“Reference” and Enhanced Rates of Suspended-Sediment Transport for Use in Developing Clean-Sediment TMDL's: Examples from Mississippi and the Southeastern United States

Andrew Simon, Roger Kuhnle, Scott Knight and Wendy Dickerson
USDA-Agricultural Research Service, National Sedimentation Laboratory, P.O. Box 1157,
Oxford, MS 38655; simon@sedlab.olemiss.edu

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. We can view sediment-transport rates and amounts as (1) “natural” or background, resulting from generally stable channel systems, (2) “impacted”, with greater transport rates and amounts, reflecting a disturbance of some magnitude and more pervasive erosion, and (3) “impaired”, where erosion and sediment transport rates and amounts are so great that biologic communities and other designated stream uses are adversely effected. Impairment of designated stream uses by clean sediment (neglecting adsorbed constituents) may occur through processes that occur on the channel bed or by processes that take place in the water column. Fully mobile streambeds, and deposition of fines amidst interstitial streambed sands and gravels can pose hazards to fish and benthic macro-invertebrate communities by disrupting habitats, degrading spawning habitat, and reducing the flow of oxygen through gravel beds. Although lethal or sub-lethal thresholds 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.

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. The USDA-Agricultural Research Service, National Sedimentation Laboratory (ARS), is conducting analytic research on suspended-sediment transport and clean-sediment TMDL development throughout the United States. This paper, however, focuses on work conducted in the southeastern United States, predominantly in Mississippi where field efforts have been initially focused. The work described in this paper was made possible by USDA-Agricultural Research Service discretionary research funds, a cooperative project with the U.S. Environmental Protection Agency, and support from the Mississippi Department of Environmental Quality.

Some Critical Issues

Availability of Data

Analysis of the impacts of suspended sediment requires a 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 (Porterfield, 1972). Collection of suspended-sediment data is time consuming and expensive in that it must take place over a broad range of flows to accurately evaluate the sediment-transport regime at a site. However, the U.S. Geological Survey (USGS) has identified more than 2,900 sites nationwide where at least 30 matching samples of suspended sediment and instantaneous flow discharge have been collected (Turcios and Gray, 2001). More than 400 of these sites coincide with locations that have been listed by States as being impaired in one way or another by sediment. Table 1 provides a list of the general cause of impairment due to sediment as interpreted by the States (U.S. EPA, 2001, written commun.) At many of the 2,900 sites, data on the particle-size distribution of suspended- and bed-material sediment are also available. Kuhnle and Simon (2000) identified additional sites containing data collected by the USGS and other agencies such as the ARS at their experimental watersheds. 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, including Hawaii and the island of Puerto Rico.

Table 1 – Causes of impairment due to clean sediment listed by States, Territories and Tribes.

Accumulated sediment	16
Erosion	2
Fine sediment	9
Sediment	1021
Sedimentation	144
Sedimentation/ siltation	98
Siltation	2972
Siltation /turbidity	21
Sludge/sediment	1
Solids	3
Stream bottom deposits	99
Suspended sediment	99
Suspended solids	1128
TSS	31
TTS	1
Turbidity	709
TOTAL	**6354**

Data from U.S. EPA Office of Water, February 2001.

To be useful for TMDL practitioners in States, Territories and Tribes, sediment-transport relations derived from this existing database must be placed within a conceptual and analytic framework such that they can be used to address sediment-related problems at sites where no such data exists. To accomplish this, sediment-transport characteristics and relations need to be regionalized according to attributes of channels and drainage basins that are directly related to sediment production, transport, and potential impairment. In a general way, these attributes include among others, physiography and ecology, differentiated collectively as an ecoregion (Omernik, 1995), and dominant stream-channel processes (channel stability), differentiated as stage of channel evolution (Simon and Hupp, 1986; Simon, 1989a). Figure 1 shows the locations of the existing historical suspended-sediment data by Level III ecoregion.

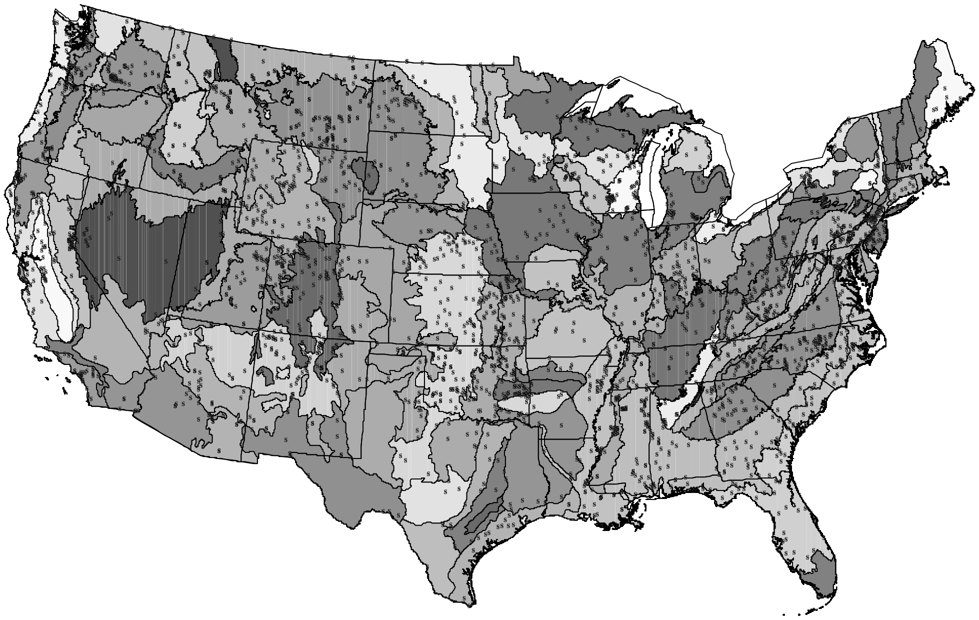

Figure 1 – Level III ecoregions of the continental United States showing locations of sites with at least 30 samples of suspended sediment and associated flow discharge.

Sites in three ecoregions containing 154 sites were analyzed for this study. They are:

1. Mississippi Alluvial Plain, incorporating parts of Arkansas, Louisiana, Mississippi, and Tennessee;
2. Mississippi Valley Loess Plains, incorporating parts of Kentucky, Mississippi, and Tennessee; and
3. Southeast US Plains, incorporating parts of Alabama, Florida, Georgia, Maryland, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia.

Because this study is ongoing (May 2001), field evaluations of channel characteristics have been accomplished only in Mississippi and West Tennessee.

“Reference” 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, among others. There is no reason to assume that “natural” or background rates of sediment transport will be consistent from one region to another. Within the context of clean-sediment TMDLs, it follows that there is no reason to assume then that “target” values should be consistent on a nationwide basis. Similarly, there is no reason to assume that channels within a given region will have consistent rates of sediment transport. For example, unstable channel systems or those draining disturbed watersheds will produce and transport more sediment than stable channel systems in the same region. This reflects differences in the magnitude and perhaps type of erosion processes that dominate a sub-watershed or stream reach.

In order to identify those sediment-transport conditions that represent impacted or impaired conditions, it is essential to first be able to define a non-disturbed, 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 the author’s own definitions, unstable (Rosgen, 1996, p. 4-5). These stream reaches, therefore, would be expected to produce and transport enhanced amounts of sediment and represent impacted, if not impaired conditions. Thus, although it may be possible to define a “representative” reach of stream types D, F, and G, for the purpose of TMDL development, a “reference” condition transporting “natural” or background rates of sediment will be exceedingly difficult to find.

As an alternative scheme for TMDL practitioners, the channel evolution framework set out by Simon and Hupp (1986) is proposed (Figure 2). 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 such as stream response to: channelization in the Southeast US Coastal Plain (Simon, 1994); volcanic eruptions in the Cascade Mountains (Simon, 1992); and dams in Tuscany, Italy (Rinaldi and Simon, 1998). Because the stages of channel evolution represent shifts in dominant channel processes, they are systematically related to suspended-sediment and bed-material discharge (Simon, 1989b; Kuhnle and Simon, 2000; Figure 3a and b), fish-community structure (Figure 4), rates of channel widening (Simon and Hupp, 1992), and the density and distribution of woody-riparian vegetation (Hupp, 1992). Finally, the nine sequences of Rosgen stream types outlining temporal variations in channel morphology as shown in Rosgen (2001) are essentially all the same stages of channel evolution.

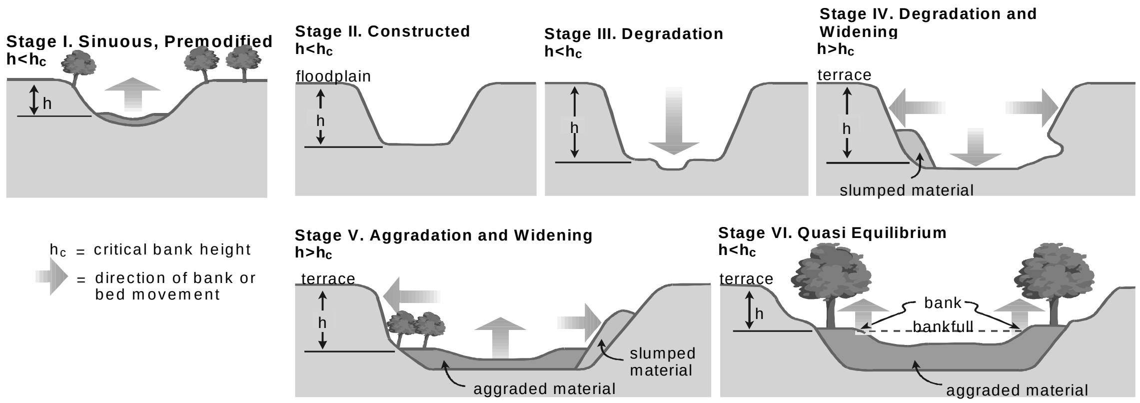

Figure 2 – Six stages of channel evolution from Simon and Hupp (1986) and Simon (1989a) identifying Stages I and VI as “reference” conditions for given ecoregions.

An advantage of a process-based channel-evolution scheme for use in TMDL development is that Stages I and VI represent two true “reference” conditions. In some cases, such as in the Midwestern United States where land clearing activities near the turn of the 20th 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 (Simon and Rinaldi, 2000) and can be used as a “reference” condition. However, in pristine areas where disturbances have not occurred or where disturbances have been far less severe, Stage I conditions can be used as a realistic “reference” target.

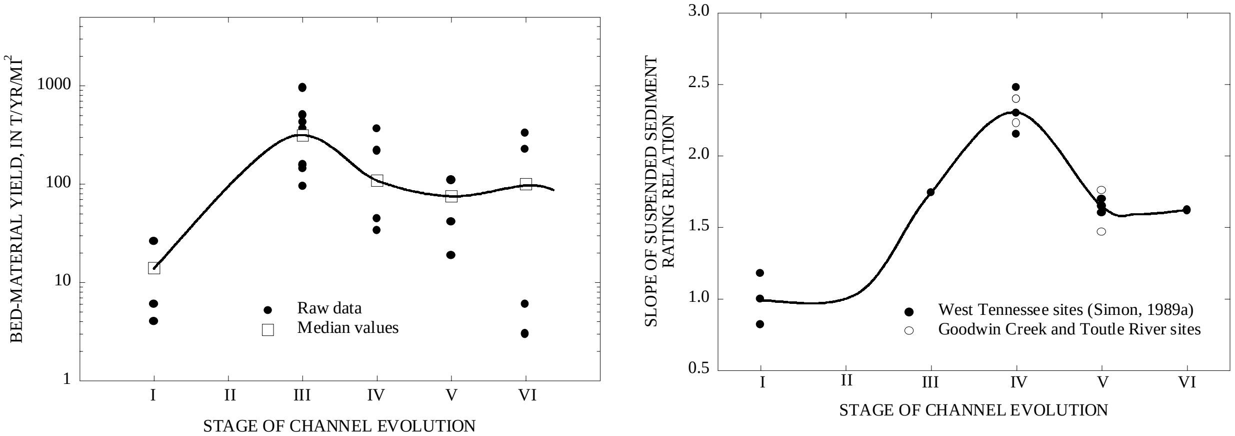

Figure 3 – Relation between stages of channel evolution and (A) bed-material discharge, and (B) suspended-sediment transport rate.

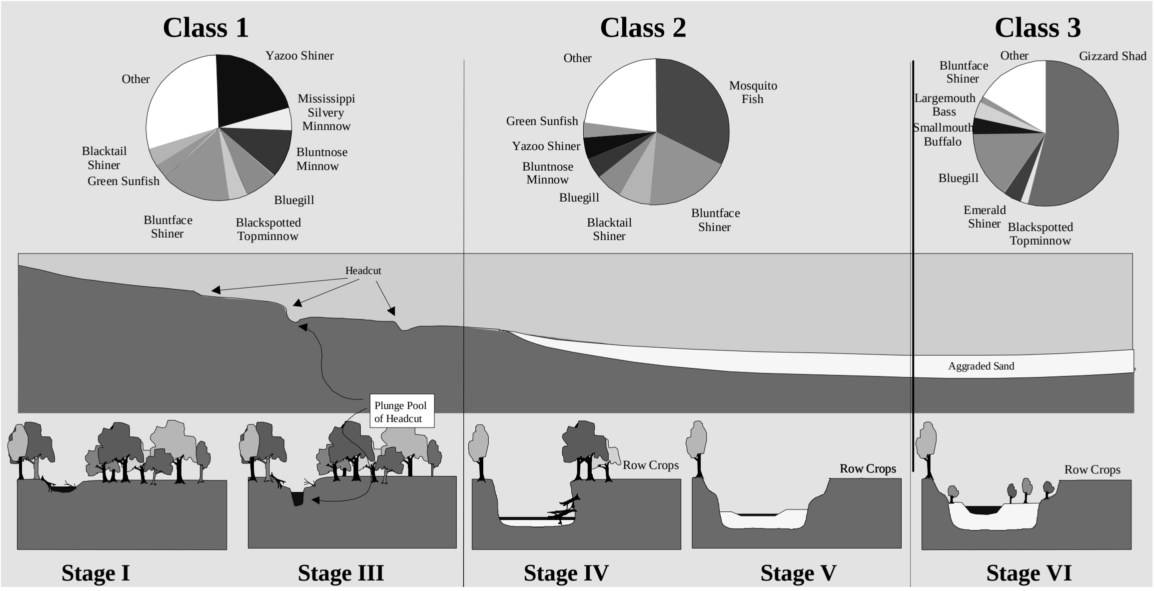

Figure 4 – Fish communities associated with stage of channel evolution for warm water streams in Mississippi.

Analysis of Suspended-Sediment Data

Analysis of suspended-sediment transport data involves establishing some type of relation between flow and sediment concentration or load. Instantaneous-concentration data combined with either an instantaneous flow value or flow data representing the value obtained from the stage-discharge relation at 15-minute intervals are best. Mean-daily values of both flow and sediment loads, which are readily available from the USGS tend to be biased towards lower flows, particularly in flashy basins. For establishing sediment-transport rating relations, instantaneous concentration and 15-minute flow data were used from USGS and ARS gauging station records. The resulting relation can be evaluated in several ways:

1. Slope of the rating relation (rate of increase in concentration/load and indicative of sediment availability in the watershed and channel system with increasing flow (Simon, 1989b; Kuhnle and Simon, 2000);
2. Coefficient of the rating relation (concentration/load at a low/base flow and indicative of background levels from the channel system);
3. Frequency and duration of suspended-sediment transport for given concentrations/loads that may represent threshold, sub-lethal or lethal levels for organisms (Kuhnle and Simon, 2000); and
4. Concentration/load at the "effective" discharge.

The "effective discharge" is defined as that discharge or range of discharges that shape channels and perform the most geomorphic work (transport the most sediment) over the long term. As such, sediment concentrations or loads at the effective discharge(s) can serve as useful indicators of regional suspended-sediment transport conditions for "reference" and impacted sites. In many parts of the United States, the effective discharge is approximately equal to the peak flow that occurs on average, about every 1.5 years ($Q_{1.5}$; for example, Andrews, 1980; Andrews and Nankervis, 1995) and may be analogous to the bankfull discharge in stable streams. Using data from 55 streams, Nash (1994) questioned the validity of the effective discharge occurring on about 1-year intervals based on concerns of transport variability and the difficulty of describing the relation between suspended-sediment concentration and water discharge with a power function. The recurrence interval for the effective discharge in this study was calculated for 10 streams in Mississippi.

Calculating Effective Discharge ($Q_{1.5}$)

Calculating the effective discharge is a matter of integrating a flow-frequency curve with a sediment-transport rating to obtain the discharge (range of discharges) that transports the most sediment. This was accomplished at the 10 sites where we could readily obtain the complete 15-minute flow record. The 15-minute flow data for the period of record was initially ranked in ascending order, the data separated into 25-33 logarithmic classes, and the percentage of time that flows of each class occurred was calculated. The next step was to develop a first approximation suspended-sediment transport rating (Porterfield, 1972; Simon, 1989b) by plotting discharge versus concentration in log-log space and obtaining a power function by regression (Figure 5a). Trends of these data (in log-log space) often increase linearly and then break off and increase more slowly at high discharges. Preliminary analyses of the studied streams show that although sand concentrations continue to increase with discharge, the silt-clay fraction attenuates, causing the transport relation to flatten. A simple transport rating developed with a single power function and with this kind of data trend commonly over-estimates concentrations at high flow rates, leading to significant errors in calculating annual loads and the effective discharge. To alleviate this problem, a second linear (in log-log space) segment is often developed with the upper end of data set (Figure 5b). This adjustment to the upper end of the rating directly addresses one of Nash's (1994) concerns regarding the use of a single power function to describe the relation between flow and sediment discharge over the entire range of flows. Following calculation of a second power function to define sediment transport at high discharges, the concentration at the midpoint of each discharge class is then calculated from the rating relation(s) and multiplied by the discharge and its percent occurrence. The sum of these values represents the average annual suspended-sediment load, and the discharge class containing the highest value by definition, is the effective discharge. For the 10 streams analyzed here, the $Q_{1.5}$ is again, on average, a good approximation (Table 2) and was used, therefore, as a measure of establishing the effective discharge at the remaining study sites.

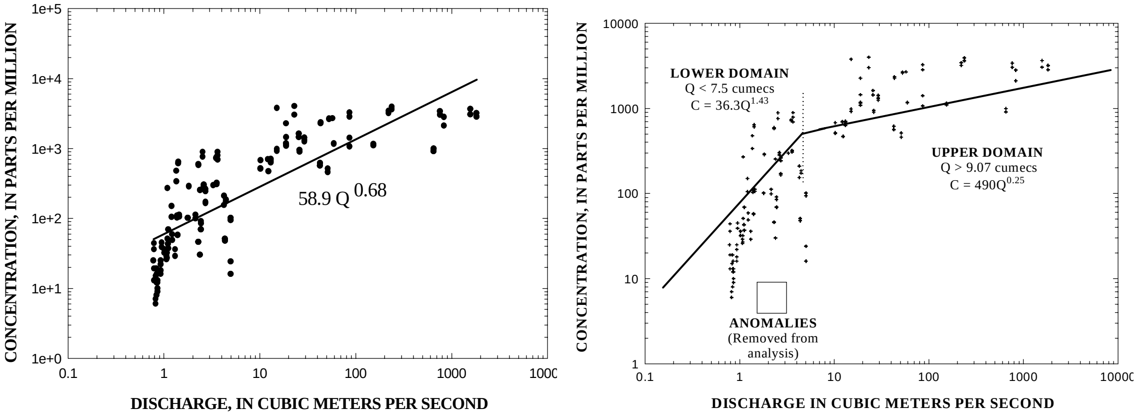

Figure 5 –Example of adjusting upper end of sediment-transport rating to reduce error in estimating the effective discharge.

Table 2—Comparison of $Q_{1.5}$ and effective discharge for 10 Mississippi streams showing close agreement.

Site	**Effective load class** m^3/s	**Q 1.5** m^3/s	**Q1.5/Qeff**
Abiaca21-Cr	**45.1**	**72.0**	**1.596**
Abiaca6-SP	**67.1**	**114**	**1.699**
Batupan	**332**	**272**	**0.820**
Fannegusha	**235**	**171**	**0.729**
Harland	**146**	**156**	**1.068**
Hickahala	**228**	**235**	**1.031**
Hotophia	**264**	**97**	**0.367**
Long	**250**	**333**	**1.332**
Otoucalofa	**85.7**	**152**	**1.779**
Senatobia	**196**	**284**	**1.449**
AVERAGE			**1.187**
MEDIAN			**1.200**

Using the annual-maximum peak-flow series for each of the 154 sites with available data, the effective discharge ($Q_{1.5}$) was then calculated from the log-Pearson Type III distribution

(Figure 6a). Where peak-flow data were not available, the $Q_{1.5}$ was calculated from regional relations based on drainage area obtained from the U.S. Geological Survey (1993) and calculated in this study.

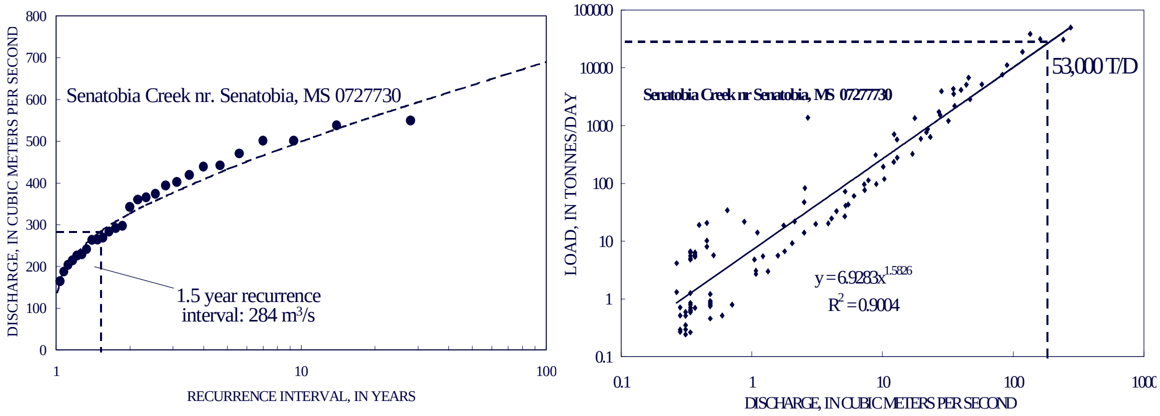

Figure 6 – (A) Obtaining the Q1.5 (effective discharge) from the log-Pearson Type III distribution, and (B) suspended-sediment load at the effective discharge.

Sediment Yield at the Effective Discharge

Once the effective discharge ($Q_{1.5}$) was determined at all sites, that discharge was applied to the transport relation for each site to obtain the sediment load at the effective discharge (Figure 6b). To normalize the data for differences in basin size, the sediment load was then divided by the site's drainage area to obtain the sediment yield at the effective discharge (in tonnes/day/km^2). Before the calculated sediment yield was accepted as reliable, particularly where values exceeded 1,000 t/d/km^2, the rating relation was checked to be sure that the upper end was accurately defined and that the $Q_{1.5}$ was within the measured bounds of the data set. If the $Q_{1.5}$ was more than 50% greater than the maximum sampled discharge, the calculated effective sediment yield was not included. Finally, the data were then sorted by ecoregion to establish the range and distribution of sediment yields that could be used as a relative measure of sediment production, transport, and degree of impairment.

For the 154 study sites in the three ecoregions investigated in the southeastern United States, values ranged over about five orders of magnitude, from 0.01 t/d/km^2 in the Mississippi Alluvial Plain (MAP) to about 830 t/d/km^2 in both the Mississippi Valley Loess Plains (MVLP) and the Southeast US Plains (SEP). Without adjustment of the upper end of many of the transport-rating relations (Figure 5b), erroneous estimates of sediment yield as great as tens of thousands of t/d/km^2 would have been reported. Notwithstanding the similar maximum-yield values for the MVLP and SEP ecoregions, the MVLP ecoregion clearly produces the greatest amount of sediment in the region (Figure 7). This is in part due to: (1) the highly erodible nature of the silt-sized sediment that dominates the region, and (2) the extensive channel dredging and straightening that has taken place in the region over the past century in response to land clearing and subsequent channel filling.

Quartile measures are used in Figure 7 to define the distribution of sediment-yield values because the data are non-normally distributed. While the minimum and maximum values provide

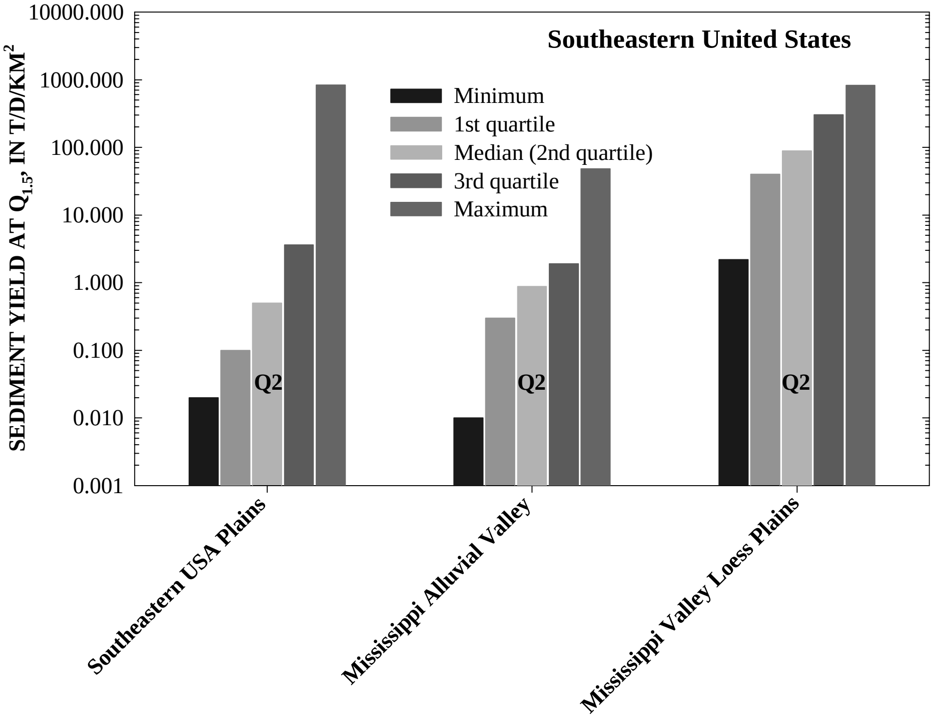

Figure 7—Quartile measures of sediment yields at the effective discharge for 154 sites in the southeastern United States

the absolute range of values for a given ecoregion, the inter-quartile range (between the 1^{st} and 3^{rd} quartiles) provides a more meaningful range of conditions, representing the central 50% of the distribution. All Q1 – Q3 ranges fall within a single order of magnitude yet may vary by more than an order of magnitude between ecoregions (Figure 7), indicating that the sediment yield at the effective discharge may be a reasonably robust parameter to describe sediment-transport characteristics within individual ecoregions. Median sediment-yield values for the three ecoregions are 0.88, 0.50, and 89.0 t/d/km^2 for the MAP, MVLP, and SEP, respectively. To make the use of sediment yields at the effective (channel forming) discharge a useful parameter for establishing target values and developing TMDLs, “reference”, “impacted”, and “impaired” conditions must be defined in terms of relative channel stability. To accomplish this we use stages of channel evolution (Simon and Hupp, 1986; Simon, 1989).

“Reference” or “Target” Sediment Yields

The working hypothesis for determining “reference” and “target” values for suspended sediment in this study is that stable channel conditions can be represented by channel evolution Stages I and VI. It follows, therefore, that effective-discharge sediment yields for Stages I and VI in a given ecoregion represent background or “natural” transport rates. To date (May 2001), evaluation of stage of channel evolution has been limited to 72 sites in Mississippi and 7 in West Tennessee. Quartile measures for Stage VI conditions occurring at Mississippi sites are shown overlaying data from all Mississippi sites in those ecoregions in Figure 8a. As expected, Stage VI sediment-yield values are considerably lower for each quartile measure in each of the ecoregions. A preliminary value of about 4.1 t/d/km^2 is obtained for the MVLP assuming the median Stage VI value (2^{nd} quartile) is used as an estimate of the stable, “reference” suspended-sediment yield

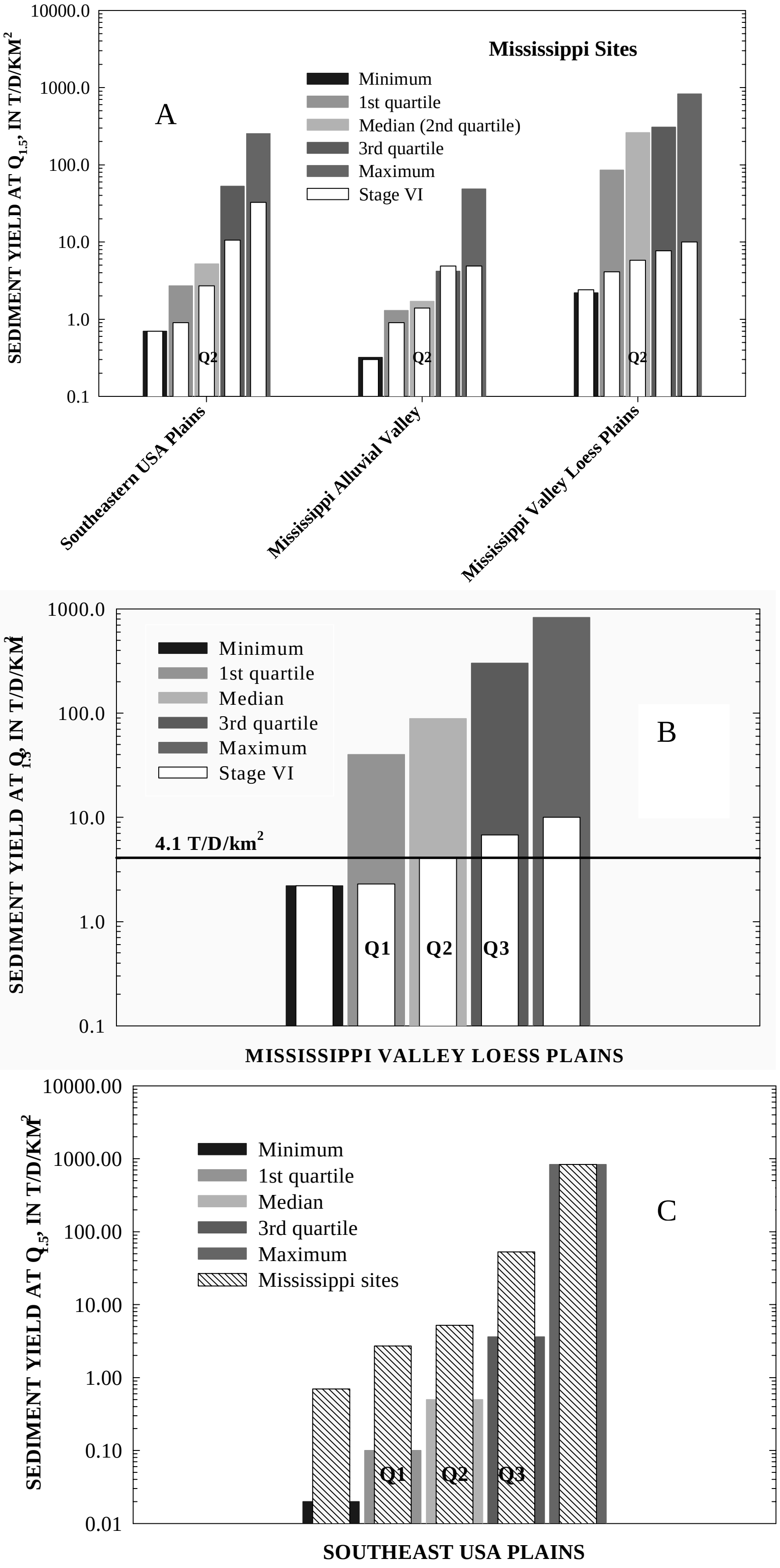

Figure 8 – Quartile measures for (A) Stage VI "reference" conditions overlaying all Mississippi data for three ecoregions; (B) for Mississippi Valley Loess Plains showing preliminary "reference" value and (C) higher yields in Mississippi portion of Southeast US Plains than other southeastern States.

for that ecoregion (Figure 8b). These results should be considered preliminary as more sites in each of the ecoregions are evaluated for stage of channel evolution, and additional Stage VI sites are identified in other states. This is particularly important in this part of the southeastern United States because suspended-sediment yields in both the MAP and SEP ecoregions in Mississippi are considerably higher (about an order of magnitude) than in the rest of the states comprising these ecoregions. The greater sediment yields for these ecoregions in Mississippi, as compared to the other states, is probably due to the close proximity of the highly erodible and unstable stream systems of the MVLP. Figure 8c displays this difference for the SEP ecoregion.

Listed versus Non-Listed

Finally, it needs to be pointed out that for some states, quartile measures of suspended-sediment yields at the effective discharge are greater (on average) for non-listed streams than for listed streams. This can be attributed to several factors including:

1. States, Territories and Tribes use different criteria to list streams;
2. Sites may be listed for a clean-sediment issue other than lethal or sub-lethal levels of suspended-sediment concentration; and
3. Sites were listed in 1998 whereas the period of historical data may not encompass the conditions represented by the current listing.

Still, it seems likely that it will be shown that many sites listed as impaired due to sediment in fact have relatively low suspended-sediment yields for their ecoregion. The methods shown in this paper will provide a simple tool for identifying those streams and, therefore, aid in potentially de-listing streams that would otherwise require the development of a TMDL for clean sediment.

Summary

“Reference” or “target” sediment-yield values indicated in Figures 8a and 8b are shown for instructional purposes and at this point, do not represent statistically significant values due to a lack of field evaluations of stage of channel evolution. Additional field evaluations throughout the region are ongoing (May 2001) and will provide the necessary data to establish “reference” conditions for each of the three ecoregions studied. Further analysis of this and similar data sets from other states and ecoregions is also ongoing and will prove useful in determining “reference”, impacted, and impaired conditions across the United States. These data are to be combined with ongoing efforts to determine lethal and sub-lethal levels of suspended-sediment concentrations, and characterization of the magnitude, frequency, and duration of suspended-sediment concentrations nationwide to establish scientifically defensible TMDL's for suspended sediment. The approach described here for suspended-sediment in the southeastern United States will also be applied nationwide to bed-material transport by comparing “reference” magnitude, frequency, and durations of excess critical shear stresses with those parameter values at all other sites.

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