CHAPTER 4. MODELING THE DECADAL INFLUENCE OF RIVER REHABILITATION SCENARIOS ON BED-MATERIAL SEDIMENT TRANSPORT IN A LARGE RIVER BASIN

Abstract

To illustrate the utility of modeling tools described in the foregoing chapters, I simulated the impact of river rehabilitation strategies on decadal bed-material flux in the Sacramento River. I used a stochastic flood generator and calibrated sediment transport formulae to compute daily sediment flux past various mainstem cross sections and net accumulation between them. I modified constants in the model space to reflect the implementation of three major river rehabilitation strategies being considered in the Sacramento Valley: gravel augmentation, setback levees, and flow alteration [*CALFED*, 1997]. I compiled the results of 50 simulations, each of 30 years, to generalize about the long-term influence of these strategies on bed-material sediment transport and storage in the Sacramento. As such, the results describe changes in habitat distribution and condition before and decades after river rehabilitation. The results indicate that rehabilitation strategies modulate imbalances in total annual bed-material sediment budgets.

Introduction

Lowland aquatic riverine ecosystems have declined over the last century, primarily in response to deforestation and engineering intended to control floods, generate hydroelectricity, irrigate agricultural fields, and provide drinking water [*American Society of Civil Engineers*, 1992; *Power et al.*, 1995; *Vitousek et al.*, 1997; *Anderson*, 2000]. Dams have altered the timing, frequency, magnitude, and duration of floods and have cut off sediment supply from upstream [*Williams and Wolman*, 1984; *Richter et al.*, 1996; *Magilligan*, In Press]. Flood control levees have disconnected rivers from their floodplains, increased in-channel flow depths and shear stresses [*Laddish*, 1997; *Gergel et al.*, 2002], and prevented sediment recruitment from bank erosion sources. Gravel mining operations in riverbeds and floodplains have further limited sediment supply, especially coarse material required by salmonids. Due to reduced sediment supply, bed-material substrates have coarsened downstream of major dams, further limiting the ability of salmonids to find suitable spawning habitat [*Kondolf and Wolman*, 1993; *Kondolf*, 1995]. Sediment transport has also been affected by localized degradation due to channelization [*Biedenharn et al.*, 2000; *Singer and Dunne*, 2001], and deposition resulting from reduced flood peaks [*Kondolf and Wilcock*, 1996; *Pitlick and Van Steeter*, 1998]. These factors have altered the forcing conditions of processes that control rivers characteristics, the links between sediment and aquatic habitats [*American Society of Civil Engineers*, 1992], and thus the habitats themselves.

Much of the previous research on rehabilitation in fluvial systems has focused on descriptions of how flow regimes have been altered (e.g. [*Richter et al.*, 1996;

Richter et al., 1998; *Richter and Richter*, 2000; *Magilligan*, In Press]) and generally how these alterations affect aquatic and riparian ecosystems (e.g. [*Vannote*, 1980; *Junk et al.*, 1989; *Sparks*, 1992; *Stanford et al.*, 1996; *Poff et al.*, 1997]). Other work has focused on the frequency and timing of flood pulses that mobilize the bed, release fines, and clean fish roe of fine sediment 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 transport to compute the effective discharge for channel maintenance in the Upper Colorado River. To my knowledge, there is only one unpublished study that has analyzed the effect of setback levees on shear stress in a river channel [*Laddish*, 1997]. This study used simplified channel geometry and hydraulics to compute the setback distance necessary to reduce channel shear stress to a value below the threshold for entrainment in a 10-mile reach of the upper Sacramento. The results were computed for the 2-year flood. Another unpublished study analyzed the effect of different setback distances on stage-discharge relationships in the lower Sacramento [*Bozkurt et al.*, 2000]. Still another quantitative study analyzed the effects of levee setbacks on riparian communities [*Gergel et al.*, 2002].

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

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 long-term influence of such strategies on sediment transport in river channels is limited.

The explicit links between channel sediment regime and aquatic riverine habitats have been reviewed elsewhere (e.g. [*American Society of Civil Engineers*, 1992]). In general, spatial and temporal patterns in sediment transport control long-term sediment budgets (e.g. net states of erosion or deposition), disturbance regimes (e.g. the frequency of gravel-bed mobilization), substrate conditions (e.g. the frequency of fine sediment flushing), and channel morphology (e.g. the habitat suitability of a particular river reach). Therefore, there is a need for modeling capability to analyze the response in sediment transport to rehabilitation scenarios within the context of streamflow variability. In this paper, I present an applied model that couples stochastic streamflow with bed-material flux calculations to simulate the adjustment in sediment flux to river rehabilitation scenarios. I demonstrate the model by simulating three river rehabilitation strategies in the Sacramento basin: gravel augmentation, flood control levee setbacks, and flow alteration.

However, to my knowledge, there is a paucity of literature on the long-term impact of proposed rehabilitation strategies on sediment transport, in general. It would be useful to know, for example, what effect rehabilitation strategies would have on sediment transport decades after their implementation. The lack of such a predictive tool may have already contributed to timing errors in a flow experiment intended to create sand bars in the Colorado River [*Rubin et al.*, 2002]. I have developed the modeling capability to assess such long-term trends, including sediment supplies from tributaries, within the context of streamflow variability. This type of prediction would allow agencies responsible for river management to anticipate the central tendency, extrema, and probabilities of outcomes of these strategies, in particular river cross sections, in river reaches, or along entire river valleys.

Study Basin

The Sacramento River basin is ~70,000 km^2 in area and drains four geologic provinces. This study focuses on rehabilitation implementation in the mainstem Sacramento, which spans ~400 river kilometers and consists of an entrenched gravel-bed in the upper reaches and a mixed sand and gravel bed with a broad, flat floodplain in the lower reaches. It is a generally low gradient river (mean slope ~2.0 x 10^{-4}) that is affected by its tectonic and geologic legacy. 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.

The bed of the upper Sacramento between Keswick and Bend Bridge (Figure 4.1) is poorly sorted [*Blott and Pye*, 2001] coarse gravel (subsurface d_{50} ~40 mm, surface d_{50} ~85 mm, unpublished data from Calif. Dept. of Water Resources), which is armored in locations due to selective entrainment of finer gravels particles without their replacement from upstream sources. Between Bend Bridge and Knights Landing, the Sacramento flows over a very poorly sorted [*Blott and Pye*, 2001] bed of gravel and sand with localized sources of dissected coarse Pleistocene gravels. Between Knights Landing and Sacramento the river flows over a moderately sorted [*Blott and Pye*, 2001] sandy bed. Flood control levees have been built upon channel banks (especially in the lower Sacramento) to concentrate flow in the mainstem and shunt flood flow into bypasses via flood diversions. In this paper, I model river rehabilitation strategies in the mainstem Sacramento from below Shasta Dam (Keswick) down to the city of Sacramento (Figure 4.1). I compute transport at the following gauging stations: Bend Bridge (BB), Hamilton City (HC), Butte City (BC), Colusa (CO), Knights Landing (KL), Sacramento (SA). I also compute net accumulation of sediment in the river reaches between these stations.

Setting for Rehabilitation

Settlement of the Sacramento Valley began in earnest at the time of the California Gold Rush. 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. Soon the combined influence of their political will and shoaling of the lower Sacramento due to hydraulic mining led to the implementation of a major flood control project funded by the United States government [*Kelley*, 1998]. The Army

Corps of Engineers constructed a system of levees and flood bypasses to convey flows below a threshold through the mainstem and shunt flows above the threshold through bypasses. The project was augmented between 1943 and 1967 with the construction of dams on the mainstem and its tributaries. Shasta Dam, constructed in 1943, has had the largest effect on streamflow in the Sacramento River [*US Army Corps of Engineers*, 1998].

Settlement of the Sacramento Valley over the last 150 years and the operation of the flood control system over the past 80 years have had negative effects on the riparian and aquatic habitats along the mainstem Sacramento, e.g. [*Thompson*, 1961; *Nielsen*, 1989; *Babcock*, 1995; *Taylor*, 1996; *Hunter*, 1999]. Terrestrial floodplain habitats have been degraded by human settlement, deforestation and severing of the connection between the Sacramento and its floodplain by high artificial levees. Aquatic habitats have declined due to alteration of natural streamflow below 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; *Reeves and Roelofs*, 1982; 1985; *Kondolf*, 1995]. Fall run chinook, for example, had 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]. 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.

The degradation of these habitats has been the impetus for a major rehabilitation effort funded by the governments of the United States and the State of California. Among other things, federal and state 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*, 1997]. Proposed 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 pre-dam natural Central Valley streamflows [*CALFED*, 1997]. I analyzed the long-term, first-order impacts of these proposed strategies on bed-material sediment flux throughout the Sacramento basin.

Model Outline

I conducted this study using the wealth of data available for the Sacramento basin including bathymetry of the river channel, decades of historical daily streamflow, bed material surveys, and bedload measurements. I made assessments of the impact of rehabilitation strategies on total annual and one-day peak sediment budgets in river reaches of the Sacramento River from Shasta Dam to the city of Sacramento (Figure 4.1).

My 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 in two previous papers [*Singer and Dunne*, Submitted-a; *Singer and Dunne*, Submitted-b], so I only outline them here. In this paper, I focus the discussion on how I alter the model space to reflect each rehabilitation strategy, the results of my modeling, and their implications for future work in river rehabilitation.

I developed a stochastic streamflow simulation model, HYDROCARLO, which semi-randomly samples from a collection of historical flood events at major tributary gauging stations [*Singer and Dunne*, Submitted-a]. HYDROCARLO was designed to simulate inflow into the mainstem of a large river from each of its major tributaries based on correlations in the flow records between them. I routed the simulated inflow through ~1000 cross sections (spaced ~800 m apart) along the mainstem Sacramento (extracted from bathymetry) using unsteady flow routing within HEC-RAS (HEC-RAS employs an implicit finite difference solution to the 1-D flow equations [*Barkau*, 1997]). Thus I simulated flow stage on a daily basis for many locations on the mainstem for a period of decades. Each simulation results in a stage and flow frequency curve for each location, which can be statistically analyzed to yield maxima, minima, and median values for each exceedence probability.

My bed-material flux model uses the stage output from HEC-RAS at selected mainstem locations to compute hydraulic variables. I modified and calibrated the Engelund-Hansen sediment transport formula [*Engelund and Hansen*, 1967] to simulate daily bed-material transport in various grain size classes [*Singer and Dunne*, Submitted-b]. The model constants are cross-sectional geometry (extracted from bathymetry), bed-material grain size distribution (from bulk surveys), the alpha parameter for the transport equation (calibrated via multiple regression on grain size and local bed-material sorting coefficient), and dimensionless critical shear stress (computed from bedload data). I computed water surface slope at each cross section as a whole, and stage, velocity, shear stress, Shields stress, and excess shear stress for each portion of the cross section. I used these variables to compute daily bed-material flux at each station. These fluxes can be generalized to compute long-term estimates of total annual or one-day peak sediment flux. In conjunction with stochastic hydrology these estimates can be presented in a probabilistic framework to assess the risk of a particular outcome.

In my model development, I assumed one-dimensional flow, no bed armoring, sediment supply is limited by the proportions of each grain size present in the bed material, even distribution of bed material grain sizes across my sections, and no cross-sectional change. Furthermore, I compute mass balance for ~60 km river reaches, but make no mechanistic assessments of the resulting morphological change. As such, my assessments of transport and net divergence are first-order approximations made using the best available data. However, the values reported here provide a systematic view of the long-term spatial patterns in sediment transport resulting from major river rehabilitation strategies.

Rehabilitation Strategies

Gravel Augmentation

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 Dept. 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 bedload 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 4.1), though it is not clear how far downstream the consequential armor layer extends.

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 were identified as active spawning sites and the added gravels were supposed to improve the existent spawning sites and create new ones [*California Department of Water Resources*, 1980]. Under the mandate of California Senate Bill (SB) 1086 (1986) and the federal Central Valley Project Improvement Act (CVPIA) (1992), ~1.5 Mt of gravel have been added to the upper Sacramento River below Shasta Dam between 1978 and 2000 at a cost of ~$26M (unpublished data from US Bureau of Reclamation). However, there has been little to no monitoring of augmented gravels to compute transport rates, nor to determine the efficacy of gravel augmentation in improving in-stream habitat for fish (J. DeStaso, US Bureau of Reclamation, pers. comm.).

In a previous bed material study [*Singer and Dunne*, Submitted-b], I estimated long-term annual erosion of ~1.2 Mt/y in Reach 0, about ~0.7 Mt/y of which was eroded gravel size fractions (Tables 4.1 and 4.2). This erosion trend exacerbates the effect of up-basin gravel mining and dam trapping, depleting Reach 0 of gravel. One-day peak sediment budgets showed the same erosional trend with ~26 kt/d, about 17 kt/d of which was gravel (Tables 4.3 and 4.4).

I modeled gravel augmentation at the Bend Bridge (BB) cross section (at the lower end of Reach 0, Figure 4.1) to assess its effect on one-day peak and total annual sediment loads at this station and net accumulation for the upstream and downstream reaches. I represented augmentation by adjusting the grain size distribution of the bed material to reflect a mixture recommended to improve spawning habitat [*California Department of Water Resources*, 1980]. This mixture is reflected in the following percentages of each grain size class: 96 mm (10%), 48 mm (30%), 24 mm (20%), 12 mm (10%), 6 mm (5%), 3 mm (5%), 1.5 mm (5%), and 0.75 mm (5%). I assume that the added gravels completely cover the bed to the scour depth and define the bed material grain size distribution. Accordingly, the new, coarser distribution (Figure 4.2) increases the d_{50} (from 9.5 mm to 23 mm) and decreases the critical shear stress (from 0.053 to 0.020). The added mixture also decreases the sorting coefficient of the whole distribution (from 2.49 to 2.09), indicating a narrower distribution of grain sizes and higher pocket angles. I re-calibrated my sediment transport equation based on these changes.

Setback Levees

Flood control levees are an integral part of the Sacramento 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. Levees in Reaches 4 and 5 were built upon the original channel banks (in most locations). Levee setbacks were proposed in SB 1086 and CVPIA to increase flood capacity and to re-establish riparian vegetation communities [*Nielsen*, 1989]. These communities would provide shade and cover from predators for fish. The allowance for overbank flow would reduce flow depths in the river channel (Figure 4.3), thus reducing the risk of systematic 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 substrate, the velocity field, sediment transport rate, and thus the aquatic habitat structure.

I modeled the effects of levee setbacks on bed-material transport in a constrained reach of the lower Sacramento River. My previous work on long-term sediment budgets identified Reach 4, between Colusa (CO) and Knights Landing (KL) (Figure 4.1), as one undergoing significant net erosion [*Singer and Dunne*, 2001; *Singer and Dunne*, Submitted-b]. I modeled levee setbacks by increasing (artificial) levee-to-levee width to ~3 km in a 16 km stretch of river (extending 8 km upstream and 8 km downstream of Knights Landing) within my HEC-RAS geometry file. It should be noted that 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, I am increasing the area of channel/floodplain that can be accessed by a given flood, thus reducing flow depth in the channel (Figure 4.3). I extracted daily stage at Knights Landing from HEC-RAS for 50 simulations of 30-year time series to determine the long-term effect of the setbacks on sediment transport at this section.

Flow Alteration

Streamflow in the Sacramento River has been dramatically altered by major dams operated for flood control, irrigation, and hydroelectricity. Figure 4.4 shows flood frequency curves for pre- (1891-1928) and post- (1964-2001) Shasta Dam discharge at Bend Bridge (Figure 4.4). These curves show a reduction in maximum peak flows at most exceedence probabilities. There is reason to believe that dam operation has had a large effect on sediment transport in the Sacramento River. For example, a flow of 1800 cms (approximately ¾ bankfull) was exceeded ~80% of the time in the pre-dam era and only ~55% of the time in the post-dam. I expect that such altered hydrology would have systematic impacts on the sediment budget throughout the Sacramento River.

Flow alteration has been proposed on the Sacramento River to increase maximum flood peaks in order to reintroduce disturbance (e.g. bank erosion, bar development) to the fluvial system. The proposal also calls 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. These authors discuss the conflicts inherent in meeting flow objectives for entire ecosystems.

For simplicity, I have modeled the influence of pre-dam hydrology on sediment transport in the recent Sacramento River channel. Although I recognize that such a rehabilitation strategy is unrealistic, I model it to understand the first-order impact of flow alteration on sediment transport. As research on the subject of flow alteration advances, my procedure could be amended to reflect a more refined flow alteration strategy.

Pre-dam hydrology represents flow simulated from all major tributaries prior to dam construction. As in my previous flow simulation study [*Singer and Dunne*, Submitted-a], I used simulated flow at Bend Bridge as my upstream boundary condition. As before, I routed this flow through the mainstem Sacramento using unsteady flow routing in HEC-RAS. I extracted stage from 50 simulations of 30-year time series at each mainstem cross section used to compute hydraulic variables and sediment transport in my previous post-dam study [*Singer and Dunne*, Submitted-b]. I was interested to know if spatial patterns in sediment transport would persist under very different flow conditions (e.g. Figure 4.4).

Results and Discussion

I present median values of total annual and one-day peak bed-material load past mainstem stations and divergence in the river reaches shown in Figure 4.1. The results of all simulations are presented in Tables 4.1-4.4. The tables also contain the percent change in transport or divergence resulting from each rehabilitation strategy. Median values represent the middle of the range of all my 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. I discuss this briefly below.

Gravel Augmentation

The modeled gravel augmentation strategy at Bend Bridge had a large effect on both total annual and one-day peak sand and gravel transport. There were large declines (~96%) in annual gravel and sand flux at Bend Bridge and consequently, in annual gravel and sand erosion in Reach 0 (Tables 4.1 and 4.2). The decrease in transport at Bend Bridge largely results from coarsened bed material and narrowing of the grain size distribution following augmentation (the added mixture is composed of only 10% sand, less than half the sand content of the pre-augmentation bed material). Because less sand and gravel are moving past Bend Bridge into the downstream reach under gravel augmentation, Reach 1 shifted from one of net bed-material deposition to net bed-material erosion (Table 4.2). Peak gravel and sand flux past Bend Bridge and peak divergences in Reaches 0 and 1 also declined (Tables 4.3 and 4.4).

The gravel augmentation strategy modeled here appears to provide local benefits to Reach 0, but may be harmful to existing spawning habitat in Reach 1. My modeling suggests that prior to gravel augmentation, Reach 1 was in a state of net gravel deposition. In other words, Reach 1 formerly benefited from high annual rates of gravel erosion in Reach 0. Eroded gravels from Reach 0 would likely form a substrate for high quality spawning habitat in this relatively wide and low-gradient reach [*Singer and Dunne*, Submitted-b]. However, following gravel augmentation, the coarse added mixture could dramatically slow the rate of gravel erosion in Reach 0 and shift Reach 1 to one of net gravel erosion, potentially degrading high quality spawning habitat. However, the results from gravel augmentation modeling are encouraging. They indicate that augmentation of gravels of an appropriate mixture could significantly impact transport 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 a mixture appropriate for maintaining a storage balance between Reach 0 and 1, three benefits would arise. First, there would be a local increase in 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 the reach such that transport decreases at its downstream end (minimizing the volumes that would have to be added). Third, although bed-material transport would decrease at Bend Bridge, gravel in volumes sufficient to benefit spawning habitat would still move into Reach 1.

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 transport rates (e.g. higher median grain size leads to lower transport rates, although this would be partially offset by a concomitant reduction in dimensionless critical shear stress). It is not surprising that grains in coarse riverbeds (armored beds are an extreme example) would move less frequently than those in fine riverbeds. Second, the sorting of grain sizes in the added mixture affects transport 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*, Submitted-b]. Careful 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 transport rates. For example, the majority of bed-material transport happens in the thalweg (e.g. average annual transport of 48 mm gravel on the bar surface at Bend Bridge is <28% of the that in the thalweg). Sediment could be added strategically within a cross section in order to maximize its benefit to habitat, while minimizing its transport. For example, instead of even application of gravel throughout a section (assumed in my 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. Fourth, gravel augmentation may affect spatial patterns in net sediment storage, which in turn, may influence the condition of riverine habitats. For example, a shift from net deposition to net erosion in a reach could degrade spawning habitat in a reach downstream of the gravel augmentation.

The cost of gravel augmentation would include the purchase and transport of the gravel mixture from an off-channel gravel mine, placement of gravel in selected locations within reaches and cross sections, monitoring of placed gravels to track their transport, and monitoring of spawning habitat and fish use.

Setback Levees

Modeled levee setbacks had major influence on the transport of gravel and sand at Knights Landing (a decline of 54%, Tables 4.1 and 4.2). Total annual gravel divergences in Reaches 4 and 5 declined similarly. Under the modeled setback strategy, the changes in net accumulation in these reaches have a huge impact on the absolute values of the largest modeled imbalances in total annual sediment budgets in the Sacramento River [*Singer and Dunne*, Submitted-b](Tables 4.1 and 4.2). One-day peak gravel and sand transport increased by 15% and 8%, respectively (Tables 4.3 and 4.4). These factors indicate that the increased resistance of the floodplain (now exposed to down-valley flow) may increase peak flood stage, and thus slightly increase one-day peak transport rates at Knights Landing. However, this effect appears to be short-lived under a strategy of levee setbacks, because the floodplain serves to modulate the effects of a prolonged flood event by providing out-of-channel flood accommodation space for flooding. Consequently, flow stage in the channel, while temporarily elevated, declines rapidly during floods, leading to lower bed-material transport volumes per flood. Thus, total annual transport of sand and gravel at Knights Landing is reduced.

The modeling suggests that setback levees are viable for reducing large reach divergences in bed-material transport. Implementation of a successful levee setback strategy, however, requires careful consideration of the changes in hydraulics during flood events. A two-dimensional flow model is necessary to assess the coupled effects of increased flow resistance and flood accommodation space on in-channel flow stage. The cost of setback levees would include the price of contiguous floodplain lands required to create a river corridor, earth-moving and construction costs, and monitoring of benefits to aquatic and riparian habitats. However, the cost of setback levees could be partially offset by obtaining easements or leasing the corridor for seasonal agricultural use (as is done in Sutter and Yolo Bypasses). Incidentally, my modeling of levee setbacks in the area around Knights Landing resulted in no change in flow stage or bed-material transport at the Colusa and Sacramento cross sections (Figure 4.1 and Tables 4.1 and 4.2).

Flow Alteration

The results of flow alteration are presented in Tables 4.1-4.4 and illustrated in Figures 4.5 and 4.6. The bars in these figures represent divergences in sand (S) and gravel load (G) under the current (Current) and the altered (Flow Alt) flow regimes. The T-bars represent the variability in median estimates associated with stochastic hydrology [*Singer and Dunne*, Submitted-b]. Figure 4.6 shows total annual divergences and Figure 4.6 shows one-day peak divergences. Erosion is positive and deposition is negative.

The influence of modeled flow alteration on total annual bed-material transport and reach divergence is systemic. Flow alteration reduces sand and gravel transport divergences for all stations (except for Sacramento, where no changes occur) and reaches, respectively. Flow alteration increases one-day peak sand and gravel transport for most stations and peak reach divergences. The interpretation is that although the pre-dam flow regime (i.e. modeled flow alteration) is more variable and peaked, it has a lower median value of reach-scale scour and accumulation. This generally results in higher transport during flood peaks (i.e. due to higher flow peaks), but shorter peaks. Reservoir operation for flood control tends to prolong the release during floods, delivering the same amount of water over a longer duration. Because much of this water is released at flows above the critical transporting flow, higher total transport results merely because of the duration of the release compared with the short, sharp peaks in the pre-dam era.

This suggests that flow alteration is a feasible strategy to benefit habitat without aggravating imbalances in total annual sediment budgets. My modeling indicates that periodic scour in a particular reach during a larger flood peak would eventually fill in on the steep falling limb of a natural Sacramento River hydrograph. 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, my modeling suggests that any strategy that simulates aspects of the natural flow regime would not cause aggravated erosion or deposition in the Sacramento River. The cost of a flow alteration strategy would include design of a flow regime that balances the requirements for flood control, habitat, irrigation, and water supply, payment to companies and/or agencies for losses in hydroelectricity generation, and monitoring of benefits to habitat.

Risk Assessment

This paper reports median values of transport and net divergence in transport. My 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 mainstem based on variability in tributary inflow. In this application of the model, a sediment transport frequency curve is produced for each simulation. Multiple curves define a band of potential risk of outcomes from a rehabilitation strategy (Figure 4.7). The median values reported in this paper represent the central tendency of the whole distribution of outcomes. The band of risk illustrated in Figure 4.7 can be also be used to define the highest and lowest values, or expected range, of sediment transport 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 my modeled outcomes. However, such an analysis is beyond the scope of this paper.

Conclusion

I assessed the effect of three river rehabilitation strategies on long-term trends in sediment transport. Gravel augmentation was found to reduce sand and gravel transport, thus affecting reach divergences. 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 transport and modulating large net imbalances in the sediment budget. Flow alteration was found to decrease total annual transport and divergence throughout the river system, though it generally increases the effect of individual flood peaks. This paper is an early attempt to assess the decadal 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 and establishing direct links between physical habitat condition and species success.

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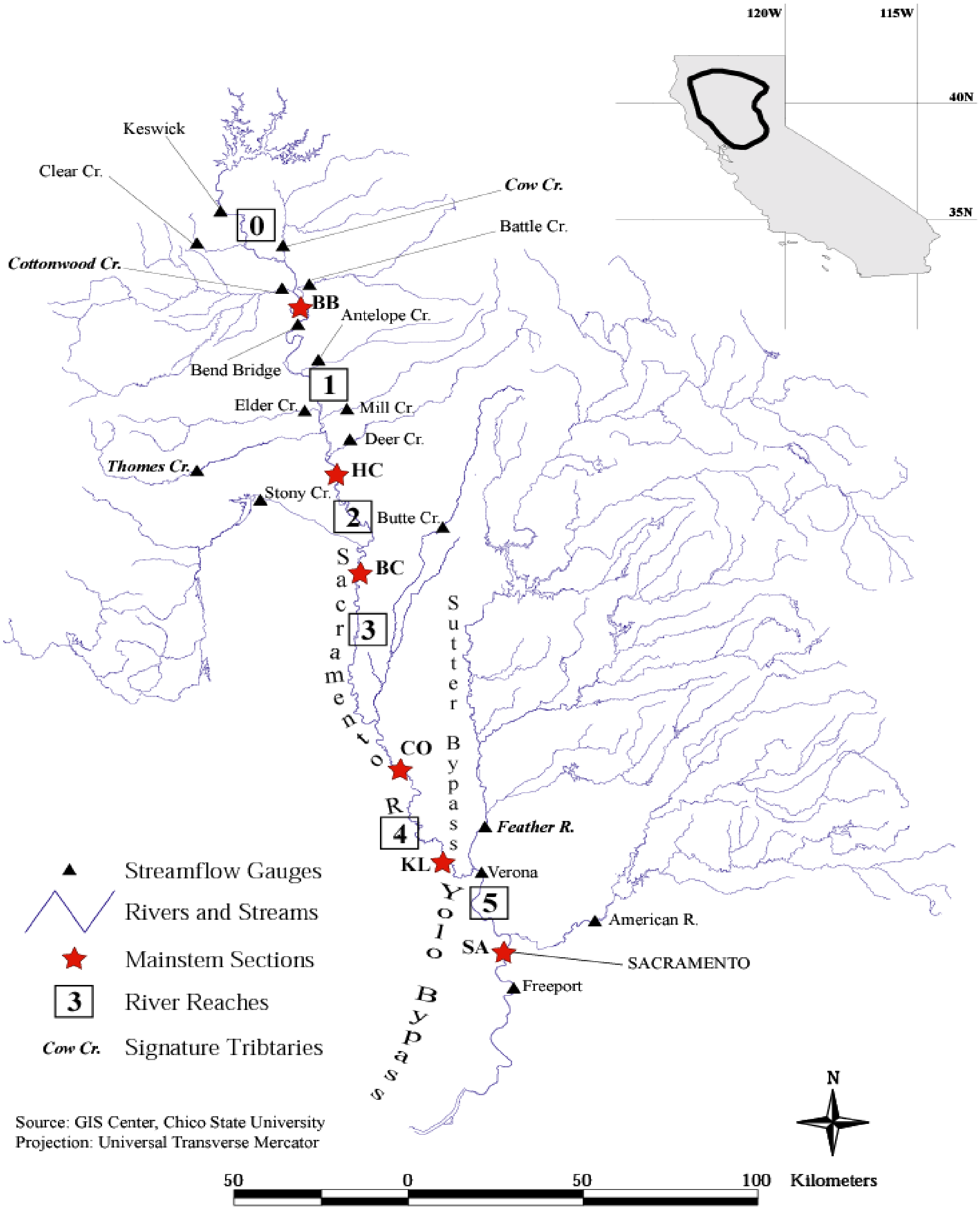

Source: GIS Center, Chico State University
Projection: Universal Transverse Mercator

Figure 4.1 Map of study basin showing streamflow gauges used for stochastic flow simulation, stream network, mainstem 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 mainstem from common geologic provinces (scaled by drainage area).

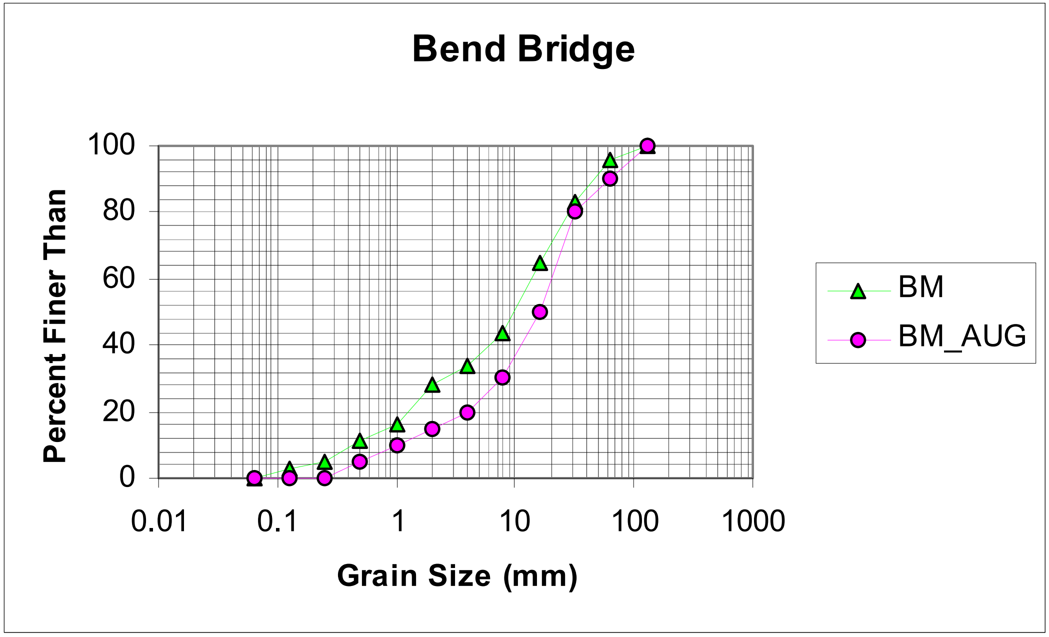

Figure 4.2 Comparison of original bed-material grain size distribution at Bend Bridge (BM) with that of the augmented gravel (BM AUG). Median grain size increased from 9.5 mm to 23 mm, sorting coefficient decreased from 2.49 to 2.09, and dimensionless critical shear stress decreased from 0.053 to 0.020.

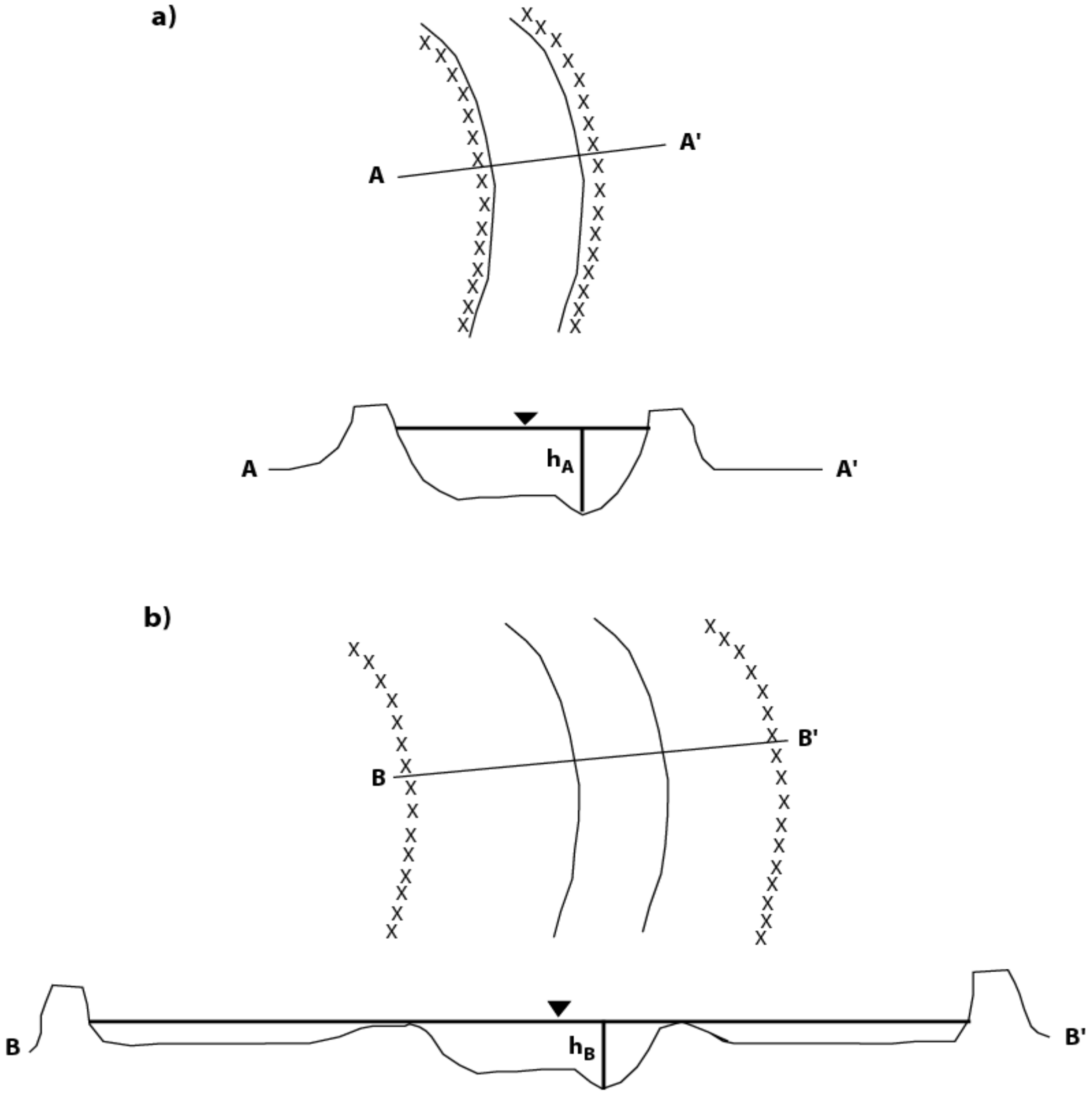

Figure 4.3 Schematic depicting the effect of levee setbacks on flow stage and thus shear stress in the channel. The figure shows (a) the original channel with levees built upon channel banks and (b) the channel under a levee setback rehabilitation strategy. The levee setbacks reduce high flow stage in the channel. Flow depth in the channel, h, would decrease for the same discharge after levees are set back (h_B).

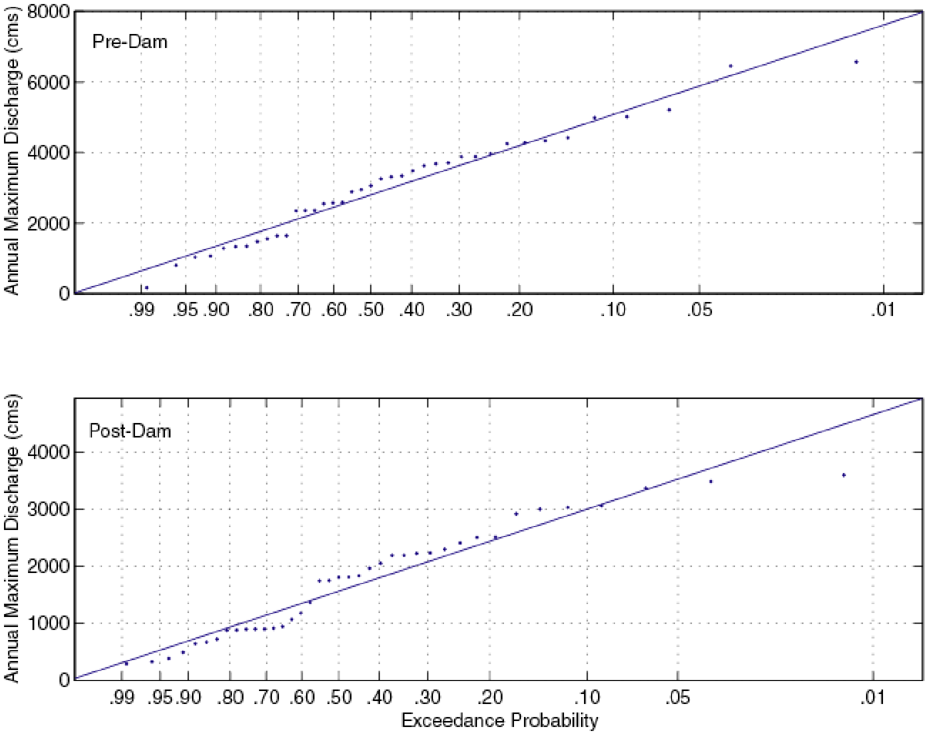

Figure 4.4 Plots show the effect of Shasta Dam (constructed in 1943) on flow frequency at Bend Bridge. The plot shows annual maxima for the pre-dam (a) and the post-dam (b) eras.

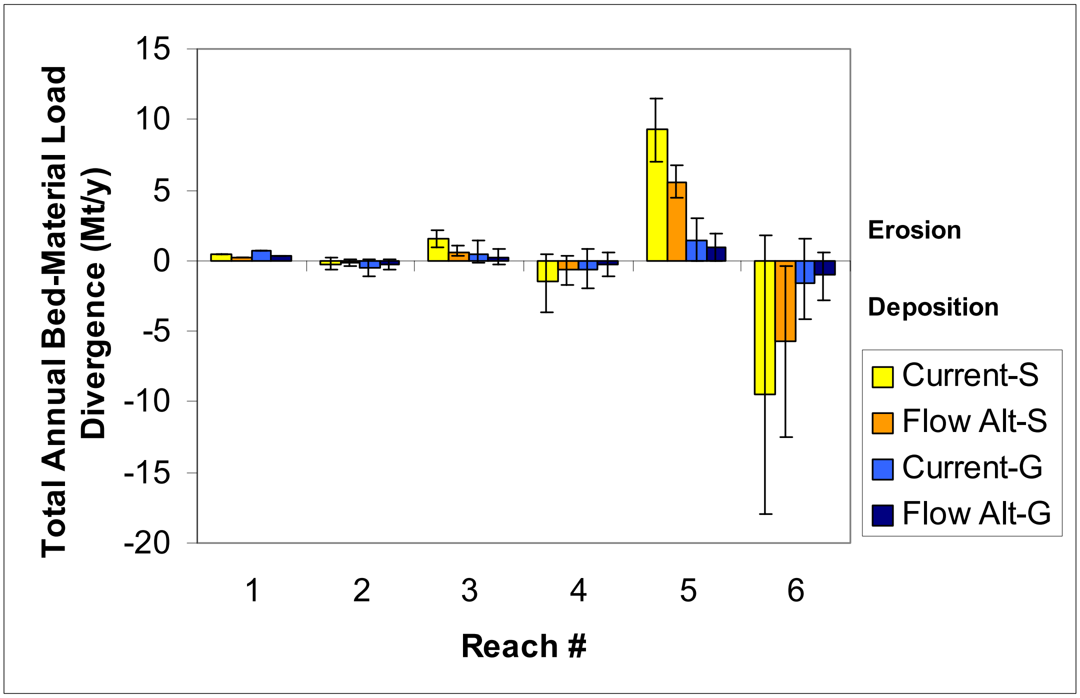

Figure 4.5 Total annual bed-material load divergence (Mt/y) for sand and gravel under current conditions (Current-S and Current-G, respectively) and for sand and gravel under a strategy of flow alteration (Flow Alt-S and Flow Alt-G, respectively). The plot shows that flow alteration modulates the long-term imbalances (i.e. erosion or deposition) in the sediment budget.

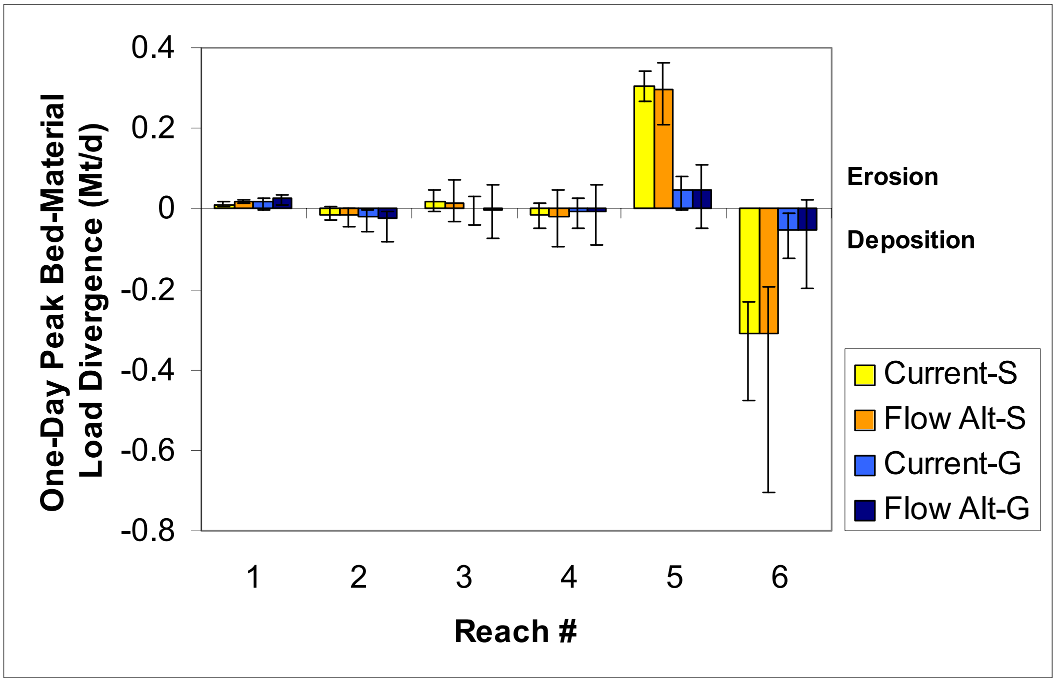

Figure 4.6 One-day peak bed-material load divergence (Mt/d) for sand and gravel under current conditions (Current-S and Current-G, respectively) and for sand and gravel under a strategy of flow alteration (Flow Alt-S and Flow Alt-G, respectively). The plot shows that flow alteration largely increases the peak imbalances (i.e. erosion or deposition) in the sediment budget.

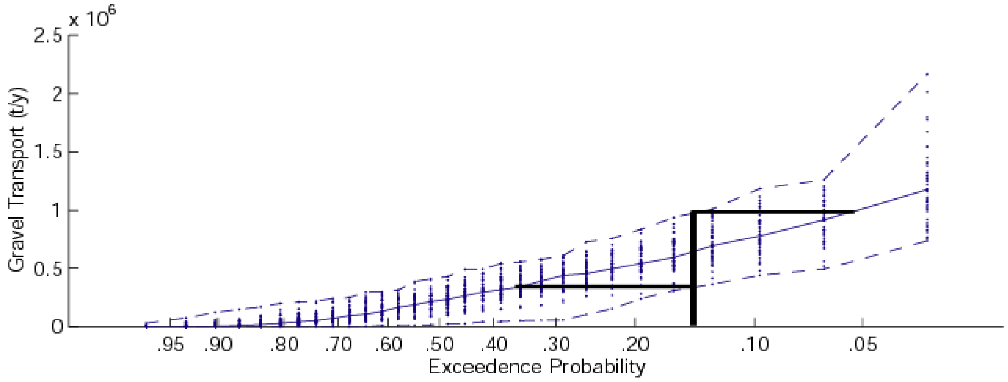

Figure 4.7 Total annual gravel load resulting from 50 simulations, each of 30 years. Gravel load (t/y) is plotted against exceedence probability. The range in transport for each exceedence probability is a result of the variability in stochastic hydrology. These ranges form of band of risk instead of 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 values at 0.15 approximately correspond to the median values at 0.05 and 0.45, respectively.

Table 4.1 Rehabilitation Strategy Modeling Results-Gravel							
Total Annual Qs (kt/y)							
Station	Current	Gravel Augment	Change	Levee Setback	Change	Flow Alteration	Change
BB	749	31	-96%			368	-51%
HC	208					109	-48%
BC	740					321	-57%
CO	149					56	-62%
KL	1627			746	-54%	969	-40%
SA	0					0	0%
Total Annual divQs (kt/y)							
Reach #	Current	Gravel Augment	Change	Levee Setback	Change	Flow Alteration	Change
0	738	20	-97%			357	-52%
1	-552	166	130%			-270	51%
2	528					208	-61%
3	-591					-265	55%
4	1478			597	-60%	913	-38%
5	-1627			-746	54%	-969	40%

Table 4.1 Results from modeling the influence of rehabilitation strategies on total annual gravel load at mainstem stations (Qs in upper) and total annual gravel divergence for river reaches (divQs in lower). The tables contain gravel load or divergence (both in Mt/y) currently (Current), following gravel augmentation (Gravel Augment), following levee setbacks (Levee Setback), and following flow alteration (Flow Alteration). The table also contains the percent change in each. Negative divergences indicate net deposition and positive values indicate net erosion.

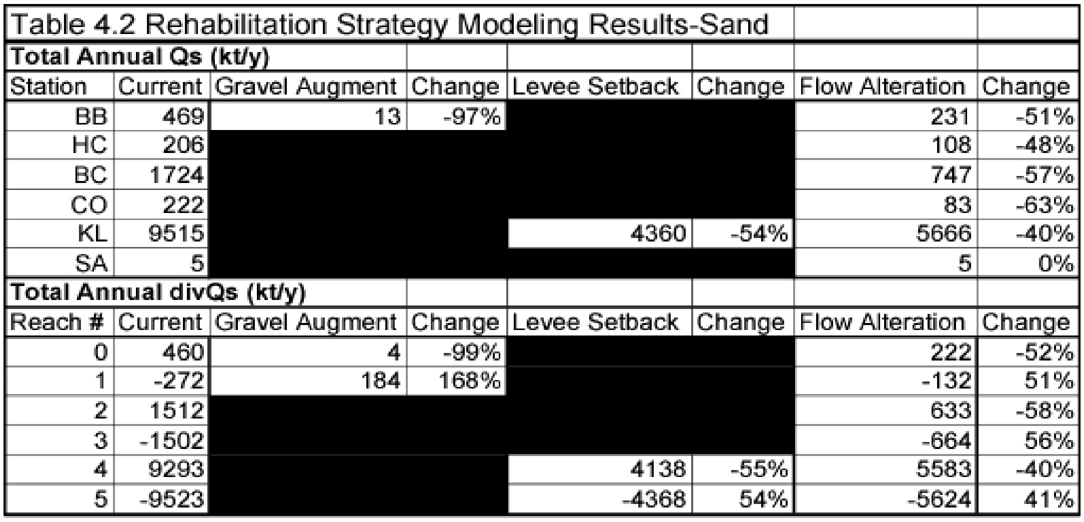

Table 4.2 Rehabilitation Strategy Modeling Results-Sand							
Total Annual Qs (kt/y)							
Station	Current	Gravel Augment	Change	Levee Setback	Change	Flow Alteration	Change
BB	469	13	-97%			231	-51%
HC	206					108	-48%
BC	1724					747	-57%
CO	222					83	-63%
KL	9515			4360	-54%	5666	-40%
SA	5					5	0%
Total Annual divQs (kt/y)							
Reach #	Current	Gravel Augment	Change	Levee Setback	Change	Flow Alteration	Change
0	460	4	-99%			222	-52%
1	-272	184	168%			-132	51%
2	1512					633	-58%
3	-1502					-664	56%
4	9293			4138	-55%	5583	-40%
5	-9523			-4368	54%	-5624	41%

Table 4.2 Results from modeling the influence of rehabilitation strategies on total annual sand load at mainstem stations (Qs in upper) and total annual sand divergence for river reaches (divQs in lower). The tables contain sand load or divergence (both in Mt/y) currently (Current), following gravel augmentation (Gravel Augment), following levee setbacks (Levee Setback), and following flow alteration (Flow Alteration). The table also contains the percent change in each. Negative divergences indicate net deposition and positive values indicate net erosion.

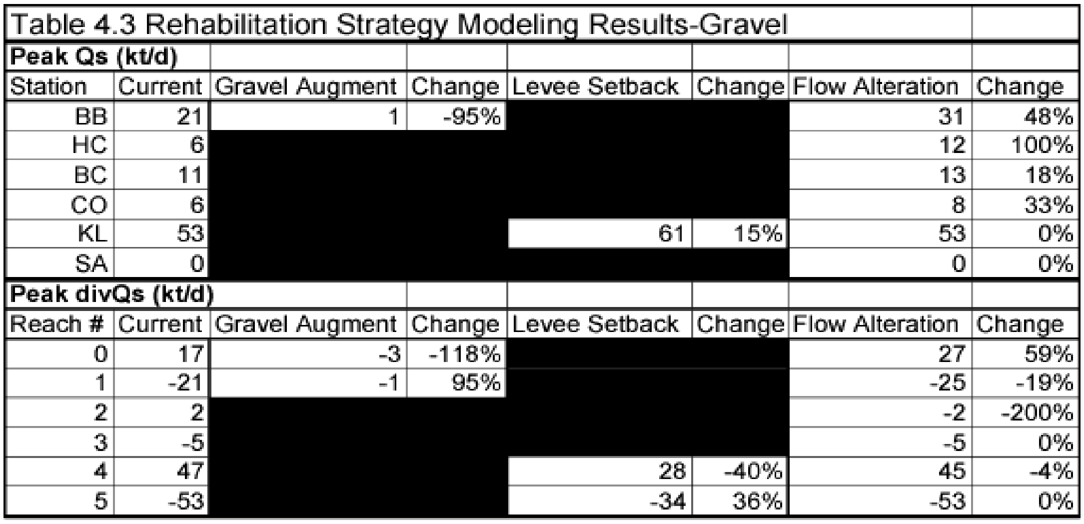

Table 4.3 Rehabilitation Strategy Modeling Results-Gravel

Peak Qs (kt/d)

Station	Current	Gravel Augment	Change	Levee Setback	Change	Flow Alteration	Change
BB	21	1	-95%			31	48%
HC	6					12	100%
BC	11					13	18%
CO	6					8	33%
KL	53			61	15%	53	0%
SA	0					0	0%

Peak divQs (kt/d)

Reach #	Current	Gravel Augment	Change	Levee Setback	Change	Flow Alteration	Change
0	17	-3	-118%			27	59%
1	-21	-1	95%			-25	-19%
2	2					-2	-200%
3	-5					-5	0%
4	47			28	-40%	45	-4%
5	-53			-34	36%	-53	0%

Table 4.3 Results from modeling the influence of rehabilitation strategies on one-day peak gravel load at mainstem stations (Qs in upper) and one-day peak gravel divergence for river reaches (divQs in lower). The tables contain gravel load or divergence (both in Mt/d) currently (Current), following gravel augmentation (Gravel Augment), following levee setbacks (Levee Setback), and following flow alteration (Flow Alteration). The table also contains the percent change in each. Negative divergences indicate net deposition and positive values indicate net erosion.

Table 4.4 Rehabilitation Strategy Modeling Results-Sand							
Peak Qs (kt/d)							
Station	Current	Gravel Augment	Change	Levee Setback	Change	Flow Alteration	Change
BB	13	1	-92%			20	54%
HC	6					12	100%
BC	26					30	15%
CO	9					12	33%
KL	312			336	8%	309	-1%
SA	1					1	0%
Peak divQs (kt/d)							
Reach #	Current	Gravel Augment	Change	Levee Setback	Change	Flow Alteration	Change
0	9	-3	-133%			16	78%
1	-13	-1	92%			-14	-8%
2	17					14	-18%
3	-17					-18	-6%
4	303			199	-34%	297	-2%
5	-312			-399	-28%	-309	1%

Table 4.4 Results from modeling the influence of rehabilitation strategies on one-day peak sand load at mainstem stations (Qs in upper) and one-day peak sand divergence for river reaches (divQs in lower). The tables contain sand load or divergence (both in Mt/d) currently (Current), following gravel augmentation (Gravel Augment), following levee setbacks (Levee Setback), and following flow alteration (Flow Alteration). The table also contains the percent change in each. Negative divergences indicate net deposition and positive values indicate net erosion.