Fine Sediment Drivers of Aquatic Ecosystem Health

By Allen C. Gellis, Judson W. Harvey, Christopher H. Conaway, and
Nancy T. Baker

Chapter D of

Knowledge Gaps and Opportunities in Water-Quality Drivers of Aquatic Ecosystem Health

Edited by Judson W. Harvey, Christopher H. Conaway, Mark M. Dornblaser, Allen C. Gellis, A. Robin Stewart, and Christopher T. Green

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic mile (mi^3)	4.168	cubic kilometer (km^3)
billion gallons (Ggal)	0.003785	cubic kilometer (km^3)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	metric ton (t)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	0.2642	gallon (gal)
cubic kilometer (km^3)	2.64172	billion gallon (Ggal)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
metric ton (t)	1.102	ton, short [2,000 lb]

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as $°F = (1.8 \times °C) + 32$.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as $°C = (°F - 32) / 1.8$.

Supplemental Information

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations

BMP	best management practices
CWA	Clean Water Act
DDT	dichlorodiphenyltrichloroethane
DNA	deoxyribonucleic acid
EPA	U.S. Environmental Protection Agency
FACET	Floodplain and Channel Evaluation Tool
FRN	Fallout radionuclides
GIS	geographic information system
HAB	harmful algal bloom
IWS	USGS Integrated Water Science
NAWQA	USGS National Water Quality Assessment
NHDPlusV2	National Hydrography Dataset Plus version 2
OC	organic carbon
p,p'-DDE	dichlorodiphenyldichloroethylene
PAH	polycyclic aromatic hydrocarbons
PCB	polychlorinated biphenyl
PFAS	per- and polyfluoroalkyl substances
RSQA	USGS Regional Stream Quality Assessment
RUSLE	revised universal soil loss equation
SPARROW	SPAtially Referenced Regression On Watershed attribute
SSC	suspended-sediment concentration
SWAT	Soil and Water Assessment Tool
TAG	technical advisory group
TMDL	total maximum daily load
TSS	total suspended solids
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WMA	USGS Water Resources Mission Area

Chemical Symbols

Al	aluminum
As	arsenic
Cd	cadmium
C	carbon
Cu	copper
Fe	iron
Hg	mercury
N	nitrogen
O	oxygen
P	phosphorus

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Chapter D

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Purpose and Scope

This chapter addresses knowledge gaps that, if filled, could improve predictions of aquatic ecosystem health as affected by fine sediment drivers. The gaps identified in this chapter are not intended to be comprehensive but are instead focused on key opportunities to fill knowledge gaps for the U.S. Geological Survey (USGS) Water Resources Mission Area (WMA, https://www.usgs.gov/mission-areas/water-resources).

Statement of the Problem

The erosion, transport and delivery of fine-grained sediment is a major issue in the United States (U.S. Environmental Protection Agency [EPA], 1999). Key Findings of the National Water Quality Inventory Report to Congress (EPA, 2017c), which examined 3.5 million miles of our Nation's rivers and streams, indicated sediment, along with pathogens and nutrients was the leading cause of pollution. Excessive sediment has caused loss of channel conveyance and reduction of reservoir storage capacity, as well as facilitated transport and storage of sorbed contaminants such as nutrients, metals, and anthropogenic contaminants (Owens and others, 2005; Larsen and others, 2010; Collins and others, 2017; DeGood, 2020). Furthermore, excess fine sediment degrades river ecosystems by clouding water supply and burying streambeds, reducing light availability for productivity, consuming oxygen, and decreasing overall habitat quality and food supply (Sutherland and others, 2010; Kondolf and others, 2014).

Fine-grained sediment (or "fine sediment") is typically the largest proportion of the suspended load in channels, typically less than 0.063 millimeters (mm) in diameter, and with a large surface area for chemical sorption of a wide range of constituents (Turowski and others, 2010). Fine sediment consists of silts, clays, and organic matter including living algal cells and bacteria. If measured as suspended sediment concentration during stormflow, it may include larger-grained sediments such as sand or flocculated fine particles with an effective diameter greater than 0.063 mm (Owens and others, 2005).

As a pollutant, the importance of sediment to stakeholders is indicated by the EPA's National Rivers and Streams Assessment that found that excess streambed sedimentation occurred in 15 percent of river and stream lengths (EPA, 2020). Impairments by fine sediment were among the most frequently reported impairments in United States rivers and streams, with fine sediment ranking 6th overall in total nationwide reporting of impairments (EPA, 2017c). Fine sediment impairments also are widespread, ranking 2nd in rating as a "top 5 impairment" in 16 out of 21 (76 percent) of the water resource accounting regions used by the EPA to summarize water quality impairments (listed under section 303(d) of the Clean Water Act [CWA; 33 U.S.C 1251, section 303(d), https://www.epa.gov/tmdl]) using information similar to what can be found in the National Summary of Impaired Waters and total maximum daily load (TMDL) information (EPA, 2017b).

Understanding and quantifying the transport of fine sediment is central to the U.S. Geological Survey (USGS) Water Mission Area's (WMA's) goal of identifying causes of impaired water quality in aquatic ecosystems. Background concentrations of fine suspended sediment in healthy aquatic ecosystems vary greatly with geologic setting and land use (Robertson and others, 2006), and therefore no comprehensive national standard exists for fine sediment in streams. The focus is on measuring and modeling the effects of fine sediment on aquatic productivity and organism health, as well as drinking water quality and loss of reservoir storage. In order to manage the excess fine sediment problem and its degradation of the Nation's rivers, it is imperative to understand the sources of fine sediment to rivers and its transit and storage times in the river network, as well as its role in transporting other constituents of concern (for example, phosphorus, metals), and the resulting effects on aquatic organisms and ecosystem functions (Gellis and Walling, 2011; Mukundan and others, 2012; Collins and others, 2017). The sources, transport, and fate of sediment and associated contaminants need to be identified to determine potential effectiveness of management strategies that will protect ecosystem services and water supply.

This chapter presents the principal knowledge gaps that the USGS identified in fine sediment drivers of aquatic ecological health. These gaps are hindering WMA's capabilities to deliver scientific information to stakeholders who are responsible for managing a growing problem with excess fine sediment in the Nation's waterways. The four knowledge gaps we identified are:

11. Understanding fine sediment sources and connectivity through the Nation’s waterways,

12. How fine sediment sources are apportioned between erosion in channel corridors versus uplands,

13. Predicting fine sediment-associated contaminants and biophysical drivers of eco-health, and

14. Ability to forecast climate and land-use driven alterations of fine sediment.

Here, we support the selection of these major knowledge gaps for fine sediment with a brief review of existing knowledge and capabilities, priorities for improvement, and initial suggestions for approaches and timelines. We discuss how renewed effort in these areas can support stakeholders who need to predict where, when, and how much fine sediment will impair aquatic ecosystems, water supply impoundments, and navigation channels.

Status of Knowledge and Capabilities Including Key Gaps and Limitations

Figure D1 illustrates the sources and storage areas of fine sediment in uplands and within the channel corridor that affect aquatic ecosystems. The general status of knowledge and information about fine sediment and related water-quality drivers is summarized in table D1, and includes fine sediment gaps, rationale, metrics and modeling, and key references. Throughout this chapter we summarize information about driving physical and biological processes and human influences, as well as the numbers and types of nationwide EPA 303(d) listings of impairments of surface waters. A supplementary table (table D2) provides information about primary constituents of concern and closely associated indicator measurements and physiochemical parameters. Table D2 provides notations and links to additional information about benchmarks for aquatic life, trends in exceedances of those benchmarks, along with notations about the general level of USGS data that are available for analysis.

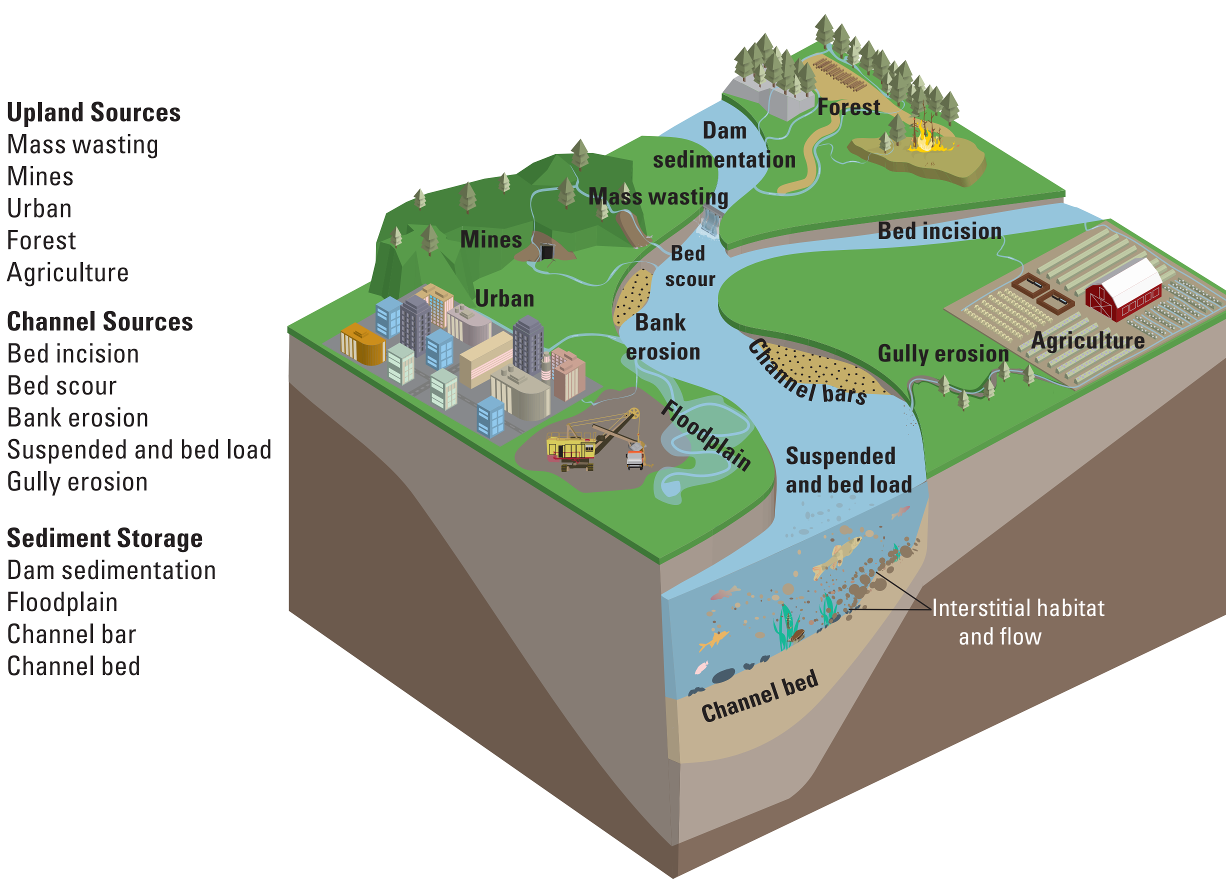

Figure D1. Diagram of drivers, sources, and storages of fine sediment and particle-associated contaminants affecting aquatic ecosystems and the four principal knowledge gaps identified by the U.S. Geological Survey (USGS) for fine sediment drivers of aquatic ecological health.

Table D1. Summary of fine sediment knowledge gaps, including background rationale, metrics, modeling, and key references for water-quality drivers of aquatic ecosystem health identified by the U.S. Geological Survey (USGS).

[SPARROW, SPAtially Referenced Regression On Watershed attribute (https://www.usgs.gov/software/sparrow-modeling-program); GIS, geographic information systems.]

What	Gap	Why	How—Measurements and modeling approaches	References
Sediment sourcing	We do not have a comprehensive national understanding of fine sediment sources, that is, is sediment coming from upland erosion (agricultural areas, construction sites, or urban areas) vs. riparian areas or in-stream sources (stream bank erosion) vs. wetland or reservoir exceeding its storage capacity?	To mitigate fine sediment as a pollutant, it is imperative to identify sources. We do not have a comprehensive national strategy to identify and manage sources of excess fine sediment.	Sediment fingerprinting, sediment budgets, expanded suspended sediment concentration monitoring, use of turbidity as a surrogate	Gellis and Walling, 2011; Larsen and others, 2015; Gellis and others, 2016; Gellis and Gorman Sanisaca, 2018; Collins and others, 2020.
Bank erosion	We do not have models that can reliably estimate bank erosion contributions and separate them from upland sources. Coupled with nutrient and contaminant data of streambanks, enhanced models could provide insight into the role streambank erosion plays in nutrient and contaminant budgets.	Streambanks have been shown to be an important (often the dominant) sediment source and in many watersheds a contributor of sediment-associated contaminants. It is therefore important to acquire new data and build modeling capacity to estimate this process.	Physical models and statistical models both have their advantages and shortcomings. The USGS SPARROW model provides an excellent platform to incorporate metric based physical model results into a statistical model. However, the problem of scaling between regional model predictions and local watershed outcomes that are of concern to stakeholders remains a key gap in sediment prediction.	Sekely and others, 2002; Van Metre and Mahler, 2005; Ishee and others, 2015; Schmadel and others, 2019; Noe and others, 2020a.
Sediment contamination	We need to understand the factors controlling new and emerging sediment-related contaminants, in stream (with special focus on emerging contaminants) and partition their sources between upland (urban and agriculture) and channel corridor.	Assessments of trends in recent and emerging chemicals of concern indicate various upland sources and their prevalence in river networks. We need better understanding of the sources, sinks, and transport pathways of these chemicals to effectively mitigate contamination through forensic tools.	Physical and statistical models to assess contaminant distribution and sourcing from depositional storage areas, such as ponds and reservoirs, examine links to water quality trends, examine sources and drivers of sediment-water partitioning, for example, redox, pH, salinity.	Wainwright and others, 2011; Schmadel and others, 2019; Gellis and others, 2020.
Sediment connectivity	We need to understand how sediment sources are connected to the fluvial systems.	To understand the transit and residence time of sediment, landscape elements controlling connectivity need to be understood.	Lidar, GIS analysis, terrain analysis, modeling tools for understanding the links and feedback of erosion, transport and delivery also include watershed hydrologic assessments, such as water balance, time-varying flow paths, storage-streamflow relations, ecohydrology, and so forth.	Borselli and others, 2008; Karwan and others, 2018) Bracken and others, 2015; Crema and Cavalli, 2018; Gellis and others, 2019.
Sediment age dating	We have little to no understanding of the age of channel deposited sediment and suspended sediment.	Unspecified sediment storage processes may vastly delay the effectiveness of management practices on downstream water quality and ecology	Precipitation fallout radionuclides, other age tracers (for example sediment associated contaminants where the location and time of "spill" into the river is known).	Skalak and Pizzuto, 2010; Gellis and others, 2017; Bernhardt and others, 2018.

Table D1.—Continued

What	Gap	Why	How—Measurements and modeling approaches	References
Turbidity[1]	Water-column light attenuation by suspended sediment decreases water clarity and photic depth, but its spatial and temporal variation and trends in the United States are poorly known; Its control on productivity, and on biological oxygen demand have not been widely estimated	Light attenuation by turbidity; turbidity is important because it affects primary productivity and food quality for healthy food webs, as well as contributing to excessive oxygen consumption that may often lead to hypoxia.	Harmonization of real-time and discrete turbidity data and analysis and remote sensing information, combined with related prediction of light attenuation, providing support for improved controls on primary productivity and ecosystem respiration in rivers.	Bussi and others, 2021; Savoy and Harvey, 2021.
Climate change drivers	We have little knowledge about how climate change affects sediment supply and transport.	In order for the management community to prepare for future sediment changes resulting from climate change, it is important to understand how climate change may affect the delivery of fine sediment to streams.	Suspended sediment, bedload, sediment budgets, sediment fingerprinting, and sediment and nutrient modeling.	Asselman, 1995; Collins and others, 2020; Moragoda and Cohen, 2020.

[1]Turbidity can be used as a proxy for suspended sediment concentration and optical clarity from which light attenuation, photic depth, primary productivity, and other outcomes for ecosystem can be estimated.

Two field measurements are commonly used to quantify fine sediment in streams: total suspended-solids (TSS) and suspended-sediment concentrations (SSC). At present there are no quantitative national benchmarks for TSS and SSC to protect aquatic life. The closest to a national criterion that exists is a narrative standard in the EPA's "Gold Book" (EPA, 1986) that is supported by discussion in Berry and others (2003). The standard reads:

> "Settleable and suspended solids should not reduce the depth of the compensation point for photosynthetic activity by more than 10 percent from the seasonally established norm for aquatic life." (EPA, 1986, p. 268).

Thus, the effects of fine sediment on light attenuation and resulting reduction in productivity and food webs are recognized, but not regulated at the National level. Each State often develops their own criteria (Berry and others, 2003) which may be better suited to account for how sediment concentrations and loads vary across the United States in response to climate, geology, and land use (Simon and others, 2004).

Aquatic ecosystems have an amount of fine sediment that varies according to contributing area, parent geology, grain size of sediment in channel bed, land use and sediment sources, and degree of organic carbon (OC) loading from the terrestrial system. The degree of fine sediment retention in the channel network is affected by flow, slope and roughness characteristics of the channel and floodplain, as well as by the rate of breakdown of fine particulate organic matter by decomposition. The "right" amount of fine sediment for an ecosystem varies but is usually present in a moderate amount at the appropriate time of year with characteristics of grain size and organic content that do not negatively affect aquatic habitats or food webs (Vannote and others, 1980; Resh and others, 1988; Wohl and others, 2007; Wohl and others, 2017). For example, coarse and fine particulate organic matter (CPOM and FPOM) input are crucial to detrital based aquatic food webs however too much FPOM during warm summer months may raise biological oxygen (O) demand and cause harm by creating hypoxic or anoxic conditions in the sediment and (or) the water column (Bernhardt and others, 2018).

One of the negative effects of fine sediment includes excessive amounts affecting biohabitats (Jones and others, 2012; Collins and others, 2015; Collins and others, 2017). Fine sediment has fundamental effects on hydraulics, river form, growth and persistence of aquatic vegetation, aquatic system productivity and respiration, and other related ecological functions. Excessive fine sediment can degrade these functions through a range of processes including: (1) raising water temperatures by absorbing heat energy, (2) reducing light transmission through the water and decreasing photosynthesis by aquatic plants that affects dissolved oxygen concentrations, (3) burying channel substrate and spawning areas, and (4) decreasing the conveyance and storage capacity of stream networks as a result of excessive deposition in ponds and lakes (Kjelland and others, 2015). Fine-grained sedimentation on streambeds can also restrict benthic algal and macrophyte productivity and respiration (Yamada and Nakamura, 2002) where much of the productivity that supports the food web occurs; furthermore, decomposition of fine particulate organic matter may directly influence food webs and secondary productivity of consumers up through fish and mammal communities. Fine sediment also affects habitat quality for aquatic organisms that spend a portion of their life cycle in close contact with sediments,

Table D2. Drivers and indicators of fine sediment dynamics and related physicochemical controls of aquatic ecosystem health.

[Information is provided on constituents, drivers, indicators, and ancillary variables; relevance to aquatic ecosystem health; U.S. Environmental Protection Agency level of concern, benchmarks, and exceedances; general availability of U.S. Geological Survey (USGS) data for analysis; and key links and references. EPA, U.S. Environmental Protection Agency; 303(d), Clean Water Act Section 303(d); SSC, suspended sediment concentration; TSS, total suspended solids; O, oxygen; NWIS, USGS National Water Information System; FNU, Formazin Nephelometric Unit; NTU, Nephelometric Turbidity Unit; USGS NAWQA, National Water Quality Assessment; NRSA, EPA National Rivers and Streams Assessment; DNR, Department of Natural Resources; FPOM, fine particulate organic matter; OC, organic carbon; Q, streamflow; ADCP, acoustic Doppler current profiler; sed., sediment; %, percent; mg/L, milligrams per liter; mg/kg, milligram per kilogram; g/kg, gram per kilogram; mm, millimeters; wt, weight; <, less than; —, unavailable). USGS parameter codes available at https://help.waterdata.usgs.gov/codes-and-parameters/.]

Constituent, or indicator, or driver, or ancillary variable	Relevance to aquatic system health	Level of concern from EPA 303(d) listings of impaired waters	Benchmarks for aquatic life and level of exceedances	References
(SSC) and (TSS)[1]	Excess fine sediment causes loss of channel conveyance and reservoir storage capacity, facilitation of transport and storage of sorbed contaminants, burying of streambeds, consuming streambed O, and decreasing, direct interference with organism soft tissue and membranes, overall reduction in habitat quality.	EPA ranked fine sediment as 6th in number of nationally reported impairments; ranked 2nd as a "top 5" concern in 76% of large river basins.	Refer to Quality Criteria for Water, 1986 ("Gold Book") for narrative statistics.	Kuhnle and Simon, 2000; EPA, 1986 ("Gold Book"); EPA, 2017a, b, c.
Turbidity (FNU)[2]	Clouds water supply and may directly harm organism metabolic functions and feeding as well as reduce light availability for aquatic productivity, may indicate high levels of organics and microbial activity in water column that consume O and cause hypoxia.	EPA ranked turbidity as 11th in number of nationally reported impairments; ranked 8th as a "top 5" concern in 14% of large river basins.	FNU; NTU standard, like suspended sediment.	Joy and Jones, 2012.
Grain size of channel bed substrate[3]	Streambeds are critical habitat for macroinvertebrates such as aquatic insects and other infauna; growth substrate for benthic periphyton and algae and associated microbial colonies which provide a rich food source for particle feeding organisms in the food web. Also serves as a nursery area for fish eggs and early life stages of aquatic insects, refuge area during floods.	Many streams throughout the United States, over various contributing areas, geology, and land use.	Might have a D_{50} standard or threshold where impairment or mortality may occur, i.e., salmon spawning gravels.	Kaufmann and others, 2009; Riebe and others, 2014; Konrad and Gellis 2018; https://www.epa.gov/national-aquatic-resource-surveys/data-national-aquatic-resource-surveys; https://www.epa.gov/national-aquatic-resource-surveys/nrsa.
Organic content of sediment (mg/kg, g/kg, or mg/L)[4]	FPOM of the right amount and quality is critical to food webs however too much FPOM raises biological O demand and may cause hypoxia or anoxia.	—	—	—
Channel morphology	Sediment, flow, channel gradient; nutrient input, physical habitat.	Entire United States	Benthic organisms	Cluer and Thorne, 2014; Jowett, 1998; Newson and Newson, 2000. https://www.epa.gov/caddis-vol2/caddis-volume-2-sources-stressors-responses-physical-habitat

[1]Mass concentration of suspended sediment, TSS method biased toward finer fraction and organics.

[2]Measure of light scattering in water by suspended particles, plankton, and colored organic particles; directly estimates optical clarity and light availability, and is a useful surrogate for SSC.

[3]Summarized by metrics such as median grain size (D_{50}), percent fines (mass fraction <0.063 mm), and others; methods include sieving field samples or in situ pebble counts, measures of soft sediment area and depth, etc.

[4]Measured both in suspended sediment and in bed sediment.

using sediment as a substrate to cling to, for spawning, or as an escape from predation or as refugia from high temperatures and stormflow. Fine sediment deposition on streambeds particularly inhibits sensitive macroinvertebrate taxa (Burdon and others, 2013). In addition to altering food sources and processing by macroinvertebrates, fine sediment clogs membranes and causes physical damage in many fish species.

Sediment-Associated Transport of Constituents

Fine sediment may transport particle-associated constituents through streams and rivers to downstream receiving waters including lakes, reservoirs, and estuaries. The sediments can sequester and may later release to overlying water a variety of nutrients (phosphorus [P] and nitrogen [N]), toxic inorganic elements [metals, metalloids, radionuclides]), industrial chemicals (petrochemicals, polycyclic aromatic hydrocarbons [PAHs]), refractory pollutants (dichlorodiphenyltrichloroethane [DDT], polychlorinated biphenyl [PCB], chlorinated dioxins, plasticizers), and many emerging contaminants (pharmaceuticals, perfluorinated chemicals). Many of these chemicals sorb to sediment, although the degree of sorption can vary with sediment properties (such as grain size, surface area, mineralogy, carbon [C] content, and associated microbial biomass) and water quality parameters (such as pH, redox, salinity, and complexing agents). These chemicals can be stored on sediments in riverbeds, on banks and floodplains, or they may be transported with sediment (as suspended sediment in surface water, stormwater, into subsurface groundwater paths, or through aeolian processes).

Many toxic and bioaccumulated pollutants can be associated with fine sediments, often by sorption or precipitation, such as nutrients, metals, radionuclides, pesticides, PAHs, and other anthropogenic compounds (Foster and others, 2000; Horowitz and Stephens, 2008). Contaminants may be associated with sediments for long or short periods of time because the weak bonding to sediment coatings is often reversable with a change in redox, pH, or salinity, all of which may influence either the sorption capacities or the stability of the geochemical coatings on the sediments. In particular, the precipitation or dissolution behavior of iron (Fe) and manganese (Mn) oxyhydroxides is pH-dependent, which affects not only the dissolved metal concentrations but also the dynamics of many potentially toxic trace metals (mercury [Hg], arsenic [As], cadmium [Cd], aluminum [Al], copper [Cu], and so forth) as well as nutrients that sorb to metal or to organic coatings on sediment. For example, sediment-associated Hg varies with size and organic content of suspended matter (Skalak and Pizzuto, 2014). In addition, P and ammonium are often sorbed to sediments and may be transported with fine sediments that are mobilized by erosion of riverbeds and banks. In the Chesapeake Bay watershed, an average of 73 percent of total P and 18 percent of total N was transported to the estuary in a form attached to sediment (Zhang and others, 2015), with a higher percent of sediment-associated nutrients being supplied by tributaries with the highest sediment loads (Zhang and others, 2015).

Sediment-associated chemicals are of particular concern to benthic aquatic organisms when the chemicals have the potential to bioaccumulate and biomagnify (for example, DDT, Hg). Within the USGS Water Resources Mission Area (WMA), the Regional Stream Quality Assessment (RSQA) has assessed the importance of many of these sediment-associated contaminants to stream ecology (Rogers and others, 2016; Moran and others, 2017). The investigation of some of these chemicals in sediment cores from lakes and reservoirs has provided (1) information on contaminant trends, (2) an assessment of the effectiveness of management actions such as banning of chemicals, and (3) important forensic tools for sediment sourcing and dating (for example, Van Metre and Mahler, 2005). Historical records of sediment-associated metal releases from mines can be derived from sediment cores in reservoirs, such as the study by Blake and others (2020) in a drinking water reservoir in New Mexico. Thus, sediment records can be integrators of constituent loading and long-term changes of ecosystem health.

A key research area in sediment-associated contaminants deals with new and emerging contaminants such as perfluorinated chemicals, bifenthrin and other current-use hydrophobic pesticides. Whereas there has been substantial research and progress in understanding organochlorines, metals, and to some extent PAHs in sedimentary records (Van Metre and Fuller, 2009; Van Metre and Mahler, 2010), much work is left to be done on emerging contaminants. Perfluorinated chemicals are of high priority, because the distribution of these chemicals in the environment can be used to date and source sediment. In addition, the distribution of perfluorinated chemicals may provide information for similar (membrane and protein-associating) emerging contaminants. Sediment cores can record long-term inputs of per- and polyfluoroalkyl substances (PFAS) (Mussabek and others, 2019). An area of future research could examine existing archive material from USGS studies, focusing on WMA Integrated Water Science (IWS) basins where possible, and identify key places in IWS basins for possible follow-up work. This approach could benefit from building on existing dated material and ancillary data (a substantial cost in coring studies is the determination and interpretation of age models and ancillary data). Studies in contaminated urban sites could provide a good starting point for perfluorinated chemicals, as PAH and PFAS are commonly co-located. A second area of research could be to extrapolate and test the fidelity of chronology from previous studies (which may cover up to the 1990s) with modern coring efforts (Van Metre and Horowitz, 2013). This approach could also provide essential knowledge to determine if recent trends match previous trends, as well as the extent of alteration of previous trends through diagenesis. These approaches could provide connections between emerging contaminants in fine sediment and sedimentary records examined by other WMA efforts.

Sediment-associated nutrients have a role in legacy contamination and eutrophication of surface waters after they are released from sediments. Watershed P budgets have shown that P from eroding streambanks can contribute a substantial amount ranging from 6 to 93 percent of the total P load (Fox and others, 2016). In Lake Champlain, Vermont–New York, the total phosphorus contributions from eroding streambanks ranged from 6 to 30 percent (Ishee and others, 2015). In the Blue Earth River, Minnesota, streambanks contributed 7 to 10 percent of the phosphorus load with more than 90 percent of the phosphorus load originating from moderate and severely eroding sites (Sekely and others, 2002). In Chesapeake Bay, a total watershed mass balance for P indicated that 23 percent of all P sources (defined as streambank, upland sediment delivery to streams, and residual term) originated from streambanks (Noe and others, 2022). What is striking about these numbers is that the models and studies on P sources and trends have examined the land-surface applied P and not the contributions from streambank erosion. Phosphorus sources from within the river corridor also come from remobilization within ponds and reservoirs. In the Lower Susquehanna River of the Chesapeake Bay watershed, the three main reservoirs are approaching an equilibrium condition where the amount of phosphorus that settles with fine sediment is balanced by scouring during high flow events (Zhang and others, 2016).

Sorbed P and N that are released from sediments can become bioavailable and (or) cause algal blooms that may lead to fish kills. For example, changes in redox conditions can be the driver of P release, which can be affected by downstream widening, slowing, and blockage of river flow, which creates pooled waters that are deeper and have a longer residence time, while also having less mixing and reaeration of dissolved O across the water surface. Under such conditions, biogeochemical reactions such as aerobic respiration can consume much of the available O, causing anoxic conditions at sediment interfaces that promote the release of P from sediments. Desorption of P from sediments in small stormwater ponds is also an important source of P in the upstream channel network (Taguchi and others, 2020). Ammonium sequestration by fine sediment can be controlled by sorption to metal coatings that have precipitated on sediments. Release of adsorbed ammonium can therefore be controlled by redox conditions that affect Fe^{3+}/Fe^{2+} redox coupling or pH that may affect precipitation-dissolution kinetics.

Temporal changes in sediment-associated contamination in waterways have been studied by examining reservoir and lake cores to reveal an integrated contamination history of the inflowing streams and rivers. An important example are PAHs, which are a common contaminant in urban lakes and streams; cores from 40 lakes in urban areas across the United States indicate an increase in PAHs from the 1970s to 2000s with coal-tar based sealcoat being the largest source, followed by vehicle-related sources and coal combustion (Van Metre and Mahler, 2010). Sediment cores from 10 reservoirs and lakes in the United States indicated an association between PAHs and the amount of urban area in the basin (Van Metre and others, 2000) with PAH concentrations increasing over the last 20 to 40 years. The increased concentrations were associated with increasing combustion sources and with increased automobile use (Van Metre and Mahler, 2010; Van Metre and others, 2004). Sediment cores collected from 38 urban and reference lakes across the United States that were used to reconstruct water-quality histories, indicated downward trends in DDT and in dichlorodiphenyldichloroethylene (p,p′-DDE) concentrations, the main metabolite of DDT known to cause abnormalities in male sex development, and in total PCBs concentrations (Van Metre and Mahler, 2005). Upward and downward trends with time were observed for accumulation of chlordane, whereas trends in PAHs were mostly upward. However, it was noted that reservoir bottom-sediment samples might underestimate concentrations of organic contaminants in some streams (Van Metre and Mahler, 2004). In a recent study, a fine-particle breakdown of tire rubber, 6PPD-quinone, was found to be the answer to a decade-long search for the contaminant that poisons coho salmon (*Oncorhynchus kisutch*) after rainstorms in Puget Sound streams, and likely affects fish in urban waterways everywhere (Tian and others, 2021).

Many stream restorations projects focus on reducing fine sediment. Stream restoration projects that facilitate greater filtration of urban stream waters through soil and streambed sediment may be an effective management practice. Age-dated sediment cores could help prioritize regions of concern as a function of population density, stormwater infrastructure age, impervious surface, and other land use factors that inform model interpretations of water-quality trends at regional and national scales (Van Metre and others, 2004).

Managing Fine Sediment

When a river is determined to be impaired by sediment, it is placed on the EPA 303(d) list and a sediment TMDL may be implemented. Identifying sediment sources is an important step in the EPA's TMDL process (fig. D2), yet the States, Tribes, and local governments charged with this assessment and source tracking are often lacking standard guidance on appropriate tools available to quantify sediment sources and develop sediment budgets (Belmont and others, 2011; Gellis and others, 2016). Comprehensive data and models may be needed to assess fine sediment sources. A similar conclusion was reached in a review of sediment TMDLs in EPA Region IV (Southeast) in 2002 by the TMDL technical advisory group (TAG), a group composed of scientists from universities, Federal and State agencies, and non-governmental organizations (Keyes and Radcliffe, 2002). Two of the goals of the TAG were to identify general characteristics of scientifically based sediment TMDLs and to recommend a protocol for establishing sediment TMDLs in Georgia.

Recommendations by the TAG for sediment TMDL source assessment protocols, as described by Gellis and others (2016) included: (1) identify the problem based on currently available information, including water quality monitoring data, watershed analyses, information from the public, and any existing watershed studies; and (2) inventory the potential sediment sources and pathways by which sediment enters the waterbody, and thus obtain a robust quantification of the relative contribution from various sediment sources (emphasizing upland soil erosion or from channel corridor sources). The last recommendation highlights the fundamental question of whether sediment originates from upland soil erosion (for example, farmland, resource extraction, urban development) or channel bank erosion (Gellis and Walling, 2011), which can have substantial economic repercussions for stakeholders who must select whether to focus on stream restoration or soil conservation efforts.

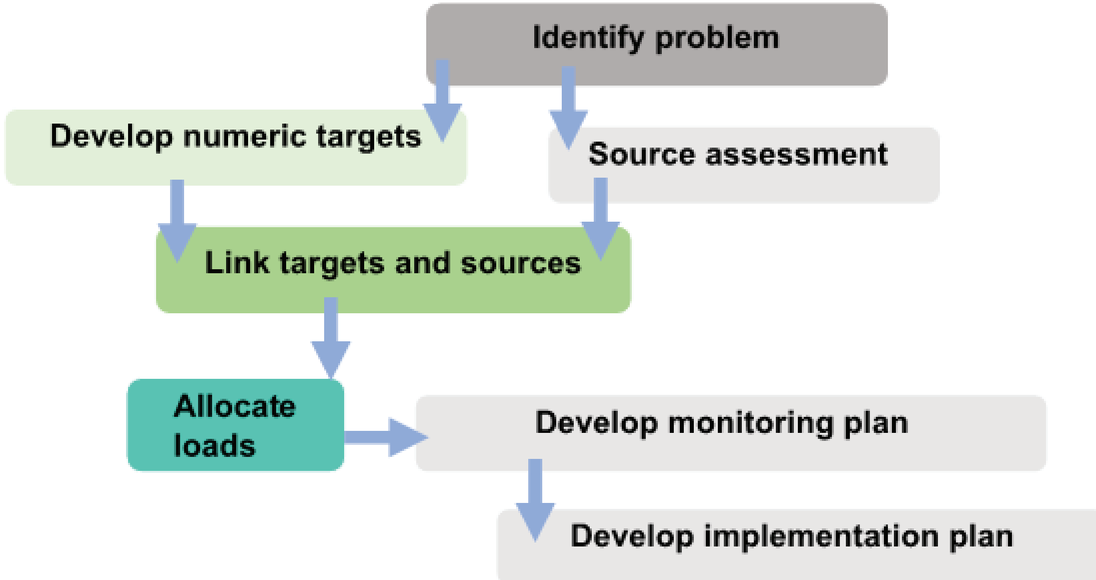

Figure D2. Flow diagram of the components in the sediment total maximum daily load (TMDL) procedure. Identifying sediment sources are important steps in the U.S. Environmental Protection Agency's (EPA) TMDL process. Modified from EPA, 1999.

Gaps in Fine Sediment Drivers and Associated Contaminants

Four principal knowledge gaps were introduced in the "Statement of the Problem" section of this chapter that limit our capabilities to predict fine-sediment impairment of ecological health:

1. Understanding fine sediment sources and connectivity through the Nation's waterways,
2. How fine sediment sources are apportioned between erosion in channel corridor versus uplands,
3. Predicting fine sediment-associated contaminants and biophysical drivers of eco-health, and
4. Ability to forecast climate and land-use driven alterations of fine sediment.

Information about sources, transport, and fate of fine sediment in streams throughout the Nation, implications for modeling sediment-associated contaminants and biophysical interactions affecting eco-health, and anticipating future changes driven by a changing climate and land use change (fig. D1) are important for enhancing the state of the science. Below we describe the four knowledge gaps in greater detail and begin to discuss how addressing gaps in fine sediment science can support stakeholders.

Gap 1. Understanding Fine Sediment Sources and Connectivity Through the Nation's Waterways

There is a gap in understanding the sources, transport, and fate of fine sediment (<0.063 mm; silts, clays, and fine particulate organic matter) in most river basins; only a few have been studied in detail. Sediment budgets quantify sediment dynamics from "source to sink" using data to estimate rates of erosion and export from other fine sediment sources to the fluvial system. Constructing a sediment budget requires compiling relevant data such as suspended sediment concentration and flux measurements and combining this information with estimates of fine sediment sources including soil and bank erosion, storage volumes and ages of sediment in channel margin, floodplain, and reservoir storage, and so forth. Computational tools such as fallout radionuclides are used to identify source areas and age-date the sediment. Extrapolation of metrics developed in well-studied cases are needed to model fine-sediment sources at scales ranging from small to medium watersheds (less than 250 square kilometers [km^2]) up to regional-sized river basins. Model output at a range of scales can inform stakeholders about the importance of landscape best-management practices (BMPs) versus stream restoration to mitigate negative outcomes. Models are used to answer questions such as, "Where is the majority of fine sediment originating from?" and "How long will it take for us to see the effects of upstream management actions on downstream outcomes that decrease the adverse effects of fine sediment?"

Gap 2. How Fine Sediment Sources are Apportioned Between Erosion in Channel Corridor Versus Uplands

A corollary of gap 1 is distinguishing sources of fine sediment from within the channel corridor versus from upland areas, including forest, agricultural, or urban areas. Identifying channel versus upland sources invokes totally different management strategies and thus it is imperative to distinguish. Source tracking methods combined with sediment budgets have been proven to partition channel versus upland sources. However, the field and laboratory work are expensive and time consuming, and thus there is a need for prioritizing key research areas that can eventually support model extrapolation throughout the Nation. Identifying source areas of excess fine sediment can provide the foundation for developing effective management strategies for stakeholders. Another key element of understanding sediment sources is determining the hydrologic pathways and sediment connectivity, over varying spatial and temporal scales, which occurs between the erosion, transport, storage, and delivery of sediment. Forecasting climate and land use changes also relies on this understanding.

Gap 3. Predicting Fine Sediment-Associated Contaminants and Biophysical Drivers of Eco-Health

Currently there is not a robust method to estimate the relative contributions of contaminants from streambank sources and how this compares with upland sources, in terms of their effect on sensitive aquatic systems. Yet, studies in a few areas have identified channel corridor processes as a dominant source of fine sediment and possibly also of certain associated contaminants (Fox and other, 2016; Noe and others, 2022). For example, bank erosion can be a source of fine sediment, as well as contaminant releases from sediments beneath slow-moving waters of ponds, wetlands, and reservoirs on the river network. Studies have shown that the mobilization of contaminants such as P from bank erosion, and from ponds and reservoirs, could be significant in the total watershed nutrient budget, yet wider spatial and temporal coverage is needed, not only for P but for a number of constituents of concern (OC, pesticides, heavy metals, and many anthropogenic contaminants). However, a full mass-balance of all sediment and P in these areas is needed to better define the sources of nutrients and other contaminants and determine the relative importance of stream bank erosion and upland sources.

Light attenuation caused by fine sediment has also been a driver of ecosystem degradation. Fine sediment which contains a high percentage of organic material can also increase O demand, which lowers O concentrations and degrades ecosystem habitat and food quality. Gaps exist in modeling fine sediment drivers of aquatic light availability and primary production, healthy O levels, and habitat quality as well as modeling particle-facilitated transport, storage, and remobilization of constituents. To be effective, modeling advancements need to be scalable and transferable to serve stakeholders wherever needed in the United States.

Gap 4. Ability to Forecast Climate and Land-Use Driven Alterations of Fine Sediment

Climate driven changes in precipitation and land use change influences flow regimes that will affect the erosion, delivery, and transport of watershed sediment sources as well as channel form and hydraulics. These changes, caused by changes in flow, in turn will redistribute loadings and mobilize new sources of fine sediment and associated contaminants. In turn, this may affect P loading, coastal sediment budgets, fine sediment colmation of streambeds, and biological O demand. Changes in climate and land-use together are likely to affect fine sediment dynamics throughout the Nation’s fluvial system for a broad range of land uses whether forested, cultivated, or urbanized. These potential changes lead to a few questions. Will increased drought and wildfires (and associated debris flows) in the western United States increase sediment loads, turbidity and biological O demand, channel aggradation, and flooding? For example, in the western United States, longer wildfire seasons and hotter fires are altering soil integrity by increasing hydrophobicity and erodibility and are expected to increase loading of fine sediment with a high black C content and biological O demand to streams under post-wildfire conditions (Wagner and others, 2015). In the northeastern United States, where a wetter and warmer climate is predicted (Rustad and others, 2012), will channel morphology and sediment-associated loadings of nutrients adjust in ways that exacerbate large river and estuarine algal blooms? For the management community to prepare for the future, an adaptive modeling capacity is needed along with well-conceived scenarios to bracket a range of potential future drivers.

Addressing Gaps—Approaches and Priorities

A summary of fine sediment gaps, including background and rationale and measurements, metrics, and modeling approaches, as well as key references is provided in table D1. Gaps are listed individually but each of the gaps is not isolated from the other gaps; rather most of the gaps are interdependent.

Tracing Sediment Sources

An understanding of the source-to-sink dynamics of fine sediment is needed to improve predictive capabilities (fig. D1). A source-to-sink characterization involves sediment source type, erosion, delivery, transport, and storage controls, all of which can benefit from the use of tracers to identify sources. Recent advances in using the geochemical properties (sediment fingerprinting), to trace sediment source areas and ages vastly improved calculating sediment budgets by providing a direct, quantitative estimate of the source contributions of fine sediment (Gellis and Walling, 2011; Gellis and others, 2016; Collins and others, 2020). This approach entails the identification of specific sources of sediment through the establishment of a minimal set of physical and (or) chemical properties, that is, tracers that uniquely define each source in the watershed. Fine sediments collected under different flow conditions exhibit a composite, or fingerprint of properties that allows them to be traced back to their respective sources. Tracers that have successfully been used in the sediment-fingerprinting approach include color (Martínez-Carreras and others, 2010; Barthod and others, 2015), grain size (Kurashige and Fusejima, 1997; Weltje and Prins, 2007); organic matter fluorescence (Larsen and others, 2015), signatures clay mineralogy (Eberl, 2004; Gingele and De Deckker, 2005), mineral-magnetism (Zhang and others, 2008; Maher and others, 2009), geochemistry (Gellis and Gorman Sanisaca, 2018), fallout radionuclides (Belmont and others, 2014; Evrard and others, 2016; Gellis and others, 2017), bulk stable isotopes and isotopic ratios (Fox and Papanicolaou, 2008), and biomarkers and biologic properties (Hancock and Revill, 2013; Alewell and others, 2016; Reiffarth and others, 2016). Sediment in channel storage on the bed of the channel (drape or interstitial) can be an important source of sediment. However, this sediment is derived from upstream sources (bed, banks, and uplands) and is a mixture of geochemical concentrations from these sources and may not have a unique fingerprint. However, recent work using microbial DNA indicates that source material can have a unique assemblage of bacteria and DNA (Zhang and others, 2016; Evrard and others, 2019). Thus, we identify that sediment deposited on the bed of the channel is a ”knowledge gap” in sediment fingerprinting science. The use of DNA to fingerprint bed sediment could be further examined.

Fallout radionuclides (FRN) (excess lead-210 [$^{210}Pb_{ex}$] and beryllium-7 [^{7}Be]) were used in the RSQA–NAWQA (National Water Quality Assessment) program to determine the sources of sediment (upland versus channel) for large regions of the United States (Gellis and others, 2017). Excess ^{210}Pb and ^{7}Be FRNs can also be used to date fluvial sediment (^{7}Be to one year and $^{210}Pb_{ex}$ to approximately 100 years). The age of sediment can inform managers of the timescales when BMPs may show an effect. If sediment ages are estimated to be relatively young (that is, a few years or less), then monitoring programs may be expected to show a relatively quick decrease in sediment related to specific management actions that target those sources. If sediment is older (that is, decades), then it is likely to take longer to see a reduction in sediment concentrations and loads. Combining sediment-source analysis with age dating can provide modelers with data needed to predict sources and outcomes that will help inform managers about effective means of control.

For modeling sediment, it has been proposed to collect bed sediment at monitoring stations in each USGS WMA study basin to determine the sources and ages of sediment. Sediment sources and sediment ages could be estimated through development of a regional sediment model for the proposed USGS large regional areas (such as the Delaware River Basin, Upper Colorado River Basin, and Illinois River Basin). The proposed statistical model could build upon existing models developed for the Delaware River Basin (Noe and others, 2020b; https://www2.usgs.gov/water/southatlantic/projects/floodplains/) which used data from field collection at 15 monitoring sites and the Floodplain and Channel Evaluation Tool (FACET, https://www.usgs.gov/software/floodplain-and-channel-evaluation-tool-facet). Dendrochronology, field surveying, and sediment physio-chemistry were used to calculate changes in floodplain deposition and streambank erosion over time to create a quasi-sediment budget for each site. FACET incorporates high resolution airborne lidar to estimate channel morphology, and along with characteristics of the upstream drainage area, was used to extrapolate the monitoring station results for large river basins. Statistical analysis which included random forest regression was used to develop statistical models of sediment flux with predictions of floodplain and streambank flux for each National Hydrography Dataset Plus version 2 (NHDPlusV2) reach (https://www.epa.gov/waterdata/get-nhdplus-national-hydrography-dataset-plus-data).

Modeling Fine Sediment Dynamics and Associated Contaminants

Sources of excess N or P may be from sources mobilized in the present season, or they may be from “legacy sources” where nutrients were stored in soils, groundwaters, or in river or reservoir sediments for several seasons, years, or decades before being released and transported to receiving waters. Commonly used water quality models do not typically quantify “legacy sources” of sediment-associated nutrients or characterize the key controls and their associated lag times, and therefore these models may overlook key dynamic processes that may trigger adverse effects such as hypoxia and anoxia and harmful algal blooms (HABs). Nutrients transported with sediments and later released to the water column can exacerbate these conditions. Conservation practices may affect legacy sources differently than contemporary sources or take longer to be effective. Modeling of legacy nutrient sources beyond the reach of conservation practices has high potential to improve management strategies.

Among the predictive models that have been applied everywhere in the Nation are the USGS SPARROW sediment models (Brakebill and others, 2010; Robertson and Saad, 2019) as well as sediment-trend analysis (Murphy, 2020). However, these approaches tend to not separate terrestrial topsoil erosion sources from channel corridor erosion sources, which all require different management strategies. For example, recent studies indicate that streambanks may not only be an important source but the dominant source of sediment in many areas (Noe and others, 2020a). In addition, studies in the Midwestern United States, Lake Champlain in Vermont, and Chesapeake Bay indicate that eroding streambanks also contain high levels of N and P, and possibly other contaminants (pesticides, insecticides, and PAHs) (Sekely and others, 2002; Schilling and others, 2009; Ishee and others, 2015).

Extended model capabilities are needed that provide:

- Statistically based and physics guided model structure (for example, SPARROW or similar) with spatial referencing of flow and transport parameters (for example, Schmadel and others, 2019);
- Dynamically enabled model structure that specifies both sources and sinks for fine sediment and constituents in the channel corridor;
- Input predictors that help identify sources, timing, and causes of excess nutrient deliveries to receiving waters, including legacy contributions, that fuel hypoxia and HABs; and

- Seasonal to decadal, scenario-based load projections to help prioritize the most effective mitigation strategies.

These new modeling strategies could help build communities of collaborators to address the grand challenge of hypoxia and HABs with new science that improves control efforts and informs new styles of management (for example, nutrient trading).

There are additional gaps in understanding fine sediment that could help address how the fluvial system could respond to climate change. Climate driven changes in flow regime could affect hydraulics and suspended sediment loads in ways that affect nutrient loading, coastal sediment budgets, fine sediment colmation of streambeds, biological oxygen demand, and others. The effects of climate change are uncertain. For example, how and where will flows change in a wetter and warmer eastern United States to affect the sediment regime? In the American west, will increasing drought and wildfires (and associated debris flows) lead to channel aggradation and flooding? Concomitantly, how and where in the watershed will climate change affect sediment sources? Lastly, how long will it take to adjust management actions to reduce sediment fluxes?

Furthermore, the USGS and its partners still do not have a robust method to estimate streambank erosion nor quantify the contributions of sediment, nutrients, and contaminants from streambank erosion. How can fine sediment from channel storage (bed material) be traced? The USGS WMA has an opportunity to develop measurement tools and modeling techniques to estimate the relative importance of streambank erosion to other sources, as well as to account for how those sources change over time along with changing channel morphology and hydroclimatic drivers.

Timelines

Near-Term (2 Years)

Within two years, the WMA could develop a proof-of-concept approach to developing a sediment budget for one of the WMA IWS basins and surrounding regional drainage basins. The focus of the sediment budget would be on sediment-source and sediment flux characterization, with modeling informed by already published and ongoing studies of upland and channel bank sediment sources, channel and floodplain fluxes, turbidity as a surrogate for fluxes, and sediment age determinations. Ideally there could be investigations using sediment sourcing and sediment age dating using fallout radionuclides (^{7}Be, ^{210}Pb$_{ex}$, cesium-137 [^{137}Cs]), as well as upland sediment modelling using the revised universal soil loss equation (RUSLE, https://www.ars.usda.gov/southeast-area/oxford-ms/national-sedimentation-laboratory/watershed-physical-processes-research/docs/revised-universal-soil-loss-equation-rusle-welcome-to-rusle-1-and-rusle-2/) or similar with remapped soil properties (for example, Chaney and others, 2019; Woznicki and others, 2020) combined with a digital elevation model (DEM) connectivity-model tracking channel and floodplain fluxes using the FACET model or similar tools. Products could include: (1) sediment budget storyboard showing how fine sediment is transferred from source to sink; (2) proof-of-concept of a method to distinguish uplands and channel bed as a sediment source; and (3) time-averaged (seasonal or monthly) statistical model of sediment sources and fluxes for one or more WMA IWS basins and the surrounding regional drainage basin.

Mid-Term (2–5 Years)

Within 5 years, the WMA could expand into additional IWS basins and their regional drainage basins with statistical models describing sediment sources and sediment fluxes. Statistical analysis could be expanded to include random forest regression or other statistical approaches (such as enhanced SPARROW models) to develop statistical models of sediment flux with predictions of floodplain and streambank flux for each NHDPlusV2 reach. Comparisons could also be made between existing USGS models and other models, that is, regional SPARROW models compared with Soil and Water Assessment Tool (SWAT) models (https://swat.tamu.edu/) where predictions from one model at a single scale could be incorporated as predictors in another model at a different scale. For example, SWAT has more process-related variables, but it also has greater requirements for data inputs; therefore, SWAT tends to be typically used only in small watersheds. Comparing SWAT results with SPARROW estimations from larger basins could improve the scaling capacity of SWAT and the process basis in SPARROW. The result may provide a scalable, process-guided statistical model of sediment sources and fluxes that could be widely applicable throughout the United States. Products from these type of efforts may include: (1) enhanced sediment budget storyboarding of how fine sediment is transferred from source to sink; (2) scalable process-guided statistical models of sediment sources; (3) sediment fluxes for multiple IWS basins and surrounding regional drainage basins; and (4) inter-agency interactions in sediment modeling, for example SPARROW-SWAT comparisons, to build process modeling skill of regional-scale statistical models could lead to further interactions between the USGS and the U.S. Department of Agriculture (USDA).

Long-Term (10 Years)

A long-range plan could be develop a national model of sediment sourcing and fluxes that includes floodplain, ponded water, and streambank erosion-deposition fluxes. By incorporating results from IWS basins (Delaware River Basin, Upper Colorado River Basin, Illinois River Basin, and future basins), we could obtain the fluvial sediment flux estimates and streambank and floodplain fluxes necessary for a model. FACET, random forest (a machine learning algorithm), and SPARROW models could be used to improve the accuracy, timeliness, and spatial extent of improved sediment flux estimates and sources in unmonitored areas across the country. This sediment information could then be used directly by resource managers and be incorporated into regional or national models to improve estimates of sediment flux which in many areas is important in describing water availability from water-supply sedimentation and turbidity. Products include: (1) National model of sediment sources, fluxes, and ages that is process guided and can therefore predict future conditions based on scenarios of land-use and climate change; and (2) full sediment budget storyboard of how fine sediment is transferred from source to sink.

References Cited

Alewell, C., Birkholz, A., Meusburger, K., Schindler Wildhaber, Y., and Mabit, L., 2016, Quantitative sediment source attribution with compound-specific isotope analysis in a C3 plant-dominated catchment (central Switzerland): Biogeosciences, v. 13, no. 5, p. 1587–1596, https://doi.org/10.5194/bg-13-1587-2016.

Asselman, N.E.M., 1995, The impact of climate change on suspended sediment transport in the river Rhine, *in* Zwerver, S., van Rompaey, R.S.A.R., Kok, M.T.J., and Berk, M.M., eds., Climate change research—Evaluation and policy implications, International climate change research conference, Maastricht, The Netherlands, December 6–9, 1994, Proceedings: Studies in Environmental Science, v. 65, p. 937–942, https://doi.org/10.1016/S0166-1116(06)80119-6.

Barthod, L.R.M., Liu, K., Lobb, D.A., Owens, P.N., Martínez-Carreras, N., Koiter, A.J., Petticrew, E.L., McCullough, G.K., Liu, C., and Gaspar, L., 2015, Selecting color-based tracers and classifying sediment sources in the assessment of sediment dynamics using sediment source fingerprinting: Journal of Environmental Quality, v. 44, no. 5, p. 1605–1616, accessed mm dd, yyyy, at https://doi.org/10.2134/jeq2015.01.0043.

Belmont, P., Gran, K.B., Schottler, S.P., Wilcock, P.R., Day, S.S., Jennings, C., Lauer, J.W., Viparelli, E., Willenbring, J.K., Engstrom, D.R., and Parker, G., 2011, Large shift in source of fine sediment in the Upper Mississippi River: Environmental Science & Technology, v. 45, no. 20, p. 8804–8810, https://doi.org/10.1021/es2019109.

Belmont, P., Willenbring, J.K., Schottler, S.P., Marquard, J., Kumarasamy, K., and Hemmis, J.M., 2014, Toward generalizable sediment fingerprinting with tracers that are conservative and nonconservative over sediment routing timescales: Journal of Soils and Sediments, v. 14, no. 8, p. 1479–1492, https://doi.org/10.1007/s11368-014-0913-5.

Bernhardt, E.S., Heffernan, J.B., Grimm, N.B., Stanley, E.H., Harvey, J.W., Arroita, M., Appling, A.P., Cohen, M.J., McDowell, W.H., Hall, R.O., Jr., Read, J.S., Roberts, B.J., Stets, E.G., and Yackulic, C.B., 2018, The metabolic regimes of flowing waters: Limnology and Oceanography, v. 63, no. S1, p. S99–S118, https://doi.org/10.1002/lno.10726.

Berry, W., Rubinstein, N., Melzian, B., and Hill, B., 2003, The biological effects of suspended and bedded sediment (SABS) in aquatic systems—A Review: U.S. Environmental Protection Agency, appendix 1, 58 p., accessed November 1, 2021, at https://archive.epa.gov/epa/sites/production/files/2015-10/documents/sediment-appendix1.pdf.

Blake, J.M., Brown, J.E., Ferguson, C.L., Bixby, R.J., and Delay, N.T., 2020, Sediment record of mining legacy and water quality from a drinking-water reservoir, Aztec, New Mexico, USA: Environmental Earth Sciences, v. 79, no. 17, article 404, 21 p., https://doi.org/10.1007/s12665-020-09126-9.

Borselli, L., Cassi, P., and Torri, D., 2008, Prolegomena to sediment and flow connectivity in the landscape—A GIS and field numerical assessment: CATENA, v. 75, no. 3, p. 268–277, https://doi.org/10.1016/j.catena.2008.07.006.

Bracken, L.J., Turnbull, L., Wainwright, J., and Bogaart, P., 2015, Sediment connectivity—A framework for understanding sediment transfer at multiple scales: Earth Surface Processes and Landforms, v. 40, no. 2, p. 177–188, https://doi.org/10.1002/esp.3635.

Brakebill, J.W., Ator, S.W., and Schwarz, G.E., 2010, Sources of suspended-sediment flux in streams of the Chesapeake Bay watershed—A regional application of the SPARROW model: Journal of the American Water Resources Association, v. 46, no. 4, p. 757–776, https://doi.org/10.1111/j.1752-1688.2010.00450.x.

Burdon, F.J., McIntosh, A.R., and Harding, J.S., 2013, Habitat loss drives threshold response of benthic invertebrate communities to deposited sediment in agricultural streams: Ecological Applications, v. 23, no. 5, p. 1036–1047, https://doi.org/10.1890/12-1190.1.

Bussi, G., Darby, S.E., Whitehead, P.G., Jin, L., Dadson, S.J., Voepel, H.E., Vasilopoulos, G., Hackney, C.R., Hutton, C., Berchoux, T., Parsons, D.R., and Nicholas, A., 2021, Impact of dams and climate change on suspended sediment flux to the Mekong delta: Science of the Total Environment, v. 755, part 1, article 142468, 12 p., at https://doi.org/10.1016/j.scitotenv.2020.142468.

Chaney, N.W., Minasny, B., Herman, J.D., Nauman, T.W., Brungard, C.W., Morgan, C.L.S., McBratney, A.B., Wood, E.F., and Yimam, Y., 2019, POLARIS soil properties—30-m probabilistic maps of soil properties over the contiguous United States: Water Resources Research, v. 55, no. 4, p. 2916–2938, https://doi.org/10.1029/2018WR022797.

Cluer, B. and Thorne, C., 2014, A stream evolution model integrating habitat and ecosystem benefits: River Research and Applications, v. 30, no. 2, p. 135–154, https://doi.org/10.1002/rra.2631.

Collins, A.L., Blackwell, M., Boeckx, P., Chivers, C.-A., Emelko, M., Evrard, O., Foster, I., Gellis, A., Gholami, H., Granger, S., Harris, P., Horowitz, A.J., Laceby, J.P., Martinez-Carreras, N., Minella, J., Mol, L., Nosrati, K., Pulley, S., Silins, U., da Silva, Y.J., Stone, M., Tiecher, T., Upadhayay, H.R., and Zhang, Y., 2020, Sediment source fingerprinting: benchmarking recent outputs, remaining challenges and emerging themes: Journal of Soils and Sediments, v. 20, no. 12, p. 4160–4193, https://doi.org/10.1007/s11368-020-02755-4.

Collins, A.L., Pulley, S., Foster, I.D.L., Gellis, A., Porto, P., and Horowitz, A.J., 2017, Sediment source fingerprinting as an aid to catchment management—A review of the current state of knowledge and a methodological decision-tree for end-users: Journal of Environmental Management, v. 194, special issue, p. 86–108, https://doi.org/10.1016/j.jenvman.2016.09.075.

Crema, S., and Cavalli, M., 2018, SedInConnect—A stand-alone, free and open source tool for the assessment of sediment connectivity: Computers & Geosciences, v. 111, p. 39–45, https://doi.org/10.1016/j.cageo.2017.10.009.

Eberl, D.D., 2004, Quantitative mineralogy of the Yukon River system—Changes with reach and season, and determining sediment provenance: American Mineralogist, v. 89, nos. 11–12, p. 1784–1794, https://doi.org/10.2138/am-2004-11-1225.

Evrard, O., Laceby, J.P., Ficetola, G.F., Gielly, L., Huon, S., Lefèvre, I., Onda, Y., and Poulenard, J., 2019, Environmental DNA provides information on sediment sources—A study in catchments affected by Fukushima radioactive fallout: Science of the Total Environment, v. 665, p. 873–881, https://doi.org/10.1016/j.scitotenv.2019.02.191.

Evrard, O., Laceby, J.P., Huon, S., Lefèvre, I., Sengtaheuanghoung, O., and Ribolzi, O., 2016, Combining multiple fallout radionuclides (^{137}Cs, ^{7}Be, $^{210}Pb_{xs}$) to investigate temporal sediment source dynamics in tropical, ephemeral riverine systems: Journal of Soils and Sediments, v. 16, no. 3, p. 1130–1144, https://doi.org/10.1007/s11368-015-1316-y.

Foster, G.D., Roberts, E.C., Gruessner, B., and Velinsky, D.J., 2000, Hydrogeochemistry and transport of organic contaminants in an urban watershed of Chesapeake Bay (USA): Applied Geochemistry, v. 15, no. 7, p. 901–915, https://doi.org/10.1016/S0883-2927(99)00107-9.

Fox, J.F., and Papanicolaou, A.N., 2008, Application of the spatial distribution of nitrogen stable isotopes for sediment tracing at the watershed scale: Journal of Hydrology, v. 358, no. 1, p. 46–55, https://doi.org/10.1016/j.jhydrol.2008.05.032.

Fox, G.A., Purvis, R.A., and Penn, C.J., 2016, Streambanks—A net source of sediment and phosphorus to streams and rivers: Journal of Environmental Management, v. 181, p. 602–614, https://doi.org/10.1016/j.jenvman.2016.06.071.

Gellis, A.C., Fitzpatrick, F.A., and Schubauer-Berigan, J., 2016, A manual to identify sources of fluvial sediment: U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Land Remediation and Pollution Control Division, no. EPA/600/R-16/210, 106 p. accessed November 1, 2021, at https://nepis.epa.gov/Exe/ZyPDF.cgi/P100QVM1.PDF?Dockey=P100QVM1.PDF.

Gellis, A.C., Fuller, C.C., and Van Metre, P.C., 2017, Sources and ages of fine-grained sediment to streams using fallout radionuclides in the Midwestern United States: Journal of Environmental Management, v. 194, p. 73–85, https://doi.org/10.1016/j.jenvman.2016.06.018.

Gellis, A.C., Fuller, C.C., Van Metre, P., Filstrup, C.T., Tomer, M.D., Cole, K.J., and Sabitov, T.Y., 2019, Combining sediment fingerprinting with age-dating sediment using fallout radionuclides for an agricultural stream, Walnut Creek, Iowa, USA: Journal of Soils and Sediments, v. 19, no. 9, p. 3374–3396, https://doi.org/10.1007/s11368-018-2168-z.

Gellis, A.C., Fuller, C.C., Van Metre, P.C., Mahler, B.J., Welty, C., Miller, A.J., Nibert, L.A., Clifton, Z.J., Malen, J.J., and Kemper, J.T., 2020, Pavement alters delivery of sediment and fallout radionuclides to urban streams: Journal of Hydrology, v. 588, article 124855, 13 p., https://doi.org/10.1016/j.jhydrol.2020.124855.

Gellis, A.C., and Gorman Sanisaca, L., 2018, Sediment fingerprinting to delineate sources of sediment in the agricultural and forested Smith Creek watershed, Virginia, USA: Journal of the American Water Resources Association, v. 54, no. 6, p. 1197–1221, https://doi.org/10.1111/1752-1688.12680.

Gingele, F.X., and De Deckker, P., 2005, Clay mineral, geochemical and Sr–Nd isotopic fingerprinting of sediments in the Murray–Darling fluvial system, southeast Australia: Australian Journal of Earth Sciences, v. 52, no. 6, p. 965–974, https://doi.org/10.1080/08120090500302301.

Hancock, G.J., and Revill, A.T., 2013, Erosion source discrimination in a rural Australian catchment using compound-specific isotope analysis (CSIA): Hydrological Processes, v. 27, no. 6, p. 923–932, at https://doi.org/10.1002/hyp.9466.

Horowitz, A.J., and Stephens, V.C., 2008, The effects of land use on fluvial sediment chemistry for the conterminous U.S.—Results from the first cycle of the NAWQA Program—Trace and major elements, phosphorus, carbon, and sulfur: Science of the Total Environment, v. 400, nos. 1–3, p. 290–314, https://doi.org/10.1016/j.scitotenv.2008.04.027.

Ishee, E.R., Ross, D.S., Garvey, K.M., Bourgault, R.R., and Ford, C.R., 2015, Phosphorus characterization and contribution from eroding streambank soils of Vermont's Lake Champlain Basin: Journal of Environmental Quality, v. 44, no. 6, p. 1745–1753, https://doi.org/10.2134/jeq2015.02.0108.

Jones, J.I., Murphy, J.F., Collins, A.L., Sear, D.A., Naden, P.S., and Armitage, P.D., 2012, The impact of fine sediment on macro-invertebrates: River Research and Applications, v. 28, no. 8, p. 1055–1071, https://doi.org/10.1002/rra.1516.

Joy J., and Jones, J., 2012, Little Spokane River watershed fecal coliform bacteria, temperature, and turbidity total maximum daily load: Washington State Department of Ecology, Water Quality Improvement Report, no. 11-10-075, 256 p., accessed November 1, 2021, at https://apps.ecology.wa.gov/publications/documents/1110075.pdf.

Jowett, I.G., 1998, Hydraulic geometry of New Zealand rivers and its use as a preliminary method of habitat assessment Regulated Rivers—Research & Management, v. 14, no. 5, p. 451–466, https://doi.org/10.1002/(SICI)1099-1646(1998090)14:5%3C451::AID-RRR512%3E3.0.CO;2-1.

Karwan, D.L., Pizzuto, J.E., Aalto, R., Marquard, J., Harpold, A., Skalak, K., Benthem, A., Levia, D.F., Siegert, C.M., and Aufdenkampe, A.K., 2018, Direct channel precipitation and storm characteristics influence short-term fallout radionuclide assessment of sediment source: Water Resources Research, v. 54, no. 7, p. 4579–4594, https://doi.org/10.1029/2017WR021684.

Kaufmann, P.R., Larsen, D.P., and Faustini, J.M., 2009, Bed stability and sedimentation associated with human disturbances in Pacific Northwest streams: Journal of the American Water Resources Association, v. 45, no. 2, p. 434–459, https://doi.org/10.1111/j.1752-1688.2009.00301.x.

Keyes, A.M., and Radcliffe, D., 2002, A protocol for establishing sediment TMDLs: Atlanta, Georgia Conservancy and University of Georgia Institute of Ecology prepared by Sediment TDML Technical Advisory Group, 31 p., accessed November 1, 2021, at https://rivercenter.uga.edu/wp-content/uploads/2021/01/A-Protocol-for-Establishing-Sediment-TMDLs.pdf.

Kjelland, M.E., Woodley, C.M., Swannack, T.M., and Smith, D.L., 2015, A review of the potential effects of suspended sediment on fishes—Potential dredging-related physiological, behavioral, and transgenerational implications: Environment Systems and Decisions, v. 35, no. 3, p. 334–350, at https://doi.org/10.1007/s10669-015-9557-2.

Kondolf, G.M., Gao, Y., Annandale, G.W., Morris, G.L., Jiang, E., Zhang, J., Cao, Y., Carling, P., Fu, K., Guo, Q., Hotchkiss, R., Peteuil, C., Sumi, T., Wang, H.-W., Wang, Z., Wei, Z., Wu, B., Wu, C., and Yang, C.T., 2014, Sustainable sediment management in reservoirs and regulated rivers—Experiences from five continents: Earth's Future, v. 2, no. 5, p. 256–280, https://doi.org/10.1002/2013EF000184.

Konrad, C. and Gellis, A., 2018, Factors influencing fine sediment on stream beds in the midwestern United States: Journal of Environmental Quality, v. 47, no. 5, p. 1214–1222, https://doi.org/10.2134/jeq2018.02.0060.

Kuhnle, R.A., and Simon, A., 2000, Evaluation of sediment transport data for clean sediment TMDLs: U.S. Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory NSL Report no. 17, 62 p., accessed November 1, 2021, at https://www.ars.usda.gov/ARSUserFiles/60600505/PDF/NSLReport17.pdf.

Kurashige, Y., and Fusejima, Y., 1997, Source identification of suspended sediment from grain-size distributions, I—Application of nonparametric statistical tests: CATENA, v. 31, nos. 1–2, p. 39–52, https://doi.org/10.1016/S0341-8162(97)00033-7.

Larsen, M.C., Gellis, A.C., Glysson, G.D., Gray, J.R., and Horowitz, A.J., 2010, Fluvial sediment in the environment—A national challenge, *in* 4th Federal Interagency Hydrologic Modeling Conference and the 9th Federal Interagency Sedimentation Conference, Hydrology and Sedimentation for a Changing Future Existing and Emerging Issues, Las Vegas, June 27–July 1, 2010, Proceedings: Advisory Committee on Water Information (ACWI), 14 p., accessed November 1, 2021 at https://acwi.gov/sos/pubs/2ndJFIC/Contents/OS_Larsen_9fisc_sediment_vision_3_4_2010.pdf.

Larsen, L., Harvey, J., Skalak, K., and Goodman, M., 2015, Fluorescence-based source tracking of organic sediment in restored and unrestored urban streams: Limnology and Oceanography, v. 60, no. 4, p. 1439–1461, https://doi.org/10.1002/lno.10108.

Maher, B.A., Watkins, S.J., Brunskill, G., Alexander, J., and Fielding, C.R., 2009, Sediment provenance in a tropical fluvial and marine context by magnetic 'fingerprinting' of transportable sand fractions: Sedimentology, v. 56, no. 3, p. 841–861, at https://doi.org/10.1111/j.1365-3091.2008.00999.x.

Martínez-Carreras, N., Udelhoven, T., Krein, A., Gallart, F., Iffly, J.F., Ziebel, J., Hoffmann, L., Pfister, L., and Walling, D.E., 2010, The use of sediment colour measured by diffuse reflectance spectrometry to determine sediment sources—Application to the Attert River catchment (Luxembourg): Journal of Hydrology, v. 382, no. 1, p. 49–63, https://doi.org/10.1016/j.jhydrol.2009.12.017.

Moragoda, N., and Cohen, S., 2020, Climate-induced trends in global riverine water discharge and suspended sediment dynamics in the 21st century: Global and Planetary Change, v. 191, article 103199, 13 p., https://doi.org/10.1016/j.gloplacha.2020.103199.

Moran, P.W., Nowell, L.H., Kemble, N.E., Mahler, B.J., Waite, I.R., and Van Metre, P.C., 2017, Influence of sediment chemistry and sediment toxicity on macroinvertebrate communities across 99 wadable streams of the Midwestern USA: Science of the Total Environment, v. 599–600, p. 1469–1478, https://doi.org/10.1016/j.scitotenv.2017.05.035.

Mukundan, R., Walling, D.E., Gellis, A.C., Slattery, M.C., and Radcliffe, D.E., 2012, Sediment source fingerprinting—Transforming from a research tool to a management Tool: Journal of the American Water Resources Association, v. 48, no. 6, p. 1241–1257, https://doi.org/10.1111/j.1752-1688.2012.00685.x.

Murphy, J.C., 2020, Changing suspended sediment in United States rivers and streams—Linking sediment trends to changes in land use/cover, hydrology and climate: Hydrology and Earth System Sciences, v. 24, no. 2, p. 991–1010, https://doi.org/10.5194/hess-24-991-2020.

Mussabek, D., Ahrens, L., Persson, K.M., and Berndtsson, R., 2019, Temporal trends and sediment–water partitioning of per- and polyfluoroalkyl substances (PFAS) in lake sediment: Chemosphere, v. 227, p. 624–629, https://doi.org/10.1016/j.chemosphere.2019.04.074.

Newson, M.D., and Newson, C.L., 2000, Geomorphology, ecology and river channel habitat—Mesoscale approaches to basin-scale challenges: Progress in Physical Geography—Earth and Environment, v. 24, no. 2, p. 195–217, https://doi.org/10.1177/030913330002400203.

Noe, G.B., Cashman, M.J., Skalak, K., Gellis, A., Hopkins, K.G., Moyer, D., Webber, J., Benthem, A., Maloney, K., Brakebill, J., Sekellick, A., Langland, M., Zhang, Q., Shenk, G., Keisman, J., and Hupp, C., 2020a, Sediment dynamics and implications for management—State of the science from long-term research in the Chesapeake Bay watershed, USA: WIREs Water, v. 7, no. 4, article e1454, 28 p., https://doi.org/10.1002/wat2.1454.

Noe, G. B., Hopkins, K. G., Claggett, P. R., Schenk, E. R., Metes, M. J., Ahmed, L., Doody, T.R., and Hupp, C. R., 2022, Streambank and floodplain geomorphic change and contribution to watershed material budgets: Environmental Research Letters, v. 17, no. 6, https://doi.org/10.1088/1748-9326/ac6e47.

Noe, G.B., Hupp, C.R., Schenk, E.R., Doody, T.R., and Hopkins, K.G., 2020b, Physico-chemical characteristics and sediment and nutrient fluxes of floodplains, streambanks, and streambeds in the Chesapeake Bay and Delaware River watersheds: U.S. Geological Survey data release, https://doi.org/10.5066/P9QLJYPX.

Owens, P.N., Batalla, R.J., Collins, A.J., Gomez, B., Hicks, D.M., Horowitz, A.J., Kondolf, G.M., Marden, M., Page, M.J., Peacock, D.H., Petticrew, E.L., Salomons, W., and Trustrum, N.A., 2005, Fine-grained sediment in river systems—Environmental significance and management issues: River Research and Applications, v. 21, no. 7, p. 693–717, https://doi.org/10.1002/rra.878.

Riebe, C.S., Sklar, L.S., Overstreet, B.T. and Wooster, J.K., 2014, Optimal reproduction in salmon spawning substrates linked to grain size and fish length: Water Resources Research, v. 50, no. 2, p. 898–918, https://doi.org/10.1002/2013WR014231.

Reiffarth, D.G., Petticrew, E.L., Owens, P.N., and Lobb, D.A., 2016, Sources of variability in fatty acid (FA) biomarkers in the application of compound-specific stable isotopes (CSSIs) to soil and sediment fingerprinting and tracing—A review: Science of the Total Environment, v. 565, p. 8–27, https://doi.org/10.1016/j.scitotenv.2016.04.137.

Resh, V.H., Brown, A.V., Covich, A.P., Gurtz, M.E., Li, H.W., Minshall, G.W., Reice, S.R., Sheldon, A.L., Wallace, J.B., and Wissmar, R.C., 1988, The role of disturbance in stream ecology: Journal of the North American Benthological Society, v. 7, no. 4, p. 433–455, https://doi.org/10.2307/1467300.

Robertson, D.M., and Saad, D.A., 2019, Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in streams of the midwestern United States: U.S. Geological Survey Scientific Investigations Report 2019–5114, 74 p., including 5 appendixes, https://doi.org/10.3133/sir20195114.

Robertson, D.M., Saad, D.A., and Heisey, D.M., 2006, Present and reference concentrations and yields of suspended sediment in streams in the Great Lakes region and adjacent areas: U.S. Geological Survey Scientific Investigations Report 2006–5066, 35 p., https://doi.org/10.3133/sir20065066.

Rogers, H.A., Schmidt, T.S., Dabney, B.L., Hladik, M.L., Mahler, B.J., and Van Metre, P.C., 2016, Bifenthrin causes trophic cascade and altered insect emergence in mesocosms—Implications for small streams: Environmental Science & Technology, v. 50, no. 21, p. 11974–11983, https://doi.org/10.1021/acs.est.6b02761.

Rustad, L., Campbell, J., Dukes, J.S., Huntington, T., Lambert, K.F., Mohan, J., and Rodenhouse, N., 2012, Changing climate, changing forests—The impacts of climate change on forests of the northeastern United States and eastern Canada: U.S. Department of Agriculture, Forest Service, General Technical Report NRS-99, 56 p., accessed November 1, 2021, at https://www.fs.usda.gov/nrs/pubs/gtr/gtr_nrs99.pdf.

Savoy, P., and Harvey, J.W., 2020, Predicting light regime controls on primary productivity across CONUS river networks: Geophysical Research Letters, v. 48, no. 10, article e2020GL092149, 10 p., https://doi.org/10.1029/2020GL092149.

Schilling, K.E., Palmer, J.A., Bettis, E.A., III, Jacobson, P., Schultz, R.C., and Isenhart, T.M., 2009, Vertical distribution of total carbon, nitrogen and phosphorus in riparian soils of Walnut Creek, southern Iowa: CATENA, v. 77, no. 3, p. 266–273, https://doi.org/10.1016/j.catena.2009.02.006.

Schmadel, N.M., Harvey, J.W., Schwarz, G.E., Alexander, R.B., Gomez-Velez, J.D., Scott, D., and Ator, S.W., 2019, Small ponds in headwater catchments are a dominant influence on regional nutrient and sediment budgets: Geophysical Research Letters, v. 46, no. 16, p. 9669–9677, https://doi.org/10.1029/2019GL083937.

Sekely, A.C., Mulla, D.J., and Bauer, D.W., 2002, Streambank slumping and its contribution to the phosphorus and suspended sediment loads of the Blue Earth River, Minnesota: Journal of Soil and Water Conservation, v. 57, no. 5, p. 243–250, accessed November 1, 2021, at https://www.jswconline.org/content/57/5/243.

Simon, A., Dickerson, W., and Heins, A., 2004, 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?: Geomorphology, v. 58, nos. 1–4, p. 243–262, https://doi.org/10.1016/j.geomorph.2003.07.003.

Skalak, K., and Pizzuto, J., 2010, The distribution and residence time of suspended sediment stored within the channel margins of a gravel-bed bedrock river: Earth Surface Processes and Landforms, v. 35, no. 4, p. 435–446, https://doi.org/10.1002/esp.1926.

Skalak, K.J., and Pizzuto, J., 2014, Reconstructing suspended sediment mercury contamination of a steep, gravel-bed river using reservoir theory: Environmental Geosciences, v. 21, no. 1, p. 17–35, https://doi.org/10.1306/eg.08151313007.

Stets, E.G., Sprague, L.A., Oelsner, G.P., Johnson, H.M., Murphy, J.C., Ryberg, K., Vecchia, A.V., Zuellig, R.E., Falcone, J.A., and Riskin, M.L., 2020, Landscape drivers of dynamic change in water quality of U.S. rivers: Environmental Science & Technology, v. 54, no. 7, p. 4336–4343, https://doi.org/10.1021/acs.est.9b05344.

Sutherland, A.B., Culp, J.M., and Benoy, G.A., 2010, Characterizing deposited sediment for stream habitat assessment: Limnology and Oceanography Methods, v. 8, no. 1, p. 30–44, https://doi.org/10.4319/lom.2010.8.30.

Taguchi, V.J., Olsen, T.A., Natarajan, P., Janke, B.D., Gulliver, J.S., Finlay, J.C., and Stefan, H.G., 2020, Internal loading in stormwater ponds as a phosphorus source to downstream waters: Limnology and Oceanography Letters, v. 5, no. 4, p. 322–330, https://doi.org/10.1002/lol2.10155.

Tian, Z., Zhao, H., Peter, K.T., Gonzalez, M., Wetzel, J., Wu, C., Hu, X., Prat, J., Mudrock, E., Hettinger, R., Cortina, A.E., Biswas, R.G., Kock, F.V.C., Soong, R., Jenne, A., Du, B., Hou, F., He, H., Lundeen, R., Gilbreath, A., Sutton, R., Scholz, N.L., Davis, J.W., Dodd, M.C., Simpson, A., McIntyre, J.K., and Kolodziej, E.P., 2021, A ubiquitous tire rubber-derived chemical induces acute mortality in coho salmon: Science, v. 371, no. 6525, p. 185–189, https://doi.org/10.1126/science.abd6951.

Turowski, J.M., Rickenmann, D., and Dadson, S.J., 2010, The partitioning of the total sediment load of a river into suspended load and bedload—A review of empirical data: Sedimentology, v. 57, p. 1126–1146.

U.S. Environmental Protection Agency [EPA], 1986, Quality criteria for water 1986 (“Gold Book”): U.S. Environmental Protection Agency, Office of Water Regulations and Standards, no. EPA 440/5-86-001, 395 p., accessed November 1, 2021, at https://www.epa.gov/sites/default/files/2018-10/documents/quality-criteria-water-1986.pdf.

U.S. Environmental Protection Agency [EPA], 1999, Protocol for developing sediment TMDLs (1st ed.): U.S Environmental Protection Agency, Office of Water, no. EPA 841-B-99-004, 143 p. [Available from https://www.epa.gov/nscep]

U.S. Environmental Protection Agency [EPA], 2016, National rivers and streams assessment 2008–2009—A collaborative survey: U.S. Environmental Protection Agency, Office of Water and Office of Research and Development, no. EPA/841/R-16/007, 119 p., accessed November 1, 2021, at http://www.epa.gov/national-aquatic-resource-surveys/nrsa [Also available at https://www.epa.gov/national-aquatic-resource-surveys/national-rivers-and-streams-assessment-2008-2009-report].

U.S. Environmental Protection Agency [EPA], 2017a, National Summary of State Information: U.S. Environmental Protection Agency, accessed January 5 2021, at https://iaspub.epa.gov/waters10/attains_nation_cy.control. [Also available at https://www.epa.gov/waterdata/attains].

U.S. Environmental Protection Agency [EPA], 2017b, National water quality inventory—Report to Congress: U.S. Environmental Protection Agency, no. EPA 841-R-16-011, 22 p., accessed January 5, 2021, at https://www.epa.gov/sites/default/files/2017-12/documents/305brtc_finalowow_08302017.pdf.

U.S. Environmental Protection Agency [EPA], 2017c, Water quality criteria, chap 3 *of* Water quality standards handbook: U.S. Environmental Protection Agency, Office of Water, no EPA 823-B-17-001, 28 p., accessed January 5, 2021, at https://www.epa.gov/wqs-tech/water-quality-standards-handbook.

U.S. Environmental Protection Agency [EPA], 2020, National rivers and streams assessment 2013–2014—A collaborative survey: U.S. Environmental Protection Agency, EPA 841-R-19-001, 65 p., accessed January 5, 2021, at https://www.epa.gov/system/files/documents/2021-10/nrsa_13-14_report_508_ci_2021-10-15.pdf.

Van Metre, P.C., and Fuller, C.C., 2009, Dual-core mass-balance approach for evaluating mercury and ^{210}Pb atmospheric fallout and focusing to lakes: Environmental Science & Technology, v. 43, no. 1, p. 26–32, https://doi.org/10.1021/es801490c.

Van Metre, P.C., and Horowitz, A.J., 2013, An 80-year record of sediment quality in the lower Mississippi River: Hydrological Processes, v. 27, no. 17, p. 2438–2448, https://doi.org/10.1002/hyp.9336.

Van Metre, P.C., and Mahler, B.J., 2004, Contaminant trends in reservoir sediment cores as records of influent stream quality: Environmental Science & Technology, v. 38, no. 11, p. 2978–2986, https://doi.org/10.1021/es049859x.

Van Metre, P.C., and Mahler, B.J., 2005, Trends in hydrophobic organic contaminants in urban and reference lake sediments across the United States, 1970–2001: Environmental Science & Technology, v. 39, no. 15, p. 5567–5574, https://doi.org/10.1021/es0503175.

Van Metre, P.C., and Mahler, B.J., 2010, Contribution of PAHs from coal-tar pavement sealcoat and other sources to 40 U.S. lakes: Science of the Total Environment, v. 409, no. 2, p. 334–344, https://doi.org/10.1016/j.scitotenv.2010.08.014.

Van Metre, P.C., Mahler, B.J., and Furlong, T., 2000, Urban sprawl leaves its PAH signature: Environmental Science & Technology, v. 34, no. 19, p. 4064–4070, https://doi.org/10.1021/es991007n.

Van Metre, P., Wilson, J.T., Fuller, C.C., Callender, E., and Mahler, B., 2004, Collection, analysis, and age-dating of sediment cores from 56 U.S. lakes and reservoirs sampled by the U.S. Geological Survey, 1992-2001: U.S. Geological Survey Scientific Investigations Report 2004–5184, 187 p., https://doi.org/10.3133/sir20045184.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., and Cushing, C.E., 1980, The river continuum concept: Canadian Journal of Fisheries and Aquatic Sciences, v. 37, no. 1, p. 130–137, https://doi.org/10.1139/f80-017.

Wagner, S., Cawley, K.M., Rosario-Ortiz, F.L. and Jaffé, R., 2015, In-stream sources and links between particulate and dissolved black carbon following a wildfire: Biogeochemistry, v. 124, p. 145–161, https://doi.org/10.1007/s10533-015-0088-1.

Wainwright, J., Turnbull, L., Ibrahim, T.G., Lexartza-Artza, I., Thornton, S.F., and Brazier, R.E., 2011, Linking environmental régimes, space and time—Interpretations of structural and functional connectivity: Geomorphology, v. 126, nos. 3–4, p. 387–404, https://doi.org/10.1016/j.geomorph.2010.07.027.

Weltje, G.J., and Prins, M.A., 2007, Genetically meaningful decomposition of grain-size distributions: Sedimentary Geology, v. 202, no. 3, p. 409–424, https://doi.org/10.1016/j.sedgeo.2007.03.007.

Wohl, E., Cooper, D., Poff, L., Rahel, F., Staley, D., and Winters, D., 2007, Assessment of stream ecosystem function and sensitivity in the Bighorn National Forest, Wyoming: Environmental Management, v. 40, no. 2, p. 284–302, https://doi.org/10.1007/s00267-006-0168-z.

Wohl, E., Hall Jr., R.O., Lininger, K.B., Sutfin, N.A., and Walters, D.M., 2017, Carbon dynamics of river corridors and the effects of human alterations: Ecological Monographs, v. 87, no. 3, p. 379–409, https://doi.org/10.1002/ecm.1261.

Woznicki, S.A., Cada, P., Wickham, J., Schmidt, M., Baynes, J., Mehaffey, M., and Neale, A., 2020, Sediment retention by natural landscapes in the conterminous United States: Science of the Total Environment, v. 745, article 140972, 11 p., https://doi.org/10.1016/j.scitotenv.2020.140972.

Yamada, H., and Nakamura, F., 2002, Effect of fine sediment deposition and channel works on periphyton biomass in the Makomanai River, northern Japan: River Research and Applications, v. 18, no. 5, p. 481–493, https://doi.org/10.1002/rra.688.

Zhang, Q., Brady, D.C., Boynton, W.R., and Ball, W.P., 2015, Long-term trends of nutrients and sediment from the nontidal Chesapeake watershed—An assessment of progress by river and season: Journal of the American Water Resources Association, v. 51, no. 6, p. 1534–1555, https://doi.org/10.1111/1752-1688.12327.

Zhang, Q., Hirsch, R.M., and Ball, W.P., 2016, Long-term changes in sediment and nutrient delivery from Conowingo Dam to Chesapeake Bay—Effects of reservoir sedimentation: Environmental Science & Technology, v. 50, no. 4, p. 1877–1886, https://doi.org/10.1021/acs.est.5b04073.

Zhang, W., Xing, Y., Yu, L., Feng, H., and Lu, M., 2008, Distinguishing sediments from the Yangtze and Yellow Rivers, China—A mineral magnetic approach: The Holocene, v. 18, no. 7, p. 1139–1145, https://doi.org/10.1177/0959683608095582.