Effects of Sedimentation on Biological Resources

Donald G. Huggins, Senior Aquatic Ecologist and Director
Robert C. Everhart, Graduate Research Assistant
Andrew Dzialowski, Post Doctoral Researcher
James Kriz, Graduate Research Assistant
Debra S. Baker, Assistant Director
Central Plains Center for BioAssessment, Kansas Biological Survey, University of Kansas

Summary
Sedimentation is a natural process, but too much sediment in aquatic ecosystems can cause loss or impairment of fish, macroinvertebrates, and other aquatic organisms. Our current ability to quantify relationships among aquatic sediment variables and aquatic biota in the Central Plains is limited by available data and the complexity of direct and indirect linkages between resource components. At present, turbidity appears to be the best indicator of suspended sediment for defining biological impairment in flowing water systems. Better coordination of existing and new research, use and analysis of well-selected indicators of suspended and deposited sediment and ecosystem function, and advanced statistical analyses will allow us to more accurately identify and quantify effects of sediment on aquatic ecosystems in Kansas.

In-stream sediments come from two sources: runoff from surrounding areas and erosion from both the sides and bed of the channel. The complex interaction of streams and the surrounding landscape can be characterized to a large extent by describing sediment movements. Erosion and sediment deposition affect many stream characteristics including channel depth, channel shape, substrate, flow patterns, dissolved oxygen concentrations, adjacent vegetation, and aquatic communities (Leopold et al., 1964; ASCE, 1992; OMNR, 1994; Rosgen, 2006).

Sedimentation is a natural process that occurs in most aquatic ecosystems, and sediment-borne organic materials provide the primary food source for a number of filtering macroinvertebrates (Waters, 1995; Wood and Armitage, 1997). However, human activities such as urbanization, agriculture, and alteration of riparian habitat and flow regimes have increased the concentrations and rates at which sediment enters streams and rivers (Wood and Armitage, 1997; USEPA, 2000; Zweig and Rabeni, 2001; Angelo et al., 2002); and losses of habitat, biota, and ecosystem services due to sediment have caused severe socioeconomic impacts (Duda, 1985). As a result, sedimentation is listed as one of the most common stream impairments in the United States (USEPA, 2000, 2004), occurring in almost one-third of the river and stream miles recently assessed by the U.S. Environmental Protection Agency (USEPA; 2004).

Introduction
Water from streams and rivers is used for drinking, irrigation, waste dilution, power generation, transportation, and recreation and provides habitat for fish and other aquatic organisms (Allan, 1995). This water also contains sediment (e.g., eroded soil particles), which can be either suspended in the water or deposited on the bottom. Sedimentation is the process by which sediment is transported and deposited in aquatic ecosystems.
Increased sedimentation and sediment loading are also threatening the ecological integrity of other aquatic systems. For example, sedimentation at higher than normal rates can reduce or impair habitat and primary production in wetlands (Gleason and Euliss Jr., 1998; USEPA, 2002; Gleason et al., 2003). Similar habitat reduction has been observed in lakes; several Kansas reservoirs are experiencing 10% to 40% decreases in conservation-pool water-storage capacity. If sedimentation continues at current rates, sediment pools of these reservoirs will be filled by the 2020s (Juracek, 2006). In other reservoirs (e.g., Perry, Tuttle Creek), increased sedimentation is occurring primarily in the riverine upper reaches, reducing both quality and quantity of habitat.

Both “clean” and “dirty” sediment directly and indirectly affect the structure and function of all aquatic ecosystems (Figure 1). Clean sediment is free from additional contaminants (e.g., volatile organics, metals, or other toxic compounds), and dirty sediment harbors these materials. Effects of dirty sediment are due to the nature and concentration of both sediment and contaminants, whereas effects of clean sediment are due to the nature and concentration of sediment particles alone. Duration of exposure is also important. In the environment, clean and dirty sediments constantly interact as contaminants are added, broken down, and removed. Because both sediment types occur simultaneously, clean and dirty sediment effects are difficult to separate. To begin understanding sediment interactions, this white paper focuses on effects of clean sediment.

Figure 1. Conceptual framework showing interactions of sediment in aquatic ecosystems
Boxes illustrate important ecosystem units with examples, and arrows represent functional directions and links between those units. Ultimate goals are to understand the links and quantify sediment effects on biota.
Although effects of sedimentation are widespread, a comprehensive theory of these effects on benthic communities does not currently exist (Zweig and Rabeni, 2001). Appropriate management of aquatic ecosystems in Kansas requires improving our ability both to more accurately quantify relationships among aquatic sediment variables and aquatic biota and to distinguish between natural and anthropogenic sediment loading in this region. As a first step in that process, this white paper summarizes current knowledge and provides recommendations for future research.

**State of the Art: Review of Science to Date**

**Brief Literature Review**

Most sedimentation research focuses on cold water systems. Representative works include basic research studies (Luedtke and Brusven, 1976; Erman and Ligon, 1988; Lisle and Lewis, 1992; Goodin et al., 1993; Maund et al., 1997; Simon et al., 2003; Dodds and Whiles, 2004), literature reviews (Cordone and Kelley, 1961; Foess, 1972; Newcombe and MacDonald, 1991; Doisy and Rabeni, 2004), and books (Ford et al., 1990; Waters, 1995). Previous studies report both direct and indirect effects of sedimentation. Direct physical effects include light interruption; smothering of organisms; and coverage of sites used for germination, feeding, spawning, and other activities. Biotic effects include direct mortality; reduced fecundity; reduced disease resistance; and inhibited feeding, growth, and reproduction. Reviews by Newcombe and MacDonald (1991) and Doisy and Rabeni (2004) have also grouped direct biotic effects into three categories:

- **Lethal effects**, which cause direct mortality of organisms, reduce populations, or damage ecosystem capacity for production
- **Sublethal effects**, which injure organism tissues or cause physiological stress, both without causing mortality
- **Behavioral effects**, which alter the activity of affected organisms

Both suspended and deposited sediment particles can affect aquatic ecosystems (Waters, 1995; Zweig and Rabeni, 2001; Richardson and Jowett, 2002). For example, increased suspended solid concentrations can reduce primary production (Van Nieuwenhuyse and LaPerriere, 1986), disrupt feeding and respiration rates of macroinvertebrates (Lemly, 1982), and reduce growth and feeding rates of many stream fish (Wood and Armitage, 1997). Both intensity (concentration) and duration (time of exposure) of suspended sediment loading contribute to biological impairment, and models that consider both are better predictors of impairment than models that use either intensity or duration alone (Newcombe and MacDonald, 1991). Increased sediment deposition can reduce the complexity of stream habitat (Allan, 1995) and smother aquatic organisms including macroinvertebrates, fish, and macrophytes (Waters, 1995; Wood and Armitage, 1997).

In addition to the abundance of studies on cold water systems, the majority of stream sediment research has been conducted in systems with either a naturally high gradient (i.e., steep downhill slope) or naturally low turbidity (Dodds et al. 2004). However, aquatic systems in the Central Plains—especially those in agriculturally dominated areas like the Central Great Plains, Western Corn Belt Plains, and,
Recent Regional Findings

To analyze complex systems, it often is necessary to construct linked individual relationships to depict indirect effects. Statistically significant relationships between indicators (i.e., representative, measurable components of the ecosystem) form the links. For example, effects of clean sediment (i.e., sediment only, without associated nutrient or chemical loading considerations) on biology can be modeled by relating a sediment loading indicator (e.g., total suspended solids) to a water quality indicator (e.g., turbidity) then relating that water quality indicator to a biological one (e.g., number of fish species) (Figure 2). Additional indirect effects are modeled in a similar fashion.

A variety of potential sediment and erosion indicators exist. USEPA uses water column indicators (e.g., suspended sediment, bedload sediment, and turbidity), streambed indicators (e.g., streambed particle size and embeddedness), and riparian indicators (e.g., buffer size and vegetation community composition) to set criteria for allowable loading of induced sediment (i.e., Total Maximum Daily Loads for sediment; USEPA, 1998). Several biological indicator groups such as macroinvertebrates and fish also respond to sediment-related effects (Luedtke and Brusven, 1976; Culp et al., 1986; Richards and Bacon, 1994; Rier and King, 1996; Birrell, 1999). However, except for a study by Whiles and Dodds (2002), linkages between sediment indicators and biological indicators both within and between streams in the Central Plains remain largely undocumented.

Sediment–Water Quality Links.

Using data from more than 500 samples in 16 small watersheds throughout the West-
ern Corn Belt Plains, the Central Plains Center for BioAssessment (CPCB; 1994) found that inorganic suspended solids (ISS) explained 99% of the variation in total suspended solids (TSS) and that TSS explained 81% of the variation in turbidity. The USEPA Region VII Regional Technical Assistance Group (RTAG) found that TSS explained 89% of the variation in turbidity for more than 13,800 sites throughout the Central Plains and across ecoregions (RTAG, 2006); and Dodds and Whiles (2004), using nationwide data, found that TSS explained 89% of the variation in turbidity. Because turbidity is highly correlated with TSS and, by extension, ISS, turbidity measurements can be used as a surrogate indicator for suspended clean sediment in streams in the Central Plains.

Figure 2. An example of relating sediment effects to biological responses using indirect effects (A) Inorganic suspended solids, a measurement of the amount of mineral sediment particles floating in the water column, is related to total suspended solids, a measure of the amount of all particles (both inorganic and organic) floating in the water column. (B) Total suspended solids is related to turbidity, and turbidity is related both (C) to the number of macroinvertebrate taxa that are known to be sensitive to sediment and (D) to the percentage of fish species that are known to be sensitive to sediment. In this example, we relate “clean” sediment (e.g., inorganic suspended solids and total suspended solids) to biological responses (e.g., sediment sensitive macroinvertebrate richness and percentage of sensitive fish species) via the indirect effects of water quality (e.g., turbidity). Additional and more complicated analyses follow this general concept.
Sediment/Water Quality–Biota Links. In most biological systems, greater diversity of organisms implies better or “healthier” environmental conditions. Models developed using RTAG (2006) data suggest that macroinvertebrate richness (i.e., number of unique taxonomic groups of macroinvertebrates) significantly declines with increasing turbidity. Such declines usually are associated with impairment or decreasing environmental quality. However, statistical analysis and modeling determined a “threshold range” of turbidity levels between 10 and 25 NTU above which macroinvertebrate richness drops very little. Even though turbidity can, and often does, increase significantly beyond this threshold range (the average turbidity level of 125 Central Plains streams is 42 NTU), relatively few taxa are lost, presumably because some ecological limit of turbidity impairment has already been reached. In other words, increased turbidity has changed ecosystem function or structure (or both) such that more turbidity does not elicit a biological response. Lack of response could be because the sensitive species are gone because of death or emigration or because the ecology has been altered to a new state that cannot be further degraded by turbidity. As a corollary, reduction of turbidity might not result in a significant increase of taxa unless turbidity is reduced below the threshold range. Such threshold ranges often are used as the basis for developing benchmarks and criteria for other types of impairments (e.g., nutrient loading).

Regional RTAG (2006) data also revealed that the taxa richness of three typically habitat-sensitive orders of aquatic insects (i.e., Ephemeroptera, Plecoptera, and Trichoptera [EPT]) and the percentage of sediment-sensitive fish also declined with increasing turbidity. Data collected during the National Wadeable Streams Assessment (USEPA, 2004) from 125 sites in Kansas, Nebraska, Iowa, Missouri, and Oklahoma showed similar trends. Total macroinvertebrate and EPT taxa richness both decreased with increasing TSS. Richness of EPT taxa and macroinvertebrate scrapers (i.e., macroinvertebrates that scrape their food off substrates) decreased as the percentage of fine substrates (i.e., silt or mud but not sand) increased, but taxa richness of macroinvertebrate shredders (i.e., macroinvertebrates that shred larger particles for food) and macroinvertebrate predators (i.e., macroinvertebrates that eat other macroinvertebrates) were generally unaffected by changes in the percentage of fine substrates. Three things are important to note about these relationships. First, evidence for impairment is consistent across many ecological and taxonomic groups because increasing sediment loading correlates with decreasing diversity. Second, though the relationships are significant, the amount of variance in biological indicators explained by changes in sediment indicators alone is relatively low (10% to 30%). Advanced statistical techniques might allow us to better understand the complexity of these relationships. Third, some groups (e.g., macroinvertebrates as a whole, EPT taxa, scrapers) are more impaired by increased sediment loads than others (e.g., shredders and predators); this is consistent with a priori expectations based on known ecology of the organisms.

Habitat–Sediment/Biota Links. Current data and quantification of interactions between small-scale habitat indicators and both sediment and biology are limited. One commonly measured habitat indicator,
“percent embeddedness,” is the degree to which sediments fill spaces around rocks, gravel, and other substrates at the bottom of water bodies. When these spaces fill with sediment, they can no longer provide habitat or shelter for fish and macroinvertebrates. Data from the National Wadeable Streams Assessment (USEPA, 2004) revealed that percent embeddedness explained about 12% of the variation in turbidity and 26% of the variation in percentage of fine substrates present. As expected, total macroinvertebrate richness and EPT taxa richness declined as percent embeddedness increased (USEPA, 2004), but the amount of explained variation in richness was limited (13% and 10%, respectively).

**Geomorphology–Sediment/Habitat/Biota Links.** Geomorphology is the measure of the physical structure and geometry of streams and rivers. Geomorphic variables include reach-scale indicators (e.g., reach length, number and length of riffles, sinuosity or “curviness”) and channel-scale indicators (e.g., channel depth, channel width, cross-sectional area). Differences in scale make it difficult to relate some ecosystem units (e.g., geomorphology) to others (e.g., habitat, biota) (see Fausch et al., 2002, for a general overview). Although geomorphology can be important for describing particular aspects of streams and rivers, more research is required to relate these aspects to smaller-scale indicators of sediment, habitat, and biota in the Central Plains. For example, though Dauwalter et al. (2007) found that substrate type and geomorphology were related to increased smallmouth bass density, the streams they examined were cold water, high-gradient, low-turbidity streams in the Boston Mountain, Ouachita Mountain, and Ozark Highland areas of eastern Oklahoma, which are not representative of the majority of streams in the Central Plains.

Analysis of 53 geomorphic variables from 16 stream reaches throughout Kansas showed no statistical correlation with any indicators of sediment, habitat, or biota. Better understanding of scale (i.e., reach-scale vs. channel-scale vs. site-scale measurements) and advanced statistical techniques (e.g., principal components analysis, regression trees) are required for regional explanations of sediment links with geomorphology, habitat, and biology.

**Conclusions**

Effects of sedimentation in low-gradient aquatic systems are complex and difficult to measure directly. Often, surrogate variables are required to relate different ecosystem components such as habitat, biota, water quality, clean and dirty sediment, geomorphology, and flow. Based on Kansas and regional data, turbidity appears to be a reliable and easily measurable indicator for clean sediment in lotic systems throughout the Central Plains.

Although data indicate that increased sediment has a negative effect on many biological variables, regional data are limited, direct relationships are statistically weak, and indirect relationships are difficult to quantify (Figure 3). In addition, factors other than sediment might contribute to these relationships. Therefore, depiction of direct and indirect sediment effects via a hypothetical framework coupled with advanced statistical analyses such as multiple linear regression, principal components analysis, regression trees, and quartile regression (Koenker, 1995, 2005; Cade
and Noon, 2003) might lead to a better understanding and quantification of complex sediment-biota relationships. Better understanding leads to better management, including more effective interventions and better estimates of socioeconomic losses associated with sediment impairment of aquatic ecosystems.

**Acknowledgments**

This white paper is based on Report no. 146 of the Kansas Biological Survey, “Effects of Sedimentation on Biological Resources” (Huggins et al., in press), which contains detailed descriptions of recent regional findings including additional figures, tables, and analyses. Kansas Biological Survey reports and other technical publications are available at: http://www.kbs.ku.edu/larc/tech/html/default.htm.

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Figure 3. Conceptual framework showing observed effects of sediment on aquatic biota. Boxes illustrate important ecosystem units, and arrows represent functional directions and links observed in this study. Specific indicators used for each ecosystem unit are listed. Relative weights of the arrows indicate relative strengths of relationships observed in this study.
Recommendations for Future Research

We offer the following recommendations, based on reviews of available literature and recent research results, to guide future research on the effects of sedimentation on biological resources:

- **Adopt a multidisciplinary approach.** The complex nature of sedimentation spans topics including hydrology, geomorphology, aquatic ecology, water chemistry, soil and sediment chemistry, and landscape-level phenomena (e.g., urban development and agriculture). Usually, sediment studies are approached from only one or two of these points of view.

- **Observe both sediment loading and biological response.** Surprisingly, little overlap exists between datasets on sediment loading and biological indicators. Future studies should emphasize concurrent collection of physical, chemical, geomorphic, and biological data to gain a more comprehensive understanding of complex and integrated relationships.

- **Begin with gaged locations.** Often, sediment loading rates are the limiting factor in a multidisciplinary suite of sediment data. To better estimate effects of sediment on biological resources, those resources should be evaluated at locations where sediment loading data is available. Typically, stream gaging stations provide available loading data or opportunities to calculate sediment loads.

- **Determine reference conditions for sedimentation.** To evaluate the extent of sedimentation effects on biological resources (i.e., how “good” or “bad” a site is), a condition of high quality must be established for comparison. Currently, there is little agreement among hydrologic, geomorphic, and biological definitions of this reference condition, making assessment of sediment-biological quality interactions problematic.

- **Consider the regional context.** In many cases, the full range of geomorphic, hydrologic, and biological characteristics of certain aquatic systems are not present in Kansas. However, such a range might be observable at a regional or multi-state scale. Study of related systems in other states is appropriate.

- **Record both intensity and duration of sedimentation events.** Research shows that an ecotoxicological model (i.e., one that considers both amount of sediment and length of sediment exposure) better predicts effects of sedimentation. However, most
current studies report only sediment concentration (intensity). Temporal cycling of sediment could be important for biological systems.

- **Distinguish between natural and induced sedimentation.** Some low-gradient, high turbidity systems in the Central Plains have elevated natural sediment loads as an ambient condition. Discerning impairment in these systems could require significant study.

- **Use advanced statistical techniques.** Interactions between response and predictor variables in ecological systems are complex. Statistical procedures used to analyze response data must be robust to account for variation, and techniques such as multiple linear regression, principal components analysis, regression trees, analysis of covariance, quantile regression, and structural equation modeling might be appropriate.
References


