

FLUVIAL SEDIMENT IN THE ENVIRONMENT: A NATIONAL CHALLENGE

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Abstract

Sediment and sediment-associated constituents can contribute substantially to water-quality impairment. In the past, sediment was viewed mainly as an engineering problem that affected reservoir storage capacity, shipping channel maintenance, and bridge scour, as well as the loss of agricultural soil. Sediment is now recognized as a major cause of aquatic system degradation in many rivers and streams as a result of light attenuation, loss of spawning substrate due to fine-grained sediment infilling, reduction in primary productivity, decreases in biotic diversity, and effects from sediment-associated chemical constituents. Recent advances in sediment measurement, assessment, source-identification, and analytical protocols provide new capabilities to quantify sediment and solid-phase chemical fluxes in aquatic systems. Developing, maintaining, and augmenting current sediment- and water-quality-monitoring networks is essential for determining the health of U.S. waterways and for evaluating the effectiveness of management actions in reducing sediment-related problems. The application of new scientific capabilities that address the adverse effects of sediment and sediment-associated constituents represents a major step in managing the Nation's water quality. A robust Federal, national-scale effort, in collaboration with vested stakeholders, is needed to address these sediment-related water-quality issues across the United States.

INTRODUCTION

The adverse effects of poorly managed land resources, which lead to accelerated erosion and altered rates of sediment transport and deposition, represent a global problem (e.g., Syvitski et al., 2005; Walling, 2006; 2008). In North America, the physical, chemical, and biological damage attributable to fluvial sediment has been estimated to range from \$20 to \$50 billion annually (Pimental et al. 1995; Osterkamp et al., 1998; 2004). Despite the magnitude of the associated costs, a detailed understanding of the spatial and temporal variability of sediment sources, fluxes, and sinks is still severely limited in the U.S. The scope of fluvial-related sediment problems has expanded dramatically during the last several decades. As a result, a much more detailed understanding of the spatial and temporal variability of sediment sources, fluxes, and sinks, based on a nationally consistent approach, is needed.

Historically, fluvial sediment was viewed solely as a physical and/or engineering issue. Within that context, programs and studies focused on problems such as reservoir infilling, channel and harbor silting, and soil erosion and loss. Monitoring, and numerous individual studies have shown that substantive changes in suspended-sediment concentrations (SSC) and annual suspended-sediment fluxes are associated with such diverse anthropogenic activities as urbanization, population growth, deforestation, mineral extraction, water supply, changing agricultural practices, dredging and channelization, and the construction and removal of dams and their associated reservoirs (e.g., Syvitski et al., 2005).

Often, substantive changes in sediment fluxes have concomitant serious environmental consequences. In some cases, these changes have resulted in increased fluxes of fine-grained sediments that have a large capacity to transport phosphorus, metals, and some organic contaminants. In other cases, reduced fluxes have resulted in habitat degradation and impairment of the beneficial use of selected resources. Examples of the latter include the annual loss of about 65 km² y⁻¹ of Louisiana coastal wetlands (Chuck Shadie, U.S. Army Corps of Engineers, oral commun., 2010), owing in part to reduced Mississippi River sediment loads; and erosion of Colorado River channel bars and beaches, owing in part to sediment starvation downstream from Glen Canyon Dam and Lake Powell.

An increased understanding of the nature and scope of sediment-related issues has occurred contemporaneously with continued improvements in monitoring equipment and methods that can produce continuous or near-continuous and quantifiably accurate physical and chemical measurements/estimates (Horowitz, 2008; Gray and Gartner, 2009; Gray and Gartner, 2010a, 2010b, 2010c). Sediment-surrogate instruments and methodologies, produced predominantly by the private sector, are evaluated for potential application in Federal monitoring programs through such multiagency programs as the Federal Interagency Sedimentation Project (2010). These instruments and methods are supported by the development, adoption, and application of nationally consistent protocols for their deployment and use (Edwards and Glysson, 1999; Gray et al. 2008; Rasmussen et al. 2009). The aforementioned progress was preceded by the wide-scale application of hydroacoustic techniques for metering streamflow. Geomorphic assessments, which support stream-corridor restoration activities including dam removal, also have progressed. These advances are supported by improved sediment and sorbed constituent modeling capabilities that can address various spatial and temporal scales (Schwarz, 2008).

Federal agencies have played a significant role in the acquisition, storage, and dissemination of fluvial sediment-related data and in collaborating with various stakeholders to target and mitigate local, regional, and national sediment-related problems. For example, information on reservoir capacity loss due to sediment deposition is available through the Subcommittee on Sedimentation's Reservoir Sedimentation (RESSED) database (Gray et al. 2009, 2010). Also, considerable interest is currently directed toward quantifying sediment- and nutrient-transport processes, based on 19 monitoring sites in the Mississippi River Basin, as they relate to Louisiana coastal wetland loss, and hypoxia in the northern Gulf of Mexico. Lastly, sediment and nutrients, a major cause of habitat degradation in the Chesapeake Bay, are monitored at 34 non-tidal stations to document annual nutrient and sediment loads and trends (Langland et al., 2007).

The purpose of this paper is to describe major sediment-related problems in the U.S., some of the new scientific tools/methods being used to provide the basic information required to address these problems, and to stress the need for a robust, national-scale monitoring effort by the Federal sector in collaboration with various stakeholders. The paper concludes with a discussion of how these partners could begin to address the Nation's sediment-related challenges through the introduction of a nationally consistent sediment and water-quality monitoring program. Such a program would serve as a framework for, and fill in the gaps of ongoing national programs, serve as a 'backbone' as well as a 'living laboratory' for evaluating new techniques and protocols, and for addressing more regional and local issues.

FLUVIAL-SEDIMENT ISSUES

Evaluating the historically recognized effects of sediment is arguably more important today than over a century ago when the U.S. Geological Survey (USGS) and other Federal agencies began monitoring fluvial-sediment concentrations and fluxes. For example, U.S. croplands lose soil from wind and water erosion at an average annual rate of 17 tonnes $\text{ha}^{-1} \text{y}^{-1}$ (U.S. Department of Agriculture, 1989). In 2001, the U.S. lost almost 2 billion tonnes of cropland soil from erosion; annual global losses average 75 billion tonnes (Montgomery, 2007). In urban areas, water-related erosion rates (specific yields) can be one to two orders of magnitude higher than baseline conditions (Horowitz et al., 2008). Substantial amounts of this eroded material eventually find their way into rivers and streams (Meade and Parker, 1985).

According to Keyes and Radcliffe (2002), among others, about 17 percent of the current total maximum daily load (TMDL) effort, required by the Clean Water Act of 1972, is sediment-related, and entails habitat degradation. In the short term, elevated fluvial SSCs affect the feeding habits of fish and benthic invertebrates by causing avoidance behavior due to elevated turbidity (e.g., Tebo, 1955; Waters, 1995). In the longer term, fine-grained sediments limit/compromise spawning areas for hyporheic fish. This results from infilling in normally sand-sized (63–200 μm) substrates, elevated levels of associated toxic chemicals, and reduced concentrations of dissolved oxygen; the last of which results from excessive nutrient loadings/eutrophication (Campbell and Doeg, 1989; Wood and Armitage, 1997; Louhi et al., 2008). Fine sediment, along with nutrients, are the leading cause of habitat degradation in our Nation's largest estuary, Chesapeake Bay (Gellis et al., 2009).

Because of a variety of physical and chemical factors, in conjunction with aquatic physicochemical conditions, fluvial-, lacustrine-bed and suspended sediments can act as both sources and carriers of a wide variety of organic and inorganic chemical constituents (e.g., Förstner and Wittmann, 1981; Luthy et al., 1997; Warren et al., 2003; Horowitz, 2008). Chemical constituents that associate with sediment are referred to as hydrophobic compounds and include heavy metals/trace elements (e.g., Cu, Zn, Pb, As, Hg), nutrients (e.g., P, N, C), and persistent organic compounds such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), dioxin, kepone, and chlorinated pesticides (e.g., Aldrin, Chlordane, Mirex, and DDT and its breakdown products DDD and DDE; U.S. Environmental Protection Agency, 1997; Simpson et al., 2005; Horowitz, 2008). Unlike Canada, Australia, New Zealand, The Netherlands, and Germany, the U.S. currently lacks regulatory limits for sediment-associated chemical constituents; however, some sediment quality guidelines exist (e.g., U.S. Environmental Protection Agency, 1997). In 1997, the U.S. Environmental Protection Agency (U.S. EPA) evaluated sediment-chemical data from about 21,000 locations in the U.S. and found that 26 percent had 'a high probability' and 49 percent had an 'intermediate probability' of having adverse effects on aquatic life and human health. The chemical constituents most often associated with these increased probabilities were PCBs, Hg, DDT, Cu, Ni, and Pb (U.S. Environmental Protection Agency, 1997).

Even in relatively unimpaired environments, some dissolved-constituent concentrations barely detectable in the water column can be simultaneously detected at levels 3–5 orders of magnitude higher in association with naturally occurring suspended and bed sediments (Förstner and Wittmann, 1981; Förstner, 1989; Horowitz, 1991; Chapman, 1992; Foster and

Charlesworth, 1996). Higher dissolved- and sediment-associated constituent concentrations also tend to be associated with anthropogenically disturbed settings (e.g., Horowitz, 2008).

Bed sediments can make substantial chemical contributions to interstitial water that also serves as aquatic habitat. Numerous studies have demonstrated that sediment-associated chemical constituents can affect aquatic organisms ranging from small zooplankton (near the base of the food chain), through benthic organisms that live in intimate contact with bed sediment and adjacent interstitial water, to humans who ultimately may be affected as constituent levels increase and bioaccumulate up the food chain (Förstner and Wittmann, 1981; Salomons and Förstner, 1984; Chapman, 1992; Förstner and Heise, 2006). Studies in large and small rivers have clearly indicated how strongly various potentially toxic constituents and nutrients are partitioned to both bed and suspended sediment (Figure 1; Förstner and Wittmann, 1981; Horowitz, 1991; Foster and Charlesworth, 1996; Horowitz and Stephens, 2008; Horowitz, 2008). Many of those studies also have demonstrated that the majority of the sediment and sediment-associated chemical constituents are physically mobilized during high-flow periods (Figure 2).

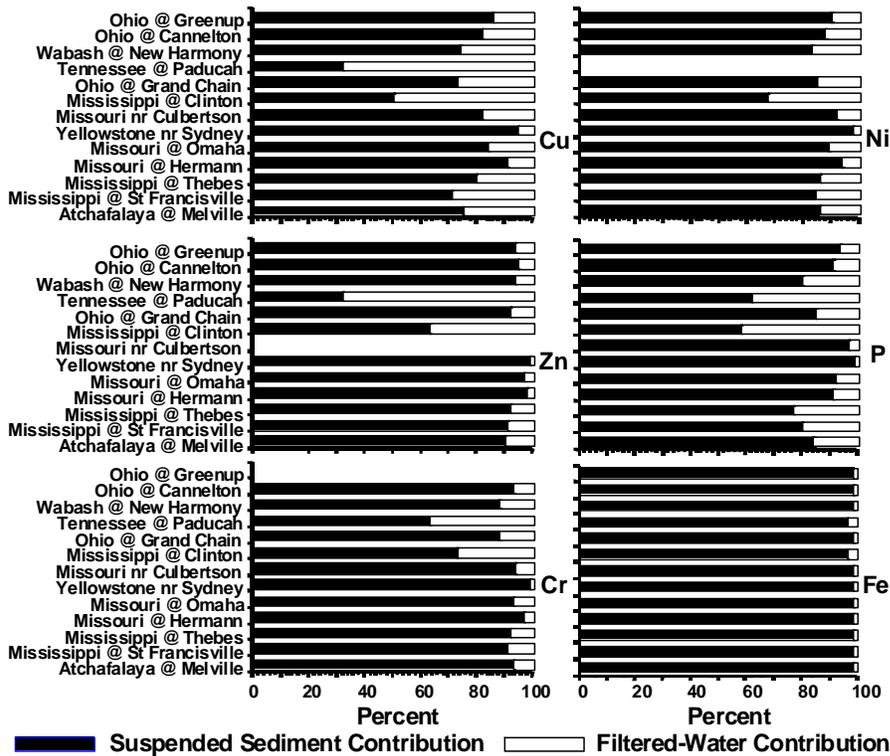


Figure 1 Annual fluxes of selected sediment-associated and dissolved constituents in the Mississippi River Basin (from Horowitz et al., 2001).

**Mississippi River @ Thebes
Five-Years of Daily Fluxes (1996 - 2000)**

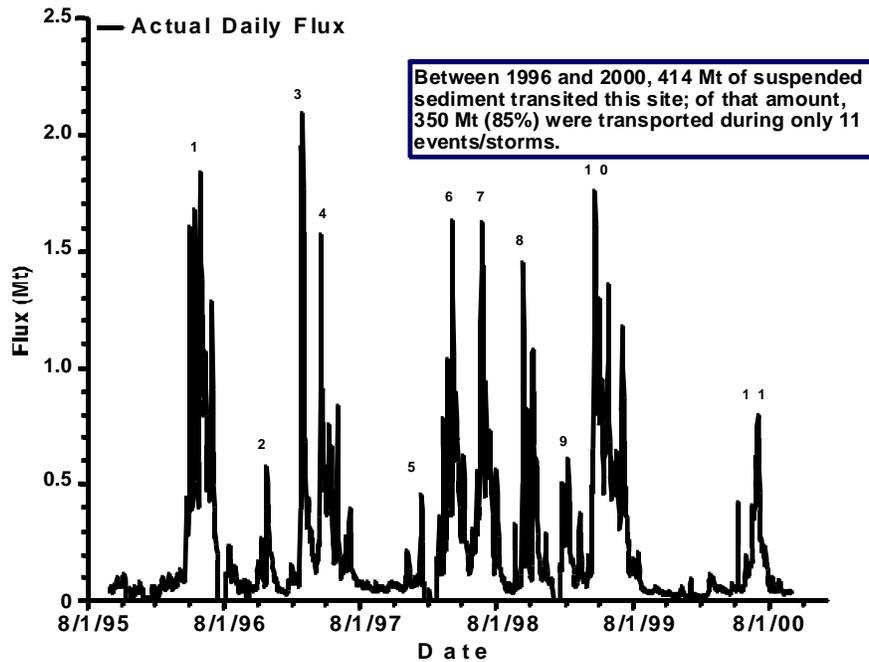


Figure 2 Graph of daily suspended-sediment fluxes for the Mississippi River at Thebes, IL, illustrating the significance of high flows to the annual fluxes at the site between 1996 and 2000 (from Horowitz, 2008).

TOOLS FOR MONITORING AND ANALYZING FLUVIAL SEDIMENT

Prior to the 1970s, the bulk of fluvial sediment-transport data—suspended sediment and bedload—produced in the U.S. were collected manually, and analyzed by gravimetric techniques (Edwards and Glysson, 1999; Gray and Glysson, 2004; Nolan et al., 2005; Davis, 2005; Gray et al., 2008). During the 20th century, except for the use of pumping samplers in some monitoring programs beginning in the 1960s, most fluvial-sediment measurements were dependent on manual collection and subsequent physical sample analyses. Manual sampling procedures can be difficult, labor intensive, time consuming, and expensive. Specialized equipment and considerable training are prerequisites for obtaining sufficiently precise and representative samples. As sediment-monitoring costs have inexorably increased, there also has been a concomitant decline in the number of USGS daily-record sediment-monitoring stations, from a maximum of 364 stations in 1981 to fewer than one hundred since 2005.

As a result of this decline in sediment monitoring, it is increasingly difficult to accurately estimate sediment fluxes at sufficient locations to define the variability in sediment transport, particularly for storm-runoff periods. Consequently, temporal interpolations and calibrations commonly are required to produce even annual estimates of suspended-sediment discharges, let alone daily estimates (Porterfield, 1972; Horowitz, 2003; Koltun et al., 2006). For example, sediment-transport curves used to estimate monthly and/or annual loads for small and medium-sized watersheds have uncertainties in excess of 100 percent (Walling, 1977). The development of continuous or near-continuous estimates of SSCs over the hydrograph, either through the collection of sufficient discrete samples or surrogate measurements, still

remains the most robust, technically supportable method to calculate suspended-sediment loads (Porterfield, 1972; Walling, 1977; Rasmussen et al., 2009). Bedload and bed-material data tend to be even more spatially and temporally sparse than suspended-sediment data.

An additional complication related to suspended-sediment monitoring derives from the fact that most Federal, State, and local regulatory agencies use the Total Suspended Solids (TSS) analytical technique to determine SSCs in streams. Several studies have shown that TSS analyses (U.S. EPA Method 160.2), when used on samples collected to determine the concentrations of suspended material in water samples collected from open channel flow, do not compare well to the ASTM Standard Method (D3977) for determining SSC (Glysson et al., 2000; Gray et al., 2000; Glysson et al., 2001; Guo, 2006). The TSS analytical techniques's sub-sampling step tends to introduce a negative bias in derived concentrations (Gray et al., 2000). Using the TSS analytical method under these circumstances can result in unacceptably large errors and is fundamentally unreliable (U.S. Geological Survey, 2000). For similar reasons, sediment-associated chemical concentrations analyzed from subsamples may also be unreliable.

Advances in Monitoring Capabilities

Recent advances in sensors operating on bulk-optic (turbidity), laser-optic, and acoustic-backscatter principles (Figure 3) have the potential for supplanting the majority of routine manual data-collection and analytical methods, and can generate cost-efficient results at spatial and temporal scales that would not have been possible even a decade ago (Gray and Gartner, 2009, 2010a, 2010c). These sensors have been evaluated based on cost, reliability, robustness, accuracy, sample volume, susceptibility to biological fouling, and available ranges

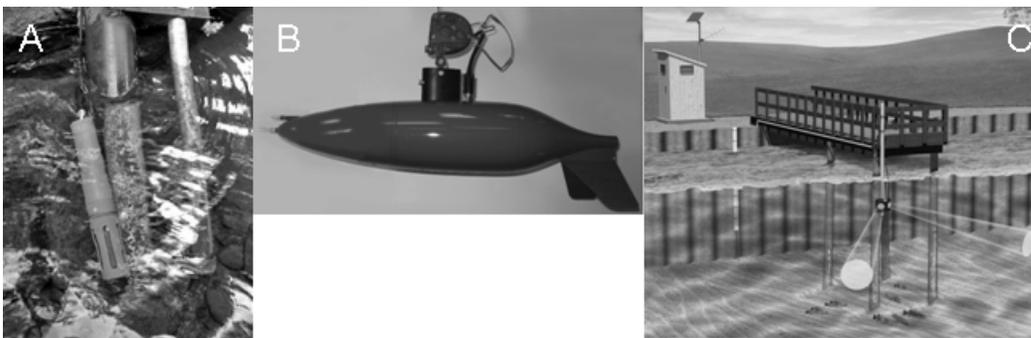


Figure 3 Photographs showing selected surrogate instruments for monitoring suspended sediment: A: Submerged nephelometer (left-most instrument; photograph by Mark Uhrich, U.S. Geological Survey) B: LISST-SL suspended-sediment concentration, particle-size, and velocity profiler (Sequoia Scientific, Inc., 2004) C: Depiction of a submerged acoustic backscatter sensor with dual hypothetical conical acoustic beams emanating from the sensor (SonTek, 2007; use of brand, firm, or product names in this report does not constitute endorsement by the U.S. Government).

of mass/concentrations, and particle-size distributions. Used in conjunction with limited manual sampling and analyses for calibration purposes and error estimation, the new techniques are expected to provide substantial improvements in the availability of continuous suspended-sediment data for computing sediment discharges. Bedload-surrogate technologies

also are advancing, albeit at a somewhat slower pace than those for suspended sediment. Active hydroacoustic techniques that rely on Acoustic Doppler Current Profilers (ADCP) primarily for sand bedload-transport; and passive hydroacoustic techniques (e.g. hydrophones and geophones) for gravel bedload-transport, are among the surrogate technologies currently being evaluated (Gray and Gartner, 2009, 2010a, 2010b, 2010c). Interrelations are developed between the recorded rate of the moving bed, and transport rates computed from bedload samples collected concomitantly with ADCP measurements in sand-bed rivers (Gaskin and Rennie, 2010). In a similar fashion, bedload-transport rates in gravel bed-rivers are computed from the acoustic energy emitted by the moving gravel, with concurrently collected bedload samples (Barton and Pittman, 2010). Although neither technology is ready for operational-scale deployment, both show substantial promise for providing bedload time-series data sets.

Advances in Sediment-Source Identification

The sediment surrogate technologies described above are designed to quantify sediment transport rates in a channel. However, the successful mitigation of sediment-related problems often requires knowledge of sediment sources. A sediment budget framework provides a useful approach to determine the important sediment sources, storage sites, and transfer pathways. This budget is generally represented by the equation:

$$I \pm \Delta S = O \quad (1)$$

Where I is the sediment input,
 ΔS is the change in sediment storage, and
 O is the sediment output.

An essential component of the sediment budget is the export term [O in equation (1)] that typically is measured as suspended-sediment load, but can include bedload and solute load.

The Leopold et al. (1966) sediment budget study of a small ephemeral watershed near Santa Fe, New Mexico, characterized watershed sources of fluvial sediment and set the standard for modern sediment budget work (Gellis et al., 2005). In that study, sheetwash was identified as the largest sediment source. Since the Leopold et al. (1966) study, the sediment budget framework has been used worldwide, at a variety of spatial and temporal scales, sometimes in great detail, to understand erosion processes, storage elements, residence times, and to address land-management questions (Dietrich and Dunne, 1978; Swanson et al., 1982; Reid and Dunne, 1996; Slaymaker, 2003; Walling and Collins, 2008).

Recent advances in sediment tracing (“fingerprinting”) techniques, combined with more traditional sediment budget approaches, have provided new opportunities to determine the primary source(s) of fine-grained suspended sediment within a watershed, and to estimate their relative contributions to measured sediment fluxes (Walling and Woodward, 1992; 1995; Collins et al., 1997a, 1997b; Motha et al., 2003; Walling, 2005). The fingerprinting approach compares selected physical and/or geochemical characteristics of potential sediment sources within a watershed with those of suspended-sediment sampled at the watershed outlet. An ‘unmixing’ model is used to estimate the relative contributions of potential sources to sampled sediment. Although sediment fingerprinting has been successfully applied in a variety of settings, current research includes examining the efficacy of using additional tracers and sediment collection methods, and the development of more robust statistical procedures that should make this method more practical and reproducible (Davis and Fox, 2009).

The sediment-source fingerprinting and sediment-budget approaches have been used separately, and/or together, in a variety of environments and at varying spatial scales, to assist land-management agencies in reducing erosion and sediment fluxes (Collins et al., 2001; Slaymaker, 2003; Walling, 2005; Jordan, 2006; Minella et al., 2008; Gellis et al., 2009). By identifying and then targeting important sediment sources using the sediment budget and fingerprinting approaches, best management practices (BMPs) are more cost-effective in reducing erosion and subsequent in-stream sediment loads. As BMPs are implemented, “before and after” sediment monitoring provides measured assessments of the success of those strategies.

In the 165,800 km² Chesapeake Bay watershed, at scales ranging from major basins (up to 70,000 km²) to subbasin scales (about 300 km²), the USGS is developing a framework to identify significant sources of sediment by incorporating a sediment budget and sediment fingerprinting approach. An important source of sediment that has been identified in several streams draining the Chesapeake Bay watershed is ‘legacy’ sediment, or sediment that was deposited in the stream corridor and in mill ponds as a result of land clearing for agricultural from the late 17th century through the early 20th century (Walter and Merritts, 2008). Future research will determine the relative importance of legacy sediment to other sources, such as agriculture, in the Chesapeake Bay watershed.

HISTORY OF FEDERAL ACTION IN MONITORING AND STUDYING FLUVIAL SEDIMENT

As early as 1938, Federal agencies acknowledged that the accuracy and usefulness of sediment data were affected by the then lack of standardization in sediment equipment and associated deployment techniques. In 1939, to address this problem, the USGS, U.S. Army Corps of Engineers, Bureau of Reclamation, Department of Agriculture, Office of Indian Affairs, and the Tennessee Valley Authority formed the still-active Federal Interagency Sedimentation Project (FISP). For the last 70 years, FISP (2010) has developed equipment and techniques that are used by the Federal sector, many State and local governments, private consultants, and foreign entities (i.e., depth-integrated isokinetic samplers, and depth-and-width integrated cross sectional sampling methods). For various reasons, the equipment and techniques developed by FISP are not universally applied and as such, substantial amounts of sediment data are neither representative nor comparable.

Another outgrowth of the 1939 coordination program is the Subcommittee on Sedimentation (SOS). Currently, the SOS (2010) is under the purview of the Advisory Committee on Water Information, which advises the Secretary of the Interior, and is administered under the Water Information Coordination Program (WICP) (<http://acwi.gov/sos/index.html>). In addition to sponsoring regular Federal Interagency Sedimentation Conferences, the SOS has developed databases, such as one on reservoir sedimentation (Gray et al., 2009, 2010), which have enhanced the use of sediment data among Federal agencies and the private sector.

In 1964, the Federal government announced the need for the coordination of Federal activities in the acquisition of certain water data and that “The Department of the Interior is responsible for the design and operation of a national network for acquiring data on the quantity and quality of surface and ground waters, including sediment loads of streams.” (Bureau of the Budget, 1964). In 1991, the Office of Management and Budget (OMB) issued Memorandum

M-92-01 “Coordination of Water Resources Information” which established the Department of the Interior, through the USGS, as the designated lead agency for the WICP. Section 2 of M-92-01 states that one of the objectives of the WICP is “to plan, design, and operate a cost effective national network for water-data collection and analysis that meets the priority water-information needs of the Federal government, and, to the extent possible within available resources, the needs of the non-Federal community, that are tied to national interests. The USGS shall have principal responsibility for operating the national network.”

In 1996, Congress passed Public Law 104-113, the “National Technology Transfer and Advancement Act of 1995,” and in 1998, OMB revised Circular A-119 “Federal Participation in the Development and Use of Voluntary Consensus Standards and Conformity Assessment Activities.” These circulars, memoranda, and laws assign the Federal government the task not only for coordinating within, but also outside the Federal government to develop and use standard equipment and procedures for the collection and processing of water-resources data. However, little of this is possible without a strong multi-agency Federal-partnership, in conjunction with stakeholder consultations.

NATIONAL-SCALE CHALLENGE: IMPROVED MONITORING, UNDERSTANDING, AND MANAGEMENT OF FLUVIAL SEDIMENT

The U.S. faces substantial problems associated with the management of soil erosion, and with altered rates of transport and deposition of fluvial sediment and sediment-associated chemical constituents — problems that only can be addressed with adequate, reliable, and consistent data and assessments to describe these processes. These problems include, but are not limited to eutrophication in large water bodies such as the Chesapeake and San Francisco Bays, expansion of the hypoxic zone in the northern Gulf of Mexico, and loss of Gulf coast wetlands due to erosion and subsidence. They also include water-quality problems in smaller watersheds such as those on various State 303D lists. Although these problems are well described, the sediment-related processes that led to these conditions are inadequately quantified. Without sufficient data on the sources, amounts, and fluxes of sediment and sediment-associated constituents responsible for these problems, the ability to manage our sedimentary resources in a thoughtful and financially responsible manner is limited.

The continuous, accurate, and consistent collection of fluvial sediment and sediment-associated chemical data are needed as part of a national water-quality-monitoring effort. Effective sediment monitoring necessarily includes determinations of sediment sources, means of entrainment and transport, the method and location of deposition, as well as evaluation of the success of management actions. A properly supported network of monitoring sites, located from headwater streams to the mouths of major rivers, is critical to meeting this objective.

As a start on meeting this responsibility, the USGS and U.S. Army Corps of Engineers have proposed a collaborative approach for a national sediment and water-quality monitoring network. This monitoring program will build on, fill in the gaps, and provide a nationally consistent framework for existing and future programs, and permit the tracking of sediments, nutrients, sediment-associated chemicals, and water quality from headwater streams [Hydrologic Benchmark Network (HBN)], through medium-sized river basins [National Water-Quality Assessment Program (NAWQA)], through major river basins [National Stream Quality Accounting Network (NASQAN)], and ultimately to coastal outlets (NASQAN). The

basic network can be enhanced by additional monitoring sites to address specific local and regional issues such as hypoxia in the northern Gulf of Mexico, and water quality in Chesapeake Bay. An initial step would focus on the Mississippi River Basin to implement, evaluate, and finalize program infrastructure, procedures, and protocols. The USGS and U.S. Army Corps of Engineers would partner with other Federal agencies such as the U.S. EPA, National Oceanic and Atmospheric Administration, Bureau of Reclamation, and the Department of Agriculture's Natural Resources Conservation Service, as well as appropriate stakeholders, to design and support this program. The National Water Quality Monitoring Council is an example of the type of Federal-State partnership needed for such an effort.

SUMMARY

“The accelerated release of sediment from soil and rock surfaces, and its movement to, through, and from streams is the most pervasive and costly form of water pollution in North America” (Pimental et al. 1995). Societal costs associated with the physical, chemical, and biological damage attributable to fluvial sediment in North America are substantial. An augmentation in sediment- and solid-phase-chemistry data collection and monitoring programs is likely to lead to successful evaluations of the most applicable control actions, such as BMPs, for dealing with sediment-related problems. Federal agencies can partner with appropriate stakeholders to coordinate the development of a nationally consistent sediment- and water-quality monitoring network that would help address this problem. An effective national sediment- and water-quality monitoring program would require a stable funding base. Such a monitoring network must be predicated on a scientifically rigorous network design that not only examines the streams that transport sediment, but also the source areas within those watersheds. Sediment, unlike water, tends to move episodically from source to sink at a relatively slow pace. As such, management actions in the upper part of a basin may take decades to manifest themselves in the most downstream part of the same system; hence, the monitoring commitment would need to be lengthy — at least decadal — to detect statistically significant changes. Federal agencies, in close partnership with stakeholders, have the responsibility for developing and sustaining a stable, long-term, and nationally consistent sediment- and water-quality monitoring program.

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