Factors Influencing Fine Sediment on Stream Beds in the Midwestern United States

Christopher Konrad* and Allen Gellis

Abstract

Fine sediment (particles <2 mm in diameter) in stream beds has wide-ranging effects on hydraulics, geomorphology, and ecology and is a primary focus for stream quality management in many regions. We identify reach- and basin-scale factors associated with fine sediment in the beds of 83 stream reaches in the Midwestern United States using recursive partitioning of sand-bed and gravel-bed streams and a generalized linear model for the fraction of a stream bed covered by fine sediment. A water-surface gradient of 0.00075 is the best single determinant (80% correct classification) distinguishing sand-bed streams (lower gradient) from gravel-bed streams (higher gradient). In the higher gradient category, sand-bed streams generally had more variable monthly precipitation than gravel-bed streams. The fractional response model indicated that the proportion of a stream bed composed of fine sediment is related to high sediment supply and low transport capacity but also high gravel transport capacity. This result is consistent with both theory and observations that bed material can be transported indiscriminately with respect to particle size under high shear stress, which will drive the particle size distribution of bed material toward the distribution of supply. Management of fine sediment in Midwestern streams has been approached largely by focusing on sediment supply, which may be immutable in some places due to the landscape position or glacial history. Retention of coarse sediment is an alternative management approach to reduce the fraction of fine sediment in the beds of some Midwestern streams.

Core Ideas

- Fine sediment in streams is important for effective management of stream quality.
- The fraction of a stream bed with fine sediment is predictable from physiography.
- Retention of coarse sediment may be needed for effective management of fine sediment.

Alluvial streams with bed material dominated by sand and finer particles are distinguished in hydraulics, geomorphology, and ecology from those with beds dominated by gravels and cobbles (coarse sediment) because of systematic differences in the near-bed velocity of streamflow, particle exposure and stability, channel forms, interstitial space and hyporheic flow, and sediment chemistry (Blench, 1955; Lelavsky, 1959; Colby, 1964; Hey, 1979; Howard, 1980; Thorne et al., 1982; Minshall, 1984; Raudkivi, 1990; Reid and Frostick, 1994; Brunke and Gosner, 1997; Church, 2006; Opdyke et al., 2006; Allan and Castillo, 2007). Given the broad physical and biological effects of fine sediment, the fraction of stream-bed material comprised by fine sediment (particles <2 mm in diameter) is a primary concern for stream quality management (Karr et al., 1985; ASCE Task Committee on Sediment Transport and Aquatic Habitats, Sedimentation Committee, 1992; Waters, 1995; Wood and Armitage, 1997; Kemp et al., 2011; Burdon et al., 2013). Effective management of fine sediment and reasonable expectations about how streams will respond to management actions depends on multiple factors that control the particle size distribution of stream bed material. This issue is particularly compelling in the Midwestern United States where both physiographic and anthropogenic factors contribute to high levels of fine sediment in streams (Wilkin and Hebel, 1982; Waters, 1995; Trimble, 1999; Brigham et al., 2001; Knox, 2006).

Physical controls on the particle size of stream bed material are generally understood in terms of the balance between sediment supply and sediment transport capacity, which are influenced by basin-scale geologic material and land use history, reach-scale channel gradient and roughness, and local sediment sources from upstream reaches, tributaries, or hillslopes (Dunne, 1979; Church and Slaymaker, 1989; Milliman and Syvitski, 1992; Walling and Webb, 1996;Buffington and Montgomery, 1999; Knighton, 1999; Shi et al., 2010; Belmont et al., 2011). Relations between a stream's sediment balance and the size of its bed material has led to reach-scale models describing the longitudinal variation in the dominant grain size of stream-bed material including the downstream transition from a gravel bed to a sand bed (Knighton, 1980; Pizzuto, 1995; Sambrook Smith and Ferguson, 1995; Sidle and Sharma, 1996; Venditti and Church, 1997).

Abbreviations: $D_{m}$, median diameter; $D_{84}$, 84th percentile; DEM, digital elevation model; PPT, ratio of maximum monthly precipitation to annual precipitation.
Regional models, however, generally do not focus on the distinction between sand-bed and gravel-bed reaches, nor on the fraction of fine sediment across different stream systems (Hack, 1957; Snelder et al., 2011; Naden et al., 2016).

Our primary objective is to identify reach- and basin-scale factors related to the fraction of fine sediment on the bed of wadeable streams in the Central Lowlands of the Midwestern United States. We identify the respective domains of sand-bed and gravel-bed reaches in terms of the dominant factors associated with each and highlight the overlap in the domains where streams may have either a sand or gravel bed. Bed material of streams in the overlap of the sand and gravel domains may be particularly responsive to land use impacts and sediment management.

We used a statistical approach based on a reach-scale mass balance presuming that bed material is a lag deposit and the dominant particle size represents the greatest positive difference between the supply to the reach and downstream transport (Fig. 1a; Happ et al., 1940; Allen, 1965; Howard, 1987; Wilkinson et al., 2006). Under this model, the size of bed material has predictable responses to aggregate changes (across all particle sizes) in sediment supply or transport capacity, provided (i) the sediment supply is well graded (a wide range of available particle sizes) and skewed toward finer fractions, and (ii) the transport capacity of the stream decreases more steeply than supply with particle size. These conditions allow the development of equilibrium channels where grain size decreases with higher aggregate supply (Fig. 1b) or with lower aggregate transport capacity (Fig. 1c) (Lane, 1955; Williams and Wolman, 1984; Dietrich et al., 1989; Bennett and Bridge, 1995).

In other cases, however, the response of bed material to changes in a stream's sediment balance depends on the particle size distribution of sediment supply in relation to the marginal changes in transport capacity with particle size. Notably, bed material can be finer in streams with high transport capacity and limited coarse sediment supply when all particle sizes are transported indiscriminately with respect to size (Fig. 1d; Little and Mayer, 1976; Gomez, 1983; Howard, 1987; Kuhnle, 1989; Shih and Komar, 1990; Wilcock and McArdell, 1993). In this case, the stream does not preferentially retain coarse material, and the particle size distribution of bed material will approach the distribution of the supply.

Streams in the Midwestern United States do not necessarily conform to the conditions for using a sediment balance aggregated over all particle sizes to account for the variation in the size of bed material across streams. The region is covered by unconsolidated deposits of glacial and lacustrine sediments formed on sedimentary rocks, with extensive loess deposits in areas without recent (late Pleistocene) glaciation (Stephenson et al., 1988). Given the dominance of sand and finer particles in their sediment supply, Midwestern streams are only likely to develop stream beds enriched in gravel and cobbles through preferential retention of these coarse particles (Allen, 1965), rather than the attrition of fractured bedrock and boulders. Although tilling of the land surface has indisputably increased sediment yield from hillslope, drainage (tile drains, ditching, and channelization) has also increased the sediment transport capacity of streams (Blann et al., 2009; Belmont et al., 2011). Thus, high fractions of fine sediment on the stream bed could be a response to an imbalance in supply and transport of fine sediment (Fig. 1b and 1c) or an imbalance in the supply and transport of coarse sediment (Fig. 1d).

Fig. 1. The particle size distribution of stream bed material represented as the difference between sediment supply and transport capacity integrated over time. Lines from Panel A are gray in Panels B, C, and D.
Materials and Methods

Factors indicating sediment supply and transport capacity were related to the fraction of bed material <2 mm in diameter of 83 streams in the Central Lowlands of the Midwestern United States using a generalized linear regression model. The USGS National Water Quality Assessment and USEPA National Assessment of Rivers and Streams investigated the streams during summer 2013 (USGS and USEPA, 2012). The streams had a median drainage area of 162 km$^2$ and median channel width of 16 m (Table 1). The investigation included synoptic stream channel surveys, weekly water quality and suspended sediment sampling, continuous stage monitoring, and compilation of pertinent geospatial information (Nakagaki et al., 2016). Selected data were used for model development (Konrad, 2017).

Reach- and Basin-scale Factors Indicating Sediment Supply and Transport Capacity in Streams

We identified reach- and basin-scale factors as potential independent variables for the regression model that were feasible to calculate from available information and had a plausible relation to the sediment balances of streams across the Midwestern United States (Table 1). Factor values were derived from field survey measurements and national geospatial data sets. We included factors specific to either fine or coarse sediment where possible. All pairs of factors had a Kendall's rank correlation coefficient (R Core Team, 2017) $<0.5$, indicating that multiple colinearity would not substantially affect parameter estimates and errors in a regression model (Freund and Wilson, 1998).

Field Data Collection and Processing

At each site, stream channel form and materials were surveyed in a reach that was at least 100 m or 10 channel widths long. Reach mean water surface slope was measured over the entire reach using an automatic level and stadia rod. Channel width at its banks, bank height, wetted width, and five water depths were measured using a tape or range finder at each of 11 transects along the reach. Bed material was observed at five equally spaced locations along each transect and between each transect (105 points). Unconsolidated sediments were classified in one of six size categories: silt (<0.0625 mm), sand (0.0625–2 mm), fine gravel (2–16 mm), coarse gravel (16–64 mm), cobbles (64–512 mm), or boulder (>512 mm). Exposed consolidated material was recorded as bedrock, hardpan, or concrete. A sample of bed sediment was collected and sieved to determine the distribution of particles <2 mm. Particle size distributions of unconsolidated sediment were characterized in terms of the fraction of material <2 mm, the median diameter ($D_{50}$) in meters, and the 84th percentile ($D_{84}$) in meters. The $D_{50}$ of bed material is typically used as a characteristic particle size in sediment transport calculations, whereas $D_{84}$ is used as a characteristic particle for grain roughness in hydraulic calculations (Wilberg and Smith, 1987; Reid and Frostick, 1994; Shvidchenko et al., 2001, Lane and Ferguson, 2005).

Current velocity was measured at a cross-section and used to calculate streamflow at the time of the survey. Stage was recorded continuously every 15 min from April through September 2013 at 36 sites where USGS operates streamflow gages and at 47 sites where submersible pressure transducers were installed for the investigation. Stage data collected with submersible transducers were corrected for barometric pressure using barometers deployed at each site. Stage measurements have an accuracy of $\pm 4$ mm and were converted to hydraulic mean depths for each reach (Konrad, 2017).

Reach-scale Hydraulic Factors Indicating the Sediment Transport Capacity of Streams

Conservation of energy limits the sediment transport capacity of streams at a reach scale to the energy that can be transferred from water to sediment, which is expressed instantaneously in terms of shear stress (force per unit area) (Reid and Frostick, 1994). Three measures related to shear stress were used as possible indicators of reach-scale sediment transport capacity:

### Table 1. Potential factors influencing sediment supply and transport capacity used in model development.

<table>
<thead>
<tr>
<th>Description</th>
<th>Percentile 10th</th>
<th>Percentile 50th</th>
<th>Percentile 90th</th>
<th>Transformation</th>
<th>Relation to pre-Wisconsin glaciation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basin-scale factors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual precipitation (mm yr$^{-1}$)</td>
<td>778</td>
<td>958</td>
<td>1130</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>Ratio of maximum monthly to annual precipitation</td>
<td>0.11</td>
<td>0.12</td>
<td>0.15</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>Last glaciated pre-Wisconsin</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>Drainage area (km$^2$)</td>
<td>27</td>
<td>167</td>
<td>1164</td>
<td>ln</td>
<td>0</td>
</tr>
<tr>
<td>Mean basin slope (m$^{-1}$)</td>
<td>0.011</td>
<td>0.024</td>
<td>0.062</td>
<td>ln</td>
<td>1</td>
</tr>
<tr>
<td>Basin convexity</td>
<td>$-0.345$</td>
<td>$-0.038$</td>
<td>0.476</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>Channel density (km km$^{-2}$)</td>
<td>0.627</td>
<td>1.190</td>
<td>1.861</td>
<td>ln</td>
<td>1</td>
</tr>
<tr>
<td><strong>Reach-scale factors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ratio of reach water-surface gradient to segment gradient</td>
<td>0.318</td>
<td>1.047</td>
<td>11.254</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>Bank height (m)</td>
<td>0.500</td>
<td>1.000</td>
<td>1.800</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>Water-surface gradient</td>
<td>0.000</td>
<td>0.001</td>
<td>0.004</td>
<td>ln</td>
<td>0</td>
</tr>
<tr>
<td>Shear velocity (m$^{-2}$)</td>
<td>0.001</td>
<td>0.014</td>
<td>0.049</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>Fraction of time that sand can be transported</td>
<td>0.056</td>
<td>0.442</td>
<td>0.998</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>Fraction of time that gravel can be transported</td>
<td>0.000</td>
<td>0.020</td>
<td>0.684</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>Fraction of basin with high intensity development</td>
<td>0.000</td>
<td>0.001</td>
<td>0.033</td>
<td>–</td>
<td>$-1$</td>
</tr>
<tr>
<td>Fraction of basin with crops</td>
<td>0.060</td>
<td>0.642</td>
<td>0.872</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>Fraction of basin with artificial drainage</td>
<td>0.000</td>
<td>0.072</td>
<td>0.498</td>
<td>–</td>
<td>$-1$</td>
</tr>
</tbody>
</table>

† 0 = no difference in median values of streams with pre-Wisconsin glaciation compared with streams with Wisconsin glaciation or not glaciated, 1 = median value is greater in streams with pre-Wisconsin glaciation, $-1$ = median value is less in streams with pre-Wisconsin glaciation.
water-surface gradient, shear velocity (a measure of shear stress with velocity units [m s$^{-1}$]), and the fraction of time that sand and gravel deposits were likely to be mobile. Shear velocity at the time of the field survey ($u'_s$) was calculated as

$$u'_s = \frac{0.4u_w}{\ln(d'/e0.1D_{90})}$$

where $u_w$ is mean velocity (m s$^{-1}$) at the time of the stream survey, and $d'$ is mean hydraulic depth (m) at the time of the stream survey (Schlichting, 1979; Wilberg and Smith, 1991; Lane and Ferguson, 2005). Correlation between $u'_s$ and $D_{90}$ could lead to a spurious finding that $u'_s$ was related to fine sediment, but the Pearson correlation coefficient between $u'_s$ and $D_{90}$ was not significant ($p > 0.1$).

Transport capacities for sand and gravel were assessed in terms of the fraction of time, nominally from 1 Apr. 2013 through 30 Sept. 2013 (depending on the stage record available at a site), that each type of deposits could be mobilized in the surveyed reach. A force balance was calculated every 15 min to determine when boundary shear stress [$\tau(i)$] exceeded the critical shear stress ($\tau_c$) for entraining sand (2 mm) and fine gravel (8 mm), respectively. Shear stress, ($\tau$) at the time of the field survey was estimated from the shear velocity as

$$\tau_s = u'^2 \rho_w$$

where $\rho_w$ is the density of water (kg m$^{-3}$). Shear stress was estimated for all times [$\tau(i)$], presuming that shear stress varies linearly with water depth:

$$\tau(t) = \frac{\tau_s + \rho_w \gamma S}{d(t) - d_i}$$

where $\gamma$ is gravitational acceleration (m s$^{-2}$), $S$ is water-surface gradient, and $d(t)$ is reach mean water depth (m) at time $t$ when depth was greater than the depth at the time of the field survey [$d(t) > d_i$], and

$$\frac{\tau(t) - \tau_s}{d(t) - d_i}$$

for periods when depth was less than the depth at the time of the field survey [$d(t) < d_i$].

Equation [3] represents the portion of shear stress acting on bed material (grain shear stress) at the time of the field survey and converges on total boundary shear stress as flow depth increases. As such, Eq. [3] may overestimate shear stress acting on bed material at higher flows, particularly in channels with high sinuosity, bed forms, debris, vegetation, or other large roughness elements.

The critical shear stress required to entrain a coarse sand deposit ($D_{50} = 2$ mm) and a fine gravel deposit ($D_{50} = 8$ mm) was calculated as function of the buoyant specific weight of a particle and its exposure to streamflow:

$$\tau_{cr} = \theta (\rho_s - \rho_w) g D_{50}$$

where $\rho_s$ is the density of sediment (kg m$^{-3}$) and $\theta$ is the dimensionless critical shear stress. The parameter $\theta$ varies with a particle’s exposure to streamflow and is indicated by the ratio of the particle diameter to the thickness of the viscous boundary layer at the bed or grain Reynolds number ($Re_{grain}$; Shields, 1936; Shvidchenko et al., 2001):

$$Re_{grain} = \frac{u'^* D_{50}}{v}$$

where $v$ is the kinematic viscosity of water. For this application, $\theta$ varies from 0.08 for coarse-grain deposits in shallow flow ($Re_{grain} > 1000$) to 0.1 for fine-grained deposits in deeper flow:

$$\theta = 0.08 + \left( \frac{0.02}{Re_{grain}} \right)$$

We use relatively high values for $\theta$ to indicate the full mobilization of a deposit (Andrews, 1983; Konrad et al., 2002; Mao and Surian, 2010), and thus high transport rates of sand or gravel rather than lower values (e.g., 0.04–0.06) typically used to represent the threshold of entrainment for individual particles. The critical dimensionless shear stress was not adjusted for variation in water surface gradient because $S < 0.01$ in all streams (Lamb et al., 2008; Ferguson, 2012). The total number of 15-min increments when $\tau(i) > \tau_c$ for coarse sand and fine gravel deposits was summed and divided by the length of the available stage record for each stream to provide the fraction of time and sand and gravel transport, respectively.

### Basin-scale Factors Indicating Sediment Supply and Transport in Streams

Physiographic attributes of the basin for each stream were compiled from a GIS (Nakagaki et al., 2016). Drainage area was determined from a flow accumulation model based on a 30-m digital elevation model (DEM) for the region (Gesch et al., 2002). Bedrock geology was generalized into four types of sedimentary rock: shale, sandstone, limestone, and a mixture of sandstone and shale (Schweitzer, 2011). Glacial history was categorized as early Pleistocene (pre-Wisconsin) glaciated, late Pleistocene (Wisconsin) glaciated, and unglaciated (Stephenson et al., 1988; Soller et al., 2012).

Mean basin slope was calculated from the 30-m DEM. Basin convexity (BC) is used to indicate the proximity of steeper hillslopes to a stream channel and is indexed by a ratio indicating the skew in the spatial distribution of land surface elevation:

$$BC = \left[ \frac{(Z_{max} - Z_{med}) - (Z_{med} - Z_{min})}{(Z_{max} - Z_{min})} \right]$$

where $Z_{max}$ is maximum land surface elevation in the stream basin, $Z_{med}$ is the median elevation, and $Z_{min}$ is the minimum elevation. Basins where $BC > 0$ have a more convex distribution of land surface elevations where the median basin elevation is closer to maximum basin elevation (e.g., an incised plateau), whereas basins where $BC < 0$ have a more concave distribution where the median basin elevation is closer to minimum basin elevation (e.g., ridge and valley).

The medium-resolution (1:100,000) National Hydrography Dataset was used to calculate drainage density and the gradient of the stream segment encompassing each reach (Nakagaki et al., 2016).
Segment lengths are longer, on the order of 10³ m, than the reaches in this investigation. The ratio of the reach gradient to segment gradient was used as a relative measure of reach-scale transport capacity, which could indicate a local sediment imbalance.

Monthly mean precipitation for 1981 to 2013 was calculated from Oregon State University’s Parameter-elevation Relationships on Independent Slopes Model (Nakagaki et al., 2016). Annual precipitation provides an indication of sediment yield (Langbein and Schumm, 1958). The ratio of maximum monthly precipitation to annual precipitation (PPT_MV) was used to differentiate streams with more variable seasonal precipitation (higher values of PPT_MV) from those where precipitation is more evenly distributed throughout the year (lower values of PPT_MV). We expect that more extreme monthly precipitation would indicate higher sediment supply relative to transport capacity (Reid and Laronne, 1995).

Three land use variables were assessed in the model: high intensity urban development and crop land determined from the 2011 National Land Cover Dataset (Nakagaki et al., 2016), and the extent of engineered drainage systems (surface and tile drains) within each basin (Nakagaki and Wieczorek, 2016). These variables were also used to assign streams to one of four categories: drainage agricultural, agricultural, urban, and low development. Drained agriculture streams (n = 33 streams) had >20% of basin with artificial drainage. Agricultural streams (n = 29) had >40% of their basin with cropland and <20% of their basin with artificial drainage. Urban streams (n = 10) had >1% high-intensity development and did not meet the agriculture or drained agriculture criteria. The remaining streams (n = 25) were classified as low development.

Reservoir storage capacity was less than the equivalent of 10 cm over the drainage area for 77 of the 82 basins and <1 cm for 58 basins. It was not included as a potential factor influencing the bed given its limited spatial influence and the availability of stage data representing the hydrologic effects of reservoirs. It may, however, affect the sediment supply of some of the streams in this investigation.

Classification of Sand- and Gravel-Bed Streams and Fractional Model for Fine Sediment

Factors differentiating sand-bed (D₈₅ < 2 mm) from gravel-bed streams (D₈₅ > 2 mm) were identified using recursive partitioning via the R package “rpart” (Therneau et al., 2017). Streams with poorly sorted, mixed-sediment beds (D₈₅ < 2 mm and D₈₅ > 2 mm) were not included to determine the values of the factors for partitioning.

A generalized linear model was used to relate the fraction of the stream bed covered by fine sediment (Fr_Sₕ) to basin- and reach-scale factors (X) via a logistic equation:

\[
Fr_S = \exp(BX)/[1 + \exp(BX)]
\]

and B is the vector of model coefficients for the explanatory factors. Explanatory factors with skewed distributions were log-transformed (Table 1). All explanatory factors were then standardized by subtracting their mean value and dividing by their SD to facilitate the comparison of effects of variables with different ranges. As such, the calibrated model is not intended to be predictive of bed material in other streams. The model was calibrated assuming errors follow a quasi-binomial distribution because the response variable is fractional on the interval from zero to one (Papke and Wooldridge, 1996). Calibration was performed by a quasi-likelihood method maximizing the Bernoulli log-likelihood implemented using the R package “frms” (Ramalho, 2015). The model with the highest R² and all coefficients significantly different than zero (p < 0.05) was identified through stepwise addition and removal of variables.

Results

The streams in this investigation can be grouped into three distinct textural classes according to the D₈₅ and D₈₅ of their particle size distribution: 32 streams with predominantly sand beds, (D₈₅ < 2 mm), 37 streams with predominantly gravel beds (D₈₅ > 2 mm), and 14 streams with poorly sorted mixtures of fine and coarse sediment (D₈₅ < 2 mm, D₈₅ > 2 mm) (Fig. 2). A water-surface gradient of 0.00075 separates most (24/32) sand-bed streams from most (31/37) gravel-bed streams (80% of streams classified correctly, Fig. 3). For streams with steeper water-surface gradient (>0.00075), six of the eight sand-bed streams and only 1 of 31 gravel bed streams had a ratio of maximum monthly to annual precipitation >0.14 (84% correct classification according to the water-surface gradient and precipitation ratio).

Nine streams had hardpan exposed on >10% of the bed and, conversely, <90% of their beds covered by unconsolidated sediment, indicating limited sediment supply relative to the transport capacity in these streams. Fine sediment comprises >50% of bed material in most (6/9) of these streams, which would indicate high sediment supply relative to transport capacity for an equilibrium channel. As a result, fine sediment may not be a reliable indicator of the aggregate sediment balance of streams in the region.

The fraction of a stream bed with fine sediment is positively related to the ratio of maximum monthly to annual precipitation, basin convexity, pre-Wisconsin glaciation, and gravel transport duration and negatively related to water-surface gradient and base-flow shear velocity (Table 2). The model accounts for much of the variation (R² = 0.54) in fine sediment on the beds of the 83 streams in this investigation and has a RMSE of 0.22 (Fig. 4). Both basin-scale factors (PPT_MV, basin convexity, and pre-Wisconsin glaciation) and reach-scale factors (gravel transport duration, water-surface gradient, and base-flow shear velocity) are significant.

Land use variables are not significant in the fractional response model, but the fraction of stream beds covered by fine sediment does vary systematically among different land uses. Agricultural streams without extensive drainage systems generally had the greatest fraction of fine sediment, and urban streams had the least (Fig. 5a). The fractional response model generally accounts for this variation in terms of other factors and has significant bias only in urban streams (Fig. 5b), where it overpredicts fine sediment (residuals are significantly less than zero, Wilcoxon rank-sum test, one-tailed p < 0.001).

Discussion

Streams in the Central Lowlands of the Midwestern United States range from low-gradient channels with bed material...
dominated by sand and finer particles to moderate-gradient channels with gravel beds. A water-surface gradient of 0.00075 provides the best single determinate of whether a stream has sand or gravel bed, but only 19\% of gravel-bed streams and 33\% of sand-bed streams would be misclassified solely based on water-surface gradient. Among higher gradient streams (>0.00075), those with sand beds have more variable monthly precipitation (PPT\textsubscript{MV} > 0.14) than the gravel-bed streams with only one exception. In contrast, gravel-bed streams with lower gradients (<0.00075) do not have a primary distinguishing characteristic that separates them from sand-bed streams. Further investigation of the conditions that allow gravel beds in these low-gradient streams would help define the domain where gravel-bed streams are possible in the Midwest.

Factors related to sediment supply including basin slope, basin convexity, and pre-Wisconsin glaciation all have positive relations to fine sediment (Table 2) such that steeper and more convex basins and a greater extent of pre-Wisconsin glaciation are associated with higher levels of fine sediment on stream beds. Two factors related to transport capacity, water-surface slope and shear velocity, have negative relationships to fine sediment such that higher gradient streams and higher shear velocities are associated with lower levels of fine sediment.

In contrast, the fraction of time that a stream can mobilize gravel deposits is positively associated with the fraction of fine sediment on stream beds. Although the positive association between fine sediment and gravel transport is contrary to equilibrium relationships where bed material adjusts to increased transport capacity through coarsening (Lane, 1955; Dietrich et al., 1989), it is consistent with theory and observations of the response of bed material where streamflow is competent to move all grain sizes and thus does not enrich the bed in coarse sediment (Little and Mayer, 1976; Gomez, 1983; Howard, 1987; Kuhnle, 1989; Shih and Komar, 1990; Wilcock and McArdell, 1993). Streams that do not preferentially retain coarse sediment could still have unconsolidated alluvium in their channel, but their particle size distribution would be similar to that of the sediment supply (Fig. 1d), which is likely dominated by sand and finer particles in the Midwestern United States. Fine sediment in these cases should be viewed as a result of limited supply and excess transport capacity for coarse sediment rather than excess aggregate supply.

Langbein and Schumm (1958) showed that sediment yield in the Midwest generally increases from east to west with aridity. Although annual precipitation is not a significant factor in the model developed here, the PPT\textsubscript{MV} was significant (Table 2) and varies directly with aridity. Three mechanisms potentially...

---

**Fig. 2.** Location of sites in the Midwestern United States with the dominant type of bed material.

**Fig. 3.** Variation in water-surface gradients for streams with gravel beds (medium diameter $D_{50} > 2$ mm), mixed sediment ($D_{50} < 2$ mm, 84th percentile $D_{84} > 2$ mm), and sand beds ($D_{84} < 2$ mm). Boxes represent the 25th, 50th, and 75th percentiles of streams. Whiskers represent the fifth and 95th percentiles.
link more variable seasonal precipitation to increased fine sediment on stream beds: lower transport capacity for fine sediment during dry seasons, higher delivery of fine sediment to channels during wet seasons, and increased gravel transport during wet seasons. These mechanisms are not easily separated (Hassan et al., 2006), but all should be considered as possible reasons for the significance of the seasonal distribution of precipitation in the fractional response model.

Most streams in basins with older glaciation (pre-Wisconsin) have sand beds (21/36 streams), whereas most streams in basins more recently glaciated (during the Wisconsin) or not glaciated in the Pleistocene have gravel beds (28/47 streams). Basins glaciated during the pre-Wisconsin era generally have four factors that favor more fine sediment on stream beds: higher PPT, higher basin slopes, lower water-surface gradients, and lower base-flow shear velocities (Table 1). These basins also have extensive, loess deposits (Stephenson et al., 1988; Bettis et al., 2003), which are highly erodible and contribute to high suspended-sediment concentrations in streams (Simon et al., 2004). Nonetheless, streams in basins with pre-Wisconsin glaciation can develop gravel beds even where there is extensive agriculture.

Land use has had multiple interacting influences on sediment fluxes through stream networks and their floodplains in the Midwest (Wilkin and Hebel, 1982; Karr et al., 1985; Trimble, 1999; Merten et al., 2016). Engineered drainage systems such as tile drains have increased runoff from the land surface, which, combined with more intense precipitation and the confinement of stream channels as a result of incision, floodplain accretion, and channelization, have increased the sediment transport capacity of streams during high flows and increased sediment delivery from stream banks throughout the Midwest (Knox, 2006; Blann et al., 2009, Belmont et al., 2011; Schottler et al., 2014), including streams in this investigation (Gellis et al., 2017). Increased sediment transport capacity during high flows would also reduce the retention of coarse sediment and increase the fraction of a stream bed with fine sediment where the supply of coarse sediment is limited (Howard, 1987). As such, increased transport capacity for coarse sediment is an alternative pathway for land use to affect fine sediment in Midwestern streams that warrants consideration as part of sediment management.

Although management practices can reduce sediment delivery to streams (Matisoff et al., 2002), reducing sediment loads enough to reduce fine sediment accumulation on stream beds remains a challenge (Greig et al., 2005). Key factors associated with fine sediment in this investigation, including a stream’s water surface gradient and the seasonal distribution of precipitation in the basin, may be determined by the stream’s position in a landscape and beyond the scope of management. In contrast, increasing gravel retention in streams by reducing its transport during high flows may be a tractable management objective. Actions such as expanding the banks of confined channels and reconnecting them to floodplains, increasing channel roughness for higher stages, and detaining runoff can reduce shear stress during high flows (Shields and Gippel, 1995; Booth et al., 2004; Konrad et al., 2008) and would increase gravel retention provided there is an upstream supply.

Conclusions

Fine sediment on stream beds in the Midwestern United States is related to both reach-scale and basin-scale factors indicating the supply of sediment to streams and their capacity to

![Fig. 4. Observed and predicted fraction of stream bed that is sand or finer (particles <2 mm in diameter).](image)

![Fig. 5. (a) Observed fraction of bed surface that is sand or finer by land use, and (b) the residuals (observed fitted values) from the fractional response model.](image)
transport that sediment. A water-surface gradient of 0.00075 differentiates most sand-bed from gravel-bed streams but does not exclude the possibility of sand beds in higher gradient channels or gravel beds in lower gradient channels. The fraction of a stream bed with fine sediment was associated with high sediment supply (basin convexity, pre-Wisconsin glaciation), low transport capacity (water-surface gradient and base-flow shear velocity), and high gravel transport, which may indicate low retention of coarse sediment in stream channels. Additional factors particularly at the basin scale or in the riparian corridor were not examined in this investigation may be important for more complete accounting of the variation in fine sediment across this landscape.

Fine sediment varies systematically with land use but does not necessarily indicate anthropogenically increased sediment delivery. Indeed, some streams with abundant fine sediment appear to have low aggregate supply relative to transport capacity given only partial coverage of the stream bed with unconsolidated material. Sediment management in the Midwestern United States may benefit from broader consideration of the landscape position of the streams and balance between supply and transport for both fine and coarse sediment. In particular, the retention of coarse sediment may a novel approach to reduce the fraction of fine sediment on the beds of some Midwestern streams where sediment management has focused on the delivery of fine sediments to streams.

Acknowledgments
This study was supported by the USGS National Water Quality Assessment Project and relies on data collected for the USEPA National Assessment of Rivers and Streams. Data are available through the USGS Science Base (doi:10.5066/F7HQ3X35).

References
Hasten, M.A., R. Egozi, and G. Parker. 2006. Experiments on the effect of hydro-