The Effects of Longitudinal Differences in Gravel Mobility on the Downstream Fining Pattern in the Cosumnes River, California

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ABSTRACT

Downstream fining in the Cosumnes River is partially controlled by longitudinal variation in sediment mobility linked to changes in cross-sectional morphology. Strong fining occurs where the channel is self-formed with section-averaged bankfull dimensionless shear stress (τ^*) near the threshold of motion (ca. 0.031), allowing for size-selective transport. In contrast, fining is minimal in confined reaches where τ^* is generally greater than twice the threshold value and transport is nonselective. Downstream fining is best described by a model that depicts fining in discrete intervals separated by a segment in which equal mobility of bed material accounts for the lack of diminishing grain size.

Introduction

Reduction in the size of bed material with distance downstream is commonly observed in gravel-bed rivers. Researchers have attributed this feature, termed "downstream fining," to the processes of selective sorting (Ashworth and Ferguson 1989; Ferguson and Ashworth 1991; Paola et al. 1992; Ferguson et al. 1996; Seal et al. 1997) and abrasion (Bradley 1970; Schumm and Stevens 1973; Werrity 1992; Kodama 1994*a*, 1994*b*). A simple exponential function developed by H. Sternberg in 1875 is typically used to describe downstream fining over a longitudinal profile with no lateral sources of coarse sediment (e.g., Shaw and Kellerhals 1982):

$$D = D_0 e^{-aL}, \quad (1)$$

where D is a characteristic grain size in millimeters (usually the median), L is the distance downstream in kilometers, D_0 is grain size at the upstream end of the study reach ($L = 0$), and a is an empirical diminution coefficient (km^{-1}) that reflects the combined effects of selective sorting and abrasion. Discontinuities or steps in downstream fining patterns may be caused by coarse lateral supply (Knighton 1980; Rice and Church 1998; Rice 1999) or anthropogenic channel modifications (Surian 2002).

The relative importance of sorting and abrasion in determining the diminution coefficient depends on the system in question, particularly on the nature of material in transport (Bradley 1970; Parker 1991; Werrity 1992; Kodama 1994*a*, 1994*b*) and whether sediment discharge is limited by transport capacity or sediment supply (Shaw and Kellerhals 1982). A number of flume experiments (Paola et al. 1992; Seal et al. 1997) and field studies in transport-limited alluvial streams (Ferguson and Ashworth 1991; Ferguson et al. 1996) have emphasized the ability of sorting to produce downstream fining with little contribution by abrasion. Dominance of sorting in aggrading streams has been linked to strong profile concavity and associated decreasing bed shear stress with distance downstream (Ferguson and Ashworth 1991; Parker 1991; Ferguson et al. 1996). In supply-limited systems where there is no aggradation to facilitate sorting, it is thought that the influence of abrasion is increased relative to or perhaps becomes greater than that of sorting (Shaw and Kellerhals 1982); however, there is a paucity of downstream fining studies aimed at addressing process in degrading streams. One study in a Mississippi creek with a stable thalweg elevation documented strong downstream fining ($a = 0.65$)

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and attributed it to selective transport despite the absence of aggradation (Kuhnle 1996).

The ability of selective sorting to produce downstream fining depends on the existence of mobility differences between fine and coarse grains. Although one may expect smaller gravel to be more easily entrained by overhead flow than larger material, numerous studies have demonstrated that the effects of hiding and protrusion in mixtures containing both fine and coarse gravel work to narrow mobility differences between grain sizes (Parker and Klingeman 1982; Ashworth and Ferguson 1989). Despite relative-size effects, exact equal mobility is not reached in natural gravel-bed streams until bed shear stress greatly exceeds the critical shear stress necessary for entrainment of the surface median and the coarse surface layer is broken apart (Parker and Klingeman 1982; Parker et al. 1982; Wilcock 1992). It may be inferred from this observation that downstream fining is strongest in stream reaches where the ratio of bed shear stress to critical shear stress is nearest the threshold of general motion and weakest where the ratio exceeds that required to destroy the surface pavement.

In graded rivers (those adjusted to imposed flow and sediment supply conditions), bed shear stress at bankfull or dominant discharge is maintained above some critical value necessary for bedload transport but below that which would cause channel instability (Parker 1979). This implies that in self-formed gravel-bed rivers, bankfull dimensionless shear stress (τ^*) approximates some threshold value and is constant with distance downstream. The expression of τ^* is

$$\tau^* = \frac{\rho_w g h S}{(\rho_s - \rho_w) g D}, \tag{2}$$

where ρ_w is water density, g is gravitational acceleration, h is section-averaged flow depth at bankfull stage, S is energy gradient, ρ_s is sediment density (considered here to be equal to that of quartz [2650 kg m^{-3}]), and D is median surface grain size. In rivers where longitudinal differences in the erosional resistance of bank material and corresponding cross-sectional morphology (Wohl and Achyuthan 2002) exist, one may expect τ^* to vary from the threshold value and that this variation is reflected in the downstream fining pattern.

The purpose of this field study is to investigate the influence of changes in τ^* and bed material mobility associated with morphological heterogeneity on the downstream fining pattern in a lowland portion of the Cosumnes River, Central Valley, California. The cumulative effects of channel modifications made during the early twentieth century (e.g., constriction to a single channel and levee construction) and watershed land use changes on flow and sediment supply induced significant incision in the study area (Constantine 2001). As a result of incision, duripan layers preserved in Tertiary and Quaternary alluvial fan deposits were exhumed and eroded. The contemporary channel in the study area consists of two reach types: self-formed reaches characterized by sequences of alluvial bedforms and duripan reaches in which outcrops of erosionally resistant duripan in the banks or bed control cross-sectional shape or local bed erosion rates.

Our results verify that longitudinal changes in cross-sectional form affect τ^* and, consequently, gravel mobility. We also provide field evidence that shows that deviations from threshold τ^* influence downstream fining patterns in systems where fining is dominated by selective sorting. In the Cosumnes River, downstream fining is strongest in self-formed, alluvial reaches where τ^* averages a threshold value of 0.031, but it is minimal in confined reaches where τ^* exceeds that required for equal mobility of bed material at bankfull discharge.

Study Area

The Cosumnes River watershed occupies an area of approximately 3000 km^2 in the Central Valley of California (fig. 1). Flow in the Cosumnes is derived mainly from rain that falls between the months of October and May. Bankfull or dominant discharge corresponding to a recurrence interval of 1.5 to 2 yr ranges from 178 to 295 m^3 s^{-1} as determined from USGS stream gauge data. Unlike most rivers draining the western slopes of the Sierra Nevada, the Cosumnes River has no large dam on it to regulate flow.

Sediment supply in the river originates primarily from andesitic, metamorphic, and granitic sources in the Sierra Nevada (fig. 1). In the study area located west of the Sierran foothills, the geology consists of sequential terraces and broad floodplain deposits. Glacial advances during the Tertiary and early Quaternary initiated repeated cycles of incision and valley filling followed by landscape stability. These events resulted in dissection of volcanic deposits and development of alluvial fans to the west of the Sierra. Within alluvial fan formations, quiescent intervals are marked by well-developed soil horizons that separate glacial outwash of different ages (Piper et al. 1939; Shlemon

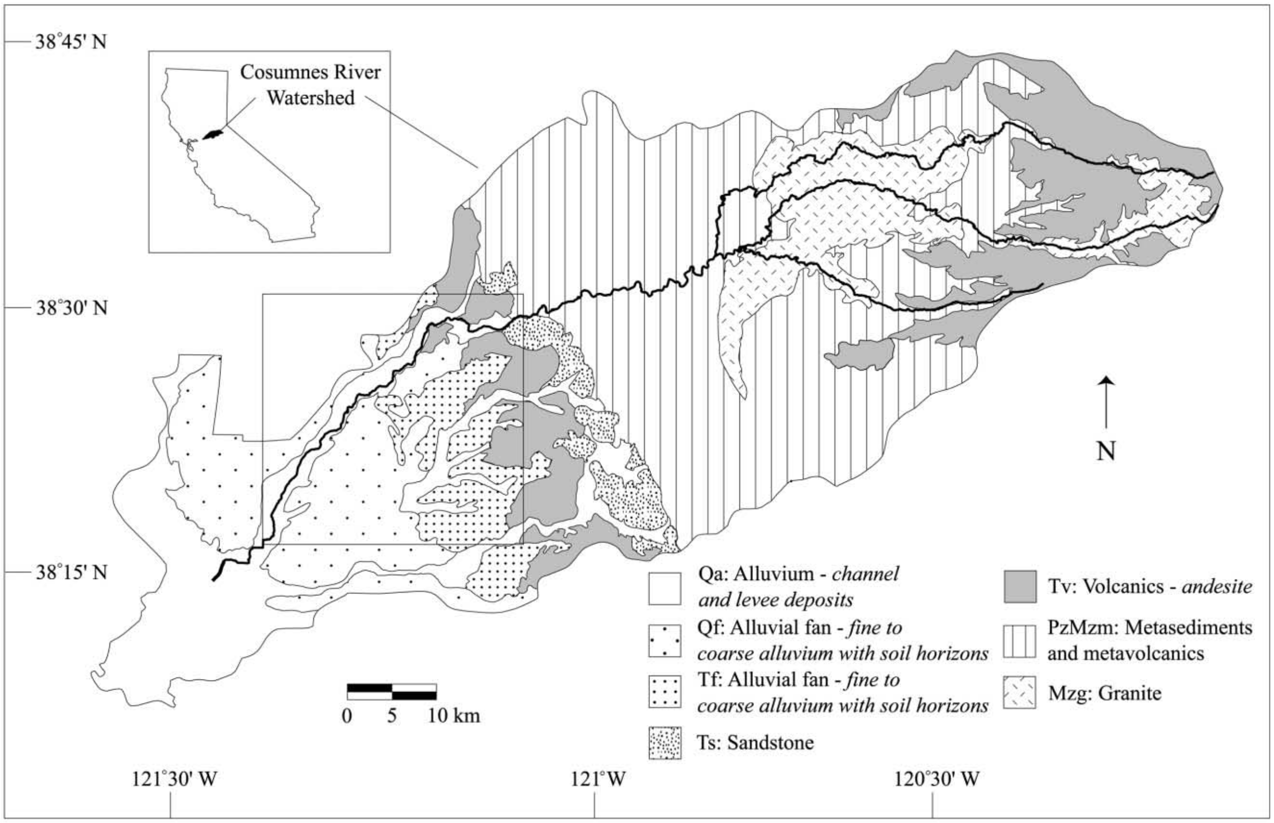

Figure 1. Generalized geologic map of the Cosumnes River watershed. The box outlines the 43-km study area. (Map modified from Wagner et al. [1981]. Digital data provided by the Nature Conservancy and Teale Data Center and compiled by the Information Center for the Environment, University of California, Davis.)

1972). Over time, the soil horizons hardened to form erosionally resistant duripan layers.

The study area is a 43-km, low-gradient segment of the Cosumnes River that has been directly altered by channel modifications completed in the last 100 yr. Examination of historical maps revealed that before European settlement of the Central Valley, the Cosumnes River system was composed of shallow anastomosing channels that experienced episodic avulsion and frequent overbank flooding (Florsheim and Mount 2002). Beginning in 1907, levees were constructed to restrict flood flow to a single channel and minimize lateral migration. Increased in-channel flow depth and corresponding heightened bed shear stress were likely the major causes of widespread riverbed lowering in the study area (Vick et al. 1997; Constantine 2001). In some reaches, substantial incision resulted in excavation and erosion of duripan layers that control local cross-sectional form and thereby affect the downstream fining pattern documented in this study.

Current planform and cross-sectional morphology of the Cosumnes in the study area are influenced by geology in addition to positions of levees and bank protection structures. The study area can be generally divided into three segments based on geomorphology and channel modifications. From 0 to 10 km, the channel is formed in unconsolidated alluvium, and levees are not continuous along either bank. Previous incision caused bank instability and subsequent widening by as much as 300% in the first 1 to 2 km of the study area where bank material is coarse and poorly sorted (Constantine 2001). Field evidence has suggested that the direction of adjustment has recently turned from degradation to aggradation in this portion of the river (Constantine 2001). A bedrock outcrop forms a knick zone at about 10 km that acts as a local base-level control for upstream reaches, perhaps supporting upstream aggradation (Constantine 2001). The second portion of the river, from 10 to about 34 km, is frequently lined by levees and contains numerous deeply incised reaches. The compositions of the banks and bed in this portion alternate between alluvium and duripan. Bank protection structures and erosionally resistant duripan appear to increase bank strength and minimize lateral erosion in some locations, and a number of small diversion dams control local bed elevation. The third portion extends from 34 km to the downstream end of the study area at 43 km. Bank and bed compositions again alternate between alluvium and duripan; however, maximum channel depth is frequently lower because levees are set farther back from the channel and allow for limited overbank flooding.

Methods

Surface and subsurface bed material samples were collected in order to define the downstream fining pattern in the study area. Samples were collected from square-meter plots at the centers of active channel bars, and sampling sites were spaced approximately 1 km apart. Spacing was greater than 1 km where bedforms were scarce in the incised portion of the study area. Surface samples were collected to the depth of the largest exposed grain according to a procedure described by Church et al. (1987). Where grains with diameters less than 2 mm comprised more than 50% of the bar surface area, the surface was not differentiable from the subsurface, and bulk samples were collected. The size of each sample was sufficiently large so that the mass of the largest grain constituted no more than 5% and usually less than 3% of the total sample mass following a method proposed by Church et al. (1987). The samples were sieved at half-Φ intervals in the field using rocker sieves. Material less than 8 mm in diameter was sieved in the lab.

A 43-km longitudinal thalweg profile was surveyed and 27 cross sections were completed at sample sites in the upstream 32 km of the profile where the bed surface is gravel dominated. In the incised portions of the study area, bankfull stage does not match the elevation of the floodplain; therefore, other field indicators were used to determine the elevation of the dominant channel-forming flow. These include change in bank slope, top of a point bar, and elevation of an undercut bank (Harrelson et al. 1994). The definitions showed some variability; thus, multiple bankfull estimates were made at many of the cross sections. Reach-averaged bed gradient measured over a distance of five to seven channel widths upstream and downstream of each site was used as a proxy for energy gradient in τ^* calculations.

At two sites (24 and 27 km), low-flow pooling and deposition of fines were responsible for surface median grain sizes of less than 2 mm. Data from these sites, which were located upstream of in-channel obstructions (a diversion dam and a duripan outcrop, respectively), were excluded from the downstream fining and τ^* analyses. Grain size and survey data from one additional site (0 km) were excluded after the discovery that a landowner periodically attempts to reconfigure the channel.

The variable τ^* was used to compare bed shear stress with components of critical shear stress for the surface median. Use of τ^* rather than excess shear stress eliminates the need to choose a value to represent dimensionless critical shear stress (k), a constant in the complete equation for critical shear stress. Published values of k range from 0.030 to 0.086 (Buffington and Montgomery 1997), and it is unknown which number would be most appropriate for application in the Cosumnes River.

Error in τ^* estimates is difficult to quantify since it stems, in part, from uncertainty involved in determining bankfull, especially in the incised portions of the study area. Another source of error is the failure of the section-averaged depth-slope product to account for spatial variations in bed shear stress and depth-velocity interactions that influence sediment entrainment (Wilcock et al. 1996). Although the estimates of depth used to calculate τ^* contain some error, the methodology employed in the field was consistent from site to site. Therefore, evaluation of τ^* is valid for discussion of relative longitudinal differences in the relationship between bed shear stress and critical shear stress. Longitudinal trends of bankfull width-to-depth ratio and channel bottom width were compared with those of τ^* in order to link changes in bed mobility to variations in cross-sectional morphology. While bankfull width-to-depth ratio measurements may be subject to error in estimating bankfull, channel bottom width is an unbiased indicator of cross-sectional form and, as such, provides a reference for evaluating the reliability of trends of bankfull-dependent variables. In this study, bottom width is defined as the width across the bottom of the channel between breaks in slope from the bed to the bank.

Results and Discussion

Downstream variation in surface median grain size in the Cosumnes River was documented, and grain size trends were compared with those of τ^*, bankfull width-to-depth ratio, and channel bottom width (table 1; tables 1–3 are available from *The Journal of Geology*'s office free of charge on request). The latter two variables were used as quantifiable measures of cross-sectional morphology. Changes in τ^* account for differences in bed mobility that are shown to influence the downstream fining pattern.

Downstream fining in the study area generally follows an exponential pattern with a diminution coefficient of 0.072 ($R^2 = 0.74$; fig. 2*a*). A power function was also tested but achieved a poorer degree of explanation ($R^2 = 0.54$). The coefficient $a = 0.072$ is slightly less than those determined for two streams with commensurate drainage area A, a variable on which a is strongly dependent (Hoey and Bluck 1999), and bed material lithology. In the Knik River, Alaska, Bradley et al. (1972) found that $a = 0.13$, and Kodama (1994*a*) estimated that $a = 0.089$ in the Watarase River, Japan.

Scatter in the downstream fining pattern in figure 2*a* reflects natural variability of the effects of sampling from centers of bars with varying dimensions and grain size distributions; it is not linked to changes in sediment supply. Previous studies have determined that discontinuities in downstream fining patterns can be explained by lateral sediment sources such as tributaries or locations of bank erosion (Knighton 1980; Rice and Church 1998; Rice 1999). However, none of the three tributaries that join the Cosumnes in the study area appears to supply sufficient coarse material to cause distinct steps in the fining pattern (fig. 2*a*). Contribution of coarse material via bank erosion is limited to the upstream 1 km of the study area where the banks contain cobbles in a matrix of loose sand. Between about 13 and 30 km, the banks and bed are frequently composed of duripan (fig. 2*b*). Cobble or gravel lenses are exposed below duripan layers in the banks at nine locations; however, contribution from the lenses is likely minimal. Erosion of the lenses is presumed limited for a number of reasons: the deposits are partially cemented, they are protected from erosion by overlying resistant duripan, and lateral channel migration is prohibited by duripan or levees and bank protection structures in most reaches between 10 and 34 km. Therefore, there are no major sources of cobble- to gravel-sized sediment downstream of 1 km besides what is carried from upstream as bedload. A recent study by Surian (2002) showed that instream structures such as diversion dams may also influence downstream fining patterns. Although there are four small agricultural dams in the study area, the resolution of the grain size data is not adequate for identifying the local effects of the dams on downstream fining.

Despite some scatter, strong fining is prevalent upstream of 17 km and also downstream of 32 km; however, there is a 15-km distance between these segments through which median surface grain size changes very little with distance downstream. This decline in fining strength is not replicated by the exponential trend line, and the majority of data points within the 15-km portion plot above the trend line. The remainder of this article is devoted to addressing the cause of this phenomenon and proposing a model that is more appropriate than the continuous exponential function for depicting the downstream fining pattern in the study area.

Effects of Changing τ^* and Bed Mobility on the Downstream Fining Pattern. Longitudinal differences in fining strength in the study area are linked to changes in τ^* and corresponding gravel mobility caused by variation in cross-sectional morphology. In segment 1 (0–17 km), τ^* maintains an average value of 0.031 (fig. 2*c*), indicating that sediment transport conditions at the sites are graded and that $\tau^* = 0.031$ represents some requirement for initiation of general motion. The majority of the sites where τ^* is near 0.031 exist upstream of 10 km where banks are composed mainly of unconsolidated, gravel- to sand-sized alluvium and levees are absent from at least one bank. These factors allow the channel to adjust to changes in flow and sediment supply in order to maintain τ^* near the threshold of motion. The value 0.031 is similar to dimensionless critical shear stress values reported in other studies (e.g., 0.035 by Parker and Klingeman [1982]), although estimates made in the literature differ on the basis of the method of determination and other factors (review by Buffington and Montgomery 1997). Andrews (1983) found that the critical value (0.033) is often exceeded at bankfull, and he therefore proposed that average bankfull τ^* is actually greater (0.047). Although it is lower than the 0.047 suggested by Andrews (1983) for bankfull, 0.031 represents a reasonable estimate of threshold τ^* in graded gravel-bed reaches.

Strong fining in segment 1 is likely caused by size-selective transport under conditions of threshold τ^* with coarse sediment fractions exhibiting only partial mobility. Size selectivity accounts for fining by allowing fine grains to move downstream more frequently and rapidly than coarse ones, resulting in a concentration of coarse material upstream. Aggradation in the upstream 10 km of the study area may facilitate fining in the segment by promoting selective deposition of large grains.

Through segment 2 (17–32 km), median grain size diminishes very little, and data suggest that this decline in fining strength is driven by a transition from size-selective transport to equal mobility of bed material. Values of τ^* in segment 2 generally exceed the threshold value of 0.031 measured upstream and reach as high as 0.189, with 70% greater than 0.116 (fig. 2*c*). This segment that exhibits high τ^* is the same length through which there is little net reduction in median grain size (fig. 2*a*, 2*c*). As previously mentioned, there are no significant lateral sources of coarse sediment in this segment; therefore, the lack of net downstream fining is probably linked to conditions of bed mobility rather than the result of compensation of fining by coarse lateral supply. It has been recognized that size selectivity of transport ceases and all size fractions become equally mobile when bed shear stress greatly exceeds the critical shear stress required for entrainment (Parker and Klingeman 1982; Parker et al. 1982). Wilcock (1992) found that for $\tau/\tau_{cr} > 2$, where τ is bed shear stress given by $\tau = \rho_w ghS$ and τ_{cr} denotes critical shear stress according to $\tau_{cr} = k(\rho_s - \rho_w)gD$, the coarse surface layer breaks up and all sizes are equally mobile. The constant k denotes dimensionless critical shear stress and is typically derived for a particular application or is assigned a previously reported value, usually one between 0.03 and 0.06. Choosing $k = 0.031$, the threshold value determined in this study, yields the condition that selective mobility ceases when $\tau^* \geq 0.062$. All but two values of τ^* measured in segment 2 are greater than 0.062, suggesting that, in general, bed material in this segment experiences equal mobility at bankfull. Increasing k to 0.047 (Andrews 1983) does not change the result significantly since τ^* values measured in this segment are greater than 0.094 at all but three sample locations. Apparently, sustained high τ^* in most reaches in segment 2 diminishes the potential for downstream fining through selective sorting by enabling transport of all surface particles regardless of size.

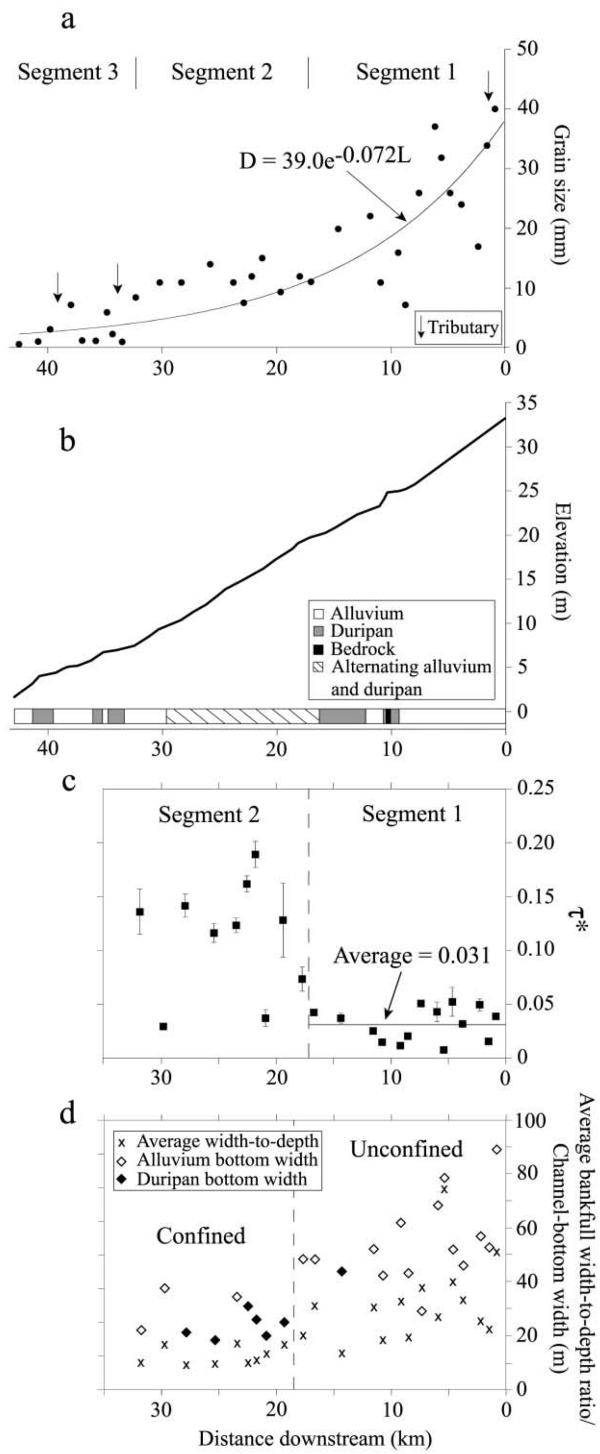

Figure 2. *a*, Downstream fining of median surface grain size. Locations of tributaries and the three channel segments discussed in the text are shown. The exponential trend was fit to data by least squares linear regression. *b*, Channel profile and downstream variation in substrate. *c*, Downstream variation in τ^* measured at sample sites from 0 to 32 km. Error bars show 1 standard deviation about average τ^* at all sites except those where the error plotted smaller than the symbol. The average for segment 1 (0.031) represents the threshold of motion. In segment 2, the channel is generally narrow and deep, leading to τ^* well above the threshold. *d*, Downstream variation in average bankfull width-to-depth ratio and channel bottom width measured at sample sites from 0 to 32 km. Both variables decrease downstream of about 18 km, indicating that cross-sectional morphology generally shifts from wider and shallower upstream to narrower and deeper downstream. This change from unconfined to confined potential for lateral adjustment may be attributed to the presence of erosionally resistant duripan banks at numerous sites in segment 2. See table 1 for figure 2 data.

Connecting τ^* and Gravel Mobility Trends to Changes in Cross-Sectional Form. Increased τ^* in segment 2 coincides with decreased bankfull width-to-depth ratio and channel bottom width, suggesting that the positive shift in τ^* is caused by a change in the dominant cross-sectional form. Average bankfull width-to-depth ratio decreases with distance downstream, and values are smallest at sites in segment 2 where τ^* is highest (fig. 2*d*). Measured bankfull width-to-depth ratio is affected by uncertainty in estimating dominant discharge stage in the field; therefore, channel bottom width, an objective measurement, was also examined as an indicator of longitudinal change in cross-sectional morphology. Channel bottom width illustrates the same trend as bankfull width-to-depth ratio: downstream of about 18 km, values drop as the channel becomes narrower and deeper. Narrow, deep, cross-sectional morphology in reaches with duripan banks reflects the relatively high resistance of the duripan to erosion. Reliance of cross-sectional form on bank material resistance has previously been noted by Wohl and Achyuthan (2002). Although others exist, only one duripan reach between 13 and 18 km was measured because of the lack of ideal grain size sampling sites. The presence of duripan banks in this portion of segment 1 suggests that segment 1 may include a limited number of reaches with small width-to-depth ratios and high τ^* values. Therefore, the chosen boundary at 18 km should be viewed as an approximation based on available data. In segment 2, alluvial sites that have small width-to-depth ratios are located in reaches where bank material is fine grained, banks are strengthened by large roots, and the channel is closely lined by levees with bank protection structures. These features, like the presence of duripan, increase bank strength and inhibit widening in response to incision.

Through confinement of flow to a narrow, deep channel in segment 2, τ^* is raised above the threshold value and sediment transport reaches equal mobility, thus causing the observed lack of downstream fining. The change to narrow, deep, cross-sectional morphology necessarily generates greater flow depth and increased τ^* since discharge is likely constant with distance downstream, and bed gradient declines less than 20% between segments 1 and 2 (fig. 2*b*; table 2).

While most of the channel in segment 2 exhibits τ^* in excess of that required for equal mobility, a few reaches exist within this segment where τ^* locally approximates the threshold value and transport may be size selective. Anomalously low reach gradient at one site and relatively wide channel cross section at another result in τ^* values near the threshold value of 0.031 at two locations in segment 2 (fig. 2*c*). Nevertheless, any downstream fining through these reaches where transport is likely size selective is seemingly muted by the abundance of reaches in which mixed-sized gravel achieves equal mobility.

Transition from Gravel to Sand: Evidence and Process. In segment 3 (32–43 km), fining resumes to produce a transition in median grain size from primarily gravel sized upstream to mainly sand sized downstream (fig. 2*a*). Although no cross-sectional survey data were collected in order to evaluate τ^*, the resumption of fining and transition from gravel to sand are likely associated with reduced bed gradient (table 2) and lower maximum channel depth because the levees are placed farther from the channel downstream of about 34 km. These changes in bed gradient and flow depth potentially cause τ^* to approach the threshold value, initiating size-selective transport in segment 3.

The absence of fining in reaches characterized by high τ^* and diminished potential for selective transport suggests that downstream fining in the study area is dominated by sorting rather than abrasion, which would operate continuously regardless of changes in τ^*. Several observations support this. The river in the study area is low gradient (gradient less than 0.1%), carries relatively resistant lithologies, and exhibits no detectable change in lithologic content of the bed surface with distance downstream.

A New Model. On the basis of the above observations and measurements, downstream fining in the study area occurs in two discrete intervals rather than continuously over the length of the profile, and this distinction is due to longitudinal changes in bed mobility. Fining is strongest in segments 1 and 3, and these segments are separated by an approximately 15-km stretch through which there is limited reduction in median grain size (fig. 3). In the medial segment, all sizes of bed material are transported downstream as a consequence of nonselective transport stemming from τ^* values that are usually greater than twice the threshold value critical for motion.

Statistical comparison shows that the interval model for downstream fining depicted in figure 3 provides a slightly better fit to the data in segments 1 and 3 than does the traditional continuous model shown in figure 2*a*. The standard error of estimate was used to test the fit of the models. First, the standard error of estimate calculated for the continuous model applied only to data in segment 1, and then for the interval model applied to the same

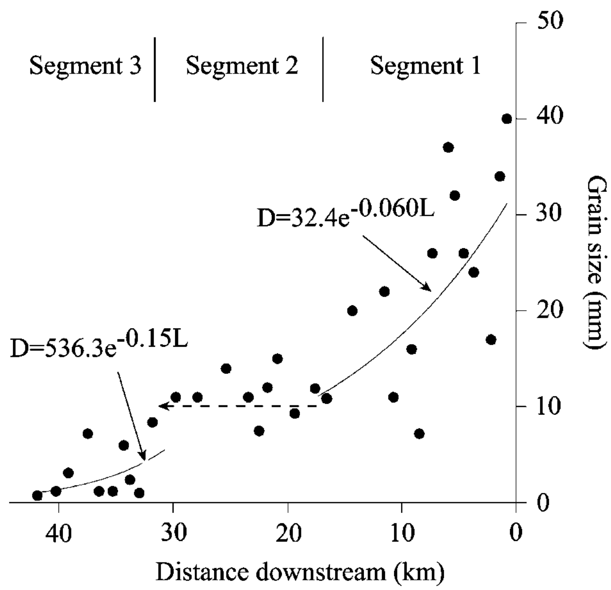

Figure 3. Alternative model of downstream fining in the study area. Fining occurs through selective sorting in segment 1, where τ^* approximates the threshold (0.031), and also in segment 3. In segment 2, where most reaches are confined and exhibit high τ^*, all grain sizes are equally mobile at bankfull, thereby resulting in no net fining.

data. The procedure was repeated for data in segment 3, and the results were tabulated (table 3). While the strength of correlation between the data in segment 1 and the models is equivalent for the two models, the data in segment 3 are statistically better represented by applying the interval model. These results combined with the evidence for equal mobility of gravel in segment 2 indicate that the interpretation presented in figure 3 is the better model of downstream fining in the study area.

Conclusions

This study demonstrates that in alluvial rivers, exponential downstream fining dominated by selective sorting is sensitive to changes in bed material mobility. Grain size measurements and estimates of τ^* show that fining is strongest in reaches where τ^* approximates the threshold required for motion (0.031) and sediment transport conditions are graded. The threshold τ^* value is primarily associated with alluvial reaches where cross-sectional morphology is free to adjust to changes in flow and sediment supply. In reaches where channel width is confined, particularly by erosionally resistant bank material, τ^* exceeds the requirement for equal mobility of all grain sizes at bankfull. Elevated τ^* and resulting equal mobility lead to reduced fining in one segment of the study area compared with that in upstream and downstream segments. Our results suggest that reach-selective fining has important implications for larger-scale downstream fining patterns in rivers with longitudinal differences in gravel mobility caused by variation in τ^*. This phenomenon may be common in incised rivers, especially those incised into erosionally resistant alluvium or bedrock.

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REFERENCES CITED

Andrews, E. D. 1983. Entrainment of gravel from naturally sorted riverbed material. Geol. Soc. Am. Bull. 94: 1225–1231.

Ashworth, P. J., and Ferguson, R. I. 1989. Size-selective entrainment of bed load in gravel bed streams. Water Resour. Res. 25:627–634.

Bradley, W. C. 1970. Effect of weathering on abrasion of granitic gravel, Colorado River (Texas). Geol. Soc. Am. Bull. 81:61–80.

Bradley, W. C.; Fahnestock, R. K.; and Rowekamp, E. T. 1972. Coarse sediment transport by flood flows on Knik River, Alaska. Geol. Soc. Am. Bull. 83: 1261–1284.

Buffington, J. M., and Montgomery, D. R. 1997. A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. Water Resour. Res. 33:1993–2029.

Church, M. A.; McLean, D. G.; and Wolcott, J. F. 1987. River bed gravels: sampling and analysis. *In* Thorne, C. R.; Bathurst, J. C.; and Hey, R. D., eds. Sediment transport in gravel-bed rivers. Chichester, Wiley, p. 43–88.

Constantine, C. R. 2001. The effects of substrate variability and incision on the downstream-fining pattern in the Cosumnes River, Central Valley, California. M.S. thesis, University of California, Davis.

Ferguson, R., and Ashworth, P. 1991. Slope-induced changes in channel character along a gravel-bed stream: the Allt Dubhaig, Scotland. Earth Surf. Proc. Landf. 16:65–82.

Ferguson, R.; Hoey, T.; Wathen, S.; and Werrity, A. 1996. Field evidence for rapid downstream fining of river gravels through selective transport. Geology 24: 179–182.

Florsheim, J. L., and Mount, J. F. 2002. Restoration of floodplain topography by sand splay complex formation in response to intentional levee breaches, lower Cosumnes River, California. Geomorphology 44: 67–94.

Harrelson, C. C.; Rawlings, C. L.; and Potyondy, J. P. 1994. Stream channel reference sites: an illustrated guide to field techniques. U.S. For. Serv. Gen. Tech. Rep. RM 245, 61 p.

Hoey, T. B., and Bluck, B. J. 1999. Identifying the controls over downstream fining of river gravels. J. Sediment. Res. 69:40–50.

Knighton, A. D. 1980. Longitudinal changes in size and sorting of stream-bed material in four English rivers. Geol. Soc. Am. Bull. 91:55–62.

Kodama, Y. 1994*a*. Downstream changes in the lithology and grain size of fluvial gravels, the Watarase River, Japan: evidence of the role of abrasion in downstream fining. J. Sediment. Res. A 64:68–75.

———. 1994*b*. Experimental study of abrasion and its role in producing downstream fining in gravel-bed rivers. J. Sediment. Res. A 64:76–85.

Kuhnle, R. A. 1996. Variations in bed material size on Goodwin Creek. *In* Proceedings of the 6th Federal Interagency Sedimentation Conference (Las Vegas, Nev.). Washington, D.C., Government Printing Office, p. II-68–II-74.

Paola, C.; Parker, G.; Seal, R.; Sinha, S. K.; Southard, J. B.; and Wilcock, P. R. 1992. Downstream fining by selective deposition in a laboratory flume. Science 258:1757–1760.

Parker, G. 1979. Hydraulic geometry of active gravel rivers. J. Hydr. Eng. Div. ASCE 105:1185–1201.

———. 1991. Selective sorting and abrasion of river gravel. II. Applications. J. Hydraul. Eng. ASCE 117: 150–171.

Parker, G., and Klingeman, P. C. 1982. On why gravel bed streams are paved. Water Resour. Res. 18: 1409–1423.

Parker, G.; Klingeman, P. C.; and McLean, D. G. 1982. Bedload and size distribution in paved gravel-bed streams. J. Hydr. Eng. Div. ASCE 108:544–571.

Piper, A. M.; Gale, H. S.; Thomas, H. E.; and Robinson, T. W. 1939. Geology and ground-water hydrology of the Mokelumne area, California. U.S. Geol. Surv. Water-Supply Pap. 780, 230 p.

Rice, S. 1999. The nature and controls on downstream fining within sedimentary links. J. Sediment. Res. 69: 32–39.

Rice, S. P., and Church, M. 1998. Grain size along two gravel-bed rivers: statistical variation, spatial pattern and sedimentary links. Earth Surf. Proc. Landf. 23: 345–363.

Schumm, S. A., and Stevens, M. A. 1973. Abrasion in place: a mechanism for rounding and size reduction of coarse sediments in rivers. Geology 1:37–40.

Seal, R.; Paola, C.; Parker, G.; Southard, J. B.; and Wilcock, P. R. 1997. Experiments on downstream fining of gravel. I. Narrow-channel runs. J. Hydraul. Eng. ASCE 123:874–884.

Shaw, J., and Kellerhals, R. 1982. The composition of recent alluvial gravels in Alberta River beds. Alberta Res. Counc. Bull. 41, 151 p.

Shlemon, R. J. 1972. The lower American River area, California: a model of Pleistocene landscape evolution. Assoc. Pac. Coast Geogr. Yearb. 34:61–86.

Surian, N. 2002. Downstream variation in grain size along an Alpine river: analysis of controls and processes. Geomorphology 43:137–149.

Vick, J.; Andrews, E.; and Williams, P. B. 1997. Analysis of opportunities for restoring a natural flood regime on the Cosumnes River floodplain. San Francisco, Philip Williams, 88 p.

Wagner, D. L.; Jennings, C. W.; Bedrossian, T. L.; and Bortungno, E. J. 1981. Geologic map of the Sacramento quadrangle. Calif. Div. Mines Geol. Reg. Geol. Map Ser., Map 1A, scale 1 : 250,000.

Werrity, A. 1992. Downstream fining in a gravel-bed river in southern Poland: lithologic controls and the role of abrasion. *In* Billi, P.; Hey, R. D.; Thorn, C. R.; and Tacconi, P., eds. Dynamics of gravel-bed rivers. New York, Wiley, p. 333–350.

Wilcock, P. R. 1992. Experimental investigation of the effect of mixture properties on transport dynamics. *In* Billi, P.; Hey, R. D.; Thorn, C. R.; and Tacconi, P., eds. Dynamics of gravel-bed rivers. New York, Wiley, p. 109–139.

Wilcock, P. R.; Barta, A. F.; Shea, C. C.; Kondolf, G. M.; Graham Matthews, W. V.; and Pitlick, J. 1996. Observations of flow and sediment entrainment on a large gravel-bed river. Water Resour. Res. 32:2897–2909.

Wohl, E., and Achyuthan, H. 2002. Substrate influences on incised-channel morphology. J. Geol. 110:115–120.