Walter, M.F. & Bruckner, L.M. (1982) Planning Guide for Evaluating Agricultural Nonpoint Source Water Quality Controls. U.S. Env. Prot. Ag., Athens, GA.
Schumm, S.A. (1977) The Fluvial System. John Wiley, New York.
Trimble, S.W. (1977) The fallacy of stream equilibrium in contemporary denudation studies. Am. J. Sci. 277, 876-887.
USDA (U.S. Dept. of Agriculture) (1975) Present and Prospective Technology for Predicting Sediment Yields and Sources. USDA ARS-S-40, Washington, D.C.
USDA (U.S. Dept. of Agriculture) (1982) Upper Tar River Erosion Report. USDA Soil Cons. Serv., Raleigh, N.C.
Walling, D.E. (1983) The sediment delivery problem. J. Hydrol. 65, 209-237.