Modeling the influence of river rehabilitation scenarios on bed material sediment flux in a large river over decadal timescales

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Received 19 January 2006; revised 18 July 2006; accepted 29 August 2006; published 21 December 2006.

[1] A stochastic flood generator and calibrated sediment transport formulae were used to assess the decadal impact of major river rehabilitation strategies on two fraction bed material sediment flux and net storage, first-order indicators of aquatic riverine habitat, in a large river system. Model boundary conditions were modified to reflect the implementation of three major river rehabilitation strategies being considered in the Sacramento River Valley: gravel augmentation, setting back of levees, and flow alteration. Fifty 30-year model simulations were used to compute probabilities of the response in sediment flux and net storage to these strategies. Total annual average bed material sediment flux estimates were made at six gauged river cross sections, and ~60 km reach-scale sediment budgets were evaluated between them. Gravel augmentation to improve spawning habitat induced gravel accumulation locally and/or downstream, depending on the added mixture. Levee setbacks to recreate the river corridor reduced flow stages for most flows and hence lowered sediment flux. Flow alteration to mimic natural flow regimes systematically decreased total annual average flux, suggesting that high-magnitude low-frequency transport events do not affect long-term trends in bed material flux. The results indicate that each rehabilitation strategy reduces sediment transport in its target reaches and modulates imbalances in total annual bed material sediment budgets at the reach scale. Additional risk analysis is necessary to identify extreme conditions associated with variable hydrology that could affect rehabilitation over decades. Sensitivity analysis suggests that sorting of bed material sediment is the most important determinant of modeled transport and storage patterns.

Citation: Singer, M. B., and T. Dunne (2006), Modeling the influence of river rehabilitation scenarios on bed material sediment flux in a large river over decadal timescales, *Water Resour. Res.*, *42*, W12415, doi:10.1029/2006WR004894.

1. Introduction

[2] Aquatic riverine habitats are affected by channel sediment transport and storage regimes (summarized by *ASCE Task Committee on Sediment Transport and Aquatic Habitats* [1992]). In general, spatial and temporal patterns in sediment flux control disturbance (e.g., the frequency of gravel-bed mobilization), substrate conditions (e.g., the availability of spawning habitat, the frequency of fine sediment flushing), and channel morphology (e.g., flow depth, in-channel refugia). River engineering in the form of dams and flood control levees affects sediment movement and accordingly, aquatic riverine habitats. Proposed rehabilitation strategies designed to mitigate the impacts of river engineering in fluvial systems will also affect the sediment regime, but their long-term effects are complicated by the interannual and intra-annual variation of natural and regulated streamflow. Since viable rehabilitation strategies must be sustained for many decades, there is a need for modeling capability to analyze the response in sediment flux to rehabilitation scenarios within the context of long-term streamflow variability. In this paper we utilize a model that couples stochastic streamflow with bed material flux calculations [*Singer and Dunne*, 2004a, 2004b] to simulate the adjustment in sediment flux and net storage over decadal timescales to three river rehabilitation strategies in the Sacramento River: gravel augmentation, flood control levee setbacks, and flow alteration.

[3] Lowland aquatic riverine ecosystems have declined over the past century, primarily in response to river engineering intended to control floods, generate hydroelectricity, irrigate agricultural fields, and provide drinking water [*ASCE Task Committee on Sediment Transport and Aquatic Habitats*, 1992; *Anderson*, 2000; *Power et al.*, 1995; *Vitousek et al.*, 1997]. Engineering structures, such as dams and flood control levees, and gravel mining operations along river channels have affected the physical boundary conditions of aquatic habitats. Dams have altered the timing, frequency, magnitude, and duration of floods and have cut off sediment supply from upstream [e.g., *Magilligan et al.*, 2003; *Richter et al.*, 1996; *Singer*, 2006; *Williams and Wolman*, 1984]. Flood control levees have disconnected rivers from their floodplains, increased in-channel flow depths and shear stresses [e.g., *Gergel et al.*, 2002; *Laddish*, 1997], and prevented sediment recruitment from bank erosion sources, the latter of which is

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0043-1397/06/2006WR004894$09.00

exacerbated by gravel mining operations in riverbeds and floodplains. The cumulative effects of such river channel engineering include coarsened bed material downstream of major dams, localized bed degradation [*Biedenharn et al.*, 2000; *Singer and Dunne*, 2001], increased mean channel flow velocity, and deposition of fine sediment due to reduced moderate flood peaks [*Kondolf and Wilcock*, 1996; *Pitlick and Van Steeter*, 1998].

[4] In response to decades of decline in the quality of aquatic and riparian habitats, river rehabilitation strategies are being proposed and implemented in major river basins such as the Sacramento in California, the Kissimmee in Florida, and the Danube in Romania. Rehabilitation in the form of flow alteration, sediment-supply manipulation, and removal of channel constraints has been proposed to improve the quality of riverine habitats over a period of decades. However, current modeling capability to assess the influence of such strategies on sediment flux and storage in river channels over decadal timescales is limited.

[5] Much of the previous research on rehabilitation in fluvial systems has focused on altered flow regimes [e.g., *Magilligan et al.*, 2003; *Richter et al.*, 1998; *Richter et al.*, 1996; *Richter and Richter*, 2000] and generally how these alterations affect aquatic and riparian ecosystems [e.g., *Junk et al.*, 1989; *Poff et al.*, 1997; *Sparks*, 1992; *Stanford et al.*, 1996; *Vannote et al.*, 1980]. Other work has centered on the frequency and timing of flood pulses that mobilize the bed, release fine sediment, clean fish roe and infuse them with oxygen [*Kondolf and Wilcock*, 1996; *Milhous*, 1998; *Pitlick and Van Steeter*, 1998; *Wu*, 2000], and "ecologically acceptable" minimum flows required to maintain instream habitats [*Anderson*, 2000; *Gibbins and Acornley*, 2000]. *Pitlick and Van Steeter* [1998] linked flow frequency and bed material flux to compute the effective discharge for channel maintenance in the Upper Colorado River. *Laddish* [1997] analyzed the effect of setback levees on shear stress in a river channel, using simplified channel geometry and steady, uniform flow hydraulics to compute the setback distance necessary to reduce channel shear stress during the 2-year recurrence flood to a value below the threshold for entrainment in a 16-km reach of the middle Sacramento River. *Bozkurt et al.* [2000] also analyzed the effect of different setback distances on stage-discharge relationships in the lower Sacramento River. One other quantitative study analyzed the effects of levee setbacks on riparian communities [*Gergel et al.*, 2002].

[6] There is a paucity of research on the decadal impact of proposed rehabilitation strategies on sediment flux. It would be useful to know, for example, what effect rehabilitation strategies would have on transport patterns decades after their implementation. We have developed the modeling capability to assess such decadal trends, including accounting for sediment supplied from tributaries, within the context of long-term streamflow variability. This type of prediction would allow agencies responsible for river management to anticipate the central tendency, extrema, and probabilities of sediment adjustment to these strategies, in particular river cross sections, in river reaches, or along entire river valleys.

2. Study Basin

[7] The Sacramento River basin is 68,000 km^2 in area and drains four geologic provinces. This study focuses on rehabilitation implementation in the main stem Sacramento, which spans ~400 river kilometers and consists of an entrenched gravel bed in the upper reaches, a mixed sand and gravel bed with a broad, flat floodplain in the middle reaches, and a sand bed between flood control levees built upon the channel banks in the lower reaches. The gradient of the river averages $\sim 2.0 \times 10^{-4}$, and its alignment is affected by its tectonic and geologic legacy [*Water Engineering and Technology*, 1990]. Channel width varies from ~100 m in the upper reaches to ~250 m in the lower reaches. Much of the floodplain has been deforested and leveled, leaving few patches of riparian forest and scroll bar topography.

[8] We compute daily and decadal flux at the following gauging stations: Bend Bridge (BB), Hamilton City (HC), Butte City (BC), Colusa (CO), Knights Landing (KL), Sacramento (SA). We also compute net accumulation of sediment in the river reaches between these stations. The bed of the upper Sacramento between Keswick and Bend Bridge (Figure 1) is coarse gravel (median grain size, $D_{50} >$ 30 mm and sorting coefficient, $\sigma > 1.83$), which is armored in several locations due presumably to selective entrainment of finer gravel particles without their replacement from upstream sources. Between Bend Bridge and Knights Landing the Sacramento flows over a bed of gravel and sand (0.3 mm > D_{50} > 30 mm, 1.83 > σ > 2.37) with localized sources of dissected coarse Pleistocene gravels. Between Knights Landing and the city of Sacramento (Figure 1) the river flows over a sandy bed (0.03 mm > D_{50} > 0.3 mm, 0.81 > σ > 1.96). Flood control levees have been built upon channel banks (especially in the lower Sacramento) to concentrate flow in the main stem and shunt flood flow into bypasses via flood diversions. In this paper we model river rehabilitation strategies in the main stem Sacramento from below Shasta Dam (Keswick) down to Sacramento (Figure 1).

3. Setting for Rehabilitation

[9] Settlement of the Sacramento Valley began around the time of the California Gold Rush in the 1850s. Settlers farmed the floodplain contiguous to the Sacramento River to take advantage of the fertile soils. These settlers soon became frustrated by the frequency of flooding, which inundated large portions of the valley on an annual basis. The combined influence of their political will and shoaling of the lower Sacramento due to the delivery of hydraulic mining sediments led to the implementation of a major flood control project funded by the U.S. government [*Kelley*, 1998]. The U.S. Army Corps of Engineers constructed a system of levees and flood bypasses to convey flows below a stage threshold through the main stem and to shunt flows above the threshold through bypasses. The project was augmented between 1943 and 1967 with the construction of dams on the main stem and its tributaries. Shasta Dam, constructed in 1943, has had the largest effect on streamflow in the Sacramento River [*U.S. Army Corps of Engineers*, 1998].

[10] Settlement of the Sacramento Valley over the past century and a half and the operation of the flood control system over the past 85 years have had negative effects on the riparian and aquatic habitats along the main stem Sacramento [e.g., *Babcock*, 1995; *Hunter*, 1999; *Nielsen*, 1989; *Taylor*, 1996; *Thompson*, 1961]. Terrestrial floodplain

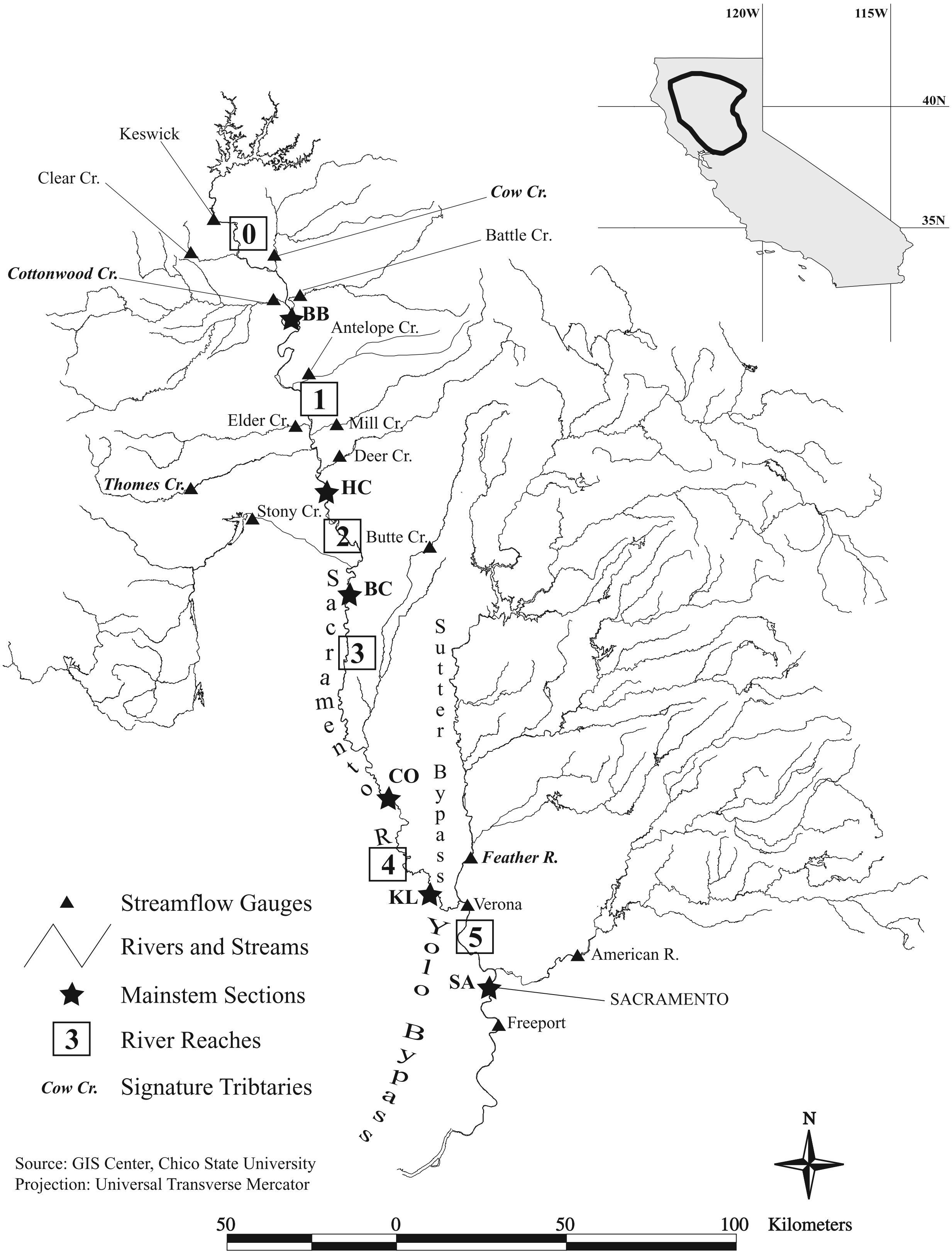

Figure 1. Map of study basin showing streamflow gauges used for stochastic flow simulation, stream network, main stem sections through which bed material transport was computed, river reaches for which simple sediment budgets were evaluated, and signature tributaries used to compute sediment entering the main stem from common geologic provinces (scaled by drainage area according to *Singer and Dunne* [2001, 2004b]). Sutter and Yolo Bypasses are wide, off-channel floodways used to convey high flows. Stations codes are BB, Bend Bridge; HC, Hamilton City; BC, Butte City: Co, Colusa; KL, Knights Landing; and SA, Sacramento. This figure was originally published by *Singer and Dunne* [2004b].

habitats have been degraded by human settlement, deforestation, and severing of the connection between the Sacramento and its floodplain by high artificial levees [*U.S. Army Corps of Engineers*, 1978]. Aquatic habitats have declined due to alteration of natural streamflow downstream of dams, increased flow velocity and stream temperature, decreased sediment supply because of bank protection and dams, and instream gravel mining [*California Department of Water Resources*, 1980, 1985; *Kondolf*, 1995; *Reeves and Roelofs*, 1982]. Fall run chinook, for example, declined to ~50% of historic numbers by 1989 [*Nielsen*, 1989]. Spawning habitat in the basin is estimated to have been reduced to 4% of its historical total [*Peterson et al.*, 1982], largely through blockage of fish passage by dams and confinement of spawning to lowland reaches. Additionally impoundments dampen flood peaks, preventing flushing flows necessary for removing fine accumulations of sediment from spawning gravels [*Kondolf and Wilcock*, 1996; *Milhous*, 1998]. Channelization has also resulted in the loss of side-channel habitat required by more sedentary species and wintering salmon (as well as a loss of terrestrial riparian vegetation and the species it supports) because it prevents overbank flooding.

[11] The degradation of these habitats has been the impetus for a major rehabilitation effort funded by state and federal government agencies. Among other things, these agencies under the auspices of the CALFED Bay-Delta Program intend to improve the state of riparian and aquatic habitats while securing water supply and flood control [*CALFED Bay-Delta Program*, 1997]. Proposed and ongoing rehabilitation strategies include (1) augmenting sediment supply to benefit anadramous fish; (2) setting back levees to create conservation areas; and (3) altering flows out of Shasta Dam to approximate the ecological benefits of predam natural Central Valley streamflows [*CALFED Bay-Delta Program*, 1997]. We analyzed the decadal, first-order impacts of these proposed strategies on bed material sediment flux and storage changes throughout the main stem Sacramento River.

4. Model Outline

[12] We conducted this study using a wealth of data available for the Sacramento basin including bathymetry of the river channel from the Army Corps of Engineers, decades of historical daily streamflow from the U.S. Geological Survey (USGS), bed material surveys from the USGS, and bed load measurements from the USGS. We made assessments of the impact of rehabilitation strategies on total annual sediment flux at key cross sections and sediment budgets in river reaches between these sections from Shasta Dam to the city of Sacramento (Figure 1).

[13] Our method employs a stochastic hydrology model, flow routing software, and a bed material flux simulation model. The development of the hydrology model and the bed material flux model is discussed in detail by *Singer and Dunne* [2004a, 2004b], and we only outline them here. We focus our discussion on how we alter the model space to reflect each rehabilitation strategy, the results of our modeling, and their implications for future work in river rehabilitation.

[14] We developed a stochastic streamflow simulation model, HYDROCARLO, which generates continuous series of daily discharge that are correlated in time by random sampling from a collection of historical flood events and interflood periods at major tributary gauging stations [*Singer and Dunne*, 2004a]. HYDROCARLO uses empirical probabilities of flood events at each station to determine whether a flood occurs and historical correlation in synchronous flood peaks at tributary gauging stations across the basin as a means of narrowing the pool of flood event selection at each time step. As such, the model produces any number of realistic simulations of daily tributary inflow to a large river from each of its major tributaries. These simulated flows can be routed through the main stem to produce a range of flow that brackets observed main stem flow [*Singer and Dunne*, 2004a].

[15] We routed the simulated inflow through ~1000 cross sections (spaced ~0.5 km apart) along the main stem Sacramento (extracted from Corps of Engineers bathymetry) using unsteady flow routing within HEC-RAS, which employs an implicit finite difference solution to the one-dimensional (1-D) flow equations [*Barkau*, 1997]). Thus we simulated flow stage on a daily basis for many locations on the main stem for a period of decades. Each simulation results in a stage and flow frequency curve for each location, and ensemble simulations can be statistically analyzed to yield maxima, minima, and median values for each exceedence probability.

[16] Our bed material flux model uses the stage output from HEC-RAS at six main stem cross sections located at USGS flow gauging stations (Figure 1) to compute hydraulic variables. The descriptions and characteristics of each section are presented in the text and in Table 1 of *Singer and Dunne* [2004b]. We modified and recalibrated the Engelund-Hansen sediment transport formula [*Engelund and Hansen*, 1967] on the basis of data sets of measured bed load flux and bed material grain size collected from gravel-bed rivers to simulate daily bed material flux in various grain size classes [*Singer and Dunne*, 2004b]. The model inputs are cross-sectional geometry (extracted from bathymetry) and bed material grain size distribution (from bulk surveys), from which the alpha parameter for the transport equation (calibrated via multiple regression on grain size and bed material sorting [*Singer and Dunne*, 2004b]) and threshold Shields stress (computed from bed load data) are computed. We computed water surface slope at each cross section, and stage, velocity, shear stress, Shields stress, and excess shear stress for each portion of the cross section. We used these quantities to compute daily bed material flux at each station. The fluxes can be generalized to estimate total annual sediment flux over a period of decades. In conjunction with stochastic hydrology, these estimates can be presented in a probabilistic framework to assess the risk of a particular outcome within the context of the inherent flow variability.

[17] We employed a stochastic approach to flow modeling, because we were interested in simulating main stem flows that are possible (based on combinations of tributary inputs) but have not necessarily occurred in the basin. The stochastic model outputs a range of flows from which statistics can be easily generated. Thus we define a median flow and extrema of frequency distributions, which can be useful for computing sediment transport for a range of conditions that may not be represented in main stem

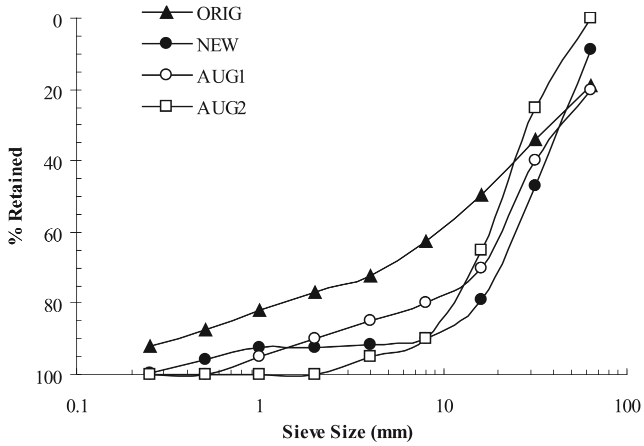

Figure 2. Comparison of four bed material grain size distributions at Bend Bridge: the original used by *Singer and Dunne* [2004b] (ORIG); the newly collected (NEW); the augmentation containing sand (AUG1); and augmentation with no sand (AUG2).

hydrologic records and for forward modeling under changed hydrologic conditions [*Singer and Dunne*, 2004b]. These simulated flows also provide a more robust depiction of median conditions, because they are generated from fifty 30-year ensemble flow series.

[18] In our model development, we assumed one-dimensional flow, no bed armoring, sediment supply is limited by the proportions of each grain size present in the bed material, uniform distribution of bed material grain sizes across our sections, and no cross-sectional change. Furthermore, we compute mass balance for ~60-km river reaches but make no mechanistic assessments of the resulting morphological change. We recognize the limits to these assumptions, many of which were outlined in model development [*Singer and Dunne*, 2004a, 2004b]. In summary, we are not representing the dynamic balance between sediment supply and bed material composition or the relationship between sediment flux, storage, and cross-sectional change. As such, our assessments of flux and net erosion/deposition are first-order approximations made using a simple model driven with the best available data. However, the values reported here provide a systematic view of the decadal spatial patterns in sediment flux resulting from major river rehabilitation strategies. They indicate the potential direction of adjustment, as well as its central tendency based on a stochastic flow regime.

5. Rehabilitation Strategies

5.1. Gravel Augmentation

[19] Gravel of suitable size for salmonid spawning habitat [*Kondolf and Wolman*, 1993] is limited in the Sacramento River due to major impoundments (e.g., Shasta Dam), bank protection [*California Department of Water Resources*, 1994], and in-channel gravel mining [*California Department of Water Resources*, 1980, 1985; *Kondolf*, 1995]. Work on sediment budgets has estimated that in-channel gravel mining can exceed rates of bed load transport by an order of magnitude [*Collins and Dunne*, 1989, 1990; *Kondolf and Swanson*, 1993]. There are additional unknown annual losses due to trapping behind Shasta Dam, itself (shown in Figure 1), though it is not clear how far downstream the resulting armor layer extends.

[20] Gravel augmentation has been proposed and implemented periodically to replenish spawning gravels at strategic points along the Sacramento [*California Department of Water Resources*, 1980, 1985]. Various sites in Reach 0 (Figure 1) were identified as active spawning sites, and the added gravels were supposed to improve the existing spawning sites and create new ones [*California Department of Water Resources*, 1980], even at sites downstream from gravel placement loci. Under the mandate of California Senate Bill (SB) 1086 of 1986 and the federal Central Valley Project Improvement Act (CVPIA) of 1992, ~1.5 Mt of gravel were added to the upper Sacramento River below Shasta Dam between 1978 and 2000 at a cost of ~$26 million (unpublished data from U.S. Bureau of Reclamation). However, there has been little or no monitoring of augmented gravels to compute flux rates, or to determine the efficacy of gravel augmentation in improving habitat for fish (J. DeStaso, U.S. Bureau of Reclamation, personal communication, 2003).

[21] In a previous paper, we estimated ~850 kt/yr annual erosion under current conditions (without rehabilitation) in Reach 0, 115 kt/yr of which is in gravel size fractions [*Singer and Dunne*, 2004b]. However, the transport calculations at Bend Bridge in that paper were based on bed material from a bar located several river kilometers downstream of the cross section used for modeling. Since the transport calculations described by *Singer and Dunne* [2004b] are highly sensitive to local grain size distribution, we recently collected bed material samples at Bend Bridge with the use of a new boat-based scooping sampling device for penetrating coarse beds in navigable rivers. We aggregated three samples across the section to obtain 21.3 kg (dry weight) of bed sediment at Bend Bridge from which the mass of the largest clast comprised less than 1% of the total sample mass, thus satisfying criteria for unbiased grain size estimates [e.g., *Church et al.*, 1987; *Mosely and Tindale*, 1985]. We recalculated our estimates of sand and gravel flux past Bend Bridge and storage in Reaches 0 and 1 using the new grain size distribution (Figure 2), which is much coarser than the one previously used and therefore resulted in a lower median annual gravel transport rate of 37 kt/yr at Bend Bridge and gravel erosion in Reach 0 of 26 kt/yr and gravel deposition in Reach 1 of 4 kt/yr (Table 1). There is no sand in the newly collected bed material, which is consistent with the modest amount of sand entering this reach from upstream tributaries (Table 2). The gravel erosion in Reach 0 (Figure 1) exacerbates the effect of up-basin gravel mining and dam trapping and is gradually depleting the reach of suitable gravel for spawning habitat. Total modeled fluxes under current and rehabilitation scenarios may be obtained by adding gravel values in Table 1 to sand values in Table 2.

[22] We modeled gravel augmentation at the Bend Bridge (BB) cross section (which is the boundary between Reaches 0 and 1, Figure 1) to assess its effect on total annual sediment flux at this station and net accumulation for the upstream and downstream reaches. The goal was to determine whether augmented gravels will stay in Reach 0 and at what rate they will be evacuated. Under current conditions, there is a slight imbalance in sediment storage between

Table 1. Flux and Net Storage Adjustments: Total Annual Gravel[a]

	Current	Augmentation1	Change	Augmentation2	Change	Levee Setback	Change	Flow Alteration	Change
				Total Annual Flux, kt/yr					
Station									
BB	37	77	108%	3	−92%	. . .	. . .	19	−49%
HC	44	. . .	. . .	. . .	. . .	. . .	. . .	14	−68%
BC	38	. . .	. . .	. . .	. . .	. . .	. . .	16	−58%
CO	11	. . .	. . .	. . .	. . .	. . .	. . .	3	−73%
KL	74	. . .	. . .	. . .	. . .	60	−19%	35	−53%
SA	0	. . .	. . .	. . .	. . .	. . .	. . .	0	0%
				Total Annual Net Storage, kt/yr					
Reach									
0	26	66	154%	−8	−131%	. . .	. . .	8	−69%
1	−4	−44	1000%	30	−850%	. . .	. . .	−16	300%
2	−12	. . .	. . .	. . .	. . .	. . .	. . .	−2	−83%
3	−27	. . .	. . .	. . .	. . .	. . .	. . .	−13	−52%
4	63	. . .	. . .	. . .	. . .	49	−22%	32	−49%
5	−75	. . .	. . .	. . .	. . .	−60	−20%	−35	−53%

[a]Results from modeling the influence of rehabilitation strategies on total annual gravel flux at Sacramento River stations (top) and total annual net gravel storage for river reaches (bottom). The table contains gravel flux or net storage currently (Current), following an augmentation including sand (Augmentation1), following an augmentation excluding sand (Augmentation2), following levee setbacks (Levee Setback), and following flow alteration (Flow Alteration). The table also contains the percent change in each value. Negative storage indicates net deposition and positive values indicate net erosion. Negative percentage is a decrease in current net storage (either erosion or deposition). Ellipses represent stations and reaches not simulated.

Reach 0 (erosional) and Reach 1 (mildly depositional). We modeled to determine how gravel augmentation at Bend Bridge would affect this imbalance.

[23] Augmentation at BB was modeled by adjusting the grain size distribution of the bed material to represent a mixture recommended to improve spawning habitat [*California Department of Water Resources*, 1980]. This mixture, which was assumed to be added instanteously, is composed of the following percentages for each phi grain size class represented by its geometric mean: 91 mm (10%), 45 mm (20%), 22.6 mm (30%), 11.3 mm (10%), 5.7 mm (5%), 2.8 mm (5%), 1.4 mm (5%), 0.7 (5%), and 0.35 mm (0%). The remaining 10% of the bed material is larger than the largest grain size modeled and is therefore assumed to be immobile. The distribution was truncated at the upper end accordingly.

[24] We assume that the added gravels completely cover the bed to the scour depth (minus the coarse fraction assumed immobile) and define the bed material grain size distribution at Bend Bridge. Accordingly, the new distribution (Augmentation1 in Figure 2) changes the median grain size from 30 to 25 mm and increases the threshold Shields stress, θ_c, from 0.025 to 0.048 because D_{50} is in the denominator. The added mixture also increases the sorting coefficient, σ, of the whole distribution from 1.83 to 1.94, indicating a wider distribution of grain sizes and lower pocket angles. Note that these values of D_{50}, σ, and θ_c under current conditions are different from those reported by *Singer and Dunne* [2004b] because of the recently collected bed material at Bend Bridge. However, computation of θ_c was done according to the procedure outlined by *Singer and Dunne* [2004b], where the threshold was calibrated according to the flow that moved both sand and gravel at 100 t/d.

Table 2. Flux and Net Storage Adjustments: Total Annual Sand[a]

	Current	Augmentation1	Change	Augmentation2	Change	Levee Setback	Change	Flow Alteration	Change
				Total Annual Flux, kt/yr					
Station									
BB	0	1043	N/A	0	0%	. . .	. . .	0	0%
HC	62	. . .	. . .	. . .	. . .	. . .	. . .	21	−66%
BC	338	. . .	. . .	. . .	. . .	. . .	. . .	145	−57%
CO	8	. . .	. . .	. . .	. . .	. . .	. . .	2	−75%
KL	139	. . .	. . .	. . .	. . .	113	−19%	65	−53%
SA	1	. . .	. . .	. . .	. . .	. . .	. . .	1	0%
				Total Annual Net Storage, kt/yr					
Reach									
0	−9	1034	−11589%	−9	0%	. . .	. . .	−9	0%
1	53	−990	−1968%	53	0%	. . .	. . .	12	−77%
2	270	. . .	. . .	. . .	. . .	. . .	. . .	118	−56%
3	−330	. . .	. . .	. . .	. . .	. . .	. . .	−143	−57%
4	131	. . .	. . .	. . .	. . .	106	−19%	63	−52%
5	−151	. . .	. . .	. . .	. . .	−126	−17%	−77	−49%

[a]Same as Table 1 but for sand.

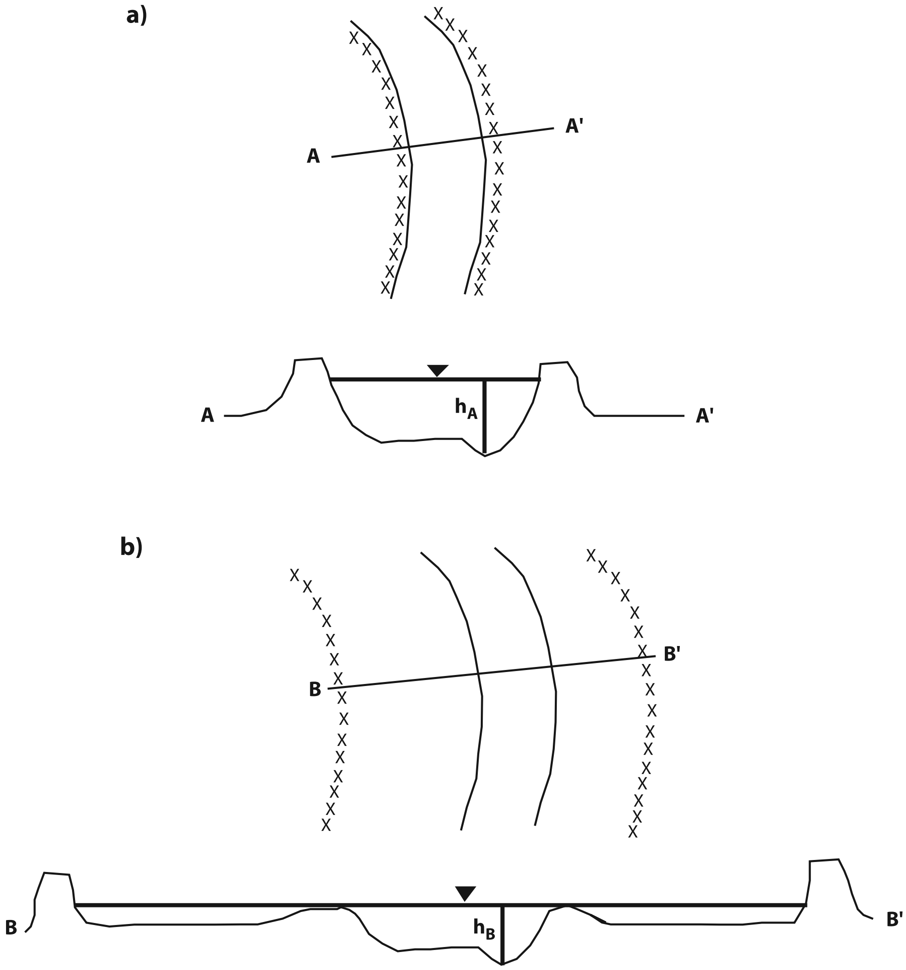

Figure 3. Schematic depicting the effect of levee setbacks on flow stage and thus shear stress in the channel. The figure shows (a) the original channel with levees built upon channel banks and (b) the channel under a levee setback rehabilitation strategy. The former levees are reduced in height to represent the natural levees that predate their construction. The levee setbacks reduce flow stage in the channel. Flow depth h would decrease for the same value of streamflow after levees are set back (h_B). Flow depth in section BB′ cannot exceed h_B until the floodplain is completely filled with water.

[25] The added mixture reflects the managers' desire to increase the amount of gravel in the spawning size range for anadramous fish (e.g. 16 mm < D_{50} < 64 mm [*Kondolf and Wolman*, 1993]. The sediment in Augmentation1 also contains a modest amount of sand (10% sand compared with the 0% sand content of the preaugmentation bed material) that may be important as a kind of lubricant, allowing anadramous fish to push against a softer subsurface matrix to move gravels in order to create their redds. In case this is deemed undesirable to managers, we also modeled an augmentation with no sand (Augmentation2) that focuses on greatly increasing the volume of spawning gravels at the expense of all other grain sizes (Figure 2). The Augmentation2 distribution had the following characteristics: D_{50} = 25, θ_c = 0.057, σ = 1.043. In both cases, we assume that amount of augmented gravel is small compared with channel capacity and therefore does not alter the cross section or its hydraulic roughness, only the bed material grain size distribution.

[26] Our sediment transport formula was used based on these changes. Reach 0 is not the only potential location for gravel augmentation, only the most common target historically. The method employed here could easily be applied to another reach, but that is beyond the scope of this research, which focuses on demonstrating the model.

5.2. Setback Levees

[27] Flood control levees are an integral part of the Sacramento Valley flood control system. To convey high flows, the Army Corps of Engineers constructed ~3-m-high levees to convey high flows in Reaches 2–5 (Figure 1). Levees in Reaches 4 and 5 were built upon the original channel banks (in most locations), which are protected to prevent erosion. Levee setbacks were proposed in Senate Bill 1086 and the Central Valley Project Improvement Act to provide shade and cover from predators for fish [*Nielsen*, 1989]. The allowance for overbank flow would reduce flow depths in the river channel (Figure 3), thus reducing the risk of progressive bed degradation. Additionally, levee setbacks could lead to channel migration and the construction of point bars. The addition of this more complex channel morphology diversifies the lateral distribution of the sub-

strate, the velocity field, sediment transport rate, and thus the aquatic habitat structure.

[28] Our previous work on decadal bed material sediment budgets identified that Reach 4, between Colusa (CO) and Knights Landing (KL) (Figure 1), is eroding by ~200 kt/yr [*Singer and Dunne*, 2004b] (Tables 1 and 2). We modeled levee setbacks by increasing (artificial) levee-to-levee width from the existing ~200 to ~3000 m in a 16-km stretch of river (extending 8 river kilometers upstream and downstream of Knights Landing), while maintaining berms that approximate natural levees (Figure 3). This levee setback distance is consistent with upstream setbacks but only incorporates a fraction of the natural floodplain [*Kelley*, 1998]. In order to enable direct comparison between current and postsetback bed material flux and storage, we only computed sediment flux within the presetback active channel through the cross section at Knights Landing. Roughness values in the expanded active floodplain were assigned the same as the presetback floodplain and the hydraulic model (originally calibrated by the U.S. Corps of Engineers) was not recalibrated. In the years following the levee setback, the floodplain roughness would be expected to increase due to growth of woody vegetation. Although this effect is not treated in the presented model, woody vegetation growth on the former channel banks might be expected to maintain more water in the channel and thereby increase local sediment transport rates. Future versions of the model could represent this process.

[29] Flood control levees are built to convey the highest floods of record. Under normal operation of the flood control system, the floodplain outside the levees is not inundated under the current flow regime. By setting back levees and maintaining their height, we are increasing the area of channel/floodplain that can be accessed by a given flood, thus reducing flow depth in the channel (Figure 3). We extracted daily stage at Knights Landing from HEC-RAS for 50 simulations of 30-year time series to determine the decadal effect of the setbacks on sediment flux at this section.

5.3. Flow Alteration

[30] Streamflow in the Sacramento River has been dramatically altered by major dams operated for flood control, irrigation, and hydroelectricity. Figure 4 shows annual peak flow and annual trough flow curves for pre- (1891–1943) and post- (1944–2002) Shasta Dam hydrology at Bend Bridge. Peak flow is defined as the annual maximum daily flow and trough flow as the annual minimum daily flow. These curves show a reduction in peak flows and an increase in trough flows at all exceedence probabilities following dam construction. There is reason to believe that dam operation has had a large effect on sediment flux in the Sacramento River. For example, an annual peak flow of 1800 m^3 s^{-1} (approximately 3/4 bankfull) was exceeded ~80% of years in the predam era and only ~55% of years in the postdam (Figure 4, middle panel). Conversely, annual flow troughs are on average 40% higher in the postdam era (Figure 4, top panel). And the number of flood days per year above 2500 m^3 s^{-1} (assumed to be a threshold for significant sediment transport) is greater in the postdam era for all exceedence probabilities (Figure 4, bottom panel). We expect such altered hydrology to have had systematic impacts on the sediment budget throughout the Sacramento River, although their combined influence is not obvious. However, it is known that Shasta Dam has caused declines in salmonid spawning habitat in the upper Sacramento River [*California Department of Water Resources*, 1980].

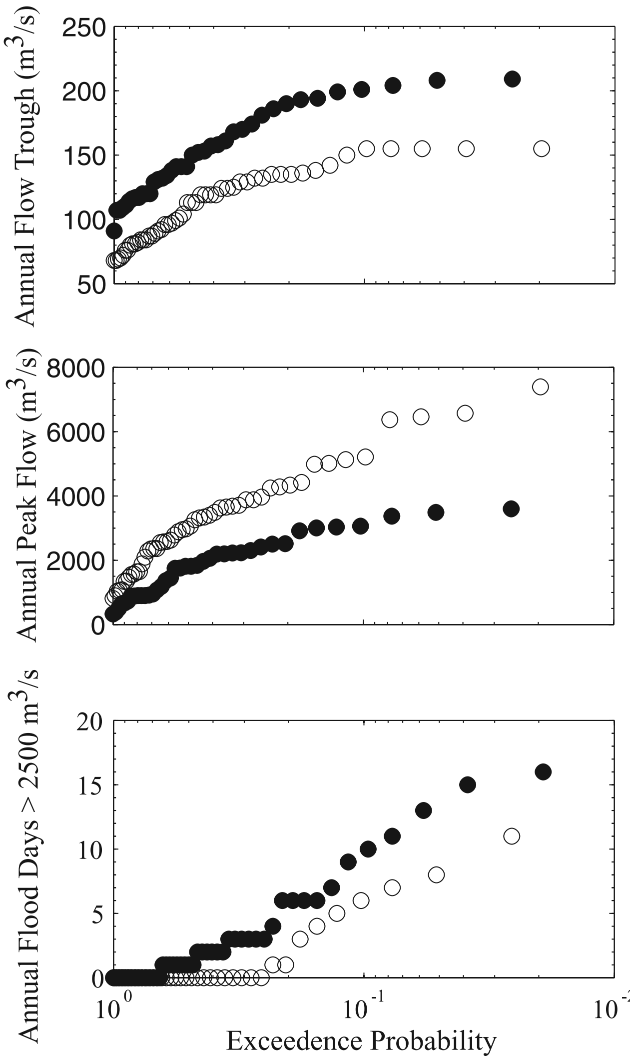

Figure 4. Plots show the effect of Shasta Dam (constructed in 1943) on (top) annual trough flow, (middle) annual peak flow, and (bottom) annual number of flood days greater than 2500 m^3/s at Bend Bridge. Predam data are depicted with open circles, and postdam data are depicted with filled circles. Adapted from *Singer* [2006].

[31] Flow alteration has been proposed on the Sacramento River to increase annual flood peaks in order to reintroduce disturbance (e.g., bank erosion, bar development) to the fluvial system. Proposals also call for an increase in the frequency of flushing flows and a decrease in summer flows, which have been elevated for irrigation diversions. Studies on flow requirements for various aquatic and riparian species and their life stages are generally descriptive in nature. Therefore optimizing a flow alteration rehabilitation strategy for entire ecosystems is problematic at this time, though it is a subject that requires further study. For example, *Kondolf and Wilcock* [1996] specify various types of flushing flows that could be prescribed to meet various aquatic and riparian habitat requirements.

[32] For simplicity, we have modeled the influence of predam hydrology on sediment flux in the current (i.e., 1997) Sacramento River channel. Although we recognize that such a rehabilitation strategy is unrealistic, we model it to understand the first-order impact of flow alteration on sediment flux. As research on the subject of flow alteration advances, our procedure could be amended to reflect a more refined flow alteration strategy.

[33] Predam hydrology represents flow simulated from all major tributaries prior to dam construction. As in our previous flow simulation study [*Singer and Dunne*, 2004a], we used simulated flow at Bend Bridge as our upstream boundary condition. As before, we routed this flow through the main stem Sacramento using unsteady flow routing in HEC-RAS. We extracted stage from 50 simulations of 30-year time series at each main stem cross section used to compute hydraulic variables and sediment flux in our previous postdam study [*Singer and Dunne*, 2004b]. We were interested to know if spatial patterns in sediment flux and storage would persist under very different flow conditions (e.g., Figure 4).

6. Results and Discussion

[34] We present median values of total annual bed material flux at main stem sections and storage in the river reaches shown in Figure 1. The results of all simulations are presented in Tables 1 and 2. The tables also contain the percent change in flux and storage resulting from each rehabilitation strategy. Median values are the middle of the range of all our simulations at the 0.5 exceedence probability and therefore represent expectable patterns. However, for the purpose of risk assessment, it may be of more interest to analyze less frequent outcomes arising from rehabilitation strategies. We discuss this briefly below.

6.1. Gravel Augmentation

[35] The modeled Augmentation1 at Bend Bridge had a large effect on annual totals of sand and gravel flux and storage. There was substantial increase in annual gravel flux at Bend Bridge (108%) and consequently, in annual gravel erosion (154%) in Reach 0 (Table 1). In addition, more than 1 Mt of sand per year moved past Bend Bridge, all of which was supplied by Augmentation1, leading to considerable net sand erosion in Reach 0 (Table 2). The approximate doubling of gravel flux at Bend Bridge results largely from the addition of sand in the bed material (Figure 2), which increased the spread in the grain size distribution and lubricated sediment movement. Because more sand and gravel are moving past Bend Bridge into the downstream reach under Augmentation1, average annual sand and gravel deposition in Reach 1 increased dramatically.

[36] Augmentation2 had the opposite influence on sediment transport and storage. This coarse addition of a narrower range of sediment sizes (Figure 2) at Bend Bridge reduced gravel flux by more than an order of magnitude (Table 1), causing a major change in the balance of gravel storage between Reaches 0 and 1. Reach 0 went from moderately erosional to mildly depositional, and Reach 1 switched in the opposite direction (Table 1).

[37] The two gravel augmentation strategies modeled here both appear to provide benefits to spawning habitat, albeit in different parts of the river. Whereas Augmentation1 increases the movement of spawning gravels at Bend Bridge and their accumulation in Reach 1, Augmentation2 increases the availability of spawning gravel locally at the Bend Bridge site and limits its downstream movement. The results from gravel augmentation modeling are encouraging. They indicate that augmentation of gravels of an appropriate mixture could significantly impact flux rates and sediment storage patterns. Thus, if gravel were added to Reach 0 in volumes sufficient to alter the bed material grain size distribution and in a mixture appropriate for maintaining a storage balance between Reach 0 and 1 (e.g., some combination of Augmentations 1 and 2), three benefits would arise. First, there would be a local increase in salmonid habitat area (i.e., increased spawning habitat in areas covered by the added gravel). Second, the added gravels would alter the bed material grain-size distribution in Reach 0 such that flux of these higher-quality gravels out of the reach would be limited (minimizing the volumes that would have to be added for maintenance). Third, although bed material flux into Reach 1 would be limited, gravel in volumes sufficient to benefit spawning habitat over several years would still move into and accumulate in Reach 1. For example, gravel deposition in Reach 1 following Augmentation1 would cover the bed ~1.2 mm thick, if evenly distributed over the entire bed (assuming: reach length = 100 km; channel width = 200 m; gravel bulk density = 1.8 t/m^3), compared with the preaugmentation gravel coverage thickness of ~0.1 mm. However, instead of accumulating uniformly over a reach, gravel accumulates on bars and in patches and riffles comprising a much smaller percent of the channel area. For example, assuming gravel accumulates in 10% of the channel following Augmentation1, 12 mm of thickness per year, or one half of a Bend Bridge D_{50} grain diameter, would be added to Reach 1. Over several years, this gravel would provide suitable habitat as it accumulates in these selective zones of deposition (e.g., patches or riffles). If higher rates of gravel accumulation were desired in Reach 1, it would be necessary (according to this modeling exercise) to augment an even wider distribution of sediment at Bend Bridge to promote transport into this reach.

[38] In summary of this modeling exercise, there are a few important issues to consider when designing a sustainable gravel augmentation strategy, in addition to where and how much gravel to add within a reach. First, the median grain size of the mixture added to a river reach affects flux rates (e.g., increase in grain size raises threshold for transport, leading to lower transport rates for a given shear stress, although this would be partially offset by a concomitant reduction in θ_c for the entire mixture). Second, the sorting of grain sizes in the added mixture affects flux rates (e.g., a well-sorted mixture of sediments would decrease the sorting coefficient and thus lower transport rates for each grain size) [*Singer and Dunne*, 2004b]. Care should be exercised in designing a sediment mixture that meets local (i.e., where the mixture is added) habitat goals and can be transported in sufficient quantities to provide benefits to downstream aquatic habitat. Third, the location of the added mixture affects cross-sectional averaged flux rates. For example, according to shear stress formulations of sediment transport, the majority of bed material transport happens in the thalweg (e.g., modeled average annual flux of 48 mm

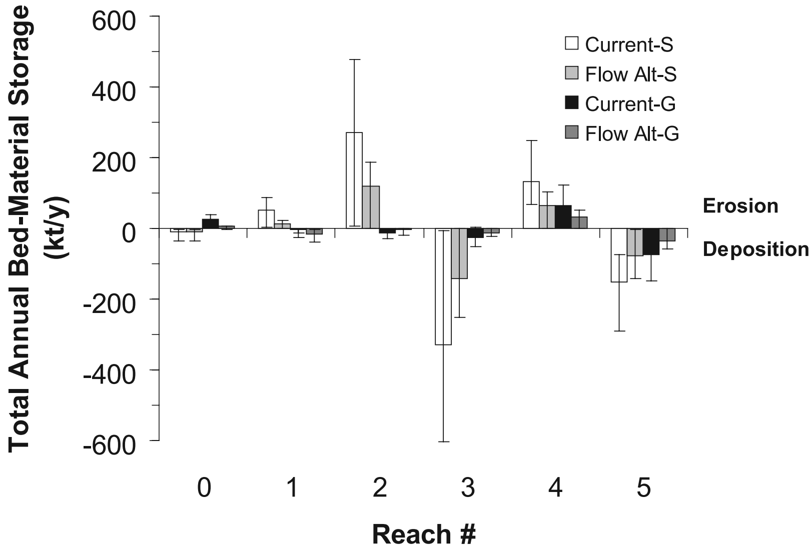

Figure 5. Total annual bed material storage for sand and gravel following 50 simulations of flow alteration on the Sacramento River plotted against reach number (reaches shown in Figure 1). Total annual bed material storage for sand and gravel under current conditions (Current-S and Current-G, respectively) and for sand and gravel under a strategy of flow alteration (Flow Alt-S and Flow Alt-G, respectively). The T-bars represent the variability in median estimates associated with stochastic hydrology as discussed by *Singer and Dunne* [2004b]. Erosion is positive and deposition is negative.

gravel on the bar surface at Bend Bridge is <28% of that in the thalweg). Sediment could be added strategically within a cross section in order to maximize its benefit to habitat, while minimizing its movement. For example, instead of even application of gravel throughout a section, such as assumed in our model due to lack of information on bed material patchiness within cross sections, gravel of an appropriate mixture could be preferentially added on bar surfaces that become inundated (to appropriate flow depths) during spawning seasons. However, it should be noted that recent research has documented high gravel transport rates on bars [*Bunte et al.*, 2006], but such findings have not yet been generalized in sediment transport models. Fourth, gravel augmentation may affect spatial patterns in net sediment storage, which, in turn, may influence the condition of riverine habitats. For example, a postaugmentation shift from net deposition to net erosion in a reach could degrade spawning habitat in a reach downstream of the added gravel.

6.2. Setback Levees

[39] Modeled levee setbacks caused decreases in the flux of gravel and sand at Knights Landing (19% in both, Tables 1 and 2). Net total annual gravel and sand erosion in Reach 4 and deposition in Reach 5 declined similarly, thus affecting the absolute values of modeled imbalances in total annual sediment budgets in the Sacramento River [*Singer and Dunne*, 2004b] (Tables 1 and 2). The floodplain serves to modulate the effects of prolonged floods by providing out-of-channel flood accommodation space for flooding. Consequently, flow stage in the channel declines rapidly during floods, leading to lower total bed material flux per flood. Thus total annual flux of sand and gravel at Knights Landing is reduced (i.e., from 74 to 60 kt/yr for gravel and from 139 to 113 kt/yr for sand). This reduction results in attenuation of storage imbalances between Reaches 4 and 5 (Tables 1 and 2). Specifically, erosion in Reach 4 and deposition in Reach 5 each decline by $\sim$20%, resulting in a more even distribution of sediment throughout these reaches. Our modeling of levee setbacks in the area around Knights Landing resulted in no change in flow stage or bed material flux at the (upstream) Colusa and (downstream) Sacramento cross sections (Figure 1).

[40] The modeling suggests that setback levees are viable for creating meander corridors without negatively affecting sediment budgets, thereby reducing reach storage imbalances in bed material flux. Reduction of cumulative bed stress in a leveed reach will lead to a reduction in sediment transport through that reach, perhaps lessening the aggravated erosion associated with flood control levees [*Biedenharn et al.*, 2000; *Singer and Dunne*, 2001]. Implementation of a successful levee setback strategy, however, requires careful consideration of the changes in hydraulics during flood events. The upstream and downstream boundaries of a reach-scale setback might be subjected to accelerated deposition and erosion, respectively, because of a nonlinear response to local width changes. Two-dimensional flow and sediment transport models are necessary to assess such responses, as well as the coupled effects of increased flow resistance and flood accommodation space on in-channel flow stage.

6.3. Flow Alteration

[41] The results of flow alteration are presented in Tables 1 and 2 and illustrated in Figure 5. The influence of modeled flow alteration on total annual bed-material flux and reach storage is system-wide. Flow alteration reduces total annual sand and gravel flux and storage for most stations (albeit not for Sacramento, where essentially no bed material transport occurs under both scenarios) and reaches, respectively. Annual flux of sand and gravel each decline by 49% to 75% and annual gravel net reach storage

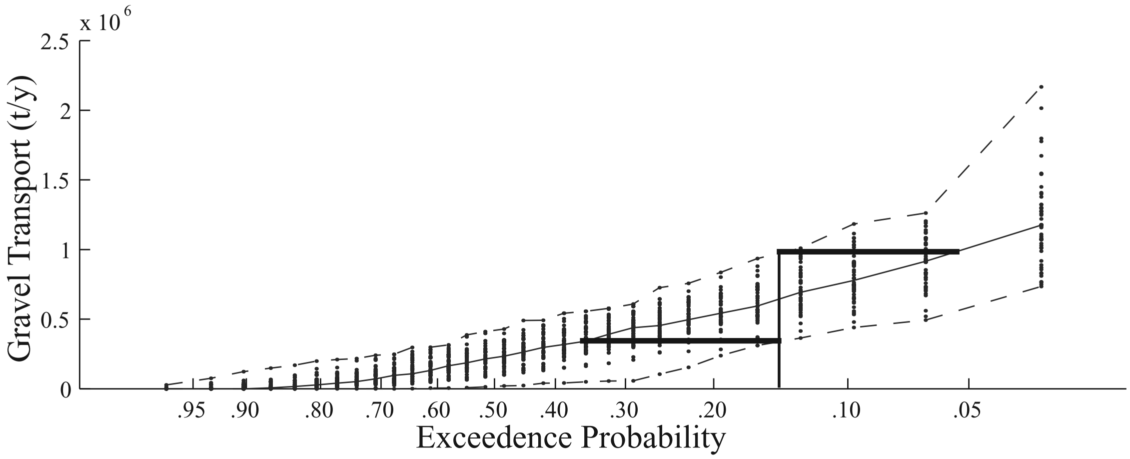

Figure 6. Annual total gravel load resulting from 50 simulations, each of 30 years. Gravel flux (t/yr) is plotted against exceedence probability. The range in transport for each exceedence probability is a result of the variability in stochastic hydrology. These ranges form of band of risk instead of a single frequency curve. This paper reports median values (i.e., solid line at 0.50 exceedence probability). However, for risk assessment, it may be more useful to analyze transport at low exceedence probabilities. For example, the figure shows that the maximum and minimum flux values at the 0.15 exceedence probability approximately correspond to the median flux values at 0.05 and 0.35, respectively.

drops by 49% to 83% for gravel and between 49% and 77% for sand (Tables 1 and 2). The exception to systematic decreases in net storage is that modeled flow alteration causes increased (300%) accumulation of gravel in Reach 1 because of dramatically reduced sediment flux at Hamilton City (Table 1 and Figure 5). This suggests that flow alteration may also contribute to the replenishment of spawning gravels in Reach 1 in the absence or in combination with gravel augmentation. Modeled flow alteration also increases 1-day peak sand and gravel storage for most reaches.

[42] The interpretation is that although the predam flow regime (i.e., modeled flow alteration) is more variable and peaked (on the 1-day timescale), it results in lower values of annual net storage in each reach. This generally manifests as higher rates of transport during flood peaks (i.e., due to higher flow peaks), but shorter peaks (i.e., fewer days of significant sediment transport). Reservoir operation for flood control in the Sacramento Valley tends to prolong the release during floods [*Singer*, 2006]. Because much of this water is released at flows above the critical transporting flow, higher total flux results merely because of the duration of the release compared with the short, sharp peaks in the predam era.

[43] The effect is illustrated in flow probability plots of annual peak discharge, annual trough discharge (lowest flow), and number of flow days above a threshold of significant sediment transport (Figure 4). Although annual peak flows are reduced for all exceedence probabilities (Figure 4, middle panel), annual trough flows are higher (top panel). More important, however, is the increase in the number of flood days per year above the threshold for sediment transport (Figure 4, bottom panel). According to this plot (from the historical flow series at Bend Bridge), there were no flow days greater than this threshold in 75% of years in the predam era, while the postdam era had 1, 2, and 3 days of such sediment transporting flows between 30% and 75% of years, depending on the station. In 4% of years, the number of flood days in the postdam era was approximately double. The two cumulative plots are significantly different according to the Kolmogorov-Smirnoff (K-S) statistic (K-S = 0.40, p-value <0.001), and the differences in their integrals indicate many more days of sediment movement and thus higher volumes of sediment flux in the postdam era, in spite of higher peak flows in the predam era (Figure 4, middle panel).

[44] These factors suggest that flow alteration is a feasible strategy to benefit habitat via a more natural flow regime without aggravating imbalances in total annual sediment budgets. Our modeling shows that 1-day peak erosion in a particular reach during a larger flood peak would not persist over the long term. It is beyond the scope of this paper to outline a strategy for flow alteration that would benefit an array of habitats and remain economically (and politically) feasible. However, our modeling confirms that a presumably extreme strategy of simulating the natural (predam) flow regime would not cause aggravated erosion or deposition in the Sacramento River.

6.4. Risk Assessment

[45] This paper reports median values of flux at select cross sections and net storage between sections. Our method is driven by a stochastic flow generator so multiple outcomes are produced. Each simulation produces a unique combination of flood frequency, duration, and magnitude along the main stem based on variability in tributary inflow. In this application of the model, a sediment flux frequency curve is produced for each simulation. Multiple curves plotted on the same diagram define a band of potential risk of outcomes from a rehabilitation strategy (Figure 6). In other words, each vertical line of dots on Figure 6 represents an aggregate of 50 simulations from which we can summarize the median and range at a particular exceedence probability.

[46] The median values reported in this paper represent the central tendency of the whole distribution of outcomes.

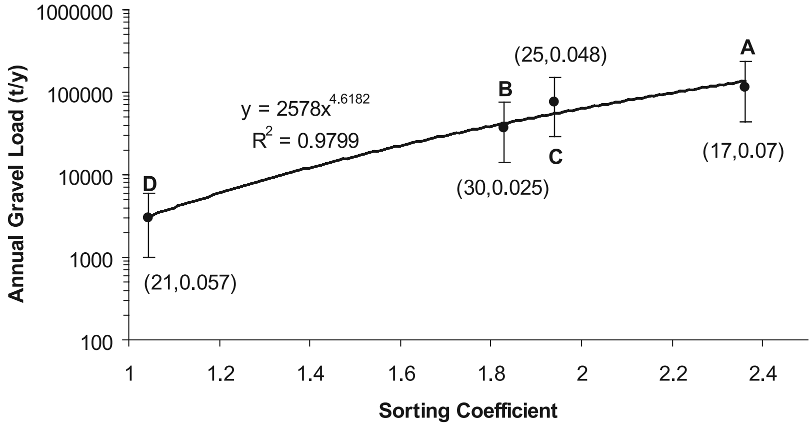

Figure 7. Model sensitivity to sorting coefficient at Bend Bridge. Four separate sets of simulations varying only the grain size distribution yield a range of median annual gravel loads. Error bars represent the range of all fifty 30-year simulations (i.e., varying hydrology). Numbers in parentheses near each point indicate D_{50} (mm) and threshold Shields stress and for each modeled grain size distribution. Bold letters refer to distributions discussed in the text.

The band of risk illustrated in Figure 6 can be also be used to define the highest and lowest values, or expected range, of sediment flux resulting from all simulations. This type of risk characterization could be useful in anticipating extremes within the distribution. In cases where large sums are being spent on major river rehabilitation, it may be necessary to more fully investigate the extremes within our modeled outcomes. Such extremes may be reflective of the current and future influence of climate change on basin hydrology [e.g., *Singer*, 2006]. The figure shows that the maximum and minimum flux values at the 0.15 exceedence probability approximately correspond to the median flux values at 0.05 and 0.35, respectively. In other words, there is a much wider range of gravel flux generated via stochastic simulation that might be anticipated and incorporated into decision tools. However, such an analysis is beyond the scope of this paper.

6.5. Model Sensitivity

[47] The reader might wonder how sensitive the presented sediment transport modeling results are to the choice of inputs. In addition to the sensitivities to the imposed hydrology previously discussed and hydraulics including bed geometry and slope, the empirical sediment transport formula derived by *Singer and Dunne* [2004b] is very sensitive to the relationship between observed transport rates and grain size distributions in the bed, the latter of which are described in the model by four quantities: sorting, median grain size, Shields stress (a function of median grain size), and the proportion of the distribution in each grain size class. We tested model sensitivity to each of these parameters by running the model with four separate grain size distributions for fifty 30-year simulations at Bend Bridge. We used the following four distributions (Figure 2): one from a downstream bar reported by *Singer and Dunne* [2004b]; one recently acquired for this paper to represent current conditions; Augmentation1; and Augmentation2. The results are summarized in Figure 7.

[48] For a given series of imposed flow, transport calculations are most sensitive to sorting in the bed (Figure 7), with significantly less sensitivity to median grain size or its covariant, threshold Shields stress. These sensitivities emerge directly from *Singer and Dunne* [2004b, equations (12) and (14)], which tie transport to the grain size distribution in a way that is consistent with prior research on the relationship between grain size distribution and mobility in the field [e.g., *Church and Hassan*, 2002; *Reid and Laronne*, 1995] and the laboratory [e.g., *Paola and Seal*, 1995; *Wilcock et al.*, 2001]. The model is also obviously very sensitive to the proportion of sediment in each grain size class because for a given set of hydraulic parameters, the flow can only move sediments above entrainment threshold that are actually locally present in the bed [*Wilcock*, 1997]. For example, a modeled gravel augmentation that replaces the bed with only coarse sediments cannot result in the transport of sand.

7. Conclusion

[49] We assessed the effect of three river rehabilitation strategies on decadal trends in sediment flux. Gravel augmentation was found to either increase or reduce sand and gravel flux, depending on grain size distribution of the added gravels. A successful strategy of augmentation requires careful thought about the grain size distribution of the added gravels, location of their placement within a cross section, and spatial patterns in sediment storage, in addition to the volumes and locations within a reach. Setting back flood control levees was found to be a viable strategy for reducing sediment flux (and aggravated levee-induced erosion) and modulating large net imbalances in the sediment budget. Flow alteration was found to decrease total annual flux and storage throughout the river system. This paper is an early attempt to assess the long-term impact of habitat rehabilitation by general assessments habitat condition (e.g., sediment transport and storage) over large river reaches. Future work in this area should be directed toward increasing the spatial resolution of transport and storage calculations, considering how sediment accumulation or removal from a reach affects the bed texture, and establishing direct links between sediment storage changes and physical habitat characteristics.

[50] **Acknowledgments.** We thank Jonathan DeStaso (U.S. Bureau of Reclamation) for providing data on gravel augmentation. We also appreciate helpful reviews by John Pitlick, Jack Schmidt, and an anonymous reviewer. We acknowledge the support of the CALFED Bay-Delta Program (grant 4600002659) and the National Science Foundation (grant 0521663). Part of this research was performed while Singer held a National Research Council Research Associateship Award at USGS Menlo Park.

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