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MANAGEMENT CONSIDERATIONS FOR A CONTINENTAL-SCALE SEDIMENT-MONITORING PROGRAM

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ABSTRACT

Decision-making can be limited by the quantity and quality of data available. The United States has begun a long-term effort to improve water quality, but data collection and analysis have not been modified to facilitate the decision-making required. Specifically, sediment monitoring may be inadequate to support this new need. Sediment-monitoring sites have not been chosen to support these goals, nor are data systematically analyzed for development of management plans to improve water quality. Given the natural variability in sediment movement and the current sediment-monitoring program, management plans at many locations are likely to be sub-optimal. Selected increases in sediment-monitoring data could facilitate water-quality planning by helping to quantify abatement goals, improve abatement allocation among sources of sediment, and assess management results, leading to a more effective and less costly water-quality program.

Keywords: Monitoring Programs; Sediment; TMDL

1 Introduction

Efforts to improve water quality in the United States are shifting from a technology-based emphasis on point-source pollution to a watershed-planning approach emphasizing nonpoint sources (Perciasepe, 1997). The responsible governmental agency, the U.S. Environmental Protection Agency (EPA) is considering the application of computerized Decision Support Systems (DSS), although decision support is currently available only as guidance documents, simulation models, and draft protocols.

States are obliged to develop and implement water-quality plans for all impaired water bodies by the year 2011 (Perciasepe, 1997). Unfortunately, data for the single most cited constituent impairing water bodies, sediment, are not systematically collected, analyzed, and provided to support this new planning obligation. This paper focuses on the quality and quantity of data needed to develop water-quality management plans, known as Total Maximum Daily Loads (TMDLs), for water bodies of the United States with sediment problems. Widespread development of TMDLs would be facilitated by the development of a DSS for that purpose. Before such a DSS could be developed however, a substantial effort to build the necessary database(s) would be needed. The paper demonstrates possible variability and error in computed pollutant loads and suggests a monitoring program that may balance computed load accuracy with the cost of monitoring.

2 Background

Extensive data are available describing fluxes of water, sediment, and dissolved solids in streams of North America, but often these data are inadequate to meet needs. Scientists advocate increased data collection to understand fluvial processes. Regulators desire data for management decisions, and elected officials seek information for knowledgeable formulation of public policy, but both are reluctant to fund the desired data collection without confidence that the expenditures will result in savings.

The desire for systematic sediment data was reflected by Day (1991), Osterkamp and Parker (1991), and Osterkamp and others (1992), and costs associated with sediment damage and a North American monitoring program were considered in Osterkamp and others (1998). Comprehensive evaluations of sediment damages in the United States were conducted by Clark and others (1985) and Crosson (1988). Costs of specific physical, chemical, and biological damages have been estimated by researchers including Heady and Vocke (1978), Crowder (1987), Forster and others (1987), Holmes (1988), Ribaudo and Young (1989), and Pimentel and others (1995). A difficulty in evaluating costs of erosion and the reduction of those costs was noted long ago by the American Society of Civil Engineers, writing that "...erosional and depositional processes are so general and apparently are so natural that they are rarely considered to be something that can be evaluated; therefore, from an economic standpoint, they are frequently ignored." (Task Committee for Preparation of Manual on Sedimentation, 1969, p. 192). A result of the perception that sediment damage is natural is that a

national network for sediment monitoring has not been implemented. Because sediment monitoring is generally undertaken for specific, local purposes, the data, particularly periodic sediment measurements, are not analyzed and applied as widely as they could be.

3 Sediment and the TMDL development process

Although the damage from erosional and depositional processes was often ignored in the past, that damage cannot be ignored any longer. As part of the reporting requirement for the Clean Water Act, each State is required to list the water bodies that are not attaining their designated uses, or where problems are expected, and to set priorities. States must report these 303(d) lists to the EPA every 2 years (US Environmental Protection Agency, 1991).

For each water body not meeting its designated use, a plan is to be developed estimating a TMDL consistent with the designated use. The term "Total Maximum Daily Load" grew out of efforts to control point-source problems and may be misleading. States are free to use time scales other than daily and can use multiple parameters, including indicators of water quality other than contaminant loads. For example, indicators of channel condition, biological indices, or pollutant loadings as a function of precipitation or runoff can be used where justified.

Essentially, the decision facing each State in developing TMDLs is to determine what, if anything, should be done to improve water quality in water bodies of the State. The EPA recommends the following approach (US Environmental Protection Agency, 1991):

1. Identification of water bodies with impaired water quality
2. Priority ranking and targeting
3. TMDL development
4. Implementation of control actions
5. Assessment of water-quality based control actions (back to 1.)

The third task, TMDL development, is subdivided into five steps:

1. Selection of the pollutant to consider.
2. Estimation of the waterbody's assimilative capacity.
3. Estimation of the pollution from all sources to the waterbody.
4. Predictive analysis of pollution in the waterbody and determination of total allowable pollution load.
5. Allocation (with a margin of safety) of the allowable pollution among the different pollution sources in a manner that water-quality standards are achieved.

The State then allocates loadings among background, point, and nonpoint sources, plus a margin of safety, to define acceptable water quality. After TMDLs are implemented, there is to be a second round of decision making, as landowners voluntarily determine and adopt management practices to meet the load allocations.

Nonpoint-source pollution is a particular problem because it is, by definition, difficult to measure. Where information is unavailable, the Clean Water Act allows TMDLs to be developed using "gross allocations." A phased approach is recommended to improve the TMDL over time. The quality of available data plays a key role in the development and implementation of TMDLs. As stated by the Federal Advisory Committee on the Total Maximum Daily Load Program (1998, p. ii): *In developing TMDLs, States and EPA must use the highest degree of quantitative analytical rigor available. A reasonable minimum amount of reliable data is always needed. Decisions and assumptions based on best professional judgment must be well-documented. TMDLs for which a high degree of quantitative analytical rigor is not possible in target identification and/or load allocation should contain relatively more rigor or detail in their implementation plans, including provisions for follow-up evaluation and potential revision based on the evaluation.*

To clarify the concept of TMDLs, the summary of the Newport Bay, California TMDL is in Table 1. Previous studies had estimated an annual sediment loading in the Newport Bay watershed of 227,000 Mg (megagrams) per year on a rolling 10-year annual average. A 50% reduction was assumed necessary to protect beneficial uses, so the total acceptable sediment load was set at 114,000 Mg annually. This quantity, the overall limit, was halved so that San Diego Creek and Newport Bay were each allowed 57,000 Mg. In this case, no specific quantities were allocated to natural background loading or to a margin of safety (US Environmental Protection Agency, 1998). Implementation plans containing best management practices will have to be developed to reduce sediment loadings to the allowable quantity for open space, agriculture, urban, and construction.

The Newport Bay TMDL addresses sediment, but often sediment is also a transport mechanism for associated contaminants. In addressing sediment problems, the EPA would like to distinguish between "clean" and contaminated sediment. Clean sediment causes damage through physical properties whereas contaminated sediment causes problems owing to associated chemicals. The EPA considers clean sediment the priority constituent to be addressed in the TMDL process (US Environmental Protection Agency, 1998).

The magnitude of the sediment issue within the TMDL process can be seen by considering the 16,747 waterbodies (or segments) listed as impaired by States in 1996. Of the total, 5424 waterbodies were listed for sediment¹ (Tetra Tech, 1998). An additional 2736 waterbodies were listed for contaminants

¹ Field names: sediment, siltation, erosion, suspended sediment, suspended solids, and turbidity.

Table 1 Total Maximum Daily Loads and Allocations for San Diego Creek and Newport Bay (Mg per year as rolling 10 year annual average).

Land Use	TMDL	Wasteload Allocations (Point Sources)	Load Allocations (Nonpoint Sources)
Total Area	57,000		
Open Space			26,000
Agricultural			17,000
Urban		2,000	
Construction		12,000	
Natural Background			
Margin of Safety			
Total	57,000	14,000	43,000

commonly associated with sediment², even though sediment was not named as a cause of impairment. Thus, of the nearly 17,000 waterbodies, sediment was listed directly or indirectly as a concern for 49% of the waterbodies. The percentage of waterbodies impaired by sediment could climb in future years. The states of Delaware, Georgia, Indiana, Maine, Michigan, New Hampshire, and Texas did not have any waterbodies listed as impaired due to the direct sediment related causes given in footnote 1. South Dakota did not have any waterbodies listed in the database.

If there are roughly 8000 water bodies for which sediment data would be useful to design and monitor TMDLs, the number of sites with sediment currently being monitoring is much lower. The number of daily sediment monitoring sites in the conterminous United States operated by the US Geological Survey (USGS) has declined from about 450 in 1981 to about 100 in 1996. In addition to the daily sites, periodic sediment data are collected at roughly 2000 sites nationally. Streamflow data are currently collected by the USGS at 6600 stations and there are roughly 18,000 sites for which some streamflow data are available in the conterminous United States (USGS, 1999). As not all of the sediment-monitoring stations are within listed waterbodies, and data from many stations are too old to be representative of current conditions, probably much less than one fourth of the waterbodies that have been listed for sediment-related problems have an ongoing sediment-monitoring station. Additional periodic sediment monitoring at existing stream-gaging stations could be operated for about \$3000 per year per station (Osterkamp and others, 1998, p. 19).

Because the EPA's clean-water program is part of a political process, it is prone to lawsuits. If a State is deemed to be insufficiently vigorous in addressing water-quality issues, environmental groups can take the EPA to court to encourage a more assertive policy. For example, the case *Idaho Sportsmen's Coalition v. Browner* (951 F.Supp. 962 W.D. Wash. 1996) forced a revision from an EPA approved list for the State of Idaho containing 36

² Field names: 4,4'DDE, Chlordane, DDT, pesticides, arsenic, beryllium, cadmium, chromium, copper, iron, lead, manganese, mercury, nickel, selenium, silver, zinc, nutrients, oil and grease, PCBs, phosphorus, contaminated sediments, and toxics.

bodies of water to a list containing 962 waterbodies. The EPA can also be forced to develop TMDLs if the States have not adequately done so, and in fact, as of 1998, the EPA was involved in lawsuits with 27 States and the District of Columbia in efforts to force the EPA to establish TMDLs. On the other hand, attempts at allocating sediment-reduction efforts among nonpoint sources within a basin could also result in lawsuits by those affected, particularly if the scientific basis for the allocation appears weak.

4 Examples

Many issues involved in sediment monitoring have been discussed in the literature (e.g. Walling 1977; Ferguson 1987; Clarke, 1990a and 1990b; Crawford, 1991). Because it is more costly to monitor sediment concentrations than streamflow, construction of sediment-transport curves is a standard approach used to estimate sediment loads based on some sediment-concentration observations and a longer record of streamflow. A sediment-transport curve is an empirical relation between the logarithm of sediment concentration and the logarithm of discharge (Colby, 1955). Recently, a number of advances have been made in defining sediment-transport curves (Glysson, 1987; Cohn, 1995).

Two major problems in estimating sediment loads are error and variability. Walling (1977, p. 533) points out that "rating-curve-derived estimates involve a large error term and may be as much as 50% or more in error." This large error and variability makes useful estimates of sediment loads in the absence of observed data almost impossible. To illustrate the problems inherent in the estimation of sediment loads, estimates of sediment loads have been made for three watersheds. The three cases are indicative of locations for which the best data are available; all come from the US Geological Survey's database of daily sediment observations.

Table 2 shows the basic information for the three sites. The site with the most data (over 5000 observations) is the Susquehanna River at Harrisburg, Pennsylvania. This is a former National Stream-Quality Accounting Network (NASQAN) site in a generally forested watershed. Salt Creek at Greenwood, Nebraska, is a primarily agricultural area, although the urban portion around Lincoln, Nebraska has been expanding. Part of the drainage basin of the Belle Fourche River near Sturgis, South Dakota has had substantial mining activity. The latter sites have over 1000 observations of sediment concentration and water discharge. Transport curves for the three sites were developed and applied to long-term flow records to estimate sediment loads assuming that the transport curves were representative of the discharge-concentration relation for the length of the streamflow record.

Separate estimates were attempted for flows above and below the 1.5-year flood, but the relation was essentially the same for the Susquehanna River, and the other two sites did not have enough observations with discharges over the 1.5- year flood to define a relation well. As the maximum flow in the Belle Fourche River's sediment database is 47 m³/s and the hydrologic record includes flows over 800 m³/s, a discharge rating was developed by regressing

Table 2 Transport Curve Data

	Susquehanna River at Harrisburg, PA	Salt Creek at Greenwood, NE	Belle Fourche River near Sturgis, SD
Station Number	01570500	06803555	06437000
Drainage Area km ²	62,419	2,722	15,203
Primary Land Use	Urban / Forest	Urban / Farms	Rural – Mining
Years of Sediment Record	1962, 1964-1968, 1970-1981	1972-1976	1956-1958
Number of Sediment Observations	5626	1827	1095
Regression intercept	-2.62	4.46	641 *
Regression coefficient	.84	.77	647 *
Adjusted R square	.62	.37	.19 *
Years of Streamflow Record	1947-1996	1951-1966	1947-1996
Coefficient of Variation of Annual Streamflow	.25	.67	.63
Estimated Mean Sediment Load Mg/yr	1,800,000	810,000	9,100,000
Coefficient of Variation of Annual Sediment Load	.54	1.27	1.68

*Regression on untransformed discharge and concentration

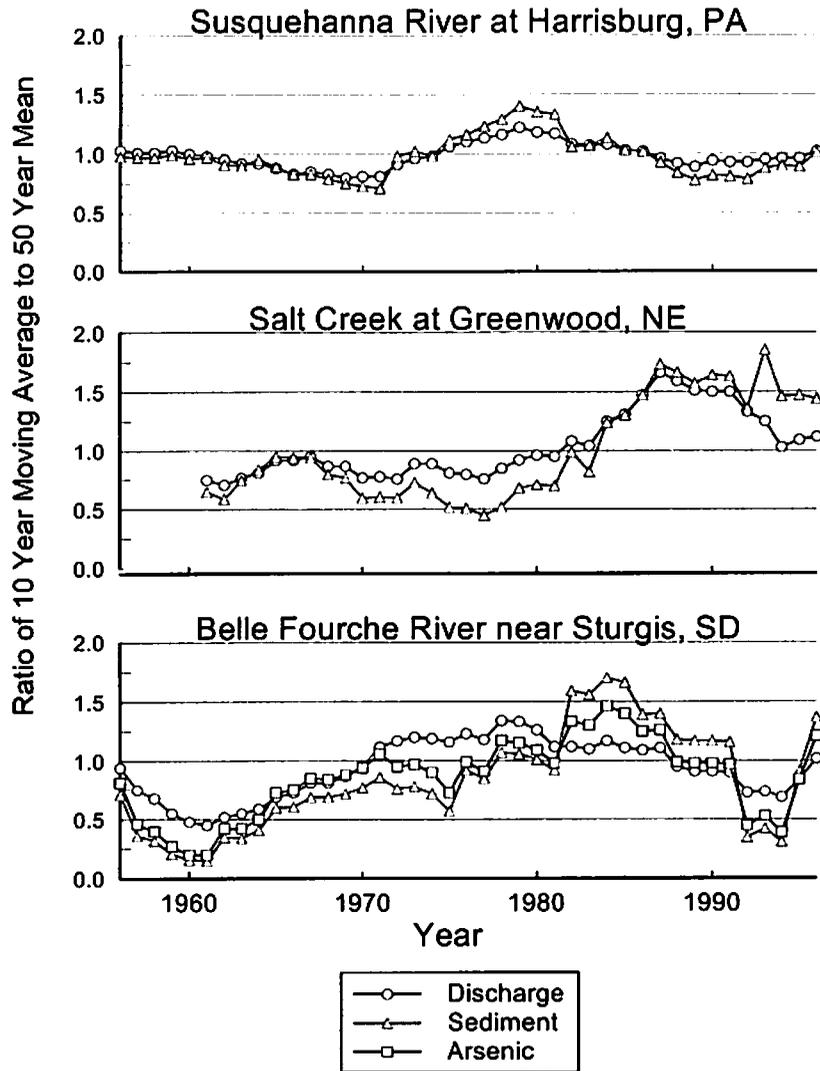
sediment concentration on discharge without logarithmic transformations to ensure that sediment loads at high flows were not overestimated. The Susquehanna River and Salt Creek transport curve relations include a term to reduce bias when concentrations are retransformed into real units, as described in Cohn (1995).

The example TMDL for Newport Bay used a 10-year rolling sediment load to smooth the variability in sediment loads. Assuming a similar indicator were defined at these three locations, 10-year moving averages were normalized by the 50-year mean discharges and sediment loads to make the three sites comparable. As can be seen in Figure 1, even with the smoothing provided by taking the 10-year moving average, sediment loads varied dramatically over time, particularly for the two western sites with smaller basin areas.

The results of Marron (1989) describing the dilution of mine tailings with uncontaminated sediment at different discharges were used to estimate arsenic loads for the same time period in the Belle Fourche River to illustrate the possibility of quantifying contaminant loads if sediment data are available. In this case, during high discharges the arsenic-rich tailings were diluted by uncontaminated sediment and the variability of the arsenic load, whereas greater than the variability in discharge, was less than the variability in sediment.

Most stream segments of the United States do not have associated daily or periodic sediment-discharge records. Where data are available from upstream or downstream sites along the same stream or in the same

Figure 1 Variability of sediment loads



drainage basin, it may be feasible to extrapolate those data to a site based on considerations of channel morphology, drainage-basin area, and basin characteristics. Where no data are available from which to generate a proxy sediment-transport curve, regional patterns of unit runoff, sediment yield, and variation of sediment concentration with discharge may be used to estimate sediment-discharge characteristics at a site.

Estimates of this sort, however, may be substantially in error if land use and geology of the drainage basin differ markedly from regional norms. In ungauged, unsampled streams suspected of having significant loads of chemical contaminants sorbed on sediment, contaminant-load estimates may be nearly meaningless without initiating a sampling and analysis program.

To highlight the difficulty of estimating sediment yields and associated contaminants without observed data, Figure 2 compares the three sediment transport curves discussed previously. The more arid and smaller western watersheds have much higher sediment concentrations. One would expect a flattening of all of the transport curves, which could be estimated if sufficient data were available for high discharges. The variability in sediment yields is indicated by the markers for plus and minus one standard deviation around the Susquehanna and Salt Creek curves. Extrapolations beyond the range of observed discharges are indicated by the dashed lines for Salt Creek and the Belle Fourche River. Two curves are shown for the Belle Fourche River, the higher curve shows the extreme overestimate of sediment concentration that would result from extrapolating concentrations from low flows to high flows that led to the use of an untransformed transport curve with much lower estimates of sediment concentration at higher discharges.

For the majority of the water bodies needing a TMDL for a sediment related problem, it is very difficult to estimate sediment and contaminant loads with accuracy before allocating reductions in sediment and contaminant loads. On ungauged, unsampled reaches, such estimates would require anticipating discharge over the year, in addition to estimating a sediment transport curve and the relations determining contaminant transport.

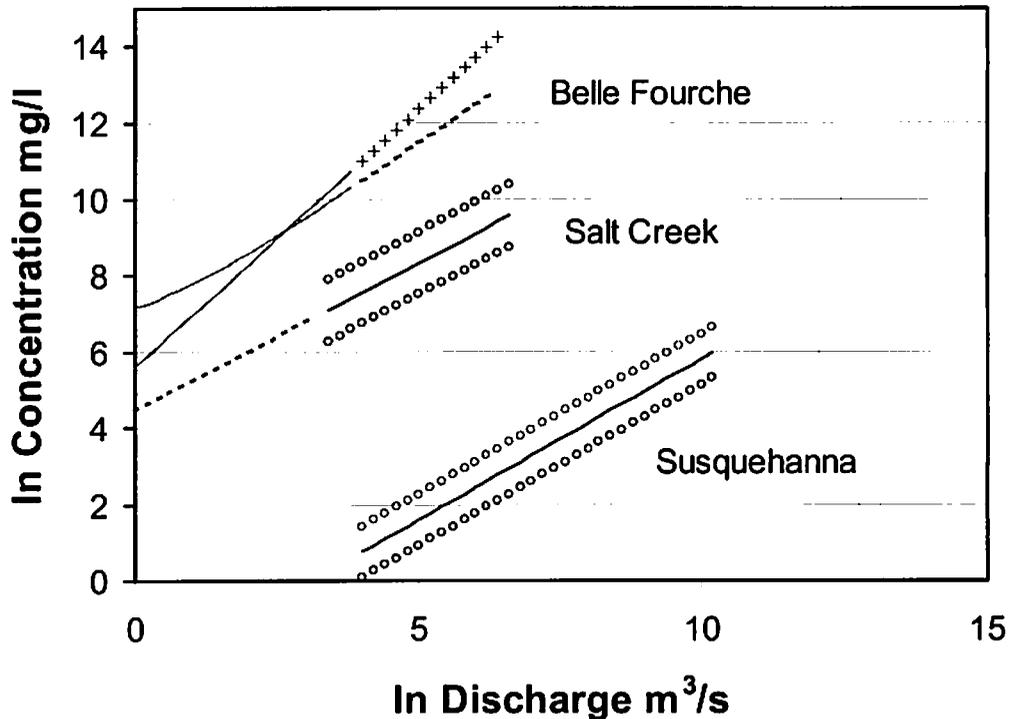


Figure 2 Sediment Transport Curves Compared

5 Economic issues related to sediment monitoring for TMDLs

As there are roughly 8000 sites where sediment is contributing to water-quality impairment, and costs average perhaps \$US 3000 to \$US 5000 per site annually for periodic sampling, data collection at all impaired water bodies would require an annual budget of \$US 24 to \$US 40 million. That amount seems an unrealistic increase over current efforts, but a properly designed national program could provide quantitative estimates for many sites at a much lower cost than if all sites were to be monitored.

In addition to the cost of a national monitoring program, the availability of data adequate to estimate sediment loads at newly established sites would be delayed. A periodic-sampling program might involve monthly samples at stream gaging stations, with additional sampling during high flows. Lacking additional data, roughly 100 observations are needed to develop a good sediment-transport curve, including observations at high flows, so a delay of 5 to 8 years from project initiation could be required. If the monitoring program is properly designed, however, information from other sites could be used to reduce that lag.

There is another issue that could significantly complicate the estimation of sediment-transport curves to support TMDL planning. Assuming TMDLs are implemented and management efforts to reduce sediment problems in water bodies are successful, sediment loads will be significantly reduced, perhaps by half at some sites. The sediment concentration to flow relations will likely be altered, so new sediment-transport curves may be required.

This paper has focused on the need for sediment monitoring to support the decision-making process inherent in the development of TMDLs. It is emphasized however, that errors in the estimation of sediment loads may yield the greatest economic difficulties when the second round of decision-making, by land-owners, occurs to develop management plans to implement the TMDL. Landowners will face a marginal cost curve with a small cost for some easily implementable practices, but higher costs to reduce sediment loads substantially. Without defensible, quantitative estimates of sediment loads, it may not be feasible to define management practices that adequately reduce sediment loads without needless overspending. Similarly, voluntary adoption by landowners will depend on the conviction that sound science underlies the requested reduction in sediment. Thus, a thesis of this paper is that the cost of developing an expanded monitoring system of periodic sediment sampling, for use with a DSS, is likely to be offset significantly by the benefits, including monetary savings that such a program would provide.

6 Conclusions

Over the next 10 to 15 years, States and the EPA must develop and implement about 8000 TMDLs to control sediment and associated contaminants. Major decisions related to TMDL development include determining how much sediment reduction should be sought, how the reduction is allocated to the sources of the water-quality problem, and evaluating and adapting the TMDL plan over time. Landowners must decide which management practices to implement to achieve their allocations.

Given the inherent error and variability in sediment estimates, as shown in the three examples, developing sediment TMDLs will be difficult. It is hard to see how defensible TMDLs could be developed without observed data on sediment loads. A carefully designed sediment-monitoring program, which does not currently exist, could collect data on representative streams and define sediment-transport curves for a majority of the impaired stream segments. As a first estimate, periodic sediment-monitoring stations could be added until 2000 of the sediment-impaired stream segments are monitored. The additional data-collection cost of such a program would be \$6 to \$10 million annually.

Computerized decision-support systems have the potential to help States and the EPA develop TMDLs rapidly and consistently. Just as important however, is emphasis on a long-term effort to improve data collection as a basis for decision-making. A carefully planned long-term sediment-monitoring and

analysis program would improve TMDLs, encourage implementation, and provide data to improve management and water quality over time.

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