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ADVANCED REVIEW

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Sediment dynamics and implications for management: State of the science from long-term research in the Chesapeake Bay watershed, USA

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Abstract

This review aims to synthesize the current knowledge of sediment dynamics using insights from long-term research conducted in the watershed draining to the Chesapeake Bay, the largest estuary in the U.S., to inform management actions to restore the estuary and its watershed. The sediment dynamics of the Chesapeake are typical of many impaired watersheds and estuaries around the world, and this synthesis is intended to be relevant and transferable to other sediment-impaired systems. The watershed's sediment sources, transport, delivery, and impacts are discussed with implications for effectively implementing best management practices (BMPs) to mitigate sediment issues. This synthesis revealed three key issues to consider when planning actions to reduce sediment loading: Scale, time, and land use. Geology and historical land use generated a template that current land use and climate, in addition to management, are acting upon to control sediment delivery. Important sediment sources in the Chesapeake include the Piedmont physiographic region, urban, and agricultural land use, and streambank erosion of headwater streams, whereas floodplain trapping is important along larger streams and rivers. Implementation of BMPs is widespread and is predicted to lead to decreased sediment loading; however, reworking of legacy sediment stored in stream valleys, with potentially long residence times in storage, can delay and complicate detection of the effects of BMPs on sediment loads. In conclusion, the improved understanding of sediment sources, storage areas, and transport lag times reviewed here can help target choices of BMP types and locations to better manage sediment problems—for both local streams and receiving waters.

This article is categorized under:

- Science of Water > Water Quality
- Water and Life > Stresses and Pressures on Ecosystems
- Water and Life > Conservation, Management, and Awareness

KEYWORDS

BMP, Chesapeake Bay, geomorphology, management, sediment

1 | WHY CARE ABOUT SEDIMENT?

Although sediment is a naturally occurring component of aquatic ecosystems, excess fine-grained sediment can cause negative impacts on the health of these environments, including streams, rivers, and estuaries. For example, 15% of stream and river length in the U.S. has been assessed to be in "poor" condition (and another 29% "fair") due to excess sediment, with disproportionate impacts of sediment on stream biota compared to other stressors (United States Environmental Protection Agency, 2016). Understanding the sources of sediment and delivery processes are critical to understand watershed impairment and target management practices to improve water quality (Gellis, Fitzpatrick, & Schubauer-Berigan, 2016; Novotny & Chesters, 1989). In addition, sediment eroded from landscapes and transported through stream networks may be subject to time-lags that delay arrival to downstream ecosystems that may be the primary focus of management interventions (Pizzuto et al., 2014; Pizzuto, Keeler, Skalak, & Karwan, 2017). A thorough understanding of sediment sources, transport, fate, and delivery is therefore necessary to efficiently and effectively target management actions with the goal of decreasing downstream loading of sediment and its negative impacts.

Here, we review the state-of-the-science of sediment dynamics in the watersheds of the Chesapeake Bay (hereafter "Chesapeake watershed") with the goal of identifying recommendations for implementing management practices to reduce fine-grained sediment loading. The Chesapeake watershed covers 166,530 km^2 with a population of more than 18 million people from six states and the District of Columbia and contains multiple major tributaries to the estuary (Figure 1a). Decades of high sediment, nitrogen (N), and phosphorus (P) loading from its watershed to the Chesapeake Bay and its tidal tributaries (hereafter "Bay") have led to impairment of estuarine biota and water clarity (W. M. Kemp et al., 2005, Figure 1b,c). In response, the U.S. EPA identified the total maximum daily loading (TMDL) of sediment, N, and P from the Chesapeake watershed to the Bay that would result in restoration of water quality and alleviate biotic impairment (United States Environmental Protection Agency, 2010). A partnership of federal, state, and local governments—the Chesapeake Bay Program (CBP)—is now responsible for implementing management actions that would reduce downstream sediment loading by 20% to meet the TMDL target (United States Environmental Protection Agency, 2010). In addition to the Bay, numerous streams in the watershed have been identified with biotic impairment due to excess sediment and are subject to individual local TMDLs. In this review, we summarize sediment sources, transport, delivery, and impacts in the Chesapeake watershed, and using examples from around the world, to help inform effective approaches for reducing sediment loading. The relatively well-studied Chesapeake watershed and Bay are typical of managed, diverse temperate landscapes, and this synthesis of long-term sediment knowledge is intended to help inform understanding and management of sediment in other similarly affected landscapes.

1.1 | Impacts on biota

An adequate supply of fine- and coarse-grained sediment is necessary to the healthy function of non-tidal and tidal aquatic systems (Stevenson, Ward, & Kearney, 1988), but human-driven alterations to the sediment cycle can result in profound ecological impairments. The overall impact of sediment on aquatic ecosystems has been recognized for over 80 years (Aitken, 1936), yet research continues to explore the complex mechanisms by which ecosystems react to sediment pressures and its exacerbation of other environmental pressures such as elevated temperature, nutrients, or contaminants (Matthaei, Piggott, & Townsend, 2010; Piggott, Lange, Townsend, & Matthaei, 2012). Furthermore, as a key constituent affecting water clarity, sediment also plays a role in perceptions of the quality and value of water for

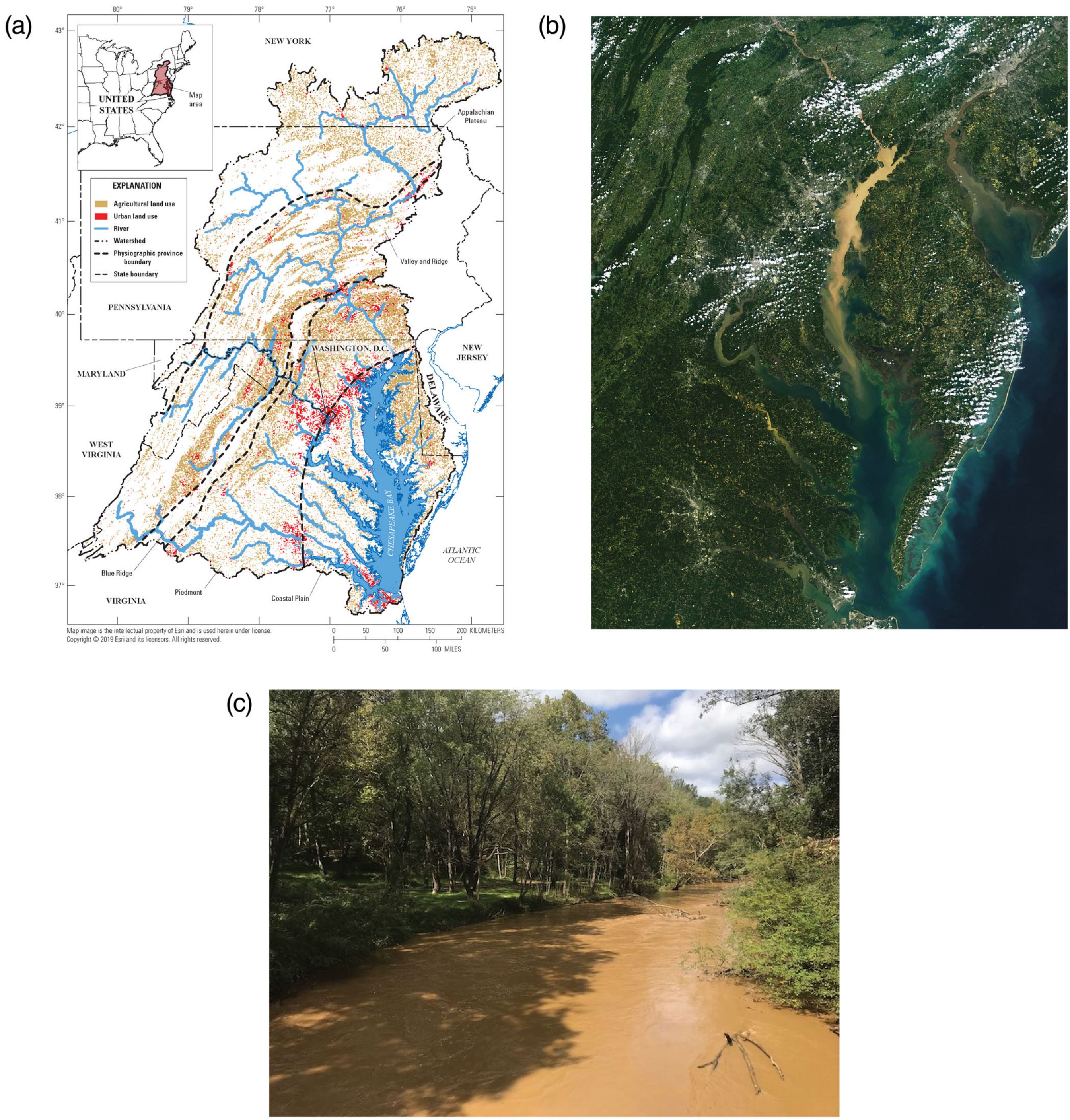

FIGURE 1 (a) Map of the Chesapeake Bay and its watershed. Red colors indicate urban/developed areas and tan color indicates agricultural areas (i.e., cultivated crops and pasture/hay) from the 2016 National Land Cover Database; (b) Satellite image of sediment plume entering the Chesapeake Bay after Tropical Storm Lee in 2011 (image courtesy of NASA); (c) Deer Creek, Maryland, with high concentrations of suspended sediment after a storm (image courtesy of USGS)

recreational use and aesthetic purposes (Gibbs, Halstead, Boyle, & Huang, 2002; D. G. Smith, Cragg, & Croker, 1991). While many of the studies and reviews of the impacts of sediment on biota have been conducted outside the Chesapeake watershed, we consider these mechanisms to be largely applicable and necessary to understand the impacts of sediment pressures on a wide variety of aquatic ecosystems, including the Chesapeake.

Numerous review papers comprehensively cover the effects of fine-grained sediment on aquatic ecosystems (Berry, Rubinstein, Melzian, & Hill, 2003; Wood & Armitage, 1997), and specifically address the effects of sediment across nontidal and tidal food webs. Fine-grained sediments impact primary producers (Cabaço, Santos, & Duarte, 2008; Jones, Collins, Naden, & Sear, 2012), low-level consumers such as macroinvertebrates (Jones et al., 2012), and higher consumers such as fishes (P. Kemp, Sear, Collins, Naden, & Jones, 2011; Kjelland, Woodley, Swannack, & Smith, 2015). These reviews highlight that the effects of sediment are wide-ranging and include community-level shifts, changes in biodiversity, behavioral alterations, physiological stress-responses, and diminished population fitness.

Sediment generally affects biota through two mechanisms—indirectly by deposition and siltation of bed habitats and directly through effects from suspended sediment. Deposited particles can indirectly impact biota as a vector for pollutants and contaminants (see section below), as well as decrease particle size of bed substrate, bury bed habitat (Wood & Armitage, 1997), and clog interstitial pore space and block hyporheic exchange (Brunke, 1999). In non-tidal systems, deposited sediment can restrict benthic algal growth (Yamada & Nakamura, 2002) and can disproportionately affect some macroinvertebrate taxa particularly vulnerable to surficial fine sediment, such as EPT (Ephemeroptera, Plecoptera, Trichoptera; Burdon, McIntosh, & Harding, 2013).

Suspended sediment can directly impact biota by decreasing light penetration and suppressing primary production in algae and macrophytes (Izagirre, Serra, Guasch, & Elosegi, 2009; Jones, Collins, et al., 2012; Yamada & Nakamura, 2002), causing direct abrasion and physical damage to soft-tissues, and clogging of membranes such as gills (P. Kemp et al., 2011). Abundant suspended sediment can induce increased drift of invertebrates in stream ecosystems (Culp, Wrona, & Davies, 1986; Doeg & Milledge, 1991) and can alter fish movement and predator–prey interactions (Kjelland et al., 2015). However, suspended sediment concentration alone has been shown to be a poor predictor of the ecological impacts of sediment; rather, impacts are a combination of concentration and duration of the elevated sediment pressure (Newcombe & Macdonald, 1991), highlighting the importance of increased temporal resolution in sediment monitoring to more fully understand impacts on aquatic ecosystems.

Research on sediment effects on biota in the non-tidal Chesapeake watershed, although limited, support these more general patterns outlined above. Sediment and turbidity are the third-most common cause of impairment on the list of impaired and threatened waters within the Chesapeake region (United States Environmental Protection Agency, 2015). Schutt (2012) reports a strong negative relationship between EPT taxa and abundance of fine sediment in streambeds in the James River, Virginia. A detailed study in three Pennsylvania streams found that increased sediment loads led to finer bed sediment and a shift in macroinvertebrate composition from amphipods to chironomids and also fewer brown trout (N. E. Wohl & Carline, 1996). Three to five years after riparian restoration to two of these streams, bank erosion, and streambed sedimentation decreased and macroinvertebrate densities increased, but drought conditions inhibited the ability to detect a response of macroinvertebrate diversity (Carline & Walsh, 2007). In a study covering seven counties of Maryland, the proportion of a catchment with contemporary developed land use or historic agricultural land use had a negative effect on riffle quality, a proxy for streambed stability and sediment pressures, resulting in a negative effect on benthic stream macroinvertebrates (Maloney & Weller, 2011).

Within the Chesapeake Bay, the impact of sedimentation on submerged aquatic vegetation (SAV) has gained considerable attention. Estuarine SAV beds provide critical habitat for juvenile fish and the iconic Chesapeake blue crab (*Callinectes sapidus*), as well as foraging habitat for local and migrating waterfowl. Sediment burial and differences in sediment grain size affect the germination, distribution, and persistence of SAV (W. M. Kemp et al., 2004). While fine-grained sediment and organic matter are important substrate components contributing to SAV germination, and moderate deposition rates can stimulate growth (Marba & Duarte, 1994), excessive sediment accumulation can negatively impact seedling emergence (Jarvis & Moore, 2015; Rybicki & Carter, 1986) and has been associated with severe declines in acreage (Orth & Moore, 1984). Persistence of SAV beds in the mesohaline portion of Chesapeake Bay correlates with high accumulation rates of sandy sediments with low organic content; in contrast, finer sediment accumulation in similar locations is correlated with SAV absence (Palinkas & Koch, 2012). Furthermore, storm- and wind-driven resuspension of previously deposited sediments can create light-limiting conditions, reducing macrophyte biomass, as seen in the Susquehanna Flats region of the upper Chesapeake Bay (Gurbisz, Kemp, Sanford, & Orth, 2016). Sedimentation rates and sediment burial also affect the behavior and mortality of benthic macrofauna, with implications for community structure and related functions such as sediment bioturbation and pelletization (Hinchey, Schaffner, Hoar, Vogt, & Batte, 2006; Schaffner, Diaz, Olsen, & Larsen, 1987). Of particular concern are the impacts of increased sedimentation on the native oyster *Crassostrea virginica* (Colden & Lipcius, 2015; Comeau, Mallet, Carver, Nadalini, & Tremblay, 2017), which plays an important economic and cultural role in the region as well as provide water-column filtration services. While *C. virginica* has demonstrated a tolerance for short-duration exposure to suspended sediment

BOX 1 Management implication: Not all sediment is equal

Sediment origin can have an important role in its impact on the biological community, as sediment from different sources can have differing size-fractions, organic content, and bound pollutants (Cashman, 2018; Kennicutt et al., 1994). Increased surface area and binding sites on fine-grained sediment are more likely to carry higher concentrations of P, heavy metals, and other contaminants (Horowitz & Elrick, 1987; Thoms, 1987). Organic sediments will likely have more associated contaminants and their decomposition on the bed increases oxygen demand and can cause localized hypoxia (Sear et al., 2016).

plumes (Suedel, Clarke, Wilkens, Lutz, & Clarke, 2015), sub-lethal and lethal effects of sediment burial have been observed, and sediment burial decreases the success of oyster restoration (Colden, Latour, & Lipcius, 2017; Schulte, Burke, & Lipcius, 2009; Box 1).

1.2 | Sediment as a vector for nutrients and contaminants

Suspended sediments are usually considered an important vector for nutrients and contaminants that can adversely affect the downstream Bay, and thus, managing sediment may help minimize the loading and impacts of other contaminants. In the Chesapeake watershed, 73% of total P load and 18% of total N load transported to the Bay is typically attached to sediment (calculated from Zhang, Brady, Boynton, & Ball, 2015), and particulate nutrient fractions (i.e., sediment-attached) generally are a larger percentage of total load where sediment loading is greater (Zhang et al., 2015). Analyses of the multi-decadal record of particulate nutrient and suspended sediment loads in the nine major river tributaries of the Bay indicate average nutrient concentrations on suspended sediment are 1.0 mg-P/g and 3.6 mg-N/g (Zhang & Blomquist, 2018).

Understanding the concentrations and sorption and desorption dynamics of bound nutrients and contaminants with sediment is important for understanding their fate during transport and storage in sediment accumulation zones. Phosphate is the most bioavailable form of P and can be responsible for fueling algal blooms (Lean & Nalewajko, 1976). Phosphate reversibly attaches (sorbs) to sediment and is transported and deposited into storage along with sediment. The desorption of phosphate off sediment can occur in response to changes in redox, pH, and microbial activity (Froelich, 1988). Once detached from sediment, phosphate can be taken up by organisms or rapidly transported downstream as a dissolved solute (Newbold, Elwood, O'Neill, & Sheldon, 1983).

In addition, organic matter, metals, pesticides, polychlorinated biphenyl (PCBs), polycyclic aromatic hydrocarbons (PAHs), and other organic contaminants are associated with sediment. In particular, many heavy metals, PCBs, PAHs, and other organic contaminants have been found to be enriched in sediments washed out of urban watersheds (Foster, Roberts, Gruessner, & Velinsky, 2000; Horowitz & Stephens, 2008). For example, mercury attaches tightly to sediment and is transported and deposited with sediment in channel beds and floodplains (Flanders et al., 2010; Skalak & Pizzuto, 2010, 2014). Sediment-bound mercury concentrations are a function of sediment particle size or organic content (Skalak & Pizzuto, 2014). Remobilization and downstream export of stored mercury is a result of sediment erosion and can take years to decades or centuries to remove contaminated sediments (Skalak & Pizzuto, 2010, 2014).

2 | THE ROLE OF LAND USE HISTORY

Past land uses have altered the characteristics of Chesapeake watersheds, changing both sediment and hydrologic inputs into the stream channel. Changes in stream dynamics slowly alter channel form and function and fine sediment storage over a range of timescales. The time required between watershed change and the corresponding change in a stream system is known as the lag time (Bain et al., 2012), with a delayed onset, peak disturbance, and lingering impact. The lag time for sediment can be decades or centuries (Pizzuto et al., 2017). The result is that changes that occurred centuries ago continue to impact stream sediment dynamics today (Belby, Spigel, & Fitzpatrick, 2019), and that the effect of current changes made to the watershed (e.g., best management practices, BMPs) may not become fully apparent until years or decades in the future. Understanding the past human alterations to streams, intentional and unintentional, is needed to understand current sediment sources, impacts, and trajectories. Although observations and deductions about sediment processes in past centuries are sparse, we attempt to summarize observations, theory, and inferences to highlight differences across important eras. The focus of this section is land use history, whereas other drivers of sediment dynamics are discussed later in the review.

2.1.1. | Pre-colonial period before European arrival

Geologic (pre-European) rates of erosion varied across the Chesapeake watershed with greater erosion in basins that are steeper and have more precipitation (Portenga et al., 2019). Notably, the Piedmont physiographic province, located between the mountains and Coastal Plain, had low natural sediment yields compared to current high yields (Gellis et al., 2009). Pre-colonial sedimentation in stream valleys was typically minimal and stream-floodplain geomorphology stable (Costa, 1975; Jacobson & Coleman, 1986), with some exceptions occurring where intensive agriculture by Native peoples led to sediment erosion (L. A. James, 2019; Stinchcomb, Messner, Driese, Nordt, & Stewart, 2011). Stream channels in the Chesapeake watershed likely looked very different in the pre-colonial period than today. In some locations, headwater streams may have had low banks, anastomosing channels, and extensive wetland marsh and swamp floodplains (Elliott, Wilf, Walter, & Merritts, 2013) with significant beaver influence (Brush, 2009; Ruedemann & Schoonmaker, 1938). Before eastern North America was settled by Europeans, streams in the Chesapeake watershed likely had sediment inputs to streams similar to outputs (Figure 2a). Overall, sediment yields to the Bay are assumed to have been relatively small, with no net deposition or erosion and much less sediment in floodplain storage along streams (Jacobson & Coleman, 1986).

2.1.2. | Colonial period

During the colonial period from the 17th to 19th centuries, uplands of the Chesapeake watershed were largely deforested for slash and burn agriculture, charcoal production, and timber harvesting, leaving hillslopes susceptible to erosion (Brush, 2009; Figure 2b). Massive pulses of sediment were transported into streams and delivered to the Bay with significant accumulation in floodplains and channel beds (Jacobson & Coleman, 1986; L. A. James, 2019). Sediment retention was also increased by the widespread construction of colonial-era milldams throughout the region (Merritts et al., 2013; Walter & Merritts, 2008). Sediment that accumulated in floodplains and channel beds during this period is often referred to as "legacy sediment" (see section below). This phenomenon was widespread where land clearing occurred across the United States (Happ, Rittenhouse, & Dobson, 1940).

2.1.3. | Post-colonial period

In the late 19th and early 20th centuries, soil conservation practices were introduced and much of the eastern U.S. began to reforest (Steyaert & Knox, 2008), which stabilized hillslopes and began reducing sediment loads to streams (Brush, 2009). Although watershed inputs from upland soils decreased, accumulated sediment stored in the stream valley continued to be mobilized in streams (Jacobson & Coleman, 1986). This is thought to have led to stream incision, which in turn, caused reductions in overbank floods and floodplain deposition (Hupp et al., 2015; Leopold, Wolman, & Miller, 1964). Simultaneously, many milldams were naturally breached or removed (Merritts et al., 2011) which decreased the volume of sediment trapped in the stream system and helped speed local erosion and degradation of channel beds. Overall, it is inferred that streams in the Chesapeake during this time were mostly erosional and sediment yields to the Bay were moderate.

2.1.4. | Urbanization period

Urbanization, the current era of regional land use, is considered to have accelerated with widespread suburban expansion after World War 2. Construction in the early stages of urbanization generated large volumes of erodible sediment that delivered large sediment pulses to streams (Wolman, 1967) that can persist for decades after initial construction

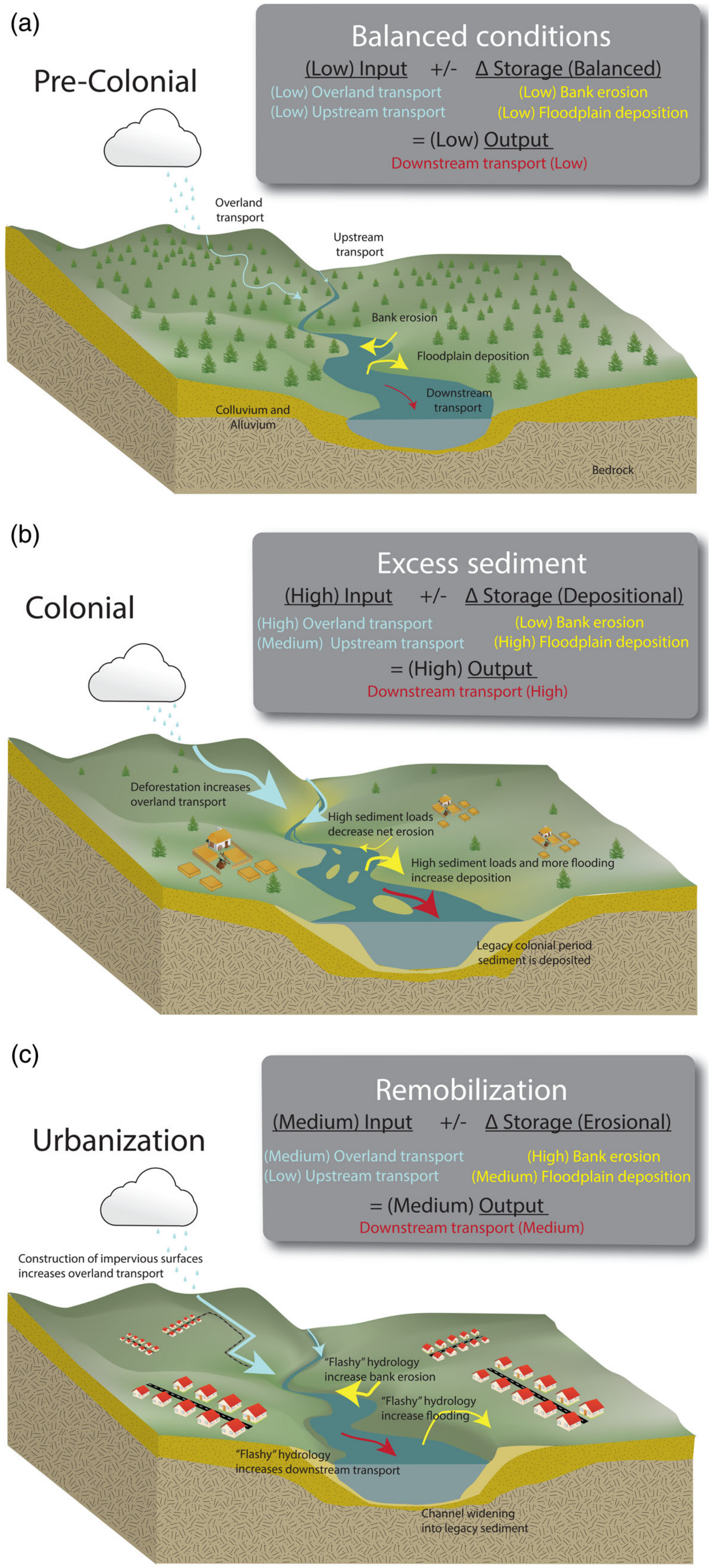

FIGURE 2 Three of the eras of sediment in the Chesapeake watershed, with inferred or measured relative rates of sediment input, storage, and export

(Gellis et al., 2017). Although urban cover can limit the area of exposed surface soils to erosion, greater impervious surface area increases the energy and volume of runoff and increases water delivery to streams. This stream "flashiness" (the quick rise and fall of the streamflow hydrograph in response to precipitation) can result in increased erosion of

BOX 2 Management implication: Legacy sediment

Legacy sediment is a high priority for future mitigation work because its presence represents a potential long-term supply that will continue to be eroded and supply sediment to downstream environments (Meade, 1982). Proposed management strategies include removal of legacy sediment through floodplain excavation, channel dredging, or armoring or grading of stream banks to prevent lateral erosion. Efficacy of these strategies largely depends on watershed context and additional study is needed to determine effectiveness and the negative side-effects of these approaches.

streambanks and beds, whereas floodplain deposition can be enhanced with increases in peak streamflow as streams flood more frequently (Hupp, Noe, Schenk, & Benthem, 2013). Symptoms of impairment common in urban streams, termed the "urban stream syndrome", include initial increases in sediment supply from hillslope erosion leading to an aggradation phase with streambed and floodplain deposition, followed by an erosional phase where flashy streams erode stream beds and banks (Paul & Meyer, 2001), although channel response can vary (Colosimo & Wilcock, 2007). Streams are even more erosional during this period than during the post-colonial period, and sediment yields to the Bay remain moderate (Figure 2c).

2.1 | Legacy sediment and stream valley storage

The term "legacy sediment" has attained widespread usage over the last decade and is defined many ways. In the mid-Atlantic of the U.S., its usage has been directly associated with sediment deposits behind former milldam impoundments (Walter & Merritts, 2008). Others have argued milldams are not required to create legacy sediment deposits (Bain, Smith, & Nagle, 2008; Donovan, Miller, Baker, & Gellis, 2015; Hupp et al., 2013). Much of the usage of this term has relied on "preconceived understandings and implications" of what legacy sediment is rather than an explicit definition (L. A. James, 2013). L. A. James (2013) suggests that a thorough identification of how sediment is produced should not be a "sticking point as long as it is clear that the deposit is associated with processes substantially accelerated by human activities." E. Wohl (2015) broadens the definition of legacy sediments further to "those for which the location, volume, and/or presence of contaminants result from past and contemporary human activities." For purposes of the Chesapeake management effort, the Science and Technical Advisory Committee of the CBP (Miller et al., 2019) has recently defined legacy sediment as:

> "sediment stored in upland and lowland portions of the Bay's tributary watersheds as a byproduct of accelerated erosion caused by landscape disturbance following European settlement, most prominently in the Piedmont and Coastal Plain provinces."

In addition to storage of this older legacy sediment in stream valleys, significant inputs into storage continued into the recent past (Costa, 1975). This historic legacy of augmented fine-grained sediment storage in stream valleys sets the stage for current sediment dynamics, which we describe next (Box 2).

3 | SEDIMENT SOURCES, TRANSPORT, AND DELIVERY

3.1 | Sediment budget framework

The balance of sediment inputs and outputs is a fundamental description of stream systems (E. Wohl, 2015), and a sediment budget is an accounting framework that can be used to understand and manage the processes of sediment erosion, transport, storage, delivery, and linkages among these elements and where they occur in a watershed (Gellis, Fitzpatrick, & Schubauer-Berigan, 2016; Leopold, 1966; Reid & Dunne, 2005; Swanson, Janda, Dunne, & Swanston, 1982; Walling & Collins, 2008). Typical inputs to a stream include upland soil erosion, gully erosion, tributary loading, and erosion of streambanks; dynamic storage can include hillslopes, upland valleys, alluvial fans, channel beds and margins, and floodplains; and export could be to either a downstream reach, estuary, or coast (where additional sources and storage may occur). Effective sediment management requires information on each of these aspects of the sediment budget, and their controls, across multiple spatial scales. For example, the accurate quantification of erosion sources is important as management approaches to mitigate erosion from upland sources (i.e., forest, pasture, crop) and channel sources are distinctly different (e.g., soil conservation vs stream restoration). However, sediment budgets provide only a snapshot of sediment processes and do not address trajectories of change or describe the localized impacts of sediment processes.

For smaller watersheds, the quantification of erosional sources can be identified by using an approach called sediment fingerprinting (Gellis, Fitzpatrick, & Schubauer-Berigan, 2016; Gellis & Walling, 2011). Sediment fingerprinting is a method which uses distinguishing tracers (e.g., chemicals, trace elements, radio-isotopes, and other attributes) to identify and quantify specific sources of eroded sediment delivered and transported within a watershed, with results used to guide management actions to reduce sediment loads (Mukundan, Walling, Gellis, Slattery, & Radcliffe, 2012). Importantly, fingerprinting specifically targets sediment that has been delivered to water bodies, which may differ from gross erosion calculated from sediment budgets on the landscape (see section on Upland Storage below). Furthermore, repeated analysis of sediment fingerprints throughout time can address how source contributions may change in response to management actions. With this in mind, specific guidelines on underlying assumptions of sediment fingerprinting, sediment source sampling, target sampling and software for statistical procedures used to apportion sources have been developed to aid in decision-making (Gellis, Fitzpatrick, & Schubauer-Berigan, 2016; Gorman Sanisaca, Gellis, & Lorenz, 2017a, 2017b).

3.1.1 | Upland erosion

Sediment eroded from uplands originates from a variety of sources. Common present-day upland sediment sources in the Chesapeake watershed include agricultural areas, forests, roads, urban areas, construction sites, gullies and ditches, and mines (Langland & Cronin, 2003), and these sources vary spatially across and within watersheds (Cashman et al., 2018; Gellis et al., 2009; Gellis et al., 2015; Gellis et al., 2017; Gellis & Gorman Sanisaca, 2018; Gellis & Noe, 2013).

Across the whole Chesapeake watershed, the statistical tool Spatially Referenced Regressions on Watershed Attributes (SPARROW) has been used to estimate sediment loads from upland sources (Brakebill, Ator, & Schwarz, 2010; Brakebill, Ator, & Sekellick, 2019) and estimated average sediment yield to be approximately 70 times greater per unit area from urban lands than from agricultural lands (Brakebill et al., 2010). Despite these differences, the model suggests agriculture contributes about 69% of the sediment delivered to the Bay (when accounting for sediment storage along streams and in reservoirs) mainly because agriculture is more widespread than any other land use (Figure 3, Brakebill et al., 2019). Direct measurements of soil erosion rates from agricultural fields have been shown to be more than 10 times greater than from forests in the Chesapeake (Gellis et al., 2015). In addition, the Piedmont physiographic setting, with its specific geology, topography, and structure, has also been well documented to have erosive upland soils and high sediment yields (Brakebill et al., 2010; Gellis, Banks, Langland, & Martucci, 2004; Trimble, 1975).

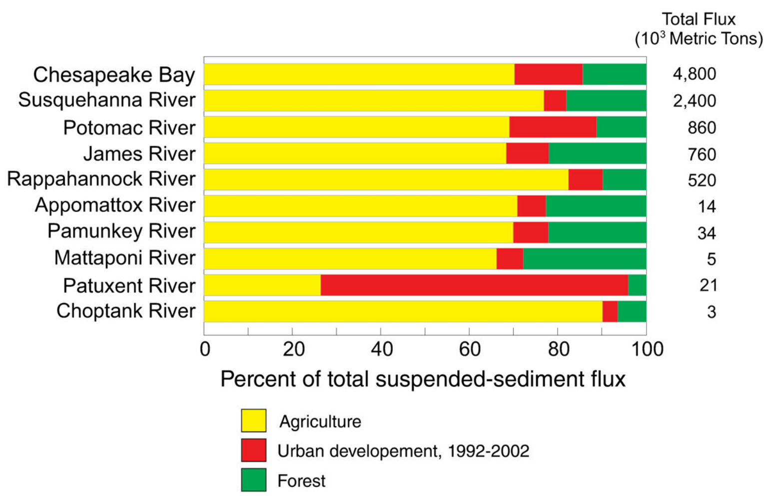

FIGURE 3 Estimates of the contribution of different upland land uses to the load of stream sediment that is transported to the outlet of individual tributaries of the Chesapeake Bay watershed (accounting for both sediment generated in the watershed of that tributary and retained during transport), derived from SPARROW modeling (Brakebill et al., 2019)

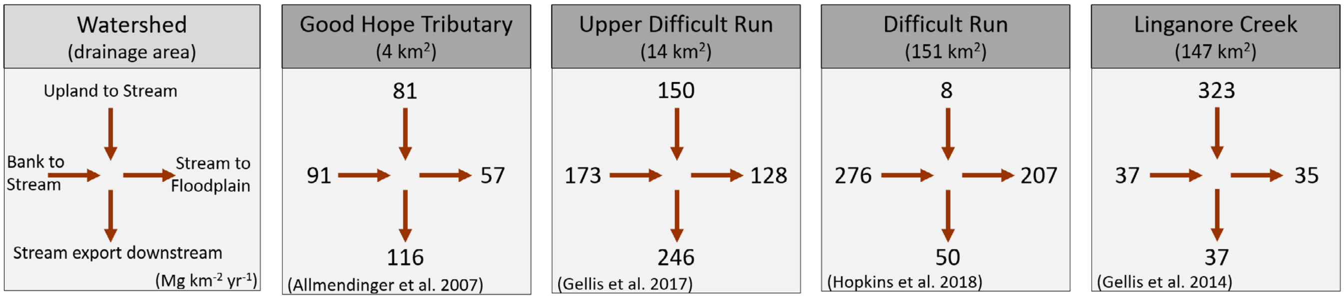

FIGURE 4 Summarized sediment mass balances derived from sediment budgets of Chesapeake small watersheds. Inputs and outputs may not balance because of unmeasured processes or measurement and extrapolation errors. Units are in mg km^{-2} $year^{-1}$

BOX 3 Management implication: Upland sediment sources

The availability of detailed information on the source of sediment (stream corridors or upland erosion) in a specific local watershed would facilitate more effective planning and implementation of sediment-reduction actions. Notably, management approaches to mitigate erosion from upland sources (i.e., forest, pasture, crop) and streambanks are distinctly different (e.g., implementing soil conservation vs stream restoration). However, management actions designed to reduce upland sediment erosion across the Chesapeake Bay watershed are likely to be most effective where sediment loading is greatest—specifically, in both urban and agricultural areas of Piedmont. Limiting delivery of sediment is likely more effective when targeting erosion in uplands located closer to streams and the Bay.

Within the Chesapeake watershed, sediment fingerprinting has been used in a variety of small watersheds (<250 km^2), ranging from highly urban to highly agricultural basins (Table S1; Devereux, Prestegaard, Needelman, & Gellis, 2010; Banks, Gellis, & Noe, 2010; Massoudieh, Gellis, Banks, & Wieczorek, 2013). Fingerprinting results are quite variable from basin to basin and across time, reflecting the interaction of land use, geology, and sediment storage in each basin, as well as characteristics of storms sampled (Cashman et al., 2018; Gellis et al., 2009; Gellis et al., 2015; Gellis & Gorman Sanisaca, 2018). Although results for each basin are unique, agriculture and urban land use have been identified as important uplands sources of sediment transported as stream load (Table S1).

Direct field measurements of erosion and deposition across the landscape can be used to develop a watershed sediment budget for a specific setting. Sediment budgets are typically calculated from measurements at fixed locations throughout a watershed that are extrapolated to estimate overall net erosion and deposition for the whole watershed. Sediment budgets in the Chesapeake watershed have indicated highly variable upland sediment yields delivered to streams among different basins (Figure 4; Box 3).

3.1.2 | Upland storage

Not all sediment eroded from uplands is delivered to streams. In construction of sediment budgets, the term "gross erosion" is used to describe sediment eroded from an area of interest, which can range from plot- to watershed-scale, and "net delivery" is used to describe sediment delivered to a downstream site (de Vente, Poesen, Arabkhedri, & Verstraeten, 2007). The sediment delivery ratio (SDR) is the ratio of net delivery to gross erosion (Walling, 1983), usually expressed as a percent, in other words, the proportion of eroded sediment that was exported at that stream sampling location.

Reports of SDRs in the Chesapeake watershed are rare. Costa (1975) examined stratigraphy of surficial deposits in Western Run, Maryland, and determined 34% of sediment eroded from hillslopes during European land clearing for agriculture in the 1700s was transported into the river system. The remaining 66% was deposited in floodplains, and as colluvium and sheetwash deposits on hillslopes. Gellis et al. (2015) determined SDRs for agricultural fields and forest to

BOX 4 Management implication: Gullies

Where gullying is of particular concern, extra consideration should be given to interpreting gullies' hydrologic context and how they would be classified into sediment source, budgeting, or modeling results to inform appropriate management interventions. Although management actions to mitigate rill initiation and expansion of disconnected field gullies might involve establishing vegetation cover or soil conservation, most actions to limit channel expansion or headcut incision might involve the management of upstream runoff and hard stabilization of gully-channels (similar to some in-channel stream restorations methods).

be 4 and 8%, respectively, for Linganore Creek, Maryland, indicating a large mass of sediment in upland storage. In addition, small ponds constructed on agricultural lands in Linganore Creek stored 16% of total eroded sediment (Gellis et al., 2015). S. Smith and Wilcock (2015) also documented substantial upland valley sediment storage.

3.1.3 | Gullies and zero-order channels

Gullies, ditches, and zero-order stream erosion can be an important source of sediment as well as effective links from the uplands to stream valleys when connected to downstream channels, increasing upland connectivity and the efficient delivery of sediment to the permanent flowing stream network (Poesen, Nachtergaele, Verstraeten, & Valentin, 2003). While gullies and zero-order channels are commonly classified under upland erosion (S. Smith & Wilcock, 2015), their expansion and erosion also share many similarities to stream-channel erosional processes, despite the ephemeral nature of their flows. Gully erosion is often triggered by extreme rainfall on intensively disturbed soils along steep slopes (Valentin, Poesen, & Li, 2005). It is important to note that various methodological approaches (e.g., sediment budget, fingerprinting, modeling) may opt to lump gullies into different sides of the upland/stream valley divide, or altogether ignore gullies (Box 4).

3.1.4 | Stream valley fluxes

Sediment stored in stream valleys can be eroded, entrained as suspended sediment or bedload and transported downstream, deposited in storage zones such as floodplains or channel deposits, and potentially eroded again and transported further downstream (Figure 5). Thus, contemporary sediment sources and transport are greatly influenced by the reworking of sediment already stored in stream valleys.

Bank erosion

Sediment eroded from streambanks is efficiently delivered to the channel and can be the predominant source of the sediment load; however, bank erosion rates are highly variable in time and space and generally poorly quantified and difficult to predict. Sediment fingerprinting studies have identified streambanks as consistently important contributors of sediment: The major source of sediment (>50%) in 5 of 8 studies and the single greatest source in 6 of 8 studies (Table S1), although some sediment fingerprinting approaches may not be able to distinguish between gully and streambank erosion (Gellis, Fuller, & Van Metre, 2016). Likewise, most Chesapeake sediment budgets have found that bank erosion is greater than the amount of upland erosion delivered to stream networks (Figure 4). Quantification of streambank sediment sources is notable since previous models used by management agencies in the Chesapeake watershed underrepresent bank erosion (e.g., the CBP partnership's Watershed Model; Shenk & Linker, 2013).

The spatial and temporal factors that influence bank erosion are being identified. Studies that have measured bank erosion found it typically increases with stream drainage area (Gellis et al., 2015; Gellis et al., 2017; Gillespie, Noe, Hupp, Gellis, & Schenk, 2018) and where bank sediment is less dense and has less coverage by woody vegetation and roots (Wynn & Mostaghimi, 2006). Conversely, bank aggradation by riparian grasses leads to narrower stream channels compared to forested riparian zones (Hession, Pizzuto, Johnson, & Horwitz, 2003; Sweeney et al., 2004).

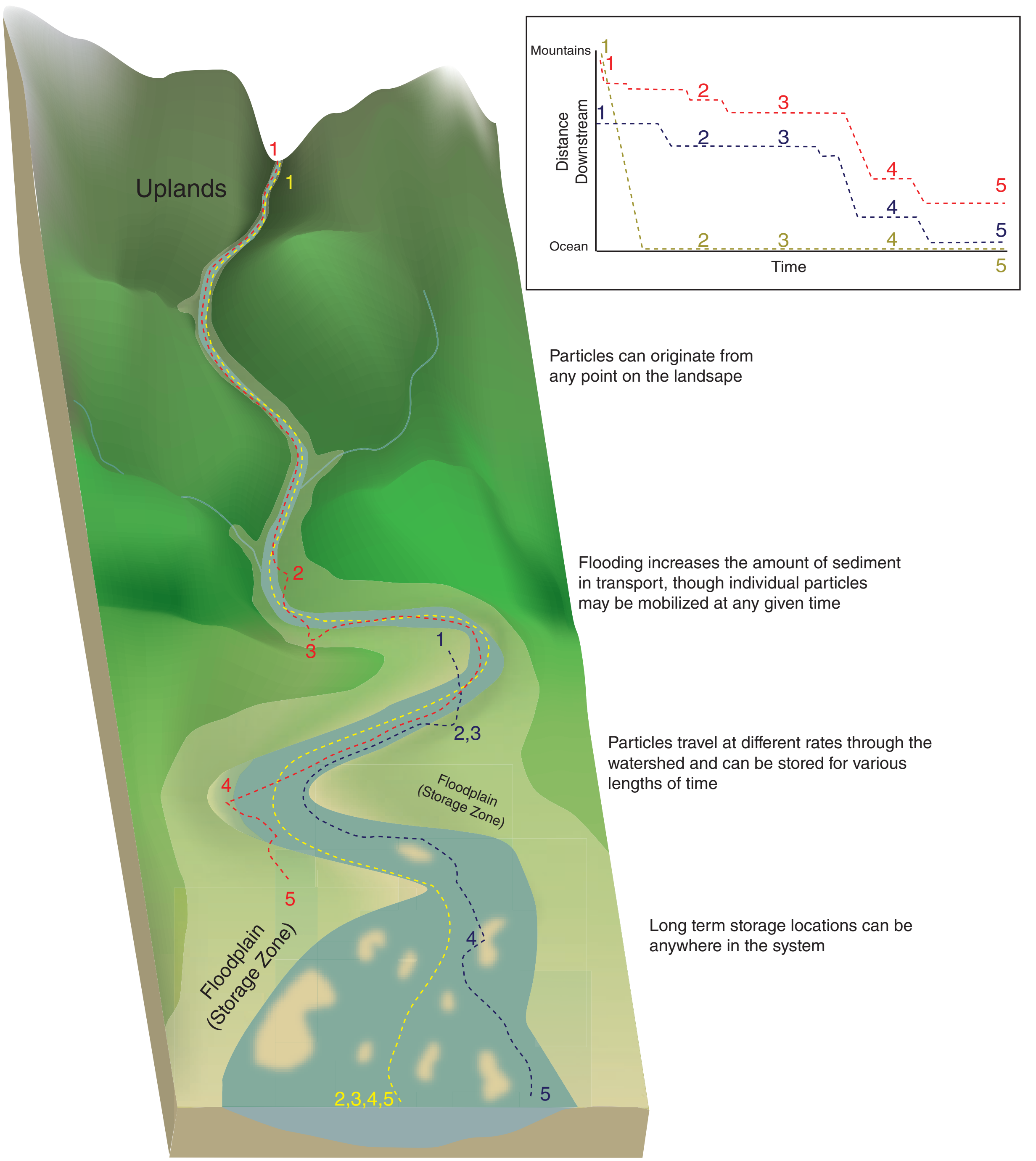

FIGURE 5 Examples of some potential pathways of transport, storage, erosion, and export of sediment within a stream valley of a watershed

Geomorphometry of stream valleys, including the shape, size, and ratios of channels, streambanks, and floodplains, has been used to predict rates of bank erosion (Hopkins et al., 2018; Schenk, Hupp, Gellis, & Noe, 2013). Although banks erode at a greater rate in larger streams, the total cumulative length of headwater streams on the landscape leads to greater sediment contributions from headwaters (Gellis et al., 2015; Gellis et al., 2017; Hopkins et al., 2018). Finally, streambanks are more likely to erode following a greater frequency of freeze–thaw cycles (Wynn, Henderson, & Vaughan, 2008), during large floods (Gellis et al., 2017), or after exposure to warmer and more acidic water (Hoomehr, Akinola, Wynn-Thompson, Garnand, & Eick, 2018).

Floodplain deposition

Floodplains can trap sediment through both deposition of channel load during overbank flooding as well as by riparian buffering of sediments eroded from adjacent uplands. Floodplain deposition is spatially variable through the watershed depending on land use, geology, reach geomorphology, and floodplain hydrologic connectivity (Gellis et al., 2009; Gillespie et al., 2018; Hopkins et al., 2018; Hupp et al., 2013; Noe & Hupp, 2005; Pizzuto, Skalak, Pearson, & Benthem, 2016; Schenk, Hupp, Gellis, & Noe, 2013; Wolf, Noe, & Ahn, 2013). In general, greater rates of floodplain sedimentation occur where greater sediment load is transported by streams, greater hydrologic connectivity exists between stream channels and floodplains, and floodplain complexity is greater (like highly variable microtopography, coarse woody debris, and plant biomass). As with streambank erosion, the geomorphometry of stream valleys can be predictive of floodplain deposition (Hopkins et al., 2018; Schenk et al., 2013).

Floodplains, including alluvial wetlands, can cumulatively trap large quantities of sediment, sometimes at rates similar to annual river loads (Phillips, 1989). For example, sediment accumulating on Coastal Plain floodplains of seven Chesapeake rivers was nearly 20% greater than the amount of sediment exported in the annual river load (Noe & Hupp, 2009). SPARROW modeling calculated that floodplains on the major Coastal Plain rivers cumulatively trap the equivalent of 32% of those rivers' total load of suspended sediment before final export to the Bay (Brakebill et al., 2010). Within a 4.8 km reach, floodplain deposition was equal to 10% of the annual river load (Pizzuto et al., 2018). Most watershed sediment budgets have measured floodplain trapping rates to be slightly smaller than bank erosion rates (Figure 4). Floodplain sediment trapping compared to annual river load evaluated in four small watersheds was 19% in 7 km^2 (Hopkins et al., 2018) and 52% in 14 km^2 (Gellis et al., 2017) upper Difficult Run headwater tributaries, 95% in the 147 km^2 Linganore Creek (Gellis et al., 2015), and over 400% of the annual load in the 151 km^2 lower Difficult Run watersheds (Hopkins et al., 2018).

Balance of erosion and deposition

Streambank erosion and floodplain deposition can theoretically balance each other under geomorphic conditions of dynamic equilibrium (Hupp et al., 2015; Leopold et al., 1964). However, legacy sediment storage and hydrologic alterations due to watershed land use change, and potentially climate change, have led to non-equilibrium stream valley sediment processes (E. Wohl, 2015). In some streams, floodplain deposition exceeds streambank erosion, leading to net retention of sediment, but in other streams, the opposite occurs leading to a net source of sediment.

Headwaters are primarily dominated by bank erosion, while floodplains along streams with larger drainage area, particularly along alluvial streams with broad valley-bottoms, can trap large amounts of sediment. In the Chesapeake watershed, Donovan et al. (2015) estimated the balance of floodplain and streambank geomorphic changes in stream valleys of the Baltimore area can change from erosional, typically in lower-order streams with small drainage area, to depositional in higher-order streams with larger drainage area. Stream reaches switched from being typically erosional in first through third-order streams, neutral in fourth-order, and depositional in fifth and sixth order streams of the Difficult Run watershed (Hopkins et al., 2018; Hupp et al., 2013). In contrast, Gillespie et al. (2018) found that sediment balance was depositional among sites in third- or fourth-order streams, but decreasingly so in larger streams, of an agricultural Virginia watershed. Pizzuto et al. (2018) measured that floodplain deposition was more than three times greater than bank erosion along a fifth-order stream. Schenk et al. (2013) found drainage area was most often not related to sediment balance among different Piedmont watersheds, but the geomorphometry of stream valleys, specifically the ratio of bank height to floodplain width, was predictive of the sediment balance of Chesapeake Piedmont streams (Hopkins et al., 2018; Schenk et al., 2013).

However, the length of headwater streams across the watershed can surpass downstream floodplain trapping efficiency, resulting in net downstream loading from stream valleys (Hopkins et al., 2018, Figure 6). Sediment budgets in the Chesapeake have indicated variable and basin-specific results, but with some generally and broadly applicable conclusions. Bank erosion is much greater than floodplain deposition in some watersheds (typically smaller drainage areas), but only slightly greater in others (larger drainage areas, Figure 4).

In-channel erosion and deposition flux

Many sediment field studies neglect the role of erosion and deposition within stream channels, often assuming channels are not a significant source or sink of fine-grained sediment and that most sediment is transported downstream. Nevertheless, channels are an active region of biogeochemical alteration of nutrients, contaminants, and carbon (Fisher et al., 1998), and can be differentiated into several geomorphic zones, including point bars, alternate bars, and other

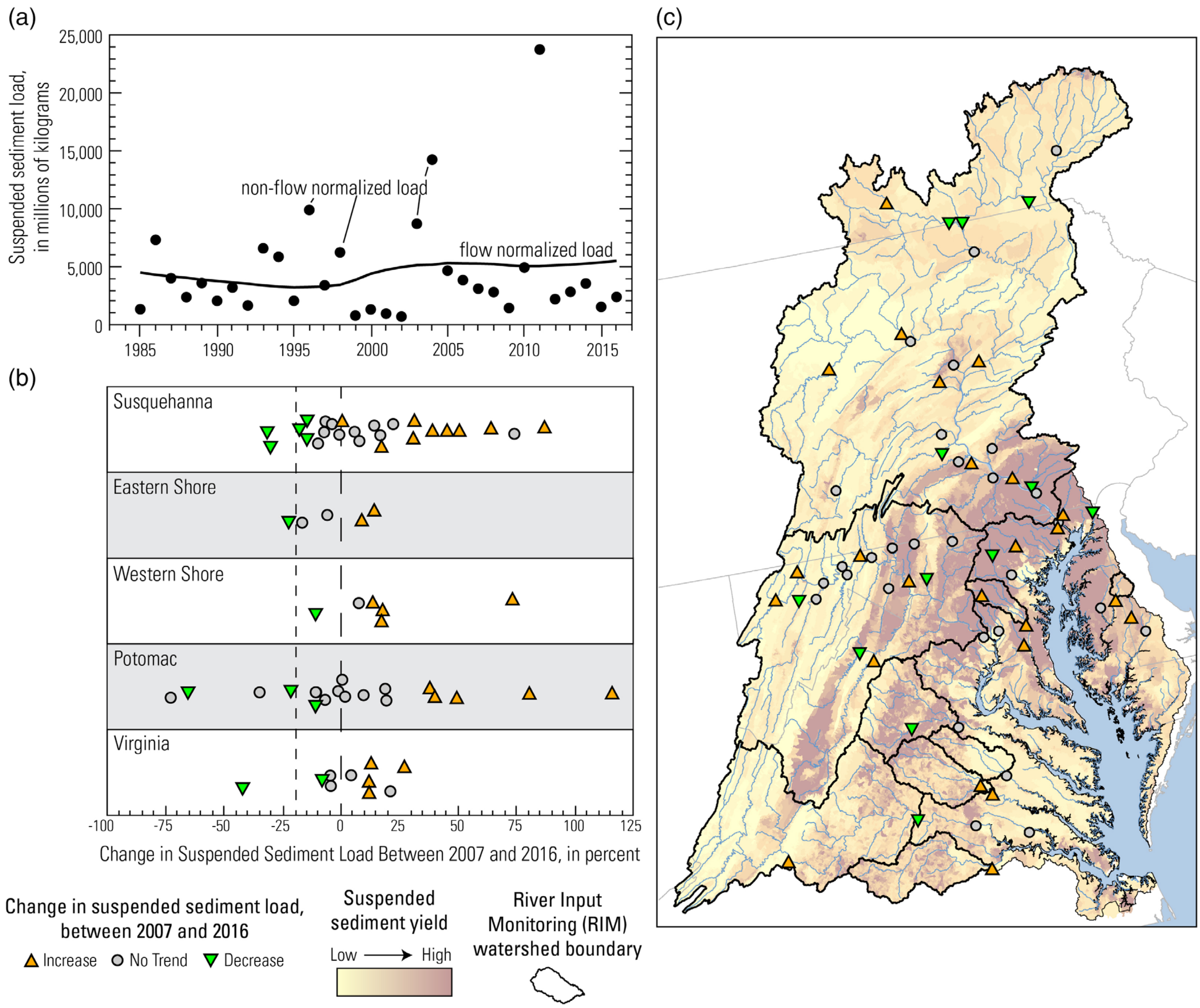

FIGURE 6 (a) Cumulative annual suspended sediment load and the trendline of flow-normalized load at the nine River Input Monitoring stations discharging to the Chesapeake Bay, from 1985 to 2016 (Moyer, Langland, Blomquist, & Yang, 2017); (b) trends in flow-normalized suspended sediment load across the Chesapeake watershed from 2007 to 2016 relative to the TMDL target of 20% reduction in loading to the Chesapeake Bay (dashed vertical line; Moyer et al., 2017); and (c) directionality of flow-normalized trends at each station (green down arrows indicate decreasing load, gray circles indicate no trend, and orange up arrows indicate increasing load, Moyer et al., 2017) overlaid on estimated suspended sediment yield by SPARROW modeling (Brakebill et al., 2010)

lateral deposits, mid-channel bars and islands, and channel beds, that store a varying amount of fine sediment over different timescales (Box 5).

The amount of fine sediment stored in active channels depends on sediment supply and channel transport capacity (Skalak & Pizzuto, 2010). Although active channels are geomorphically dynamic with highly variable rates of erosion and deposition, in general stream beds and point bars are often a small proportion of sediment budgets (Gellis et al., 2015; Gellis et al., 2017). However, by comparing sediment budget and fingerprinting results in Upper Difficult Run, Cashman et al. (2018) estimated that a minimum of 34% of the total bank-derived material in the sediment load was eroded bank material from previous years re-mobilized from temporary in-channel storage.

Other deposits, such as lateral fine-grained channel margin deposits or lateral accretion elements that form in nearbank regions, are typically caused by bank obstructions such as large wood debris (Skalak & Pizzuto, 2010). These deposits often tend to be more stable than other forms of channel storage and thus have longer residence times (see

BOX 5 Management implication: Headwater versus larger streams

Among the streams in a watershed, where should efforts be targeted to address the goal of reducing downstream sediment loading? Because of the fundamental differences in sediment transport between headwater vs. larger streams, it is useful to discriminate based on drainage area or stream order. Headwater systems, typically first through about third-order streams, are net erosive because of bank erosion occurs but little active floodplain exists to support offsetting deposition. Here, stream restoration and stormwater control can be implemented to reduce bank erosion. Larger streams, typically third order and larger, are often net depositional because their wider active floodplain and shallower slopes can support extensive deposition. Here, the conservation and restoration of hydrologic connectivity to floodplains can be implemented to maintain or augment sediment trapping. However, choosing the best management approach also is a question of spatial scale and concentration of effort. The greater cumulative stream length in headwater streams makes them a larger contributor to downstream sediment load than larger streams; however, the greater rates of erosion and deposition in larger stream reaches makes them more efficient to manage than headwater streams and their proximity to downstream water bodies makes it more likely achieve more rapid reductions in sediment delivery.

Section 3.2, below). However, more work is needed to develop better estimates of both the quantity of fine sediment stored in active margins of channels as well as their storage and remobilization timescales and response to management practices.

Reservoirs

Reservoirs temporarily store water and slow water velocity for many reasons including water supply, recreation, agricultural and sediment management, and flood control. Reservoir size can range from small farm ponds to large water supply and hydroelectric facilities. When water velocity is slowed, sediment can drop out of suspension and become temporally or permanently trapped in reservoirs. The SPARROW model has estimated that large reservoirs trap 29% of long-term sediment load in the Chesapeake watershed with the efficiency of sediment trapping depending on the ratio of average inflow to surface area (Brakebill et al., 2010).

The three reservoirs in the Lower Susquehanna River (Lake Clarke and Lake Aldred in Pennsylvania and Conowingo Reservoir in Maryland and Pennsylvania) have a particularly important impact on sediment delivery to the Bay. Over the past 80+ years, about 426 million metric tons of sediment were transported into these reservoirs, about 254 million metric tons trapped, and 172 million metric tons transported to the Bay, indicating a 60% long-term trapping rate (Langland, 2015). However, the three reservoirs are in differing stages of filling with sediment. On the Conowingo Reservoir, bathymetry surveys from 1990 to 2011 indicate loss of water-storage capacity and thus an increase in sediment-storage in each successive survey. The ratio of sediment output to input from the lower Susquehanna reservoirs has been increasing over the past 30 years with a marked decrease in retention in the mid-2000s as Conowingo Reservoir was filling (Zhang, Hirsch, & Ball, 2016). As the ratio between the water- and sediment-storage capacities change, and more sediments are deposited, eventually a condition of "equilibrium" occurs resulting in negligible sediment trapping efficiency. Such is the case in the Lower Susquehanna River, as Lake Clarke and Lake Aldred have been in equilibrium for several decades and Conowingo Reservoir is nearing or at equilibrium. Brief high-flow events, such as Tropical Storm Lee in 2011, now scour large amounts of sediment from the Lower Susquehanna reservoir system and export it to the Bay (Hirsch, 2012; Figure 1b). The issue of decreased reservoir trapping, thereby increasing sediment and nutrient loads downstream, has posed new challenges to the attainment of TMDL goals for the Chesapeake Bay, and is currently being factored in the assessment of regulatory load reduction requirements by the CBP partnership.

3.2 | Residence times

After sediment is deposited, it remains in storage until it is remobilized and transported downstream. This storage time can range from days to millennia largely dependent on characteristics of the watershed, the stream, the storage zone, and the sediment. In-channel sediment typically has a younger age, shorter residence time, and shorter storage timescales than floodplain sediment. Channel sediment is mobilized by flow at smaller thresholds of shear stress and hence more frequently. The average age of the material stored in channel beds is often less than a year because the active layer of channel beds is generally assumed to exchange annually (Gellis et al., 2017). Storage timescales of sediment within in-channel deposits such as point bars, active bars, and mid-channel bars are variable, but generally assumed to be remobilized on annual timescales, although other in-channel locations such as fine-grained channel margin deposits have longer storage timescales ranging from less than a year to over 70 years (Skalak & Pizzuto, 2010).

Outside channels, floodplain storage timescales can extend from decades to millennia (Pizzuto et al., 2014; Pizzuto et al., 2017). Data from the Chesapeake watershed suggest floodplain sediment age is typically about 500 years (Pizzuto et al., 2014). Sediment stored in floodplains is largely reintroduced to channels through bank erosion or vertical floodplain erosion. This phenomenon of long time-scales for reworking of floodplain sediment can have implications for management (Pizzuto et al., 2017). First, there is likely to be a lag between the introduction of a management practice onto the landscape and its anticipated benefit on downstream sediment loads. Second, long sediment storage times in conjunction with large masses of sediment in floodplain storage would lead to elevated downstream sediment loads into the future. Thus, reworking of sediment storage in floodplains is likely to lead to difficulty in detecting the signal of reduced downstream sediment loading due to upstream BMP implementation. Finally, sediment is more rapidly delivered to downstream waters, like the Bay, from streams lower in the stream network.

3.3 | Suspended sediment characteristics, yields, and loads

Sediment transported through the Chesapeake watershed and delivered to the Bay is primarily fine-grained (i.e., silt or clay). Considering all nine of the major tributaries monitored from 1984 to 2016, Zhang and Blomquist (2018) reported that 90% of suspended sediment is fine-grained. They reported that suspended sediment exported from the monitored portion of the watershed was strongly dominated (90%) by the three largest tributaries, namely, the Susquehanna, Potomac, and James rivers. Susquehanna River sediment consisted of almost entirely fine-grained sediment throughout the period of record, which indicates strong modulation of sediment characteristics by the Conowingo Reservoir located near the river outlet.

Suspended sediment yields from streams (i.e., sediment load divided by drainage area) vary across the Chesapeake watershed according to differences in watershed land use, size, and physiographic setting. Average sediment yields ranged from approximately 20–2,000 kg/ha between 2007 and 2016 at 65 Chesapeake Bay nontidal network stations (Moyer et al., 2017). Urban, Piedmont, and headwater streams have the greatest sediment yields in the Chesapeake watershed (Figure 5, Brakebill et al., 2010; Gellis et al., 2009). Regardless of land use, sediment yields typically decline with increasing watershed area because of increasing trapping of sediment along larger streams and rivers (Donovan et al., 2015; S. Smith & Wilcock, 2015).

Changes in sediment yields over time can result from alterations to the balance of erosional inputs and depositional storage. A decrease in yield over time could result from reduced rates of streambank or overland erosion or increased rates of floodplain trapping. Sediment yields between 2007 and 2016 were reduced at 18%, increased at 37%, and had no discernable statistical trend at 43% of the 65 analyzed Chesapeake nontidal network stations (Figure 5; Moyer et al., 2017). A −20% median reduction was observed at stations with decreasing yield and +31% increase was observed at stations with increasing yield. Sediment yields increased or remained unchanged at the five stations draining urban watersheds. Sediment yields increased or remained unchanged in 13 of 14 streams that drain predominantly agricultural watersheds. Two-thirds of stations with reduced sediment loads drain mostly undeveloped watersheds. To summarize, trends in sediment yield are disparate across the Chesapeake watershed with little evidence of widespread declines over time. Continued research is needed to link trends in sediment yield to watershed and climate changes.

There has been little change in the total annual suspended load of sediment delivered to the Chesapeake Bay over the past 30 years from the nine major tributaries that drain 78% of the watershed, with large interannual variability associated with differences in precipitation and runoff (Figure 6). Flow-normalized sediment loads increased at four and decreased at three stations between 1985 and 2016. Annual sediment loads approximately doubled from 1.1 million metric tons from the late 1990s and early 2000s to present at the Susquehanna River at Conowingo, MD (USGS station ID: 01578310). This station contributes the largest load of sediment to the Bay of all tributaries and increases have been associated with sediment filling of the Conowingo Reservoir (Langland, 2015). The increased sediment load coming from the Susquehanna has effectively offset large reductions that occurred at the Potomac River at Washington, DC (USGS station ID: 01646580) between 1985 and 1995. Annual sediment loads in the Potomac River decreased from approximately 2.3 to 0.9 million metric tons during this period, possibly as erosion rates fell after a period of intense urban and agricultural development in the mid-1970s and early 1980s.

4 | EFFECTS OF MANAGEMENT PRACTICES

A wide variety of BMPs for sediment control continue to be implemented in the Chesapeake watershed to meet the Chesapeake Bay TMDL. The TMDL requires installation of BMPs and other management actions to reduce sediment inputs to the Bay by 20% by 2025 compared to baseline conditions in 2009. This equates to a reduction in sediment loading of more than 0.73 million metric ton per year (United States Environmental Protection Agency, 2010). As of the 2017 Midpoint assessment, Bay jurisdictions have met the interim milestone of implementing practices to achieve the required 60% in [predicted] sediment reductions (United States Environmental Protection Agency, 2018). Meeting this milestone required investment in a diverse menu of BMPs including agricultural practices to better manage crops, pasture, and animal facilities, urban practices to better manage stormwater, and practices to better manage timberlands and roadways.

The Chesapeake Bay Program has compiled an inventory of approximately 150 different BMPs implemented in the Chesapeake watershed (Chesapeake Bay Program, 2018a) and uses this inventory in the CBP Watershed Model to predict the effect of management on sediment loading (United States Environmental Protection Agency, 2010). The inventory includes BMP implementation that was federally, state, nongovernmental organization, and voluntarily funded (Hively, Devereux, & Claggett, 2013), and BMP implementation is reported annually to the CBP by jurisdictions. The CBP Chesapeake Assessment Scenario Tool (CAST; Cast.chesapeakebay.net) can be used at a state, county, or watershed scale to assess predicted changes in sediment loads due to current or proposed management actions.

4.1 | Review of BMP efficiencies

Each type of BMP is expected to have a different sediment removal or trapping efficiency and therefore different impacts on sediment loads to streams. While field-scale estimates of sediment removal efficiencies exist for some BMPs in the scientific literature, actual BMP removal efficiencies can be affected by confounding local or regional factors as well as the level of implementation and maintenance routines (Liu et al., 2017). A recent synthesis of BMP monitoring studies across the U.S. documented a wide range of sediment removal efficiencies for agricultural and urban BMPs (Liu et al., 2017). The CBP convenes expert panels of scientists and practitioners to evaluate state of the science to develop standardized efficiencies for each BMP type or methods to calculate efficiencies for individual BMPs that are then incorporated into the CBP Watershed Model (e.g., Tables S2 and S3). However, there is still substantial uncertainty in the actual performance of BMPs. Numerous factors should be considered when selecting BMPs in a specific setting, including cost effectiveness, site constraints on BMP function (e.g., stormwater treatment vs. runoff reduction practices), maintenance requirements, limitations due to local topography and soils, and possible co-benefits (nutrient reduction, habitat improvement, etc.).

4.2 | Expected BMP effects on sediment loads

The CBP Watershed Model can be used to estimate the expected total reduction in sediment mass delivered to streams due to implemented BMPs as well as the average effect of different types of BMP. Sekellick, Devereux, Keisman, Sweeney, and Blomquist (2019) ran the CBP Watershed Model with a selection of specially designed scenarios to evaluate effectiveness of BMPs from 1985 through 2014. BMPs were estimated to reduce time-averaged sediment loads to streams in the Chesapeake watershed by 23% in the model year 2014 as compared to a 2014 model scenario without BMPs (Sekellick et al., 2019). The expected reduction in sediment loads to streams due to BMP implementation varies across the Chesapeake watershed. In some areas, such as the Eastern Shore, sediment reductions are estimated to be as high as 85% in 2014 due to high rates of implementation of conservation tillage practices. Large percentage reductions in sediment loads are also expected in West Virginia and the Potomac river watershed due to widespread implementation of pasture fencing practices. Although modeling suggests that the suite of implemented BMPs across the landscape should lead to large reductions in downstream sediment loading, there is a paucity of on-the-ground monitoring studies that document short- and long-term impacts of BMPs within the Chesapeake watershed. Furthermore, as described above, few streams across the Chesapeake watershed (18% of load stations) currently show declines in sediment loading over time. However, as the Phase 5.3.2 CBP Watershed model, which was used in this study, does not account for the lag times inherent in sediment erosion, storage, and transport, these estimated effects may be delayed or attenuated across longer time scales.

About 82% of the total estimated reductions in stream sediment loads in 2014 is due to BMP implementation on agricultural lands, particularly due to conservation tillage, pasture fencing, and conservation plans (Sekellick et al., 2019). The USDA NRCS estimates agricultural conservation practices in 2011, that compared to the baseline condition (2003–2006), resulted in a 63% reduction in sediment loss from fields and a 57% reduction in sheet and rill erosion rates (National Resources Conservation Services, 2013). Greater use of cover crops in 2011 provided a reduction in sediment loss by an average of 78% and winter cover crop adoption reduced sediment losses by 37% compared to the baseline (National Resources Conservation Services, 2013). While conservation tillage was estimated to account for a large proportion of reduction in sediment loads to streams, other agricultural BMPs were estimated to be more effective per unit of implementation (Table S2). These include streamside grass buffers that were estimated to reduce sediment loads by 11,000 kg/ha and pasture fencing was estimated to reduce sediment loads by 8,576 kg/ha (Sekellick et al., 2019).

BMPs on developed land were estimated to account for 12% of the total reduction in sediment load to streams due to implemented BMPs in 2014, with the largest estimated reductions from erosion and sediment controls, dry ponds, and abandoned mine land reclamation (Sekellick et al., 2019). BMPs that were estimated to be most effective at reducing sediment loads to streams were bioretention, abandoned mine land reclamation, and street sweeping. Bioretention BMPs were estimated to reduce sediment loads by 5,876 kg/ha, the greatest magnitude of load reduction from among developed land BMPs (Sekellick et al., 2019; Table S3).

4.3 | New research on BMP effectiveness

The arrangement, density, and placement of stormwater control BMPs within urban and suburban watersheds can strongly affect BMP performance. A year of monitoring sediment export during storm events in two suburban watersheds in Clarksburg, Maryland indicated that the study area with a distributed network of infiltration-focused stormwater BMPs exported 30% less sediment during storm events than a study area with a centralized set of detention-focused stormwater BMPs (Hopkins, Loperfido, Craig, Noe, & Hogan, 2017). This result suggests that distributing BMPs throughout the watershed can be a more effective strategy to reduce sediment export compared to installing a few large detention ponds. However, sediment export from the two study areas became more similar as precipitation amount and intensity increased and the performance of BMPs declined as water storage within the facility was exceeded (Hopkins et al., 2017). During large precipitation events, few BMPs can adequately mitigate peak flows which can result in substantial stream bank erosion downstream of the BMPs. This is consequential because the majority of sediment load (>94%) is transported during stormflow conditions that occur less than 20% of the year (Horowitz & Stephens, 2008).

Installing BMPs within stream channels can also retain and trap sediments from being transported downstream. These strategies often involve armoring the bed and banks to prevent erosion or alternatively to reconnect the stream with its floodplain by raising the base elevation of an incised stream channel or by grading bank slopes. Stream restoration strategies like natural channel design can be effective at increasing sediment trapping through in-channel storage and floodplain creation, with rates of sediment trapping increased by the degree of hydrologic connectivity to the stream channel (McMillan & Noe, 2017). An alternative approach to reconnect the channel to the floodplain involves lowering the floodplain to the elevation of the incised channel via the mass-removal of all legacy sediment from the floodplain. In one monitored instance of this restoration design, 20,000 metric tons of legacy sediment were excavated from a 1.5 km section of Big Spring Run, an agricultural stream in Pennsylvania, restoring a pre-colonial stream valley morphology. This legacy sediment removal project resulted in 10,000 m^3 of extra water storage and a reduction in the effective sediment load by 85% (Langland, Duris, Zimmerman, & Chaplin, 2020).

5 | NEWER SCIENTIFIC TOOLS

As the Chesapeake Bay TMDL continues to be implemented to reduce sediment loading, new models and measurement capabilities will redefine and improve how we assess, monitor, and manage sediment within the watershed.

5.1 | Models

The CBP partnership uses the CBP Watershed Model to develop nitrogen, phosphorus, and sediment reduction targets to meet the Chesapeake Bay TMDL and to track progress toward those targets (Chesapeake Bay Program, 2018b). At the direction of stakeholder groups, the model was revised and simplified in 2018 such that the primary model structure for management scenarios is time-averaged using coefficients based on long-term hydrology. For time-averaged coefficients arising from dynamic models, a 10- to 30-year hydrology is typically used. Sediment transport modeling was also updated to improve representation of upland erosion and delivery and sediment exchange in stream valleys (Chesapeake Bay Program, 2018b).

Time-averaged field-scale sediment erosion yields from uplands are estimated using the Revised Universal Soil Loss Equation (National Resources Conservation Services, 2007) at a 10-m scale. Sediment delivery ratios (delivery to streams) are then calculated relative to slope, area, roughness, and flow-path length at a 10-m scale following the sediment connectivity method of Cavalli, Trevisani, Comiti, and Marchi (2013). Small stream and small reservoir attenuation is estimated by the SPARROW regression model (Brakebill et al., 2010). An average yield and sediment delivery ratio is calculated for each land use type for model segments averaging 75 km^2, and small water body effects are summarized at the same scale. Stream bed, bank erosion and floodplain deposition are estimated based on large-scale average rates. A closely related dynamic model based on Hydrologic Simulation Program—Fortran (Bicknell, Imhoff, Kittle, Jobes, & Donigian, 2005) is used to calibrate to observed water quality data over 1985–2015. Estimates of large river and reservoir sediment balances from the dynamic model are used in the time-averaged model as loss coefficients. Full documentation of both the time-averaged and dynamic models is available on the CBP website (Chesapeake Bay Program, 2018a).

The CBP Watershed Model effectively predicts measured suspended sediment yields at monitoring stations ($R^2 = 0.96$; Chesapeake Bay Program, 2018b). Boomer, Weller, and Jordan (2008) demonstrated that models incorporating Universal Soil Loss Equation and sediment delivery ratio poorly predict observed sediment yields, but that multiple regression models incorporating the effects of soil erodibility, streamflow, topography, land use, and physiographic province have moderate predictive performance ($R^2 = 0.55$). The SPARROW regression model had similar, moderate predictive performance for sediment yield ($R^2 = 0.57$) when accounting for upland and stream-corridor sources, landscape factors affecting sediment transport, and fluvial and reservoir retention (Brakebill et al., 2010).

5.2 | New measurement capabilities

Recent advances in data collection techniques have substantially increased both the resolution and spatial scale of data on sediment dynamics. While previously a gap existed in linking small, site-scale measurements of erosional and depositional processes in the field with large-scale modeling efforts, new approaches are enabling direct measuring and quantification of sediment erosion and deposition across large-spatial scales.

The new Floodplain and Channel Evaluation Toolkit (FACET; Lamont et al., 2019) is able to use aerial lidar datasets to automatically derive standard field-scale geomorphic metrics (e.g., channel width, bank height, active floodplain width) and is in the process of being applied to most of the Chesapeake watershed. Furthermore, FACET outputs are being used to link field-derived estimates of localized sediment erosion from streambanks and retention on floodplains to enhance predictions throughout local watersheds (Hopkins et al., 2018).

Additional lidar acquisitions coordinated through the USGS 3D Elevation Program is resulting in high-quality of temporally-repeated lidar datasets that will enable topographic change detection across entire counties (>1,000 km^2). Similarly, historical aerial photography has the potential to be processed with newer structure-from-motion photogrammetric (SfM) algorithms to create high-resolution topographic datasets for change detection (Chirico, Bergstresser, DeWitt, & Alessi, 2020; Warrick, Ritchie, Adelman, Adelman, & Limber, 2017). Although these approaches may not be as sensitive to change as traditional field-based approaches, the ability to identify erosional hotspots across the landscape, particularly in locations without historical monitoring, has potential to revolutionize the identification and monitoring of sediment erosion.

Despite these improvements, highly accurate measurements at the field scale are still necessary, especially in the monitoring of individual restorations or sediment management projects. These new approaches help address the current limitations of field-based approaches, the representativeness of measurements, and the error associated with extrapolation across unmeasured areas (Gellis, Fitzpatrick, & Schubauer-Berigan, 2016). Spatially continuous data from terrestrial laser scanners (TLS) and ground-based SfM allow for sub-centimeter resolution mapping across 10–100 s of meters, functionally similarly to the scale of traditional field-based approaches (e.g., bank pins). Pairing SfM with small Unmanned Aerial Systems (sUAS) allows rapid monitoring and evaluation of erosion (M. R. James, Robson, & Smith, 2017) across entire reaches, or river segments of interest (<1–10 km) with high temporal repeatability (weekly–monthly).

Finally, advances in fluvial sediment monitoring, particularly of advanced acoustic methods, are drastically improving collection and quantification of suspended sediment. Acoustic Doppler methods for deriving discharge also collect backscatter data, a value of the intensity of the signal of rebounding acoustics off particles in the water column, which can be used to directly calculate suspended sediment concentrations (Medalie, Chalmers, Kiah, & Copans, 2014). This approach collects data at multiple points across a cross-section, avoiding potential bias of a single-point turbidity probe, and is more resistant to biofouling (Gray & Gartner, 2009). Furthermore, the use of multi-frequency systems (i.e., multiple single-frequency instruments) can not only capture suspended sediment concentration, but can separate concentrations of silt and clay, and sand, in real-time, at accuracy levels equal to, or more accurate than, traditional sampling methods (Topping, Wright, Melis, & Rubin, 2007).

6 | CONCLUSION: SUMMARY FOR WATERSHED MANAGEMENT

The delivery of sediment to Chesapeake streams and the Bay is controlled by both natural and anthropogenic factors (Box 6). Geology and historical land use have generated a physical template that is influenced by present-day land use, climate, and management actions. Variations in these factors across the watershed and over time result in complex landscape processes and interactions. Locations of dominant sediment sources in the Chesapeake Bay watershed include the Piedmont, urban and agriculture land use, and headwater streams. BMPs have a wide range in efficiencies and their implementation is predicted to have meaningfully reduced sediment loading. However, trends in downstream monitored sediment loads are not yet consistent with the estimated effects of upstream BMP implementation. Active sediment storage in streams and rivers can introduce long transport and lag times, attenuating the effects of management actions and delaying detection on sediment loads. Enhancing knowledge of sources and lags of sediment can help managers improve BMP location and selection to increase efficiency and cost-effectiveness of management actions. Furthermore, the impact of sediment on ecosystem health can also vary due to grain size and other factors. Fine-grained sediment has been shown to have the largest impacts on stream biota; meanwhile, coarse sediment can be necessary for stream habitat and downstream estuarine wetlands. Contaminated sediment can be

BOX 6 Management implication: Three important geomorphic principles to guide management

Scale: Sediment starts in the uplands and moves through stream storage compartments before being exported from a watershed to a downstream waterbody. Sediment "hops and rests" downstream, in and out of different storage zones (like floodplains), trapping large amounts of sediment (and nutrients), and causing lag times (sometimes short, often long) in responses to management actions. However, sediment processes differ in headwater streams and larger rivers.

Time: Historical legacies matter—actions from 200+ years ago continue to influence sediment issues in the present. Despite current implementation of BMP and sediment management efforts, reworking of legacy sediment and time-lags inherent in sediment transport and storage may influence long-term sediment loading rates and the detection of these management effects in the future.

Land use: Agricultural, developed land, and stream banks are all important sources of sediment, but are locally and temporally variable. Urban streams export a larger sediment yield than agricultural streams, but agriculture is more widespread and contributes the largest cumulative sediment load among Chesapeake land uses. Sediment-bound pollutants vary depending on the source of eroded sediment. Based on models, BMPs implemented in various land uses of the Chesapeake Bay watershed are expected to have reduced the 2014 sediment load to streams by about a quarter, although this effect is not yet apparent in the measured trends of downstream suspended sediment loads.

BOX 7 Management implication: Specific guidance for targeting management

Landscape setting	Sediment summary	TMDL implication	Co-benefits of implementation
Headwater streams	First and second-order channels erode their streambanks but typically have minimal active floodplains	Consider practices associated with stream restoration and runoff control to prevent bank erosion	Improve stream health and fish habitat
Larger streams and rivers	If well connected to channels, floodplains can trap much of the sediment eroded upstream	Conserve and restore hydrologic connectivity to floodplains	Improve wildlife and fish habitat and biodiversity, and mitigate flooding
Urban areas	Bank erosion is the dominant source of sediment export	Consider stormwater control in the uplands with stream restoration to prevent bank erosion	Improve stream health, fish habitat, and recreation
Agricultural areas	Both bank erosion and upland soil erosion are important sediment sources in agricultural areas; the two can often be directly assessed	Consider practices to reduce upland soil erosion and implement stream buffers	Improve stream health and fish habitat and forest buffer
		Legacy sediment removal can prevent bank erosion and restore floodplain connectivity	Improve wetland and fish and wildlife habitat

targeted by specific BMPs to improve ecosystem health. Although changes in hydrology associated with climate change could influence sediment dynamics, insufficient information exists on current impacts or predictions of future changes.

Despite the vast body of sediment research conducted in the Chesapeake watershed synthesized in this review, further study is still required to improve quantitative, geographically specific predictability of sediment loads, fate, transport, impacts on stream health, and the effectiveness of BMPs throughout stream networks. In particular, the targeting of BMP type and location would benefit from improvements in spatial prediction of sediment dynamics everywhere, at the fine resolution needed for managers to make decisions (e.g., individual stream reaches, individual catchments, or individual fields), and in predictions of changes in sediment storage and downstream transport through time. This holistic understanding of sediment, being developed in the Chesapeake Bay watershed, may be relevant to other regions that require management actions to reduce downstream loading of fine-grained sediment for the benefit of people and ecosystems (Box 7).

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CONFLICT OF INTEREST

The authors acknowledge no conflict of interests with this work.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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