Monitoring Geomorphology to Inform Ecological Outcomes Downstream of Reservoirs Affected by Sediment Release

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PURPOSE: Increasingly, reservoir managers are seeking techniques that improve sediment management while considering long-term sedimentation and reduced operational flexibility. These techniques, often termed *sustainable sediment management*, involve passing sediment through reservoirs and into downstream rivers. Conceptually, restoring sediment continuity can benefit ecosystem function by increasing floodplain connectivity, contributing to the heterogeneity of channel geomorphology, and supporting the continuity of nutrient cycling. However, when a change is made to operations, geomorphic changes may need to be monitored to document benefits and mitigate any unexpected effects of the change. This investigation develops a geomorphic monitoring plan for downstream reaches affected by sediment-release operations at reservoirs. The monitoring objectives are aligned with potential geomorphic change caused by changes to sediment supply and the associated effects on river function. A tiered approach is presented to explain the quality of information that can be assessed from increasing levels of data collection. A general conceptual model is described in which geomorphic data may be linked to physical habitat conditions and, therefore, ecological processes. The geomorphic monitoring plan for the Tuttle Creek Reservoir water injection dredging (WID) pilot project is presented as a case study. This technical note establishes a general framework for monitoring the design for sustainable sediment management in different ecological and geomorphic contexts.

BACKGROUND: Reservoirs have been constructed throughout the world to manage streamflow, reduce flood risk, and provide hydropower. However, sediment retention reduces the effectiveness of reservoirs by reducing their water storage capacity (White 2012) and disrupts the natural sediment regime (Wohl et al. 2015). Sedimentation in United States reservoirs is estimated to have reduced total water storage capacity by 10%–35% (Tullos et al. 2021). Other effects of sedimentation include reduced recreational space, damage to intakes and outlets, and effects on ancillary reservoir features (e.g., navigation channels, boat ramps, and water depth for recreation; Randle et al. 2019).

Trapped sediment also deprives river reaches downstream of reservoirs, affecting channel geomorphology and aquatic habitat (Ligon et al. 1995; Kondolf et al. 2014; Morris and Fan 1998). Withheld sediment contributes to downstream channel narrowing, incision, and disconnection from the floodplain (Bednarek 2001). According to Randle et al. (2019), a sustainable goal for reservoir sediment management is to pass sediments downstream annually in quantities that are similar to the volume of inflowing sediments. Sediment sluicing from reservoirs has been shown to have regenerative downstream effects, reverting to wider channels that are better connected to the floodplain. Impounded sediment release may be the most important control that managers have to influence physical and ecological effects downstream of reservoirs (Foley et al. 2017; Espa et al. 2016). The degree of reconnection and change varies greatly due to local conditions, such as river geometry and sediment characteristics (East et al. 2018).

While the effects of dam removal on geomorphology and ecosystem function have been characterized (Bednarek 2001; Bellmore et al. 2019), it is unclear how the potential variance of continual sediment pass-through practices will differ from the sediment pulse associated with dam removal. The characteristics of the stored sediment, the method of pass-through (e.g., free flowing or dredge assisted; Crosa et al. 2010), streamflow volume, and stream geomorphology (East et al. 2018) may all contribute to this variance. In addition, the magnitude, duration, and timing of flow are all conditions that relate to ecological outcomes (Poff et al. 2007, 1997). Given the potential variability of sediment and water-release operations, reservoir-valley configurations, and ecosystem response, a geomorphic monitoring protocol is warranted.

This investigation reviews selected literature related to monitoring the downstream effects of sediment management practices at reservoirs as they relate to geomorphic change and ecosystem function. The value of increased data collection is presented as a tiered approach, from leveraging widely available monitoring data (e.g., USGS stream gages and aerial photography) to collecting data of sufficient resolution to develop numerical models. To ground the guidance, a case study on a sustainable sediment management pilot at Tuttle Creek Reservoir is presented. Guidance linking geomorphic monitoring to ecological outcomes is discussed to bolster feasibility and adaptive management planning around sustainable sediment management.

DIMENSIONS OF A GEOMORPHOLOGICAL MONITORING PROTOCOL: When implementing a novel sediment management program, the direct and indirect effects of sediment release should be considered. Monitoring plans should measure or allow inference of these effects as a means of controlling risk and measuring benefits. A change in sediment regime is likely to influence geomorphology, but the magnitude, duration, and extent of change may be highly variable (Foley et al. 2017).

There are two primary dimensions of sediment transport in this context: the suspended sediment load and the bed load. Figure 1 presents the potential effects to stream ecosystem function and structure based on these two phenomena. In general, bed load sediment mostly affects habitat quantity (e.g., islands and channel bed armoring), and suspended sediment mostly affects quality (e.g., nutrient availability and light penetration), but these are interconnected and exert changes in biological and ecological components of the riverine system. Another difference between the effects of suspended sediment versus bed load is that the effects of suspended sediment may be acute (e.g., fish behavior with turbidity changes), while the effects of bed load may be chronic or long-term (e.g., changes to habitat). Monitoring activities are also proposed in the figure. The timeline for monitoring should include a period prior to implementation to measure the baseline conditions and gain an understanding of the variability of the system before operational changes are implemented.

The influx of sediment to downstream waters may change channel morphology and water quality. The extent and duration of the effects of repeated sediment release are uncertain. The magnitude of change from sediment transport is attributed to sediment volume and particle size, both of which affect the sediment’s fate. There may be acute or chronic changes to the aquatic and riparian areas that affect fauna and their food sources and potential influences on vegetative recruitment (Kemp et al. 2011; Staentzel et al. 2018). Bed material and suspended sediment load affect habitat for macroinvertebrates and riverine fish (Jones et al. 2011; Kemp et al. 2011). Transported sediment may affect aquatic habitat quantity (e.g., embeddedness) and water quality (e.g., dissolved oxygen and turbidity) for fish species (Hernandez-Abrams et al. 2022).

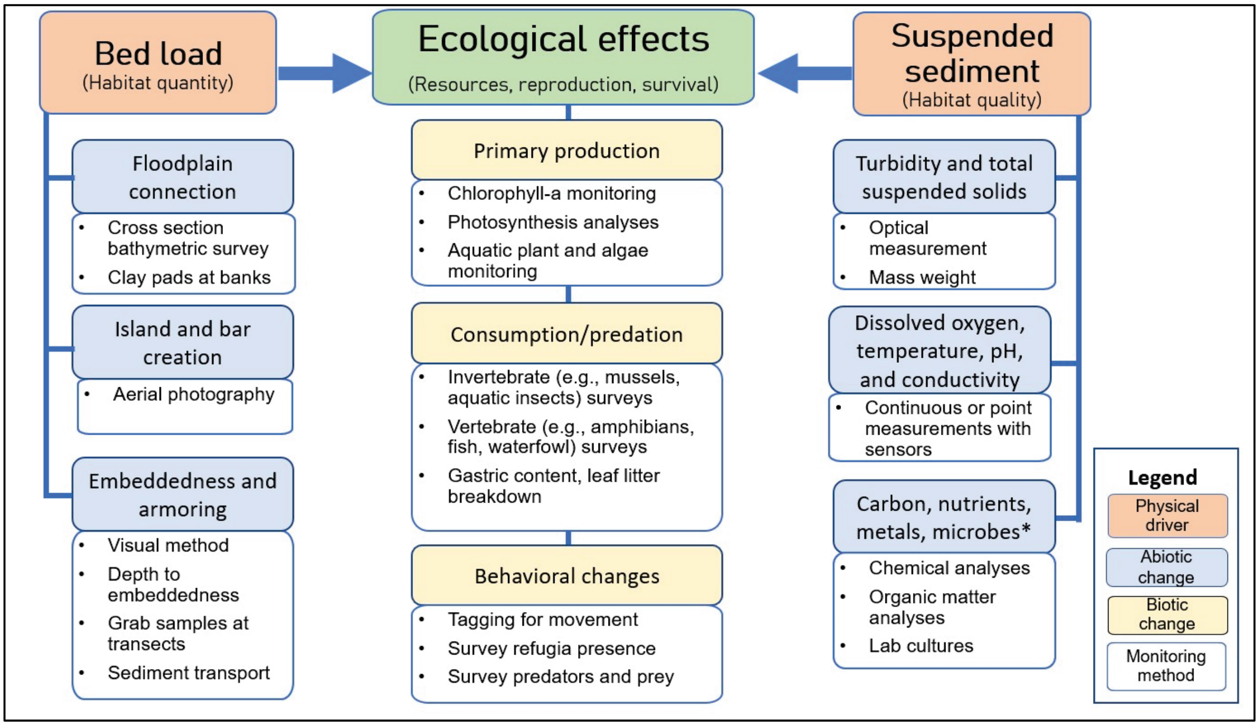

Figure 1. Diagram relating physical outcomes (from bed load and suspended sediment; *orange and blue boxes*) of a release to foreseeable effects to the aquatic species resources, reproduction, and survival (biological effects; *yellow boxes*) and how these can be monitored (*white boxes*). *Microbes are biotic but are often monitored with the other water quality indicators listed here.

Channel responses to sediment input are highly specific to the river valley's morphology and the character of the flow pulse (East et al. 2018). In sediment-starved or floodplain-disconnected systems, erosion may affect in-stream benthic and pelagic habitat and riparian areas (Bellmore et al. 2019). Increased sediment loads may lead to a reduction in bank erosion and possible channel bed aggradation. Increased sediment loads also affect the presence and exposure of sandbars, which in turn affect the habitat for several species, including sandbar nesting birds (e.g., piping plover and least tern), invertebrates, and fish (TNC and USACE 2021).

Ecosystem responses are complex when considering the biological, chemical, and physical system components and interactions affected by the hydrological (Poff et al. 1997) and sediment (Wohl et al. 2015) regimes. Conceptual models aid in communicating and evaluating these complex ecosystem drivers and responses to sediment pulses (Hernandez-Abrams et al. 2022). The conceptual model should be sufficiently robust to help reservoir managers determine operations protocols (i.e., the duration and frequency of sediment release). By articulating potential drivers and their thresholds to affect change, uncertainties associated with new approaches for sediment and habitat management are assessed simultaneously. These uncertainties can be linked back to system components and could be addressed with monitoring methodologies such as those highlighted in Figure 1.

CASE STUDY OF TUTTLE CREEK RESERVOIR WATER INJECTION DREDGING (WID): Tuttle Creek Dam was closed in 1959 and is operated by the US Army Corps of Engineers (USACE) Kansas City District (CENWK). It is on the Big Blue River, which flows about 10 miles below the dam until merging with the Kansas River. By 2070, the Kansas Water Office (n.d.) estimates that Tuttle Creek will have lost 89.9% of its storage capacity due to sedimentation. In 2024, CENWK plans to pilot a sustainable sediment management protocol by mobilizing stored sediment through the dam's low-level outlets via WID. WID uses water jets to disaggregate, hydraulically lift, and entrain bed material into a density current. Theoretically, this sediment is transported in density currents to low-level reservoir outlets and sediment is passed to the downstream ecosystem, restoring reservoir pool capacities and sediment regime downstream. Previous work evaluated potential sediment management methods and the environmental effects of sediment release at Tuttle Creek Reservoir (Shelley 2015, 2019; Shelley et al. 2016; Hernandez-Abrams et al. 2022). However, the pilot study will be the first to document actual effects that are being monitored as a management action (i.e., the WID) is implemented.

TUTTLE CREEK MONITORING PLAN: The proposed multi-agency (i.e., USACE, US Army Engineer Research and Development Center [ERDC], USGS, and Kansas State University) coordinated monitoring plan follows a BACI (before-after-control-impact) design, which is a common approach to evaluating the effects of human or naturally induced perturbations in ecosystems (Conner et al. 2016). The same sites before and after a perturbation (e.g., a WID sediment release) and a control site that is upstream of the confluence and will not be affected by the WID will be monitored. The overall monitoring plan is for two years: one year prior to WID operations (i.e., a baseline year) and the year of WID operations, with ecological data collection before and after every WID event. A baseline year of monitoring is necessary to characterize natural hydrologic seasonal variability and current reservoir operating conditions. Three WID operations are to be conducted in the spring, summer, and fall, so ecological baseline data will be collected in the same seasons the year prior (i.e., three times). During the year of WID operations, ecological data will be collected before and after every event in each of the three seasons (i.e., six times).

Two scales are to be monitored for the geomorphic and hydraulic studies: a reach-scale and a higher resolution site at the confluence of the Big Blue River with the Kansas River. The reach-scale covers more than 65 miles of the Big Blue and Kansas rivers, with transect spacing from 1 mile (labeled *Bathymetric Cross Section* in Figure 2) to 15 miles apart (*Fish Sampling*; Figure 2); the confluence study area covers 7 miles of river, with transects spaced from 500 feet to 1.5 miles apart. Bathymetric and bed material data were collected one time during the baseline data collection year (April 2023) and will be collected three times during the WID operation year.

The characteristics of flow (including backwater effects from the Kansas River), the outcomes of the sediment pulse, and their relation to habitat conditions will be assessed via several monitoring methods (Table 1). The reach-scale analysis leverages existing transects and assesses the longitudinal extents of WID effects on a larger scale. The higher resolution at the confluence (approximately 7 miles of river) will allow researchers to evaluate change, including island generation and bed adjustments, at a mesohabitat scale. Channel confluences are affected by abrupt changes in energy. Sediment transport at these locations may be affected by several temporal and spatial factors, such as discharge ratios and flow depth (Nazari-Giglou et al. 2001). Discharge ratios affect riverbed topography and flow structure, which affect habitat quality and the movement of sediment, and have potential affects throughout the river network (Zhang and Lin 2021), including adjustments to bed slope and channel hydraulics upstream of the confluence (Bombar and Cardoso 2020).

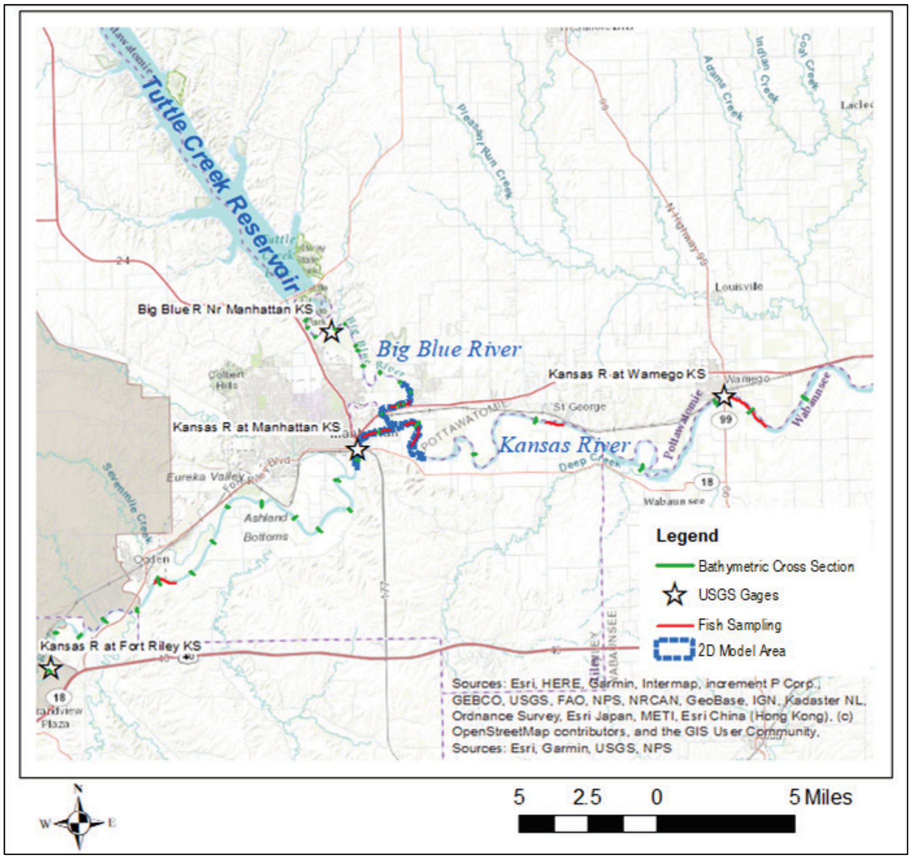

Figure 2. Map of the distributed monitoring of different types for the Tuttle Creek water injection dredging (WID) project. (Map image is the intellectual property of Esri and is used herein under license. Copyright 2020 Esri and its licensors.)

CENWK has historically collected bathymetric transects downstream of the Big Blue River and throughout the Kansas River as "degradation lines." These lines document active channel change due to sediment retention in upstream reservoirs. Additional bathymetric cross sections and sediment transects are to be collected surrounding the confluence of the Big Blue River and the Kansas River (map of these presented in Figure 2). To meet Kansas Department of Health and the Environment (2018) surface water quality regulations and standards, CENWK has added bed material, water quality measurements, and macroinvertebrate data collection at these transects as part of the Stream Biological Monitoring Program (SBMP). Channel adjustment can be assessed using repeated locations, both for the duration of WID and for long-term trend observation. In addition, water quality and hydrologic data will be continuously sampled at the USGS gages shown in Figure 2.

As part of the pilot study, sediment mobilization in the reservoir and sediment concentration downstream near the outlet will be monitored during WID (funded by Dredging Operations and Environmental Research; principal investigator: Mr. Zachary Tyler, ERDC Coastal and Hydraulics Laboratory [CHL]). This will include using an acoustic doppler current profiler (ADCP) for sediment volume measurement and water quality sampling. The purpose of this monitoring effort is to evaluate the effectiveness of WID as a long-term, sustainable sediment management protocol. These data support estimates of the influx of sediment into the downstream monitoring locations.

Table 1. Field data for the pre- and post-WID time frames. Bathymetric data and bed material transects were collected one time during the baseline data collection year and will be collected three times during the WID operation year. Fish and macroinvertebrate monitoring occurred three times during the baseline year and six times during the WID operating year, pre- and postevent, respectively. Water quality data at USGS gages will be collected continuously.

Data Collection	Monitoring Purpose	Method	Location	No. of Transects or USGS Gage No.
Bathymetric transect	To assess aggradation, degradation, and change in channel shape	SonarMite Echo beam with Trimble R12 base stations and R8 rovers on 12 foot and 16 foot boats; 90 total transects every 500 feet	BBR	36
			Confluence (2D model area)	48
			KSRU	10
			KSRD	18
Bed material transect	To assess substrate that is an indicator of sediment transport and habitat quality	5–9 grab samples taken at some transects in 20 ounce jars Sieve analysis; if the silty/clay component >5%, laser diffraction will be used	BBR	2
			Confluence	2
			KSRU	1
			KSRD	2
Macro-invertebrate monitoring	To assess macroinvertebrate community composition, linking direct ecological responses to the WID, and to assess changes in fish feeding behavior	Kick samples with D-net	BBR	2
			Confluence	4
			KSRU	1
			KSRD	2
Fish monitoring	To assess fish community composition, linking ecological responses to the WID; to assess fish behavior and biological condition as part of the Aquatic Life Use Support (ALUS) index.	Electro shocking with boat and backpack; seining near shore in shallow areas	BBR	2
			Confluence	4
			KSRU	1
			KSRD	2
Water quality	To assess changes in water quality parameters and comply with state standards	USGS gages; Stream Biological Monitoring Program (SBMP)	BBR	06887000
			Confluence	No gage
			KSRU	06879820; 06879100
			KSRD	06887500

Note: BBR = Big Blue River upstream of confluence with Kansas River; KSRU = upstream of confluence with BBR; KSRD = Kansas River downstream of confluence with BBR.

Fish and additional macroinvertebrate community monitoring will occur at nine sites throughout the Kansas River (two upstream of the confluence for control) and two sites in the Big Blue River, approximately 6 miles below the dam. Fish and macroinvertebrate monitoring evaluate the community assemblages as related to sediment release effects on habitat, food source, and prey resource availability. These data are collected by Kansas State University and supported by the state of Kansas for long-term aquatic population monitoring.

LEVERAGING EXISTING DATA: While direct field monitoring is instrumental in characterizing geomorphic change following sustainable sediment management, there are also external data sources that are informative for characterizing elements of the geomorphic and environmental condition. These also extend the observational dataset to a larger temporal scale so that changes from operations and long-term trends may be assessed.

Aerial and Satellite Imagery. Aerial photography can be collected from Planet (n.d.) on a frequent (i.e., weekly or monthly) basis. The aerial photography is at a 40-meter resolution, which enables the assessment of channel morphology (e.g., sinuosity and width) and movement. Historical data over the period of record should also be reviewed to assess changes due to development, instream infrastructure, or natural change. Changes in channel sinuosity, width, or energy slope are typical geomorphic responses to change in sediment loads (Schumm 1973). Geomorphic adjustments are responsible for the presence and persistence of islands, and they reflect mesohabitat diversity, including vegetative patterns and food sources. The magnitude of change in the channel planform, whether it be sand bar elongation or generation, can be compared over the time series to delineate variability under current reservoir operations relative to variability during and after WID operations.

Water Quality and Hydrologic Gage Data. USGS stream gages create a network of hydrologic and water quality information throughout much of the United States. Depending on the locations of USGS gages and their collection parameters, a network of gages can be used to infer how reservoir discharge affects water quality at reach-scales. USGS gages may document both continuous water quality data via sondes and more detailed water quality constituent information from field samples. USGS gages adjacent to the higher resolution sampling area include Big Blue River (06887000; with daily discharge dating back to 1990) and the Kansas River at Manhattan, Kansas (06879820; gage height only, dating back to 2008). Through interagency coordination, USGS is aware of the pilot project and intends to restart continuous water quality monitoring and sediment data collection for the pilot timeline. The reach-wide monitoring area encompasses two additional gages: (1) Kansas River at Fort Riley (06879100) at the upstream extent and (2) Kansas River at Wamego (06887500) at the downstream extent. These extend the daily discharge period of observation on the Kanas River to 30 years, beginning circa 1990. Generally, these gages have limited water quality monitoring data, composed mostly of field samples. The Wamego gage has had continuous water quality monitoring since as early as 2012.

Bathymetric Data. As mentioned previously, CENWK has been monitoring bathymetric transects as degradation lines. In coordination with flood management projects, they have developed one-dimensional hydraulic and sediment transport models and geomorphic analyses in the Kansas River and Big Blue River. Not only can long-term trends, including rates of incision and variability, be inferred from these monitoring data, but numerical models can be used to estimate hydraulic habitat conditions that are also related to prevailing substrate, aquatic species, and riparian conditions.

Environmental Flows Analysis. While monitoring helps characterize geomorphic, water quality, and hydrologic conditions, understanding how these relate to habitat conditions and ecosystem processes requires conceptual model development (Hernandez-Abrams et al. 2022). The Kansas River Sustainable Rivers Program (SRP) identified seasonal flows as they relate to species life cycle requirements; they are termed *environmental flows* or *e-flows*. SRP is interested in pairing environmental flows with potential changes in reservoir operation (TNC and USACE 2021). The objective is to integrate these data into ecological models for analysis of management alternatives that mitigate the negative effects and increase the ecological benefits of sediment release (Bonner and Wilde 2002).

Existing geomorphic planform, sediment transport, and hydrology affect the environment, including bed substrate, water quality, and physical habitat (e.g., sandbar exposure). Baker et al.'s (2021) report on environmental flows identified fish species whose populations have changed significantly since the closure of Tuttle Creek Dam; the report includes their preferred mesohabitat (i.e., backwater and pools), spawning habitat, current and depths, turbidity, and substrate. These linkages between streamflow, sediment, and geomorphic conditions are important for grounding the observed ecological outcomes to the effects of reservoir operations and sustainable sediment management on the system.

COUPLING MONITORING WITH MODELS: Geomorphic monitoring is an important step in assessing the downstream ecological outcomes of sustainable sediment management in reservoirs. All monitoring programs are developed under constrained resources, including the capacity to collect data and temporal or spatial scales of observation. As in the Tuttle Creek pilot study, detailed field observances are planned based on the interests, resources, and expertise of project stakeholders (e.g., academic researchers and government agencies). In addition, data (e.g., USGS water monitoring network data and aerial photography) are readily available throughout the United States, and they should be leveraged when possible.

While observational data describe measurable physical change, some form of modeling is necessary to delineate the drivers of change. Table 2 lists various analysis approaches, which are organized according to increasing levels of detail. At a minimum, conceptual ecological models describe the cause and effect of physical habitat conditions. This links data collection to the characterization of the effects of sustainable sediment management on ecologic and geomorphologic conditions.

By leveraging stream gages and species life history, environmental flow analysis relates flow conditions with mesohabitat availability. By assessing pre- and postoperation hydrology and sediment transport, inferences on changes to bed substrate, water quality, and flow magnitude relative to ecosystem trends can be discussed with greater confidence.

Finally, integration with a numerical hydraulic model allows the mechanistic properties of flow to be related to habitat quality and availability. The linkage of geomorphic observations to hydraulics also enables forecasting and alternative evaluation of WID-induced sediment and water transport. For any reservoir project, these analyses are useful for informing physical habitat availability and hydraulic or geotechnical engineering design (e.g., bank stability and material selections).

Table 2. List of data requirements and outputs for three levels of geomorphic analysis, each further refining an ecological model related to sediment release.

Level	Minimum Data Requirement	Outputs
Conceptual paired geomorphic-ecological model	• Aerial photography to derive historical and current river widths, vegetated island formation, and channel sinuosity • Bathymetric and bed material transects • Species presence and abundance	• Characterize the system and its change over time, including the relative abundance of mesohabitat types (i.e., islands and riffles) • Link long-term trends in geomorphic planform to ecological observances
Environmental flows analysis	• Hydrology, sediment, and water quality information via USGS gages	• Analyze flow frequency prior to and following installation of major instream structures • Identify characteristics of natural and regulated peak flows (e.g., duration, recession rate, magnitude) relative to ecosystem processes
Numerical hydraulic model	• Bathymetric transects spaced according to bank-full width; water surface elevations, bathymetric transects with depth and velocity, bed material transects • If using sediment transport or water quality modules, water quality and sediment measurements adjacent to model area	• Characterize habitat hydraulics (e.g., shear stresses, depths) within the cross section (one-dimensional) and islands (e.g., inundation frequency, sediment distribution; two-dimensional) • Forecast characteristics of regulated flows (e.g., hydraulics, water quality, sediment transport) in between monitored events or for long-term trends • Link field observances to physical quantities (e.g., thresholds) to identify drivers of change or outcomes

CONCLUSIONS: This technical note discusses how monitoring protocols can be developed to evaluate the effects of sustainable sediment release on downstream ecosystems. Conceptual models of sediment transport and how it affects aquatic and riparian species were leveraged to identify multiple dimensions of geomorphic and ecological monitoring. Different levels of data collection and their applications in conceptual and numerical modeling were described. The guidance was grounded with a pilot project at Tuttle Creek Reservoir near Manhattan, Kansas. The case study can also be applied to other reservoirs with proposed sediment releases. This study and multi-organization effort support data collection and project scoping and inform various regulatory mechanisms (e.g., National Environmental Policy Act, Clean Water Act, or Endangered Species Act) related to these types of projects.

Despite increased demands for sustainable sediment management solutions, sedimentation in reservoirs continues to reduce reservoir capacities. To inform future projects, the researchers provided a variety of monitoring methods that use national tools and explained how they relate to ecosystem function. Levels of data collection and their use in integrating with other models were provided to aid in understanding potential environmental effects.

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