Suspended-Sediment-Transport Rates at the 1.5-Year Recurrence Interval for Ecoregions of the United States: Transport Conditions at the Bankfull and Effective Discharge

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Abstract

Historical flow and suspended-sediment transport data from more than 2,900 sites across the United States have been analyzed in the context of estimating flow and suspended-sediment transport conditions at the 1.5-year recurrence interval flow ($Q_{1.5}$). This is particularly relevant with the renewed focus on stream restoration activities and the urgency in developing water-quality criteria for sediment. Arguments are developed that in lieu of form-based estimates of say the bankfull level, a flow of a given recurrence interval ($Q_{1.5}$) is more appropriate to integrate suspended-sediment transport ratings for the purpose of defining long-term transport conditions at a site. At the $Q_{1.5}$ the highest median suspended-sediment concentrations occur in semi-arid environments the highest yields occur in humid regions with erodible soils and steep slopes or channel gradients. Suspended-sediment yields for stable streams are used to determine "background" or "reference" sediment-transport conditions in eight ecoregions where there is sufficient field data. The median value for stable sites within a given ecoregion are generally an order of magnitude lower than for non-stable sites.

Keywords: TMDL, bankfull, effective discharge

Introduction

Sediment is listed as one of the principle pollutants of surface waters in the United States, both in terms of sediment quantity ("clean sediment") and sediment quality due to adsorbed constituents and contaminants. Fully mobile streambeds, and deposition of fines amidst interstitial streambed gravels can pose hazards to fish and communities of benthic macro-invertebrates by disrupting habitats, degrading spawning habitat, and reducing the flow of oxygen through gravel beds. Although lethal or sub-lethal levels are unknown at this time, high concentrations of suspended sediment, perhaps over certain durations can adversely affect those aquatic species that filter and ingest water. It is critical, therefore, to clearly identify the potential functional relation between an impact due to sediment and the sediment process so that appropriate parameters are analyzed.

Hundreds of thousands of kilometers of stream channels have been designated as being impaired due to sediment. States, Territories and Tribes are required to determine the maximum allowable loadings to, or in a stream that does not impair the "designated use" of that particular water body. This measure has been termed a "TMDL" (total maximum daily load). However, this by no means indicates that a TMDL for sediment transport should be expressed in terms of a total load, or a daily-maximum load. In fact neither of these metrics is probably appropriate for sediment and other means of describing reference, impacted and impaired sediment-transport conditions at a site are more meaningful and scientifically defensible. In lieu of form-based estimates of the bankfull level, a flow of a given frequency and recurrence interval is perhaps more appropriate to integrate suspended-sediment transport rates for the purpose of defining long-term transport conditions at sites from diverse regions.

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Bankfull and effective discharge

The *bankfull discharge* is the maximum discharge that can be contained within the channel without overtopping the banks (Leopold et al. 1964) and generally accepted to represent the flow that occurs, on average, every 1.5 years ($Q_{1.5}$). Dunne and Leopold (1978) described the discharge at the bankfull stage as the most effective at forming and maintaining average channel dimensions. This has led to the term “bankfull discharge” being often used interchangeably with the terms “effective discharge,” “channel-forming discharge,” and “dominant discharge.” One of the primary reasons for this confusion is that originally defined bankfull discharge and the dimensions represented by hydraulic geometry relations refer to stable channels. A bankfull level in unstable streams can be difficult to identify particularly in erosional channels because of a lack of depositional features and because channel dimensions, including water-surface elevations (of specific discharges), are changing with time. In searching for a meaningful discharge or range of discharges to compare sediment-transport rates it may be best to avoid form-based “bankfull” criteria, instead using a consistent flow-frequency value that can be linked to geomorphic processes, alluvial channel form, and hence, sediment-transport rates, such as the effective discharge.

The *effective discharge* is the discharge or range of discharges that transports the largest proportion of the annual suspended-sediment load over the long term (Wolman and Miller 1960). Pickup and Warner (1976) found the return period of the effective discharge to range between 1.15 and 1.4 yr (using the annual maximum series) using bed load transport equations to estimate sediment transport.

The purpose of the research reported here was to test the hypothesis that suspended-sediment concentrations and yields could be regionalized for the conterminous United States. Although clean sediment can adversely affect habitat and other designated uses in a variety of ways, this paper will be limited to discussions and analysis of methods and techniques for analyzing impacts due to suspended sediment.

Availability of Data and Regionalization

Analysis of suspended-sediment transport at the national scale requires a large database of suspended-sediment concentrations with associated instantaneous water discharge. Data of this type permit analysis of sediment-transport characteristics and the development of rating relations (Glysson 1987). The U.S. Geological Survey (USGS) has identified more than 6,000 sites nationwide where at least 1 matching sample of suspended sediment and instantaneous flow discharge have been collected (Turcios and Gray 2001). At more than 2,900 of the sites there is sufficient data (minimum of 30 matching samples) to develop relations between flow and suspended-sediment concentration and load. This massive historical database serves as the foundation for analyzing sediment-transport characteristics over the entire range of physiographic conditions that exist in the United States. It should be stressed that the sediment-transport rates reported here represent two phases of sediment movement; wash load (generally silts and clays) and suspended bed-material load (generally sands) but excludes bed load. Stream systems dominated by bed load, therefore, may not be well represented here.

To be potentially useful for practitioners in stream restoration and water quality studies, sediment-transport relations derived from this existing database must be placed within a conceptual and analytical framework such that they can be used to address sediment-related problems at sites where no such data exist. Sediment-transport characteristics and relations need to be regionalized according to attributes of channels and drainage basins that are directly related to sediment production and transport. In the following eight ecoregions a sufficient number of sites were visited to determine relative channel stability, thereby providing a basis to compare differences in suspended-sediment transport between stable and unstable sites: Coast Range (#1), Northern Rockies (#15), Arizona/New Mexico Plateau (#22), Flint Hills (#28), Central Irregular Plains (#40), Middle Atlantic Coastal Plain (#63), Southeastern Plains (#65), Mississippi Valley Loess Plains (#74). A stable channel is one that over a period of years does not experience net changes in width, depth, gradient, or planform and can essentially transport all sediment delivered from upstream without net erosion or deposition.

Methods

Effective discharge calculations

To provide a check on the validity of the $Q_{1.5}$ as an estimate of the effective discharge for suspended sediment a three-step process is required: (i) construct a flow-frequency distribution; (ii) construct a sediment-transport rating relation; and (iii) integrate the two relations by multiplying the sediment-transport rate for a specific discharge class by that discharge.

The discharge class with the maximum product is defined as the effective discharge (Andrews 1980). The flow data used for this analysis should be of the greatest available frequency, such as those corresponding to 15-minute stage data, but these are often hard to obtain. We were able to obtain 15-minute flow data for 10 sites located in Mississippi, and in lieu of the 15-minute flow data, mean-daily flow data were obtained for about 500 sites representing 17 different ecoregions. Flow data were ranked and then subdivided into 33 discharge classes (Yevjevich 1972). This procedure was used for the 10 sites in Mississippi and the other 500 sites across the United States to test the recurrence interval of the effective discharge.

Suspended-sediment transport rating relations

A first approximation, suspended-sediment transport rating (Glysson 1987, Simon 1989a) of discharge versus concentration was plotted in log-log space and regressed with a power function. Trends of these data often increase linearly and then break off and increase more slowly at high discharges because although sand concentrations continue to increase with discharge, the silt-clay fraction attenuates, causing the transport relation to flatten. To alleviate the problem of overestimation of concentrations at high flow rates caused by this attenuation, a second (or even third) linear segment (in log-log space) is often fitted with the upper end of the data set (Simon 1989a). The concentration at the midpoint of each discharge class is then calculated from the rating relation and multiplied by the discharge and its percent occurrence. The discharge class containing the highest value is, by definition, the effective discharge.

Recurrence interval of the effective discharge for suspended sediment

The effective discharge (Q_{eff}) was calculated using the above procedure for the 10 sites in Mississippi using 15-minute flow data and the other 500 sites using mean-daily flow data. Results show, that for a given ecoregion, the median recurrence interval of the effective discharge for suspended sediment ranges from 1.1 to 1.7 yr. The $Q_{1.5}$ was obtained for all sites from log-Pearson III analysis of the annual-maximum series and compared to the effective discharge calculated by the above procedure. For the 10 Mississippi streams analyzed, the $Q_{1.5}$ proved to be a good approximation being on average, about 10% greater than the calculated effective discharge (Simon et al. 2001). Results from the other ecoregions show, as expected, a greater range given the diversity of geomorphic conditions, with the median ratio of Q_{eff} to $Q_{1.5}$ between 0.6 to 1.3. Still, results showing the remarkably consistent recurrence interval value for the effective discharge indicate that using the $Q_{1.5}$ as a *measure* of estimating the effective discharge at the remaining study sites is reasonable. We may then be able to extend this argument to the bankfull discharge given the numerous authors that have found that the bankfull and $Q_{1.5}$ discharges are similar for regions as diverse as the arid American Southwest (Odem et al. 1999) and the Pacific Northwest (Castro and Jackson 2001).

The consistent results supporting the use of the $Q_{1.5}$ as a measure of the effective discharge are not meant to be definitive for all streams in every ecoregion of the United States but as a mechanism to define and compare suspended-sediment transport rates from historical datasets from the different ecoregions spanning the country. Further, the selection of a single flow frequency, in this case the $Q_{1.5}$, provides a degree of internal consistency by which to compare suspended-sediment transport rates from diverse regions of the United States.

Regional flow relations at the $Q_{1.5}$

The annual maximum peak-flow series for each of the sites with available data was used to calculate the effective discharge ($Q_{1.5}$) from the log-Pearson Type III distribution. The resulting $Q_{1.5}$ data were sorted by Level III ecoregion and regressed with drainage area. In eight of the ecoregions, there were an insufficient number of sites to develop regression relations. Of the remaining 76 ecoregions, 75% of the derived relations included at least 17 sites and had r^2 values of at least 0.60; 50% of the relations included at least 27 sites and had r^2 values of 0.80.

Suspended-sediment transport rates at the effective discharge by Level III ecoregion

Using the procedures for developing suspended-sediment transport relations and the $Q_{1.5}$ described above, values of concentration and yield (load divided by drainage area) were obtained for each site. This was accomplished by applying the calculated $Q_{1.5}$ to the suspended-sediment rating relation to obtain the transport rate. So as not to extrapolate relations beyond measured bounds, sites were excluded from the analysis if the $Q_{1.5}$ exceeded the maximum sampled discharge by 50% or more. The remaining dataset (2430 sites) was sorted by ecoregion to differentiate between regional trends in suspended-sediment transport. Suspended-sediment transport data at the $Q_{1.5}$ are reported in terms of concentration (mg/l) and also as a yield (t/d/km^2) to compare streams of varying size within ecoregions.

Results

Values of suspended-sediment transport within a single ecoregion may represent a broad range of conditions including various states of channel and watershed stability, dominant bed-material size class, and anthropogenic influence. Still, about 70% of the ecoregions have inter-quartile ranges for suspended-sediment yield within a single order of magnitude. Large inter-quartile ranges (two orders of magnitude) in ecoregions such as the Mississippi Valley Loess Plains (#74), Coast Range (#1), and Northern Piedmont (#60) represent areas where anthropogenic disturbances combined with erodible soils and high, seasonal rainfall create conditions for large increases in suspended-sediment yields.

Measured suspended-sediment concentrations at the $Q_{1.5}$ reached more than 100,000 mg/l in some of the semiarid streams of the southwest such as in the Arizona/New Mexico Plateau (ecoregion 22). In fact, ecoregions in this part of the United States have some of the highest median concentrations in the nation owing to large quantities of available sediment in storage, limited vegetative cover, and the flashy nature of runoff events. Examples of these ecoregions include the Southwest Tablelands (#26; 9530 mg/l), Mojave Basin and Range (#14; 5150 mg/l), and the Arizona/New Mexico Plateau (#22; 4140 mg/l). Midwestern ecoregions such as the Central Great Plains (#27; 3770 mg/l), the Nebraska Sand Hills (#44; 2110 mg/l), and the Mississippi Valley Loess Plains (MVLP) (#74; 2170 mg/l) also showed high median values at the $Q_{1.5}$. Of these, only the MVLP can be considered a humid region and the high median concentration reflects the highly erodible nature of the loess hills and the generally unstable conditions of the stream systems. As expected, the lowest values occurred in ecoregions characterized by gently sloping gradients such as the Southern and Middle Atlantic Coastal Plains (#s 75 and 63, respectively) and those characterized by shallow soils and resistant bedrock such as the Northern Rockies (#15) and the Laurentian Plains and Hills (#82).

A somewhat different picture of peak values emerges from the national distribution of suspended-sediment yields at the $Q_{1.5}$. The highest median-yield values occur in humid regions such as the MVLP (#74; 173 t/d/km^2) and the Coast Range (#1; 55.8 t/d/km^2) where plentiful flow energy is available for sediment transport and where over-steepened channel gradients in the case of the former and accelerated mass wasting in upland areas in the case of the latter produce high suspended-sediment yields. Areas of the semiarid southwest have moderate suspended-sediment yield values where flows tend to attenuate rapidly downstream through infiltration, thereby reducing transport rates with increasing drainage area. The geographic distribution of lowest median yields shows a similar pattern to the distribution of the lowest median concentrations. Differentiation based on Level III ecoregion is further supported by the expected systematic decrease in both median concentrations and yields as one moves downslope from the Blue Ridge (#66) through the Piedmont (#45), Southeastern Plains (#65) to the Middle Atlantic (#63) and Southern (#75) Coastal Plains.

These yield results differ somewhat from the classic paper by Langbein and Schumm (1958) who reported peak annual sediment yields in semiarid environments where the dominant vegetation type changed from desert shrub to grassland. Whereas our results showed some of the highest suspended-sediment concentrations in these areas, the greatest median yield values in the continental United States occurred in the humid, yet unstable systems of the MVLP and the Coast Range of the Pacific Northwest. Ample supplies of precipitation and flow energy in the disturbed streams of the MVLP provided large quantities of channel sediments, particularly streambank materials, while mass wasting of disturbed uplands areas in the Coast Range made available plentiful amounts of sediment that produced great quantities of suspended sediment per unit area. Areas of the lower Midwest and areas flanking the Appalachians showed moderately high suspended-sediment yields. The relatively high values for these areas could largely be due to land disturbances and the consequent remobilization of historically stored sediment.

Background or “reference” suspended-sediment transport conditions

Rates and concentrations of suspended-sediment transport vary over time and space due to factors such as precipitation characteristics and discharge, geology, relief, land use, and channel stability. It is unreasonable to assume that “natural” or background rates of sediment transport will be consistent from one region to another. Within the context of channel design for stream restoration and developing water quality targets for sediment, there is no reason to assume then that “target” values should be consistent on a nationwide basis. Similarly, it is unreasonable to assume that channels within a given region will have consistent rates of sediment transport. This reflects differences in the magnitude and perhaps type of erosion processes that dominate a subwatershed or stream reach.

To identify those sediment-transport conditions that represent impacted or impaired conditions, one must first be able to define a nondisturbed, stable, or “reference” condition for the particular stream reach. In some schemes, the “reference” condition simply means “representative” of a given category of classified channel forms or morphologies (Rosgen 1985) and as such may not be analogous with a “stable,” “undisturbed,” or “background” rate of sediment production and transport. Although the Rosgen (1985) stream classification system is widely used to describe channel form, stream types D, F, and G are, by definition, unstable (Rosgen 1996). These stream reaches, therefore, would be expected to produce and transport enhanced amounts of sediment and represent impacted conditions. Thus, although it may be possible to define a “representative” reach for stream types D, F, and G, a “reference” condition transporting “natural” or background rates of sediment will be difficult to find.

As an alternative scheme, the channel evolution frameworks set out by Schumm et al. (1984) or Simon and Hupp (1986) and Simon (1989b) are proposed. With stages of channel evolution tied to discrete channel processes and not strictly to specific channel shapes, they have been successfully used to describe systematic channel-stability processes over time and space in diverse environments subject to various disturbances. An advantage of a process-based channel-evolution scheme is that Stages I and VI represent two true “reference” conditions. In some cases, such as in the midwestern U.S. where land clearing activities near the turn of the twentieth century caused massive changes in rainfall-runoff relations and land use, channels are unlikely to recover to Stage I, pre-modified conditions. Stage VI, re-stabilized conditions are a more likely target under the present regional land use and altered hydrologic regimes and can be used as a “reference” condition. However, in pristine areas where disturbances have not occurred or where they are far less severe, Stage I conditions can be used as a reference.

The working hypothesis for determining background or “reference” values for suspended-sediment transport in this study is that stable channel conditions and therefore background or “natural” sediment transport rates can be represented by channel evolution Stages I and VI. As expected, Stage VI sediment-yield values are considerably lower for each quartile measure in each of the ecoregions. The median value for stable sites within a given ecoregion are generally an order of magnitude lower than for nonstable sites. The results show a four order-of-magnitude range of median “reference” values for the eight ecoregions, further supporting the premise that water quality targets for sediment need to be done at least at the Level III ecoregion scale, if not smaller. These results should be considered preliminary as more sites in each of the ecoregions are evaluated for stage of channel evolution, and the data set is further differentiated by dominant bed-material size class.

Summary and conclusions

Using the ecoregion concept devised by Omernik (1995), historical flow and suspended-sediment transport data from more than 2,900 sites nationwide have been analyzed to develop regional-flow curves and suspended-sediment transport rates for each ecoregion. Data from about 500 sites across the U.S. were used to calculate the recurrence interval of the effective discharge for suspended sediment transport. Median values for the 17 ecoregions tested ranged from 1.1 to 1.7 yr. Thus, the $Q_{1.5}$ proved to be a reasonably good measure of the effective discharge for suspended sediment and was used in conjunction with derived suspended-sediment transport relations to calculate concentrations and yields at all sites. Peak median concentrations occurred in the semiarid areas of the southwestern U.S., while maximum yields occurred in the Mississippi Valley Loess Plains and the Coast Range. Background or “reference” suspended-sediment transport conditions were determined by sorting the data into stable and unstable sites using the Simon and Hupp (1986) and

Simon (1989b) model of channel evolution and by taking the median value for stable sites (Stages I and VI) in a given ecoregion.

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