The Natural Sediment Regime in Rivers: Broadening the Foundation for Ecosystem Management

ELLEN WOHL, BRIAN P. BLEDSOE, ROBERT B. JACOBSON, N. LEROY POFF, SARA L. RATHBURN, DAVID M. WALTERS, AND ANDREW C. WILCOX

Water and sediment inputs are fundamental drivers of river ecosystems, but river management tends to emphasize flow regime at the expense of sediment regime. In an effort to frame a more inclusive paradigm for river management, we discuss sediment inputs, transport, and storage within river systems; interactions among water, sediment, and valley context; and the need to broaden the natural flow regime concept. Explicitly incorporating sediment is challenging, because sediment is supplied, transported, and stored by nonlinear and episodic processes operating at different temporal and spatial scales than water and because sediment regimes have been highly altered by humans. Nevertheless, managing for a desired balance between sediment supply and transport capacity is not only tractable, given current geomorphic process knowledge, but also essential because of the importance of sediment regimes to aquatic and riparian ecosystems, the physical template of which depends on sediment-driven river structure and function.

Keywords: sediment, adaptive management, river restoration, sediment balance

River systems—rivers, riparian zones, and floodplains—around the world are undergoing enormous changes as a result of human influences. Efforts to balance water supply, navigation, power generation, and other river uses against the need to protect river communities and ecosystem services demand an understanding of physical processes in river systems. Water and sediment supplied to and transported by rivers are the fundamental drivers of river condition, affecting water quality, thermal regime, habitat and aquatic communities, river stability, and natural hazards. Effective management of river systems therefore requires knowledge of water and sediment interactions.

This article builds on Poff and colleagues' (1997) paper on the natural flow regime. Since the publication of that paper, management programs oriented around modifying flow releases from dams to restore some natural (preimpoundment) patterns and, therefore, to achieve downstream ecosystem objectives have been implemented in a number of rivers (e.g., Arthington et al. 2010, Shafroth et al. 2010, Olden et al 2014) and have guided water management activities in some states (Kendy et al. 2012). Modified flow releases may seek to promote the recruitment of native riparian vegetation species, create new habitat, or increase lateral and longitudinal connectivity for organisms by facilitating migration to spawning areas or access to floodplain nursery habitat. Modified flow releases may achieve limited restoration success, however, if management does not include explicit consideration of sediment inputs to and transport within the river system.

Sediment regimes are crucial to aquatic and riparian ecosystems in many ways. The physical habitat template is a fundamental concept in ecology (e.g., Southwood 1977) that, in rivers, encompasses a range of sediment-related processes that determine channel morphology, bed conditions and heterogeneity, disturbance regime, community structure, and water quality. Many aquatic and riparian organisms depend on certain sizes and size distributions of bed materials for various life stages. For example, salmonids can be sensitive to excess fine sediment in the bed (as are other benthic organisms; Jones et al. 2011), and they require gravels in a suitable size range for spawning (Riebe et al. 2014) and that can provide interstitial spaces for juvenile rearing. Aquatic organisms may also be sensitive to the mobility of bed materials, such that life history timing may be adapted to the typical timing of bed disturbances (e.g., Lytle et al. 2008). Suspended sediment and turbidity can influence aquatic food webs—for example, by altering visibility for predators (Newcombe and MacDonald 1991). Sediment conditions are also important for riparian plants: Fine-sediment patches are commonly key colonization sites;

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doi:10.1093/biosci/biv002 Advance Access publication 25 February 2015

grain sizes influence moisture retention; and plant scour is strongly influenced by the size-dependent scour of surrounding substrates (e.g., Merritt 2013).

In this article, we discuss the physical processes involved in sediment regimes and their interactions with river condition. We have four primary objectives. The first is to highlight the challenges to integrating sediment regimes into river management. Second, we provide a conceptual framework for sediment regime that is applicable to rivers across a wide geographic and geomorphic spectrum. This includes explicitly discussing the temporal and spatial components of sediment regimes and the variability among rivers. Our third objective is to increase the awareness that sediment is a vital component of river systems and to explore differences in water and sediment regimes. Sediment is commonly viewed as a disturbance or pollutant that needs to be minimized. However, the natural disturbances associated with sediment are integral to river ecosystems, and even fine-grained sediment can be beneficial to the river condition. Our fourth objective is to broaden the natural flow regime concept into a more inclusive paradigm for river management that includes natural—or, at least, balanced—sediment regimes in order to promote more holistic, effective restoration and conservation of river systems. As part of this objective, we discuss key information gaps and metrics that can be used to characterize sediment regimes.

Challenges to integrating sediment regime into river management

Because water and sediment interact to create habitat structure and dynamics within a river system, effective river management requires that water and sediment be managed in concert, and neglecting considerations of sediment supply and transport can produce unintended results (Poff et al. 2006). High-flow releases below dams into sediment-starved reaches lacking sediment inputs can cause channel downcutting and disconnection from the floodplain, streambed coarsening, and the loss of fish spawning habitat, or bank erosion and the loss of channel-margin and riparian habitat (Collier et al. 1996, Jacobson and Galat 2008). Conversely, low flows below dams combined with abundant sediment supply can cause siltation of the streambed, the loss of benthic and fish habitat (Bhowmik and Demissie 1989), and altered hyporheic exchange along with associated changes in water chemistry and thermal regime (Hoehn and Cirpka 2006). Regulations in the United States specifying instream or channel maintenance flows but ignoring sediment regime exemplify management focused solely on hydrology (Stalnaker et al. 1995). In this article, we provide a framework for understanding why and how informed river management should include sediment regimes in the context of flow management.

Incorporating sediment in river management is challenging for several reasons. Rivers respond to changes in water and sediment inputs at varying temporal and spatial scales, but such scales can be substantially different for sediment and for water. Particulate sediment (differentiated from solutes) is transported downstream as suspended load (e.g., sand, silt, and clay) and as bed-material load remaining in contact with the streambed (e.g., sand and coarser sediment). Sand and coarser sediment, in particular, move via nonlinear and episodic processes, reflecting thresholds limiting sediment mobilization and grain–grain interactions during movement. Moreover, the paucity of long-term data sets on sediment inputs, transport, or storage makes it difficult to quantify sediment regime, let alone assess natural, least-disturbed, or reference sediment conditions. For example, whereas over 23,000 US Geological Survey gaging stations have long-term (i.e., longer than 10 years) records of water discharge in the United States, only 1640 sites have more than 10 years of suspended-sediment concentration data (see *http://cida.usgs.gov/sediment* and *http://waterdata.usgs.gov/nwis/sw*). Only nine sites (in seven rivers) have suspended sediment records more than 50 years old (figure 1). Such long-term data sets are necessary for characterizing the magnitude, frequency, duration, timing or predictability, and rate of change or flashiness (*sensu* Poff et al. 1997) of sediment transport for different regions and rivers. Direct measurements of bed-material load, which may be especially important in shaping channels and therefore creating the physical template for rivers, are especially rare. Evaluating sediment regimes to guide management is further complicated by the magnitude and duration (centuries to millennia in most river basins) of human alterations to sediment supply, transport, and storage within rivers and their catchments.

The spatial density and duration of water discharge records allow for regional assessments of long-term trends and the degree to which human activities have altered these (Richter et al. 1996, Carlisle et al. 2010), but this type of assessment does not exist for sediment discharge. The analogous evidence of altered sediment discharge comes primarily from major deltas around the world—of the Nile, the Mississippi, the Colorado, the Yangtze, the Yellow, the Ebro, the Danube, the Godavari, and the Krishna, among others—that have experienced accelerated erosion during the past century (Yang et al. 2011).

A sediment balance approach for river management

The complications of understanding the role of sediment in river systems do not, however, diminish the importance of sediment for river management. Although the current understanding of spatial and temporal sediment regime rarely allows the prescription of management actions and although data are limited in most river systems, tools and conceptual frameworks are available that can provide insight into the degree and types of alteration of sediment supply, transport, and storage, as well as into the implications for successful management intervention.

Sediment regime includes inputs and outputs of mobile sediment from a length of channel and storage of sediment within the channel and floodplain over a specified time interval. We use the phrase *natural sediment regime* to describe

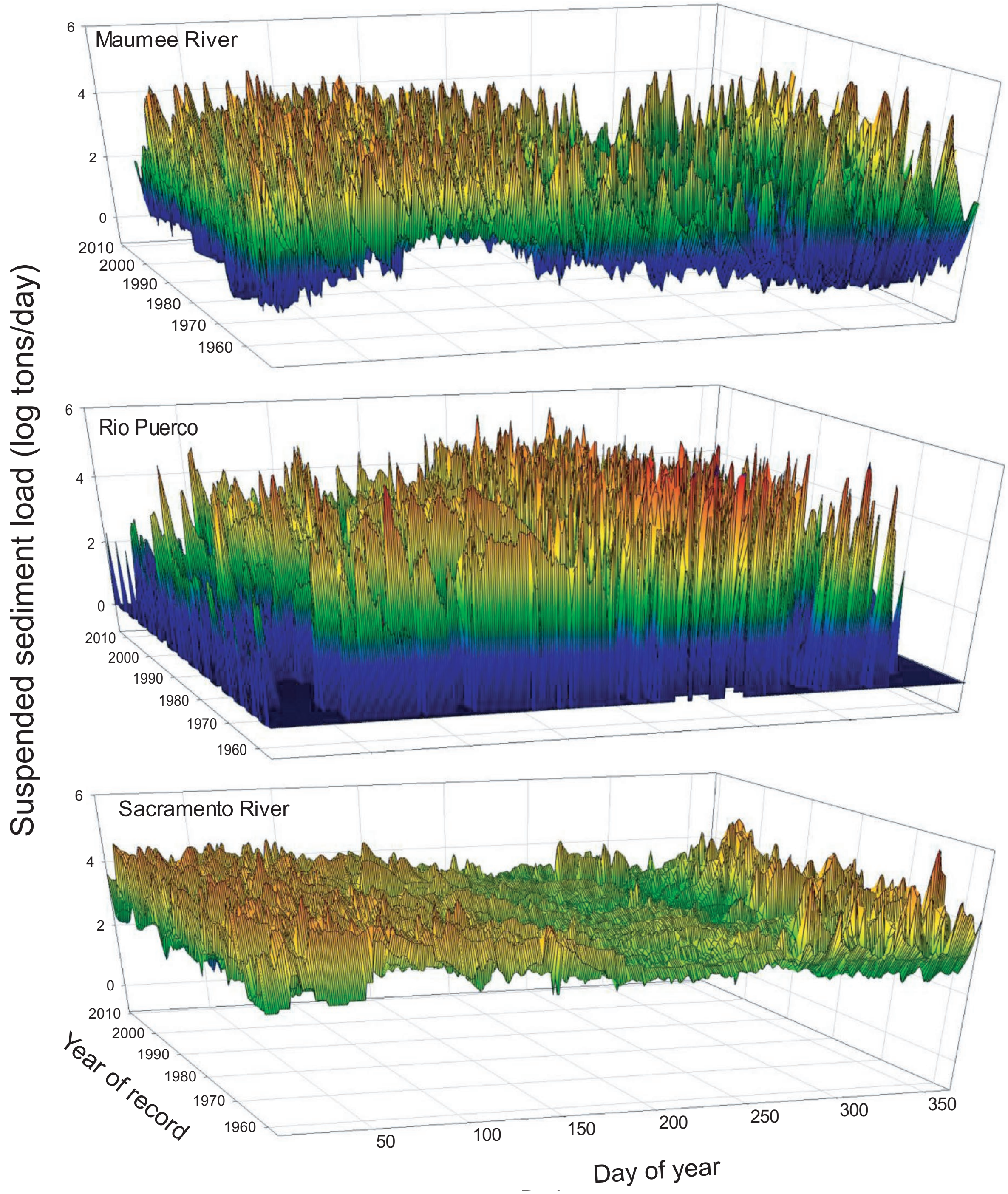


Figure 1. Suspended sediment histories from long-term (more than 50 years), daily mean records showing interannual and within-year variation for the Maumee River, Ohio (USGS gage 4193500) with a temperate climate; Rio Puerco, New Mexico (USGS gage 8353000) with an arid climate and summer monsoonal rains; and the Sacramento River, California (USGS gage 11447650) with a Mediterranean climate. The day of year begins on 1 January. The data were retrieved from **http://cida.usgs.gov/sediment** *on 16 April 2014.*

conditions prior to the construction of dams and the intensive human disturbance of topography and land cover in the form of removed native vegetation through crops, timber harvest, urbanization, and other land uses. Analogous to a natural flow regime, a fundamental benchmark for a natural sediment regime is that patterns of ecosystem organization and adaptations of riverine (aquatic and riparian) species reflect the spatial pattern and temporal variability of interacting water and sediment regimes. Key features such as natural disturbance, the spatiotemporal dynamics of hydraulic habitats, and specific types of depositional and erosional features arise from interactions of water and sediment.

The natural sediment regime is rarely observable, given the intensity of human alteration of land cover (inputs) and instream modification (storage and transport). Therefore, we distinguish between natural and balanced sediment regimes. A balanced sediment regime is present when the energy of flow available to transport sediment is in balance with sediment supply, such that the river form remains dynamically stable over a specified time period. This may reflect the absence of human alteration, as in a natural sediment regime, or it may reflect a human-altered condition in which both altered water and sediment supplies are in balance. In a management context, a balanced sediment regime is one that results in a channel that transports the sediment supplied to it with the available flow.

Although we believe that understanding the natural sediment regimes provides fundamental insight into the conditions to which a river system has adjusted over centuries to millennia, we recognize that because of the duration and extent of human modifications of sediment regimes, natural reference systems are rare, and the recreation of natural sediment regimes may be neither feasible nor desirable. As a result, we build on the premise that human activities have so fundamentally altered the natural sediment regime within rivers that identifying a balanced sediment regime may provide the most realistic management guideline. Although it may be expensive and politically difficult, for example, water can be released from a dam in a manner approximating a natural hydrograph, but downstream releases of sediment stored in a reservoir in a manner approximating natural sediment fluxes are much more problematic (Kondolf et al. 2014).

If water and sediment supply and other conditions in a river system have been altered by human activities, the resulting dynamically stable river system can be distinctly different than what would be present under natural conditions and to which ecosystems and biota are adjusted. Consequently, the key management questions may be *What are the supplies of water and sediment?* and *What river system structure and function can be achieved under a modified flow regime and balanced sediment regime?* (e.g., Wilcock 2012). The answer to the second question should be based on an understanding of the linkages between water and sediment regimes and river biota.

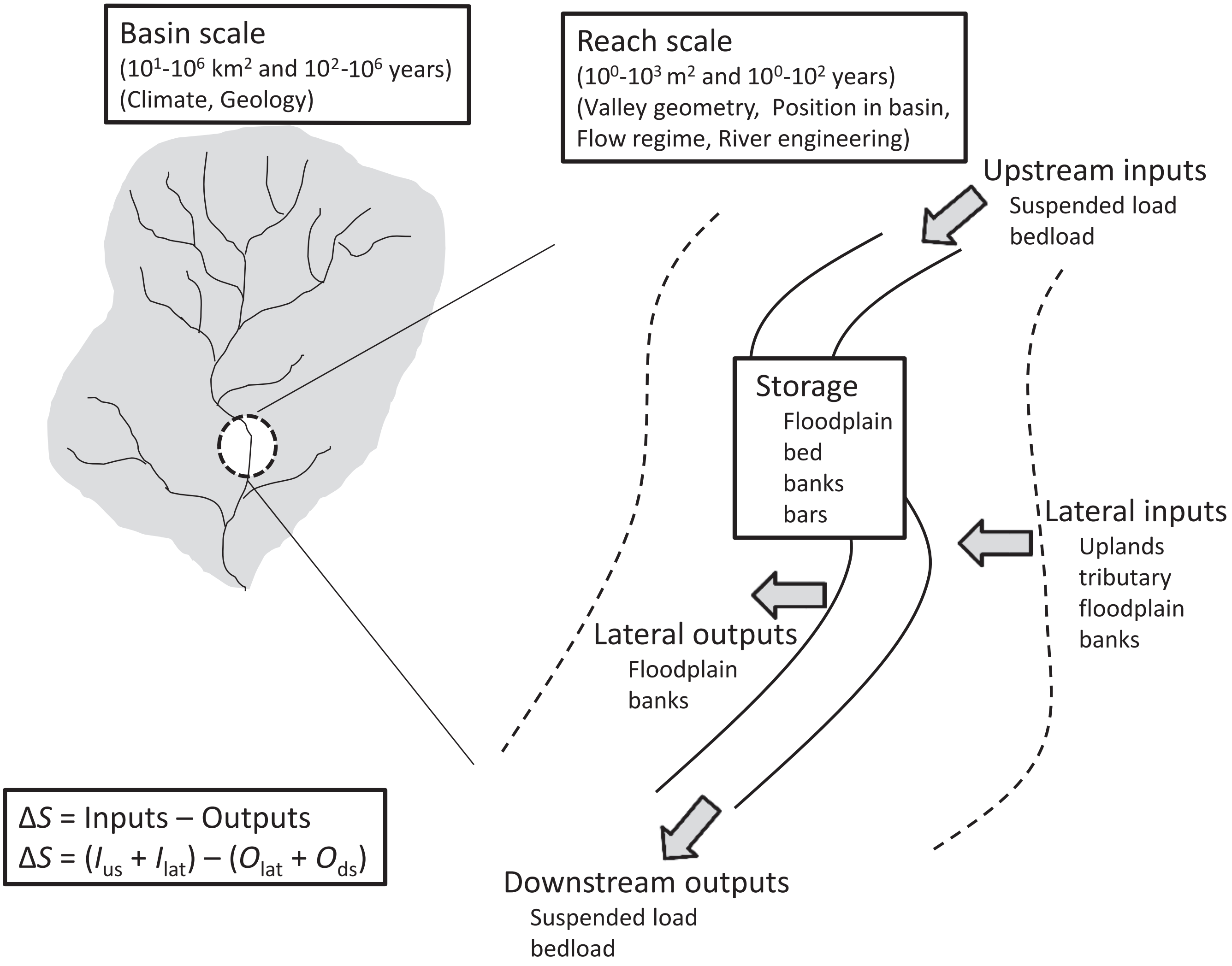
Managing for a balanced sediment regime may involve restoring more natural water and sediment inputs to a river system, or it may involve adjusting water inputs—flow regime—to create desired levels of sediment transport given an existing sediment supply (Schmidt and Wilcock 2008). In either scenario, the effective management of river condition requires knowledge of sediment regimes.

Conceptual framework for characterizing sediment regimes

Our conceptual framework for characterizing sediment regimes includes two primary parts. The first is a sediment budget (Reid and Dunne 1996) that includes inputs and outputs of sediment transported through a length of channel and exchanges between sediment mobile in the channel and sediment stored in the bed, banks, bars, and floodplain within a river system (figure 2). A sediment budget provides an organizing framework for tracking and relating these components of sediment regimes. Interactions among variables influencing sediment budgets govern where, how much, and for how long sediment is transported and stored in a river system and, therefore, the abundance, distribution, and stability of river habitat.

Sediment budgets can be applied at any spatial and temporal scale. Two examples are shown in figure 2 (basin and reach scales), with associated spatial and temporal ranges and primary controls on sediment regimes. Characteristics such as the magnitude, frequency, and duration of inputs and outputs are likely to vary throughout a river network. Suspended load inputs, for example, may be driven primarily by overland runoff in headwaters and primarily by bank erosion in lower portions of the network. The timing of sediment inputs or outputs, in terms of the seasonality and sequence of flows capable of transporting the sediment, can strongly influence river condition because sediment movement can constitute a disturbance that alters river habitat and directly stresses organisms via turbidity, abrasion, fine-sediment infiltration, and movement of the streambed (e.g., Jones et al. 2011). For the storage component, characteristics such as volume, grain-size distribution, and turnover time are likely to vary throughout the network and among different types of storage. An important aspect of figure 2 is that factors operating at the basin scale will influence sediment regimes, but factors operating at smaller spatial scales, such as the reach scale, will exert the strongest control on habitat abundance, distribution, and stability—and, therefore, river biota (Frissell et al. 1986, Beechie et al. 2008)—at spatial and temporal scales typically important for river management.

The relative importance of different sediment inputs, storage categories, and sediment outputs varies longitudinally (figure 3, top row). Some inputs vary progressively downstream (e.g., floodplains typically grow more extensive downstream and therefore store progressively more sediment; suspended load inputs from upstream reaches typically increase downstream as banks become more erodible), whereas others are less predictable because of local influences (e.g., tributary inputs of sediment to the main channel). The relative importance of sediment inputs via bank erosion from the headwaters to the mouth will depend on other conditions. Headwaters in a mountainous region are likely to have minimal sediment input from banks formed in bedrock or boulders, whereas headwaters in a low-relief environment could have more sediment input from banks in relatively fine-grained sediment such as sand. Regardless of the bank composition, bank inputs typically reach a maximum midway downstream. If the river is in dynamic equilibrium, inputs from bank erosion will be balanced by bank deposition.



$$\Delta S = \text{Inputs} - \text{Outputs}$$
$$\Delta S = (I_{us} + I_{lat}) - (O_{lat} + O_{ds})$$

Figure 2. Aspects of sediment budgets, including the temporal and spatial scales relevant to sediment regime within entire drainage basins and individual river reaches and variables controlling sediment production and flux (in parentheses). The inputs and outputs to a channel are the sediment moving within the channel. The sediment budget equation at the lower left includes a simplified version and a slightly expanded version, listing the components of upstream and lateral inputs and lateral and downstream outputs. Abbreviations: ds, downstream; I, inputs; km, kilometers; lat, lateral; m, meters; O, outputs; us, upstream; S, storage.

The bottom row of figure 3 illustrates changes in the relationships shown in the first row that occur in response to specific human alterations. For example, construction of an upstream dam that traps most incoming sediment will directly alter the downstream inputs of suspended and bed-material load sediment and indirectly increase inputs from the banks and floodplain, as well as decreasing the storage in all components because of reduced sediment inputs from upstream. The construction of levees reduces lateral outputs to banks and largely eliminates outputs to floodplains, while likely increasing downstream outputs of suspended and bed-material load (e.g., Fitzpatrick et al. 2009).

The second part of our conceptual framework involves water and sediment interactions as they drive river condition within a valley context (figure 4, supplement 1). Valley context includes valley geometry (gradient and width of the valley bottom relative to the active channel), the substrate in which the active channel is formed and the living and dead vegetation, which can strongly influence bank stability and channel complexity. Water and sediment interact within the valley context to govern river geometry, aquatic and riparian habitat, and the disturbance regime for river biota (Bellmore and Baxter 2014).

Characterizing sediment inputs, outputs, and storage within a river system is important, because changes in these factors play a key role in channel form adjustments and the disturbance regime. At the simplest level, a river in which sediment inputs increase whereas water inputs remain constant is likely to accumulate sediment. This accumulation can take many forms, some of which are sequential

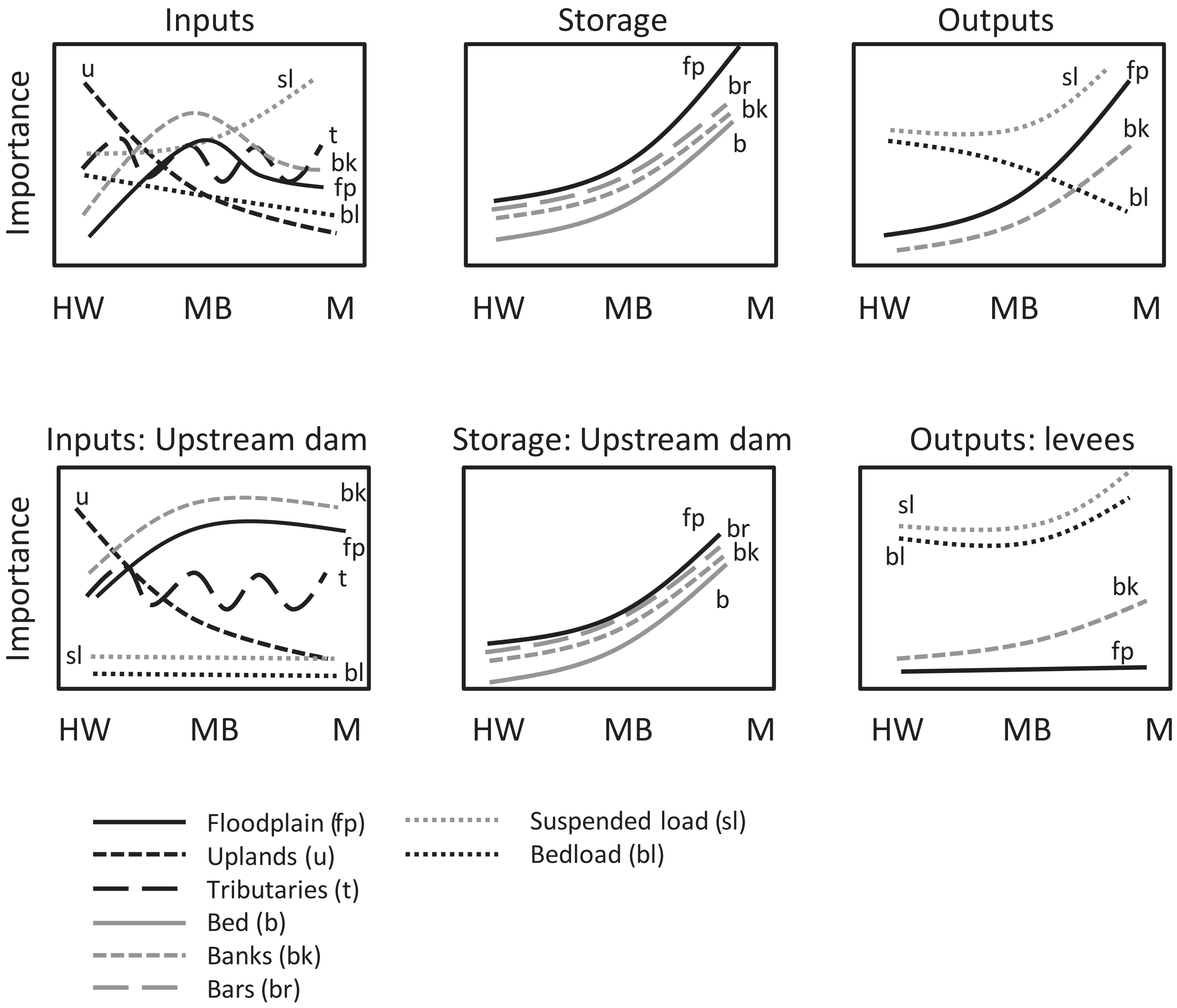


Figure 3. The relative importance of different sediment inputs, outputs, and storage areas moving downstream from headwaters (HW; first- to second-order streams) to midbasin (MB; third order and higher) and the mouth (M; the highest levels of stream order present) for unaltered rivers (top row) and in response to specific human alterations along the river profile (bottom row).

(figure 5). Conversely, a river in which sediment inputs decrease under stable water inputs (e.g., grade-control structures that reduce downstream sediment transport) is likely to have net erosion. Most scenarios of changing inputs are more complicated, with both water and sediment inputs changing, as well as changes in riparian vegetation and other components of valley context (e.g., in response to river damming and water export from the reservoir). Under these conditions, the sediment balance—the ratio between the flow energy available to transport sediment and the supply of sediment, with both variables integrated through time—is more important than absolute changes in either water or sediment inputs. Sediment balance still has to be evaluated in the spatial context of valley geometry and its location within the drainage basin and in the temporal context of the ongoing trajectory of river response to past changes.

The scales governing sediment regimes

Sediment inputs, transport, and storage in river systems vary over temporal and spatial scales different from those of water, and sediment inputs and transport are commonly nonlinear and episodic. The majority of water entering rivers moves downslope and downstream over timescales of less than a year. Because of the responsiveness of river flow to precipitation and the seasonality of precipitation, natural flow regimes have seasonal patterns such as spring snowmelt peak flows or winter rainfall floods that are predictable despite interannual variations (Poff et al. 1997). Although

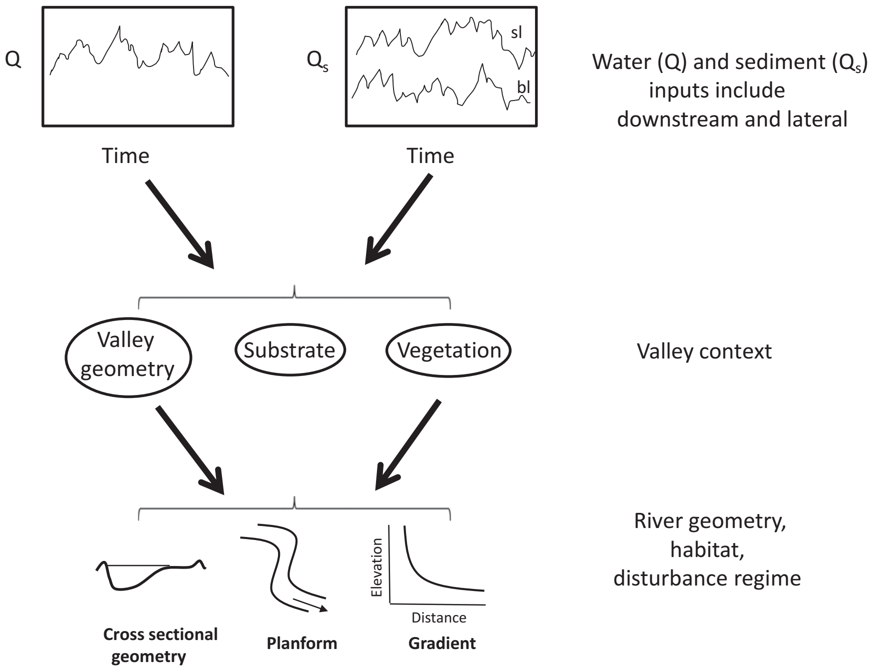


Figure 4. Interactions between water (Q) and sediment (Q_s), including suspended load (sl) and bed-material load (bl), discharges in the context of a specific valley configuration and erosional resistance created by substrate and vegetation to influence river geometry. Human alterations at the upper level (Q, Q_s) and intermediate level (substrate, vegetation) strongly influence river geometry (the bottom level). River management can manipulate water and sediment discharge and valley context to influence river geometry. Adapted from Thorne (1997).

most sediment inputs are driven directly by precipitation or by streamflow that reflects precipitation, sediment inputs tend to be even more nonuniformly distributed through time and space and much less predictable than water inputs. Disproportionate sediment inputs typically originate from small parts of drainage basins over a small fraction of time, whether they are considered annually or over multiple decades. For example, the Peruvian and Bolivian Andes constitute only about 10% of the basin area of the Amazon River but supply more than 80% of the sediment load (Meade 2007). More than 75% of the multiyear sediment flux from rivers in Taiwan occurs in less than 1% of the time (Kao and Milliman 2008). Sediment introduced to a river system, rather than immediately moving long distances downstream, is typically stored for periods much longer than a year and can be repeatedly exchanged among bar, bank, and floodplain storage, such that downstream transport during a river journey can last for as long as 10,000 years on a river such as the Amazon (Mertes et al. 1996).

Although sediment can be conceptualized in a simplified context of only longitudinal (mainstem) dynamics, the sediment regime in most basins is strongly influenced by the basin-wide configuration and network-scale processes (Jacobson and Gran 1999). Equal or greater volumes of sediment can be introduced to the mainstem from adjacent uplands and from tributaries as from mainstem downstream transport (Dunne et al. 1998). Tributary junctions and downstream changes in valley geometry create the potential for major discontinuities in sediment inputs and storage, as well as the associated river physical and ecological condition and disturbance regime (Rice et al. 2001, Benda et al. 2004). A key point here is that managing sediment regimes requires an understanding of the inputs of sediment originating beyond the mainstem channel.

The different forms and spatial scales of sediment connectivity are another important element of sediment regimes. Sediment connectivity describes both the movement and the storage of sediment into channels and along river networks (Fryirs et al. 2007). Highly connected river segments minimize sediment storage, whereas features such as a wider, lower gradient valley segment can create sediment disconnectivity along a river network by storing sediment. Sediment connectivity can vary in relation to sediment size, with high connectivity for suspended sediment, for example, but limited connectivity for cobble-size bed material.

Geomorphically and ecologically relevant spatial scales for river management relative to sediment can be highly variable, depending on the river or river segment under consideration. We illustrate this variability in the context of three examples of dammed rivers in which different forms and spatial scales of sediment connectivity strongly influence sediment regime and aquatic habitat.

On the mainstem Lower Missouri River, upstream dams trap sand-sized sediment, resulting in channel erosion and greater downstream sediment supply and transport. This, along with discrete points of sediment introduction at tributary junctions, discrete areas of sediment removal for commercial aggregate production, and channelization, has increased sediment transport capacity. The resulting channel adjustments to sediment surpluses and deficits on the Missouri River are apparent over decades. These combined processes create a complex longitudinal pattern of sediment mobilized via channel erosion and sediment deposited along the channel, with implications for flood hazards and ecological restoration efforts (Jacobson et al. 2009). Along the Missouri, the lack of longitudinal sediment connectivity because of dams exerts a particularly important limitation on habitat availability for pallid sturgeon (*Scaphirhynchus albus*), piping plover (*Charadrius melodus*), and interior least tern (*Sterna antillarum athalassos*) (Jacobson et al. 2009, Skalak et al. 2013).

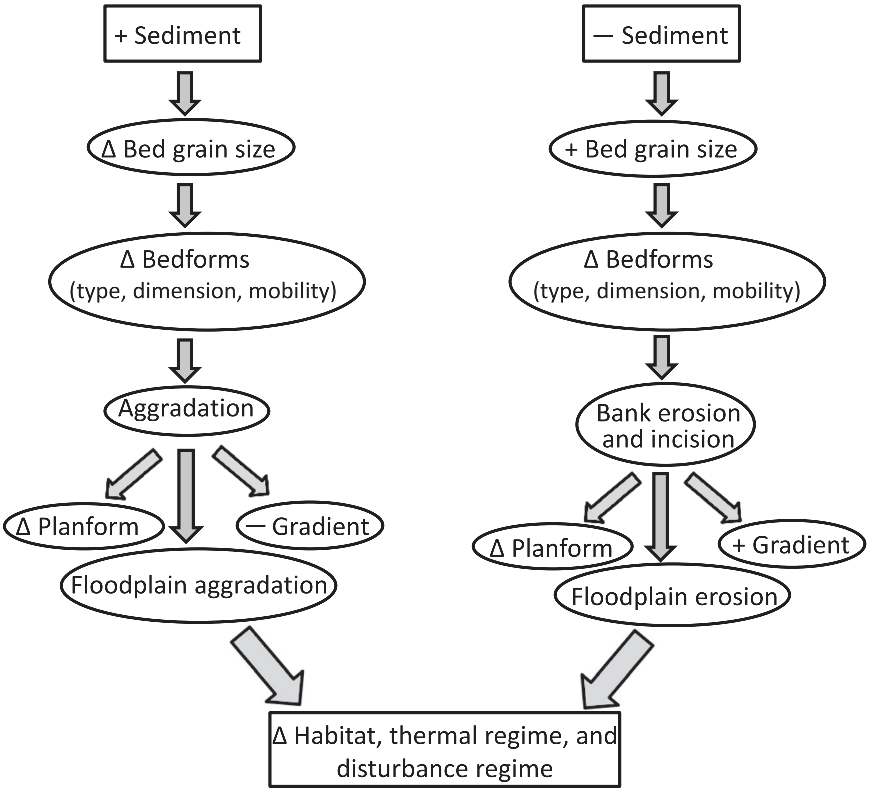


Figure 5. Hypothetical responses to increased sediment inputs (left) and decreased sediment inputs (right), with each change in sediment inputs occurring in the absence of changes in water inputs. Not all stages of response shown here will occur in every channel, and the sequence of responses could vary. Change, indicated by Δ, reflects the fact that the direction of change is highly dependent on specific details (e.g., conditions within a reach). An increase in fine-grained sediment will likely cause a decrease in bed grain size, for example, whereas an increase in coarse-grained sediment will likely cause an increase in bed grain size. At the lower level of the sequence on the left, an increase in sediment supply could cause a meandering channel to become braided (Δ planform), could reduce reach-scale gradient (Δ gradient), or could cause increased overbank sedimentation (floodplain aggradation), or could result in all three changes simultaneously.

In contrast, sediment supply in the Black Canyon of the Gunnison River, Colorado, is less influenced by the presence of a large upstream dam than by local inputs from the canyon walls and short, steep tributaries that extend only a few kilometers from the mainstem. These local boulder-size sediment inputs form channel constrictions and step–pool sequences that create channel-margin irregularities and distributions of hydraulic forces that strongly influence entrainment and deposition of finer sediments, as well as aquatic and riparian habitat (Friedman and Auble 1999, Dubinski and Wohl 2007). Along the Gunnison, lateral sediment connectivity between the channel and uplands strongly influences the sediment regime and its associated river process and form.

A third example comes from the Bill Williams River, Arizona, a dammed, dryland, sand-bed river. Here, dam-induced sediment deficits are restricted to a relatively short reach downstream from the dam; farther downstream, the availability of sediment from large alluvial valleys mitigates the reduction in supply from the upstream watershed (Wilcox and Shafroth 2013). Prescribed flow releases (environmental flows) have been used to maintain native willow (*Salix gooddingii*) and cottonwood (*Populus fremontii*) riparian forests (Shafroth et al. 2010), which depend not only on flows but also on the deposition of suitable-size sediment for seedling recruitment and moisture availability.

Sediment regime in the context of river management

The complexities outlined in the preceding sections do not preclude using metrics of river form to infer sediment regime, including metrics of changes in river form as indicators of changes in sediment regime. These complexities do, however, highlight the importance of several considerations.

The first consideration is the importance of designating the timescale of interest in a management context. Short-term fluctuations of days to weeks may function as hydrologic disturbances for river biota, for example, but they may or may not indicate a significant, persistent shift in river process and form over a period of multiple years. A large flood that elevates turbidity and suspended sediment transport may be a transient phenomenon that does not indicate a continuing change in sediment regime. An example comes from the North Fork Poudre River, in Colorado, where a large input of sand and silt released from a dam temporarily overwhelmed transport capacity, causing the infilling of pools and the fining of cobble-boulder riffle substrate. The next year's snowmelt peak flow exported much of the introduced sediment and returned the river system to its former configuration, including substrates suitable for native benthic macroinvertebrates and fish (Wohl and Cenderelli 2000). Analogously, dam removals can produce sediment pulses and downstream disturbances from which rivers, depending on geomorphic conditions and post-dam-removal flows, can recover within a few months to a year (Wilcox et al. 2014).

A second important consideration is synchronicity—or the lack thereof—between sediment production and routing across a river network. An example comes from Trimble's (2013) work in the Upper Mississippi Valley Hill Country of the north-central United States, where nineteenth-century clearing of native upland vegetation resulted in massive increases in sediment inputs to the river network. As native vegetation recovered during the twentieth century, changes in sediment budgets were markedly asynchronous among the tributaries, the upper main valley, and the lower main valley over a 60,000-square-kilometer area. Spatial and temporal variability in sediment inputs and sediment transport capacity are particularly important in the context of synchronicity between river components.

A third consideration is that, although most management is focused on smaller spatial and shorter temporal scales, an awareness of the greater context is crucial. The start of agriculture in any region is recorded by a change in the volume and type of sediment stored along river corridors, for example, as well as changes in river form and stability (Wohl 2014). Likewise, the damming of rivers, urbanization, and other land-use changes have greatly altered sediment supply, channel geometry, and sediment flux, with effects evident over decade to century time frames (Syvitski et al. 2005, Walter and Merritts 2008). Management occurring at the reach scale (figure 2) that ignores basin-scale influences is unlikely to achieve the desired ends. For example, river restoration designed to achieve a meandering river is not likely to succeed if sediment inputs from upstream reaches are conducive to the maintenance of a braided river (Kondolf et al. 2001).

A final consideration in characterizing the sediment regime in a management context is that, in most river systems, it is more useful to focus on deviation or alteration from natural conditions than to focus on absolute standards. This reflects the inherent variability of natural systems, whereby fluctuations occur within some range of variability (Rathburn et al. 2013). Also, because individual rivers are diverse with respect to sediment inputs, transport, and storage, designating some absolute standard that applies to multiple rivers or regions can be misleading and inappropriate (e.g., figure 1; Brierley and Fryirs 2005). Although sediment is widely recognized as a common pollutant in rivers, the diversity of natural sediment transport rates among rivers has made setting sediment-related water quality standards problematic, especially in view of rivers such as the Colorado and the Missouri and their tributaries, in which natural aquatic ecosystem processes have been disturbed by sediment deficits (NRC 2011).

Focusing on deviations from natural conditions is inappropriate, however, under at least two scenarios. First, if all of the river systems in a region have been altered for many decades or centuries, inferring the natural sediment regime may be impossible. Second, where alteration has been very intensive, has been extensive, or is ongoing, restoring the natural sediment regime may not be feasible. In these situations, sediment should be examined in the context of the sediment balance and how that balance relates to the achievement of management objectives. This can be done by comparing sediment regimes above and below a specific anthropogenic alteration such as a dam (e.g., Grant et al. 2003, Schmidt and Wilcock 2008). The sediment balance can also be assessed as an indicator of likely trends in river adjustment based simply on whether sediment supply exceeds, equals, or falls below transport capacity (Schmidt and Wilcock 2008). In these scenarios, managing for a balanced sediment regime that results in desired river system structure and function is likely to be more realistic and appropriate.

Relevant metrics for characterizing sediment regime

With these considerations in mind, we suggest several river characteristics that can be measured to assess contemporary sediment regimes, including assessing existing conditions in relation to natural sediment regimes in river systems altered by human activities (table 1, supplement 2). The only direct measure of sediment regimes that we include is the measurement of suspended-sediment concentrations. This reflects the difficulty, expense, and time required to measure bed-material load. Without question, the bed-material load is of fundamental importance in river form, process, and physical habitat characteristics, but bed-material load data are seldom available at present. The paucity of direct, long-term measurements of sediment in transport is the key gap in our understanding of river sediment regimes.

In the absence of past direct measurement of sediment transport, diverse tools are available for assessing river sediment regimes. Sediment regimes can be indirectly measured via changes in river form, substrate characteristics, and floodplain characteristics through time or with respect to reference reaches. These changes can be assessed over a time span ranging from instantaneous, ground-based measurements to decadal differences inferred from remote-sensing imagery. Changes in river form and floodplain characteristics can reflect net increases or decreases in the relative sediment supply, but because they result from a change in storage, they do not necessarily provide useful information for sediment flux (Church 2006).

Many methods and metrics exist for assessing sediment dynamics in rivers (table 1). However, even quantitative assessments of the specific river parameters listed in table 1 will allow only first-order predictions of potential future changes, rather than fine-scale understanding, because of the complexities of sediment regimes. If the management objective is to manage or restore to a more natural condition, then being able to demonstrate that a river system is outside the natural range of variability, as well as the direction in which deviation occurs (e.g., is the floodplain more or less diverse in terms of sediment grain size, turnover time, and wetland habitat?), can provide an important context. Knowledge of the parameters in table 1 can also provide important context when the management objective requires assessment of likely trends in river geometry resulting from changes in relative sediment supply above and below a specific alteration such as a dam or a basin-wide alteration such as urbanization and associated changes in water and sediment regime.

Of the characteristics listed in table 1, the most integrative approach is to assess the sediment balance, particularly as reflected in changes to the sediment balance caused by human activities. Of the methods available for assessing the sediment balance (supplement 2), the most comprehensive is the time-integrated ratio of sediment transport capacity and the time-integrated sediment supply, or the capacity supply ratio (CSR; Soar and Thorne 2001). CSR is defined as

Table 1. Metrics useful for assessing sediment dynamics.

Category	Potential metrics	Description
Cross-sectional channel geometry	Width, depth, width:depth ratio, bedform type and dimensions, bank stability, residual pool volume	Bedform type and dimensions refers to infrequently mobile bedforms such as gravel-bed pool-riffle sequences, with dimensions including downstream spacing and vertical variation in bed elevation (Wohl 2014). Bank stability can be assessed using qualitative and quantitative measures, as well as numerical simulation (Simon and Rinaldi 2013). Residual pool volume is the volume in a pool below the elevation of minimum flow surface, when flow barely spills over the downstream lip of the pool (Lisle and Hilton 1992).
Bars and islands	Number and successional stages	Development of bare sediment bars and vegetated islands reflect interactions among water, sediment, and riparian vegetation, including instream wood. Gurnell and colleagues (2012) discusses how to infer sediment dynamics from characteristics of islands and bars.
Substrate	Grain-size distribution, particle stability	Most useful for channels with bed material coarser than sand size. Particle stability refers to the frequency with which some measure of bed grain size (e.g., fiftieth percentile in a particle size distribution) is mobilized: this can be estimated via equations for critical shear stress or velocity, which are then related to a threshold discharge and frequency of exceedance of the threshold discharge.
Suspended sediment	Concentration, grain-size distribution	
Bedload sediment	Mass or volume per unit time, grain-size distribution	
Floodplain	Lateral extent, longitudinal extent, turnover time via chronology (e.g., radiocarbon, tree rings, ^{137}Cs), topographic/substrate diversity	Floodplain lateral and longitudinal extent may be discernible in remote sensing imagery. Field measurements may be needed to quantify spatial or temporal diversity of floodplain topography or substrate. Floodplain turnover time is average time period required to completely replace sediment within a floodplain segment; can be assessed using chronologic indicators such as radiocarbon ages, cosmogenic isotopes (Wittmann et al. 2011), ages of woody riparian vegetation, or via numerical simulations or simple extrapolations of known annual erosion rate and floodplain area (Mertes et al. 1996).
Channel planform	Sinuosity, number of channels	Most readily measured from remote sensing imagery, but may require field-based coring or stratigraphic assessment. Number of channels in a braided channel can be assessed using a braiding index based on remote imagery, although such indices depend on flow stage at time of measurement (Ashmore 2013). Number of channels in an anabranching channel planform is less likely to be stage dependent. Sinuosity and the degree of braiding or anabranching can change as relative sediment supply changes.
Vegetation patterns	Spatial heterogeneity of species and plant ages	Channel cross-sectional geometry and planform, as well as floodplain characteristics, reflect interactions among water and sediment regime and aquatic and riparian vegetation. The spatial distribution of different types of vegetation and the successional stages of vegetation communities can provide insight into sediment dynamics. Seedling establishment and germination may be severely reduced along river segments that lack replenishment of bar and floodplain sediments, for example, leading to even-aged riparian forests (Nilsson and Berggren 2000, Gurnell et al. 2012).
Sediment balance	S, CSR, T*	S* is changes in water and sediment supply pre- and posthuman modification; or dimensionless sediment supply ratio above and below dam (Schmidt and Wilcock 2008). CSR is capacity supply ratio (Soar and Thorne 2001). T* is fractional change in sediment-transporting flows pre- and postdam construction (Grant et al. 2003). See supplement 2
Channel evolution models (CEM)	Models describing multiple stages of channel adjustment following changes in base level, water supply, or sediment supply	CEMs describe adjustments in width, depth, gradient, and planform of alluvial channels and can be used to assess sensitivity of channel form to disturbances and altered hyrology and sediment regimes. Most sequence start with a deep, narrow channel that subsequently widens, accumulates sediment, and eventually stabilizes (Simon and Rinaldi 2013). Planform simulation models have also been applied usefully to evaluate sensitivity to disturbances, quantification of bank erosion rates and channel widening, and evaluation of erodible corridors (Larsen et al. 2007, Parker et al. 2011).
Emerging technologies	*In situ* produced cosmogenic nuclides, fallout radionuclides, airborne and terrestrial lidar, indirect monitoring of suspended and bedload, numerical models of sediment transport, reservoir sedimentation	See supplement 2

the bed-material load transported through the river reach by a sequence of flows over an extended time period divided by the bed-material load transported into the reach by the same sequence of flows over the same time period:

$$CSR = \frac{\int_{time\ 1}^{time\ 2} \textit{Sediment transport capacity of response reach}}{\int_{time\ 1}^{time\ 2} \textit{inflowing sediment supply from upstream reach(es)}}$$

Box 1. How to fail by managing water without considering sediment dynamics.

Continuing inputs of sediment accumulate within the channel and floodplain as a result of flow regulation that limits frequency and duration of flows capable of mobilizing sufficient volumes of sediment. Flow regulation focused solely on maintaining minimum flow depths for navigation or base flows for water supply exacerbates problems. Aquatic and riparian habitat abundance and diversity are reduced (e.g., Illinois River, Illinois; Bhowmik and Demissie 1989).

Urbanization-induced increase in impervious area and stabilization of surfaces increase runoff and reduce sediment inputs to streams, resulting in erosion of channel boundaries. Efforts to reverse problems by reducing storm runoff will be of limited success if sediment supply reduction is neglected—for example, Pennsylvania (Pizzuto et al. 2000) and Japan (Kadomura 1980).

Upstream dam reduces inputs of bedload and suspended sediment, resulting in erosion of channel boundaries, deltas and nearshore areas, or the loss of biologically important elements such as silica that travel with sediment. Experimental flood releases from the dam will not restore desired habitat and ecosystem services in the absence of sufficient sediment supply—for example, the Colorado River, Arizona (Collier et al. 1996); the Missouri River (Jacobson and Galat 2008); the Danube Delta and Black Sea (Lancelot et al. 2002); rivers throughout Japan (Guangwei 2011); the Ganges River, India (Thakur et al. 2012); the Yangtze River and its delta (Yang et al. 2011).

Numerous types of river contaminants (e.g., heavy metals, synthetic chemicals, radioactive isotopes, and excess nutrients) readily adsorb to fine sediment that moves primarily in suspension. Periods of suspended sediment transport can redistribute contaminants and increase contaminant exposure for riverine organisms—for example, the Mississippi River (Goolsby et al. 1993) and the Ob River, Russia (Kenna and Sayles 2002).

When CSR is less than 1, sediment is likely to accumulate in the channel. When CSR is greater than 1, the channel is likely to erode. Values close to 1 are most likely to result in channel stability. The CSR can be applied to any spatial or temporal scale (Thorne et al. 2011), but the CSR of a reach is typically calculated at timescales of years to decades in a management context.

The utility of numerical simulations to model catchment sediment supply through time lags far behind that for hydrologic regimes (Richter et al. 1996, Smith 2011); however, numerous options exist for modeling sediment inputs to a river reach, transport through the reach, and resulting river form (supplement 2). This information can guide management actions to change the balance by altering either water or sediment supply in order to potentially achieve the desired river form and associated habitats.

Understanding sediment regime has been central to many river restoration efforts. For example, the recognition of gravel deficits downstream from dams has motivated gravel augmentation for salmonid spawning habitat on several California rivers (e.g., Zeug et al. 2013). Similarly, sand has been augmented (through the direct addition of sediment) on the Platte River, Nebraska, to restore nesting habitat for endangered interior least terns and roosting habitat for whooping cranes along river reaches in sediment deficit (Smith 2011). The augmentation amount has been calculated as the difference between transport capacity and empirically measured sand transport rates. The extensive research and monitoring of sand budgets on the Colorado River in the Grand Canyon have been used both to assess the effects of experimental flow releases from Glen Canyon Dam and to adaptively manage those releases by, for example, accounting for estimated sand inputs occurring from unregulated tributaries downstream from the dam (Wright et al. 2008, Melis et al. 2012). Recently implemented restoration efforts in Europe (e.g., Habersack and Piégay 2008; REFORM, *www.reformrivers.eu*, and Room for the River, *www.ruimtevoorderivier.nl/room-for-the-river-programme*) also explicitly include sediment regime.

Management implications

Either sediment excess or sediment deficit in a river system can result in fundamental changes to river form and process and, therefore, the loss of ecosystem services and other societal costs. For example, excess sediment from mining operations in the catchment of the Fly River, Papua New Guinea, has led to aggradation of the streambed, increased flooding, and the accelerated delivery of copper-rich sediment to the floodplain, with negative effects on fish and floodplain vegetation (Day et al. 2008). Sediment excess in the Illinois River, Illinois, has resulted in an accelerated filling of floodplain lakes and the loss of aquatic habitat, as well as deposition along the mainstem and continual dredging to maintain navigational pathways (Bhowmik and Demissie 1989). Sand deficit in the Grand Canyon has resulted in the loss of habitat for endangered native fish and recreational sites for river rafters (Melis et al. 2012). In these and many other rivers, it is clear that effective management must include a consideration of the sediment regime and not just of the flow regime.

The conceptual understanding of sediment regime can limit internally contradictory or counterproductive actions, such as allowing aggregate mining in a sediment-limited river (box 1) or narrowly implementing elements of a natural flow regime that exacerbate sediment-deficit conditions (e.g., Schmidt and Wilcock 2008). For example, an attempt to naturalize the flow regime of the Lower Missouri River in order to achieve floodplain connectivity led to greater amounts of riparian vegetation. As a result, the deposition of unvegetated sandbars for shorebird nesting habitat was severely hampered by sediment deficits and the associated channel incision that prevented floodplain connectivity over a large part of the river (Jacobson and Galat 2008).

Finally, the conceptual understanding of sediment regime can facilitate the consideration of nested scales of space and time, such as sediment regime within individual river reaches over a period of weeks to months, considered in the greater context of the entire drainage basin over a period of years to decades. In some cases, for example, channel erosion upstream creates a source of excess sediment inputs to downstream reaches. In other cases, upstream management actions such as installing grade-control structures can induce channel erosion downstream by limiting longitudinal sediment transport. Changes in land use and river configuration, including urbanization, channelization, and flow augmentation, can increase transport capacity and decrease sediment supply, resulting in a sediment deficit and the erosion of downstream river reaches. In this context, large dams receive a great deal of attention for their effects on sediment supply (Syvitski et al. 2005), but smaller, spatially extensive changes in sediment and water balance throughout a river network can have substantial cumulative effects (Walter and Merritts 2008).

Despite complications introduced by nonlinear interactions among water, sediment, and river geometry, in many cases, sediment regime can be managed to achieve desired ends within some flow-sediment balance. Passive intervention can involve strategies such as allowing the river to access its historic floodplain or distributary channels in order to restore channel–floodplain or channel–delta sediment exchanges, thereby enhancing habitat for fish spawning, fish rearing, and waterfowl (Florsheim and Mount 2002). Active intervention can involve methods such as gravel augmentation below dams or in other sediment-impoverished river segments (Zeug et al. 2013), or larger experimental releases from dams that facilitate redistribution of sediment already present within the river system (Kondolf 2011). Either type of intervention requires reliable knowledge of where sediment enters a channel, how and when sediment moves down the channel, and where and for approximately how long the sediment is stored—in other words, a sediment budget. This sediment budget can be used to guide management so as to create a balanced sediment regime in which flow is able to transport available sediment in a manner that maintains a desired sediment balance, as well as river structure and function.

Conclusions

Our intent in this article is to heighten awareness of the many interacting components that govern sediment regime in river systems and that must, therefore, be managed explicitly to achieve many restoration goals. A more focused discussion of how to integrate flow regime and sediment regime in management applications is greatly overdue. Although the concept of developing a balanced sediment regime is straightforward, the difficulties of quantitatively predicting sediment mobilization and transport in rivers create uncertainties and challenges for management.

The ability to understand and manage the temporal and spatial dynamics of water or sediment depends on the precision of the records of these dynamics through time and among locations. Direct data on sediment transport, in particular, are severely limited relative to discharge records. The management of river systems will be handicapped until we invest in the more-comprehensive collection of sediment data. In the absence of direct measurement of sediment transport, isotopic and other emerging technologies (table 1) can be used to understand sediment regime in river systems.

At a minimum, the current understanding and tools allow us to predict the trajectories of river change in response to changes in sediment regime. Decreasing the relative sediment supply will trigger the types of river responses indicated on the left side of figure 5, and increasing the relative sediment supply will trigger those on the right side of this figure. Measures of sediment balance can be used to determine whether the relative sediment supply is increasing or decreasing within a river segment and to assess the magnitude of change. These variables can also be used to design management that creates a balanced sediment regime and facilitates channel stability. A channel in dynamic equilibrium may not necessarily create the desired river system structure and function required to support native biota, however, so channel stability in itself may not always be a sufficient management goal. An understanding of sediment regime can be used to manage for a dynamically stable channel in which water and sediment interact to create the habitat and disturbance regime needed to support river biota. With the tools and understanding currently available, there is no justification for managing river systems without explicitly considering sediment regime and every incentive to do so.

Acknowledgments

Gregor Auble participated in the research discussions from which this article grew, and we appreciate his contributions to the process of developing the manuscript. This research was subjected to US Geological Survey review and approved for publication. The mention of trade names or commercial products does not constitute an endorsement or a recommendation for use. We thank Faith Fitzpatrick and three anonymous reviewers for useful comments.

Supplemental material

The supplemental material is available online at *http://bioscience.oxfordjournals.org/lookup/suppl/doi:10.1093/biosci/biv002/-/DC1.*

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Ellen Wohl (ellen.wohl@colostate.edu) and Sara L. Rathburn are affiliated with the Department of Geosciences, Brian P. Bledsoe is affiliated with the Department of Civil and Environmental Engineering, and N. LeRoy Poff is affiliated with the Department of Biology at Colorado State University, in Fort Collins. Robert B. Jacobson is affiliated with the US Geological Survey, in Columbia, Missouri. David M. Walters is affiliated with the US Geological Survey's Fort Collins Science Center, in Fort Collins, Colorado. Andrew C. Wilcox is affiliated with the Department of Geosciences, at the University of Montana, in Missoula.