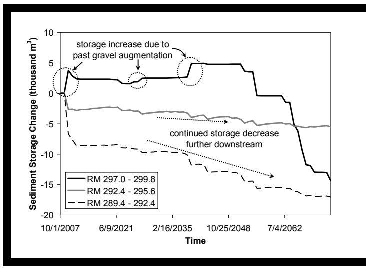

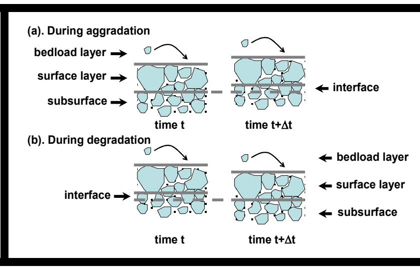

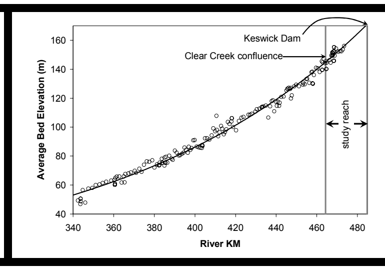


# Sacramento River Ecological Flows Study:

# The Unified Gravel and Sand Model (TUGS) simulation of the Sacramento River between Keswick Dam and Clear Creek Final Report

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# 1 INTRODUCTION

The storage and movement of sediment in a river channel regulates the extent and quality of spawning habitat for many fish species. For example, salmonid spawning gravel generally needs to have low concentrations of fine sediment, so that permeability is high enough to promote intra-gravel water flow, which is essential for delivering life-sustaining dissolved oxygen to incubating eggs while at the same time preventing the toxic build-up of metabolic wastes.

In large river systems like the Sacramento River, the amount and caliber of sediment in the channel is in continual flux due to effects of sediment transport and factors that affect sediment supply (e.g., changes in land use that affect erosion rates). High flows can mobilize and scour coarse sediment, changing the distribution and depth of spawning-sized gravel and thus affecting the location and suitability of salmonid spawning habitat. Lower flows mobilize finer sediment, which has a tendency to infiltrate into the channel bed in intervals between periodic bed-scouring events (and thus degrade spawning habitat quality by decreasing permeability). On the Sacramento River, even relatively low flows in summer may often mobilize sand as bedload, such that it can readily infiltrate into the subsurface. On such a river, large, bed scouring flows may be crucial for maintaining gravel quality at spawning sites because they are necessary for "flushing" away any fine sediment that has become locked the subsurface.

The continually changing nature of sediment in a channel makes it difficult to evaluate and predict the effects of stochastic events and anthropogenic activities on spawning habitat extent and quality. Several existing sediment transport models are able to use measurements of flow and sediment supply to realistically predict sediment scour and routing, but not the concentrations of fine sediment in gravel deposits (which would be useful indicators of their suitability for spawning). To overcome this limitation, we developed a new sediment transport model, The Unified Gravel-Sand (TUGS) model, which predicts changes in the distribution of both coarse and fine (i.e., particles finer than 2 mm) sediment in the channel bed. Results from TUGS model are consistent with both laboratory data (Cui 2007a) and two separate sets of field observations from the Sandy River, Oregon (Cui 2007b).[1] This implies that it can be used to realistically evaluate the effects of a wide range of natural events (e.g., periodic flood events), anthropogenic activities (e.g., increases in fine sediment supply caused by forest denudation in a tributary), and management/restoration interventions (e.g., gravel augmentation, flushing flow releases).

TUGS model was developed as part of a larger project initiated by The Nature Conservancy (TNC) to define ecological flow needs for the mainstem Sacramento River between Keswick Dam (RM 302) and Colusa (RM 143). The general goal of the project was to define flow characteristics (e.g., magnitude, timing, duration, frequency) and associated management actions (e.g., gravel augmentation, changes in bank protection) that influence the creation and maintenance of habitats and habitat conditions for several native species that occur in the Sacramento River corridor. The overall project includes:

- a Linkages Report that identified key process-habitat-biotic linkages in the Sacramento River;
- several field studies for evaluating gravel, off-channel water bodies, and bank conditions;

[1] A brief overview of model development and testing are provided in Section 2 of this report. For more complete documentation, see Appendices A and B, where we include pre-prints of the two published papers.

- the development and application of both TUGS and a meander migration model; and
- the development of the Sacramento Ecological Flow Tool (SacEFT) to evaluate the likely effects of different management scenarios using the principles of decision analysis.

The project components are interrelated. The TUGS model was developed and applied using historical hydrologic conditions (documented in the Linkages Report) as well as simulated hydrologic conditions under different management conditions, both with and without gravel injection (with the help of new data from the field studies). The results of TUGS model are in turn being used as input for the SacEFT model.

Results provided in this report pertain to the Sacramento River mainstem between Keswick Dam (RM 302) and its confluence with Clear Creek (RM 290), a reach which has no major sediment-bearing tributaries. Model simulation did not extend all the way to Colusa (RM 143) (at the downstream limits of the Project area) because sediment supply data from the river's many tributaries are not available at this time, and data collection from tributaries is out of the scope of work of this study. We expect that TUGS model will be a useful tool in the future for better understanding of the sediment transport dynamics, including the dynamics of fine sediment transport, in the reach downstream of Clear Creek confluence, once better information with regard to tributary sediment supply is available.

This work was funded through a grant to The Nature Conservancy's Sacramento River Project by the CALFED Ecosystem Restoration Program (CALFED grant #ERP-02D-P61).

# 2 OVERVIEW OF TUGS MODEL

TUGS model was developed based on (1) the surface-based bedload equation of Wilcock and Crowe (2003); (2) gravel-transfer function of Hoey and Ferguson (1994) and Toro-Escobar et al. (1996); (3) a hypothetical sand transfer function developed based on experimental and field subsurface and surface sand fraction data; (4) mass conservation of different sized sediment particles; and (5) the governing equations for open-channel flow. The model allows for study of reach-averaged sediment transport dynamics in channels, including disturbance-driven effects such as channel aggradation and degradation and changes in grain-size distributions in channel deposits (which might result from changes in hydrology, sediment supply, or gravel augmentation).

TUGS model results were compared with laboratory data from three runs (Paola et al. 1992, Seal et al. 1995, 1997) on a large-scale flume at St. Anthony Falls Laboratory (SAFL) of the University of Minnesota. Results indicate that the model is able to accurately predict channel-bed slopes, bed material grain-size distributions, and the fraction of fine sediment in deposits of the flume experiments (Cui 2007a). Comparison of TUGS model results with the experimental data of Wu and Chou (2003) further indicates that the model is able to predict the evolution of fine sediment concentrations in a deposit during a flushing flow event following adequate model calibration (Cui 2007a). Figure 1 illustrates one example of the reasonably close agreement between model predictions and flume experiment results.

On the Sandy River, Oregon, enough data are available for evaluation of TUGS model performance for a 48-km reach downstream of Marmot Dam. Results indicate that the model qualitatively reproduces the river's sediment transport dynamics, including spatial and temporal variations in its bed material and surface grain-size distributions (i.e., as a function of distance downstream and as a function of time-varying changes in both flow and sediment supply) (Cui 2007b). TUGS model simulations of sedimentation processes upstream of Marmot Dam during its more than 90 years of operation indicate that the model is able to reproduce the stratified sediment deposit in the reservoir—including details of two gravel lenses deposited during two large flow events (Figure 2) without any calibration and with only rough estimates of the long-term-averaged rate and grain-size distribution of sediment supply (Cui 2007b). Taken together, results from the field- and lab-based tests of TUGS (Cui 2007a, b) indicate that it produces realistic results and can be applied elsewhere for evaluation of semi-quantitative, reach-averaged trends in sediment transport dynamics, including changes in the relative concentrations of fine and coarse sediment in the bed.

# 3 APPLICATION OF TUGS MODEL TO THE SACRAMENTO RIVER

TUGS model was applied to the Sacramento River between Keswick Dam (RM 302) and the confluence of Clear Creek (RM 290) to evaluate (i) geomorphic responses due to aggregate mining during dam construction, (ii) the subsequent elimination of bedload supply resulting from the construction of the dam, and (iii) gravel augmentation since the construction of the dam. Model runs were also conducted to project the potential future geomorphic responses under various conditions, including (iv) the current condition (i.e., current Shasta Dam operations), (v) increasing Shasta Dam by 185 ft, and (vi) the development of an off-site reservoir in the Cottonwood Creek basin (i.e., the North-of-Delta Off Stream Storage Site, referred to hereafter as the "off-site reservoir"). The latter two scenarios require alteration of the hydrologic regime in the study reach.

## 3.1 Overview of Modeling Procedures

TUGS model requires estimates of several key initial conditions including channel gradient, channel width, and surface and subsurface grain size distributions. Historical data on geomorphic conditions prior to Shasta dam construction, however, are mostly unavailable. This poses a challenge for simulating the evolution of sediment transport processes in the post-dam era. To overcome this challenge, we established a hypothetical pre-dam condition based on a combination of (a) the current longitudinal profile and the few post-Shasta Dam grain-size measurements that are available; (b) a general understanding of geomorphology and sediment transport dynamics in low-gradient gravel-bedded rivers; and (c) TUGS model trial-and-error testing. The hypothetical pre-dam condition is at best an educated guess that can only be used as the initial condition for qualitative modeling with TUGS. Details about how we determined the hypothetical pre-dam condition are provided below.

Cui et al. (in press) demonstrated that one-dimensional sediment transport models must be applied on a reach-averaged basis. To establish a reach-averaged pre-dam profile in the study reach, we first used the cross sections collected by California Department of Water Resources (CDWR) and U.S. Army Corps of Engineers (USACE) in 2001 for their HEC-RAS modeling efforts (unpublished data) to calculate cross-sectionally averaged bed elevations, as presented in Figure 3. A regression curve used to fit the CDWR and USACE data is also presented in Figure 3. As implied in Figure 3, the CDWR and USACE data did not extend all the way to the upstream end of the study reach. The average channel gradient of 0.0011 within the study reach, as derived from the regression curve, however, should provide a reasonable approximation of the reach-averaged channel profile for the entire reach (Cui et al. in press). This average channel gradient of 0.0011 is subsequently assumed to be the pre-dam, reach-averaged channel gradient in the study reach.

Data on subsurface and surface grain size for the pre-dam era are not available for the study reach. On the other hand, post-dam data on surface and subsurface grain size are available at select locations within the study reach. Figure 4 shows that, in the post-dam era, the median grain size ($D_{50}$) of the surface has ranged from roughly 20 to 200 mm across the study reach, with most surface $D_{50}$ values falling between 30 and 100 mm.

To estimate rates of pre-dam bedload supply and assign initial reach-averaged grain-size distributions for each node along the channel in the study reach, we used the following ten-step, iterative procedure:

1. Estimate a hypothetical reach-averaged surface grain-size distribution for pre-dam conditions.
2. Using the hydrologic record from water year (WY) 1941 and 2005 at the Keswick gauge (USGS station #11370500), together with an estimated reach-averaged bankfull width of 120 m and a reach-averaged channel gradient of 0.0011, apply Wilcock and Crowe's (2003) bedload transport equation (as implemented in BAGS software; Pitlick et al. in press; Wilcock et al. in press) to estimate the long-term average sediment supply rate and the grain-size distribution associated with the discharge record. This estimate helps establish a bedload supply rate and grain-size distribution that is in equilibrium with respect to recorded discharge. It does not necessarily provide a precise estimate of the pre-dam conditions (because the hydrologic record mostly post-dates dam construction).
3. Estimate the reach-averaged subsurface grain-size distribution by combining the surface grain-size distribution (Step 1) and bedload grain-size distribution (Step 2) using the formulation of Toro-Escobar et al. (1996).
4. Amend the estimated surface-grain size distribution based on a comparison of predicted subsurface grain size with the post-Shasta Dam measurement, assuming pre-and post-Shasta Dam subsurface grain size distributions are similar. Go back to Step 2, if the resulting subsurface grain-size distribution does not fall within the range of current conditions, or proceed to the next step. Later we will demonstrate that changes in subsurface grain-size distributions have likely been minimal enough that the current subsurface grain-size distribution at a given point along the bed should provide a reasonable first approximation for what it was under historical conditions.
5. Assuming a longitudinal profile with a slope of 0.0011, and using the bankfull width derived from the CDWR and ACOE HEC-RAS modeling, set the initial surface grain-size distribution to be identical to the surface grain size-distribution from Step 4, and run a TUGS simulation using the WY 1941–2005 discharge data from the Keswick gauge assuming a long-term-average sediment supply and grain-size distribution as obtained in Step 2. The simulation will adjust the local surface grain-size distributions according to local variations in channel width.
6. Use the output of Step 5 and the grain size distribution for sediment supply in the formulation of Toro-Escobar et al. (1996) to adjust subsurface grain-size distributions locally.
7. Reset initial conditions so that the surface and subsurface grain-size distributions along the channel match the conditions calculated from Steps 5 and 6. Add a large dredging pit at Turtle Bay to simulate effects of aggregate dredging during Shasta Dam construction.
8. Simulate post-dam sediment transport dynamics within the study reach by eliminating all bedload supply and adding gravel at historical augmentation sites with timing and rates that are consistent with historical records (this was "Run 0", as discussed in detail in Section 3.2 below).
9. Compare the simulated post-dam grain-size data with the available field data.
10. Go back to Step 2, if the comparison in step 9 is not satisfactory, or finish Run 0, the results of which provide the initial conditions for subsequent runs that simulate future sediment transport dynamics.

The satisfactory post-dam simulation is presented below in Section 3.2 as "Run 0". The predicted surface and median grain sizes of bed material from this run for year 1980 are presented in Figure 4 and compared with field data collected in 1979, 1980 and 1995. Following Run 0, twelve additional runs were conducted to simulate the future sediment transport dynamics under different management scenarios as summarized in Table 1.

**Table 1.** List of numerical runs.

| Run # | Brief Description | Hydrologic Data | Gravel Augmentation |
|---|---|---|---|
| 0 | Post-Shasta Dam (WY 1941–2005) | Keswick Station record WY 1941–2005 | As occurred during the period |
| 1 | Base run for WY 2007–2073 | Keswick Station simulated record WY 1939–2004[1] | No gravel augmentation |
| 2 | Increasing Shasta Dam height by 185 ft for WY 2007–2063 | Keswick Station simulated record WY 1939–1994 adjusted for increased height of Shasta Dam[2] | No gravel augmentation |
| 3 | North-of-Delta Off-stream Storage (Off-site Reservoir) for WY 2007–2063 | Keswick Station record WY 1939–1994 adjusted for off-site reservoir[2] | No gravel augmentation |
| 1s | Sensitivity test for Run 1 | Same as Run 1 | No gravel augmentation |
| 2s | Sensitivity test for Run 2 | Same as Run 2 | No gravel augmentation |
| 3s | Sensitivity test for Run 3 | Same as Run 3 | No gravel augmentation |
| 1g | Base run for WY 2007–2073 with initial gravel injection | Same as Run 1 | Initial gravel injection in WY 2007 |
| 2g | Increasing Shasta Dam height by 185 ft for WY 2007–2063 with initial gravel injection | Same as Run 2 | Initial gravel injection in WY 2007 |
| 3g | North-of-Delta Off-stream Storage (Off-site Reservoir) for WY 2007–2063 with initial gravel injection | Same as Run 3 | Initial gravel injection in WY 2007 |
| 1gs | Sensitivity test for Run 1g | Same as Run 1 | Initial gravel injection in WY 2007 |
| 2gs | Sensitivity test for Run 2g | Same as Run 2 | Initial gravel injection in WY 2007 |
| 3gs | Sensitivity test for Run 3g | Same as Run 3 | Initial gravel injection in WY 2007 |

1. Recorded daily discharge record at USGS gauge station at Keswick Dam (#11370500);
2. Simulated daily average discharge with CALSIM, provided by Clint Alexander (personal communication, February 2007).

In the next few sections, we discuss the results from the numerical runs to demonstrate the potential future sediment transport dynamics under different management scenarios (e.g., different hydrology and with or without gravel augmentation). Results from all the runs were also supplied to ESSA Technologies Ltd. for input into their SacEFT model.

## 3.2 Run 0: Simulation of the Post-dam Period

Run 0 simulates the sediment transport dynamics following the closure of Shasta Dam and the dredging of Turtle Bay during dam construction. As discussed above in Section 3.1, Run 0 started with hypothetical initial conditions that were estimated from a ten-step trial-and-error approach. The initial surface and subsurface grain-size distributions are, at best, educated guesses of pre-dam conditions on the river. Even so, the results of the simulations should still demonstrate, in a general sense, the sediment transport dynamics in the study reach following construction of Shasta Dam and into the future under different management alternatives.

Post-dam sediment transport dynamics were simulated by (a) cutting off upstream sediment supply; (b) producing a dredging pit in Turtle Bay in the initial profile to mimic aggregate mining during dam construction; (c) running the model with the discharge from Keswick station for WY 1941 to 2006; and (d) providing gravel augmentation at documented rates within the study reach (shown in Table 2).

Results of the simulation are presented for three sub-reaches: RM 297.0–299.8 (alluvial reach upstream of Turtle Bay); RM 292.4–295.0 (immediately downstream of Turtle Bay), and RM 289.4–292.4 (immediately upstream of the confluence with Clear Creek), as detailed below.

**Sediment storage:** Sediment storage for the three sub-reaches decreased following the termination of sediment supply following Shasta Dam closure (Figure 5). The sub-reach immediately upstream of the Turtle Bay (RM 297.0–299.8) experienced the largest decrease in sediment storage due to the local base-level lowering as a result of aggregate mining in Turtle Bay during dam construction (Figure 5). It needs to be noted, however, that the magnitude of the initial rapid decrease in sediment storage in the reach immediately upstream of Turtle Bay is a first approximation only; it may not be very accurate because channel degradation in the reach was set by the bedrock depth, which is unknown to this modeling effort. Even with more conservative estimates of bedrock depth, our results suggest that the sub-reach upstream of the Turtle Bay has been the most heavily impacted reach in the upper river in the post-dam era (excepting Turtle Bay itself).

**Sediment grain size:** Simulated reach-averaged estimates of $D_{50}$ indicate that significant surface coarsening occurred in the sub-reach upstream of Turtle Bay (RM 297.0–299.8) following Shasta Dam closure (Figure 6). The surface $D_{50}$ values also show several sustained declines, which reflect the effects of gravel augmentation (Figure 6). Simulated reach-averaged values of $D_{50}$ for the subsurface (Figure 7) indicate that changes in subsurface grain size are not as noticeable as they are in the surface layer (compare Figures 6 and 7), and that gravel augmentation actually increases the subsurface grain sizes because the augmented gravel is coarser than the existing subsurface sediment (Figure 7).

The simulated fraction of surface sediment that is coarser than 128 mm shows a monotonic increase over time, except following episodes of gravel augmentation (Figure 8). Results from the gravel study—another, separate element of the Sacramento River Ecological Flows Study—have shown that the percent coverage by sediment with grain sizes greater than about 128 mm may be an important indicator of spawning habitat quality (Stillwater Sciences 2007); Chinook salmon of the Sacramento River do not appear to be able to successfully build redds in deposits that are more than 40% covered by particles with intermediate axis diameters >130 mm (Stillwater Sciences 2007), presumably because these particles are simply too big for fish to move under hydraulic conditions that typically occur in the river. Indications of increasing reach-averaged coverage by excessively coarse material (Figure 8) imply that an increasing number of individual gravel deposits may have become too coarse for spawning in the post-dam era. This is consistent with an independent analysis based on grain-size data and observations of spawning use in the upper river (Stillwater Sciences 2007). Moreover, the augmentation-related decreases in coverage by coarse material highlight the importance of maintaining (and possibly expanding) the ongoing program of gravel augmentation in the upper river.

**Table 2.** Gravel augmentation in the study reach.

| Site | Year | Location (RM/RKM) | Volume ($m^3$) |
|---|---|---|---|
| Caldwell Park | 1978 | 298.3/477.3 | 1,800 |
| Gasline Riffle | 1978 | 298.0/476.8 | 1,800 |
| Redding Riffle | 1979 | 297.7/476.3 | 6,700 |
| Turtle Bay West | 1986 | 297.1/475.4 | Unknown, assumed to be negligible |
| Turtle Bay East | 1986 | 296.6/474.6 | Unknown, assumed to be negligible |
| Turtle Bay West | 1987 | 297.1/475.4 | Unknown, assumed to be negligible |
| Turtle Bay East | 1987 | 296.6/474.6 | Unknown, assumed to be negligible |
| Salt Creek | 1988 | 301.0/481.6 | 12,200 |
| Turtle Bay West | 1988 | 297.1/475.4 | Unknown, assumed to be negligible |
| Turtle Bay East | 1988 | 296.6/474.6 | Unknown, assumed to be negligible |
| Keswick | 1989 | 302.0/483.2 | 6,100 |
| Salt Creek | 1990 | 301.0/481.6 | 18,300 |
| Diestlehorst | 1990 | 298.8/478.1 | 900 |
| Market St | 1990 | 298.3/477.3 | 8,500 |
| Redding Riffle | 1990 | 297.7/476.3 | 9,600 |
| Turtle Bay West | 1990 | 297.1/475.4 | 11,900 |
| Turtle Bay East | 1990 | 296.6/474.6 | 4,000 |
| Tobiasson | 1990 | 291.6/466.6 | 9,500 |
| Shea Levee | 1990 | 290.0/464 | 13,600 |
| Keswick Dam | 1997 | 302.0/483.2 | 3,700 |
| Salt Creek | 1997 | 301.0/481.6 | 12,700 |
| Keswick Dam | 1998 | 302.0/483.2 | 4,200 |
| Salt Creek | 1998 | 301.0/481.6 | 7,900 |
| Salt Creek | 1999 | 301.0/481.6 | 13,200 |
| Keswick Dam | 2000 | 302.0/483.2 | 4,700 |
| Tobiasson | 2000 | 291.6/466.6 | 12,100 |
| Salt Creek | 2002 | 301.0/481.6 | 7,900 |
| Salt Creek | 2003 | 301.0/481.6 | 4,600 |
| Keswick Dam | 2004 | 302.0/483.2 | 2,200 |
| Salt Creek | 2004 | 301.0/481.6 | 2,200 |
| Keswick Dam | 2005 | 302.0/483.2 | 1,900 |
| Salt Creek | 2005 | 301.0/481.6 | 1,900 |
| Keswick Dam | 2006 | 302.0/483.2 | 3,200 |

## 3.3 Run 1: Simulated Effects of Continued Evolution under Current Hydrologic Conditions without Gravel Augmentation

Each of the runs presented hereafter pertains to geomorphic evolution under future hydrologic and gravel augmentation scenarios. The runs start with the WY 2006 conditions predicted at the end of Run 0 and provide the model with a discharge series that was based on what was recorded at the Keswick station between WY 1939 and 2006. In the case of Run 1, the future hydrologic record is identical to the measured post-dam record. In other runs, the measured record is modified to account for proposed modifications to the system (e.g., an increase in the height of Shasta Dam or construction of an off-site reservoir) based on CALSIM simulations. TUGS model simulation results for Run 1 are discussed below.

**Sediment storage:** Modeling results indicate that sediment storage will remain roughly stable for more than 50 years in the alluvial reach upstream of Turtle Bay (RM 297.0–299.8), even without any further gravel augmentation, due to the downstream propagating legacy of gravel that has already been added upstream at the Salt Creek and Keswick Dam injection sites (Figure 9). It is important to recognize, however, that the downstream migrating benefits of gravel augmentation is accompanied by a net depletion of deposits in the upstream sub-reach not documented in Figure 9 that may currently be benefiting salmon at (or near) the gravel injection sites. The simulated gravel loss in the upstream sub-reach (i.e., between Keswick Dam and RM 299.8) during the 56 years simulation period, for example, amounts to approximately 87,000 metric tons (or approximately 55,000 $m^3$ storage, assuming a particle density of 2,650 $kg/m^3$ and porosity of 0.4).

Sediment storage in the two sub-reaches downstream of Turtle Bay (i.e., RM 292.4–295.6 and RM 289.4–292.4), on the other hand, will continue to decrease, similar to conditions so far in the post-dam era, because no bedload from upstream can pass through Turtle Bay. This highlights the importance of conducting new gravel augmentation activities downstream of Turtle Bay.

**Sediment grain size:** Simulated reach-averaged estimates of $D_{50}$ for the surface (Figure 10) indicate that substantial bed coarsening will occur in the sub-reach immediately upstream of the confluence with Clear Creek (RM 289.4–292.4). The percent coverage by relatively coarse material (Figure 11) also shows the continued coarsening of sub-reach RM 289.4–292.4. Results in Figures 10 and 11 complement the results shown in Figure 9, which demonstrates that gravel augmentation downstream of Turtle Bay would be beneficial for maintaining sediment storage in the reach.

## 3.4 Run 2: Simulated Effects of Increased in Shasta Dam Height Without Gravel Augmentation

In Run 2, we predict the geomorphic effects of the proposed 56 m (185 ft) increase in Shasta Dam height using daily average discharges estimated from CALSIM simulations, which are based on the WY 1939–1994 hydrologic record, with a projected post-construction operation rule for Shasta Lake (data provided by Clint Alexander, ESSA Technologies Ltd., personal communication, Feb. 2007). The simulated discharge record is shown in Figure 12, together with the discharge used for Run 1, highlighting the reduction in peak flow magnitudes that will result from the proposed increase in Shasta Dam height.

**Sediment Storage:** Based on results of Run 2, sediment storage is predicted to be more stable if Shasta Dam is raised, as compared to what it would be with the dam at its current height for each of the three modeled sub-reaches (compare Figure 13 with Figure 9). This result makes good intuitive sense, when one considers that the reduced peak flows of Run 2 would reduce rate of coarse sediment transport in the river.

**Sediment grain size:** Simulated reach-averaged estimates of $D_{50}$ for the surface (Figure 14) indicate that the bed will become increasingly coarse in the sub-reach immediately upstream of the confluence with Clear Creek (RM 289.4–292.4). This coarsening is also reflected in simulated changes in the fraction of coarse surface sediment (Figure 15). Taken together, comparisons of grain size results from Run 2 and Run 1 indicate that the rate of bed coarsening will decrease after the height of Shasta Dam is increased.

## 3.5 Run 3: Simulated Effects of North-of-Delta Off-stream Storage (Off-site Reservoir) Without Gravel Augmentation

In Run 3, we predict the geomorphic effects of the proposed operation of a new off-site reservoir using daily average discharges estimated from CALSIM simulations, which are based on the WY 1939–1994 hydrologic record, with a projected operation rule for the reservoir (data provided by Clint Alexander, ESSA Technologies Ltd., personal communication, Feb. 2007). The simulated discharge is shown in Figure 16, together with the discharge used in Run 1, highlighting the reduction in peak flow magnitudes that will result from the proposed off-site reservoir operations.

Results for Run 3 are shown in Figures 17, 18, and 19, with results from Run 1 for comparison. Results from Run 3 are almost identical to those from Run 2 (compare Figures 13–15 with Figures 17–19 and note the pair-wise similarities). That is, the off-site reservoir scenario is predicted to induce roughly the same changes in sediment transport dynamics as the proposed increase in Shasta Dam height, in large part because the changes in the hydraulic regime are very similar (note the similarities in Figures 12 and 16). Readers can therefore almost interchangeably refer to the discussion of Run 2 in Section 3.4 for evaluation of relative effects of the off-site reservoir on future sediment dynamics.

## 3.6 Sensitivity Tests for Runs 1 Through 3

Any sediment transport equation can be expected to have errors of a factor of 2 to 3 (e.g., Brownlie 1982). Here we conduct sensitivity tests for Runs 1 through 3 by increasing the predicted sediment transport rate by a factor of 3. The three sensitivity runs are denoted as Runs 1s, 2s, and 3s, respectively. By increasing the sediment transport rate in the simulations we effectively increase the estimated rates of spawning gravel depletion and bed coarsening in the study reach. In this way, the sensitivity test provides results that will lead to relatively conservative actions when it comes to evaluating potential gravel augmentation scenarios for restoring lost spawning habitat. Below we discuss the results from Runs 1s and 2s, and provide relevant comparisons. As was the case in the baseline simulations of Runs 2 and 3, the comparisons between Runs 2s and 3s show that results are almost identical. We henceforth refrain from making a distinction between results of Run 2s and Run 3s.

Results for Run 1s are presented in Figures 20, 21, and 22 for changes in sediment storage, $D_{50}$ of the surface, and the fractional coverage by coarse (>128 mm) sediment, respectively. Figures 20, 21, and 22 indicate that there will be a continued decrease in sediment storage and more bed coarsening in all three sub-reaches if no gravel is added. In particular, there will be significantly more gravel depletion and surface coarsening in sub-reach RM 297.0–299.8, in part because bedload transport capacity is three times higher than predicted with the bedload equations of the baseline simulations.

Results for Run 2s are presented in Figures 23, 24, and 25 for changes in sediment storage, $D_{50}$ of the surface, and the fraction of surface sediment that is coarser than 128 mm, respectively. Results from Run 1s are also shown on the plots for comparison. Much as was the case for the lower transport rates of the baseline analysis (Runs 1 and 2), results from the sensitivity analysis indicate that increasing Shasta Dam by 56 m (185 ft) will result in less gravel depletion and surface coarsening in all three sub-reaches relative to what we would expect from no increase in dam height (Figures 23, 24 and 25), due to relatively lower peak flows for a system with a higher dam over the interval (Figure 12).

We offer the following synthesis of results and implications from Runs 1, 2, 3, 1s, 2s, and 3s:

- The bedload transport capacity in the reach is relatively low due to the low channel gradient (~0.0011), as evidenced in Run 1 (Figures 9, 10 and 11) where sub-reach RM 297.0–299.8 receives downstream migrating benefits from past gravel augmentation efforts upstream for $40^+$ years. This result highlights the importance of considering future gravel augmentation projects that spread the gravel to a wider area (farther downstream) and of constructing fish spawning habitat instead of augmenting gravel in piles for later transport by the river, which is very slow and can imprecisely deliver gravel to sites that may not be very suitable for spawning. By distributing augmented gravel in more naturally shaped deposits at spawning sites, it should more immediately provide functional spawning habitat, and the relatively low bedload transport capacity in the river will help preserve it in the augmented morphology.
- The depletion of sediment storage and surface coarsening are progressive processes that are gradually propagating downstream, as evidenced by indications that gravel depletion and bed coarsening is most intense the downstream-most sub-reach (i.e., RM 289.4–292.4) (Figures 9, 10 and 11). To combat the downstream propagating effects of sediment storage depletion (and to reverse surface coarsening), gravel augmentation projects should begin to focus on the area downstream of Turtle Bay, recognizing (i) that anything that is added in the reach upstream of Turtle Bay will eventually become trapped in the bay and will not pass to the downstream sub-reaches, and (ii) that downstream propagating effects of past augmentation projects will continue to benefit the reach upstream of Turtle Bay for many years.
- The two options examined in Runs 2 and 3 (i.e., increasing the height of Shasta Dam and installation of an off-site reservoir) and the associated sensitivity test runs (Runs 2s and 3s) will reduce the future peak flow (Figures 12 and 16) compared to the extrapolated hydrologic conditions, and as a result, both options will reduce the rate of sediment depletion (Figures 13, 17 and 23) and bed coarsening (Figures 14, 15, 18, 19, 24 and 25) in the three sub-reaches.

## 3.7 Simulated Effects of an Initial Gravel Injection

To evaluate whether gravel augmentation is effective at improving and maintaining spawning habitat, we used TUGS to simulate the effects of an initial gravel injection of approximately 583,000 metric tons (or approximately 367,000 $m^3$ in bulk volume, assuming a gravel particle density of 2,650 $kg/m^3$ and a porosity of 0.4) at the beginning of the run (i.e., at the beginning of WY 2007). Approximately half of the simulated gravel injection was placed downstream of

Keswick Dam in a 3.5-km-long reach, and half was placed downstream Turtle Bay in a 2-km-long reach, with a uniform thickness in each case of approximately 0.45 m (1.5 ft).

Numerical simulations were conducted for the three hydrologic scenarios of Runs 1, 2 and 3 (denoted as Runs 1g, 2g, and 3g, respectively), and for sensitivity tests (denoted as Runs 1gs, 2gs, and 3gs, respectively) with predicted sediment transport rates that were higher than baseline conditions by a factor of 3.

Results for Run 1g are presented in Figures 26, 27, and 28 for changes in sediment storage, $D_{50}$ of the surface, and the fractional coverage by coarse (>128 mm) sediment, respectively. Sediment storage in the sub-reach upstream of Turtle Bay (RM 297.0–299.8) is predicted to increase dramatically due to the gravel injection and the downstream transport of previously augmented gravel from Salt Creek and Keswick Dam augmentation sites upstream (Figure 26). Sediment storage immediately downstream of Turtle Bay (RM 292.4–295.6) will also increase due to the initial gravel injection. The sub-reach upstream of Clear Creek confluence (RM 289.4–292.4), however, is predicted to continue to display a decrease in sediment storage despite the gravel injection in the sub-reach upstream.

For the reach upstream of Turtle Bay (RM 297.0–299.8) there should be a slight decrease in median grain size as the injected gravel in the upstream sub-reach is transported into it (Figure 27). The $D_{50}$ of surface sediment in the sub-reach downstream of Turtle Bay (RM 292.4–295.6) is predicted to decrease significantly due to the initial gravel injection, while the $D_{50}$ of surface sediment in the sub-reach upstream of Clear Creek confluence (RM 289.4–292.4) shows that gravel is continuing to coarsen there.

Inter-comparisons of results from Runs 2g and 3g and their corresponding sensitivity tests (Runs 2gs and 3gs) show that they are very similar. Thus only the results from Runs 2g and 2gs are presented below.

Results for Run 2g are presented in Figures 29, 30 and 31 for sediment storage, $D_{50}$ of the surface, and the fractional coverage by coarse (>128 mm) sediment, respectively. Results from Run 1g are included for comparison. The conditions imposed by the increase in Shasta Dam height are predicted to be better at retaining gravel in the two sub-reaches downstream of Turtle Bay (i.e., RM 292.4–295.6 and RM 289.4–292.4) (Figure 29). In the sub-reach upstream of Turtle Bay (i.e., RM 297.0–299.8), the relatively lower peak flows of Run 2g should delay the transport of upstream gravel into the reach, relative to what we observe in Run 1g, and as a result, sediment storage for Run 2g should be lower than predicted in Run 1g for the first 20 years. Figures 30 and 31 show that the surface in Run 2g should generally be finer than it is in Run 1g.

Results for Run 1gs are presented in Figures 32, 33, and 34 for changes in sediment storage, $D_{50}$ of the surface, and the fractional coverage by coarse (>128 mm) sediment, respectively. Sediment storage in the sub-reach upstream of Turtle Bay (RM 297.0–299.8) decreases significantly in the early years of the simulation (Figure 32), despite the initial gravel injection, in part because the early part of the simulation is based on high flow data from WY 1939 and also because sediment transport capacity is three times higher than it was with the bedload equation of the TUGS model. The sub-reach immediately downstream of Turtle Bay, on the other hand, retains most of the augmented gravel despite the higher sediment transport capacity. As is more or less the case in the other runs, the sub-reach upstream of the Clear Creek confluence (i.e., RM 289.4–292.4) continues to show a decrease in sediment storage (Figure 32). Despite the decline in sediment storage in sub-reach RM 297.0–299.8, the surface becomes significantly finer after the gravel injection (Figures 33 and 34). The surface also becomes finer in the sub-reach downstream of the Turtle Bay (RM 292.4–295.6), possibly signifying improved spawning habitat quality. The sub-reach upstream of Clear Creek confluence (RM 289.4–292.4), on the other hand, continues to coarsen, much as it did in the other runs.

# 4 CONCLUSIONS

The TUGS sediment transport model was developed using the surface-based bedload-transport equation of Wilcock and Crowe (2003), the Exner equation of sediment continuity, and the governing equations for one-dimensional open channel flow (Cui 2007a, b, provided as Appendices A and B). Comparison of model results with data from experiments (i.e., SAFL and Wu and Chou 2003) and field observations (Cui 2007a, b) indicate that TUGS model produces realistic estimates of bed profiles, grain-size distributions, fine sediment entrainment, and even patterns of stratified sediment deposits in reservoirs (Cui 2007a, b).

We used TUGS model to simulate reach-averaged geomorphic responses of the Sacramento River between Keswick Dam and the Clear Creek confluence after the closure of the Shasta Dam. We also used TUGS to simulate future geomorphic responses under a series of hydrologic and gravel supply scenarios. A total of 13 runs were conducted, and results were provided to ESSA Technologies Ltd. for input into their SacEFT model. Main conclusions from the 13 numerical runs are provided below.

For the post-dam interval (i.e., from ~1940 to present), the numerical simulations predict a progressive decline in sediment storage and an overall coarsening of the bed-surface due to the system-wide, dam-related shutdown in sediment supply. Simulation results for the post-dam period also indicate that gravel augmentation has increased sediment storage and locally mitigated the effects of surface coarsening.

Future changes in sediment transport dynamics were simulated using three different hydrologic scenarios based on three management options: (a) maintain current conditions; (b) increase the height of Shasta Dam by 56 m (185 ft), and thus increase water storage in Shasta Lake; and (c) construct and utilize the North-of-Delta off Stream Storage site (off-site reservoir) for water resource management. For the simulation of extrapolated current conditions, we used the daily discharge record of Keswick Dam (USGS station #11370500) from the post-dam era (i.e., with daily discharges from WY 1939 assumed to serve as a proxy for WY 2007, and so on). For the other two management options, we used daily average discharges from the CALSIM model (Clint Alexander, ESSA Technoligies Ltd., personal communication, Feb. 2007) to serve as TUGS model input.

Comparison of the TUGS model runs for the three different management options indicates that increasing the height of Shasta Dam and use of an off-site reservoir will both reduce peak flow, which in turn will reduce rates of sediment depletion and bed-surface coarsening within the study reach.

Changes in sediment transport dynamics were also simulated for each of the management options with the added condition that 583,000 metric tons of gravel is injected into the river during the first year of simulation, such that half is placed downstream of Keswick Dam and the rest is placed in the reach downstream of Turtle Bay, covering a total of 816,000 $m^2$ of channel bed to a thickness of 0.45 m (1.5 ft). Simulated effects of the gravel injection are suggestive of long-lasting (i.e., 50+ years) improvements in sediment storage and surface sediment grain size for sub-reaches that initially receive part of the injected gravel. The effects of the gravel injection would be preserved for longer if Shasta Dam is raised or if the off-site reservoir is installed and operated as planned, due in both cases to the predicted reduction in peak flows (which would reduce the coarse sediment transport capacity of the river).

We assessed the sensitivity of model results to errors in sediment transport rates by repeating all runs with sediment transport rates that were higher than baseline conditions by a factor of 3. Results of the sensitivity tests indicate that (1) there will be faster gravel depletion and surface coarsening under the condition of faster bedload transport; and (2) the relative differences among results from the three management options remains similar despite the change in sediment transport rates. That is, the increase in Shasta Dam height and installation and operation of an off-site reservoir will both stabilize sediment storage and median grain size compared to what we predict would occur for a simple extrapolation of current hydrologic conditions (i.e., maintenance of the status quo).

In addition to the changes predicted by TUGS, there may be other important geomorphic changes that would result from implementation of one or more of the different management options. For example, the reduction in peak flows associated with raising Shasta Dam and operating the off-site reservoir is likely to reduce bed mobility, which in turn may result in a build-up of fine sediment in deposits in reaches with significant fine sediment input. Although this is not an issue in the study reach due to the limited fine and coarse sediment supply, it is likely an issue farther downstream, where tributaries such as Cottonwood Creek may deliver a significant fine sediment supply to the river. Quantifying such a phenomenon is not feasible at present, because we lack sufficient data on fine sediment supply from the tributaries.

We expect that reductions in peak flow magnitude (associated with raising Shasta Dam and operating an off-site reservoir) would also reduce bank erosion, which is the only natural gravel recruitment mechanism left in reaches that lack a tributary supply. Reducing bank erosion might therefore have significant impacts on spawning gravel availability, especially if little gravel is added in the future. In addition to affecting the local supply of sediment to gravel bars, bank erosion is also critical to the maintenance of other habitat types. In particular, bank erosion is a key mechanism of lateral channel migration, which is essential for generating off-channel habitats that are crucial to many species of the Sacramento River corridor. Bank erosion is also crucial for maintaining steep cutbanks and is therefore essential for renewing bank swallow nesting habitat. Hence, in the overall assessment of the various flow management options, it will be very important to consider the many other factors that are at play besides the likely effects on sediment storage and bed surface coarsening, which are discussed here with the help of TUGS model results.

We expect that the effects of reduced bank erosion on sediment dynamics become increasingly important with distance downstream of Clear Creek (i.e., outside the study reach), where the river is less confined and therefore more likely to erode into its banks. Potential bank erosion due to channel meandering is provided in a separate modeling effort and can be found in Larsen (2007).

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## Figures

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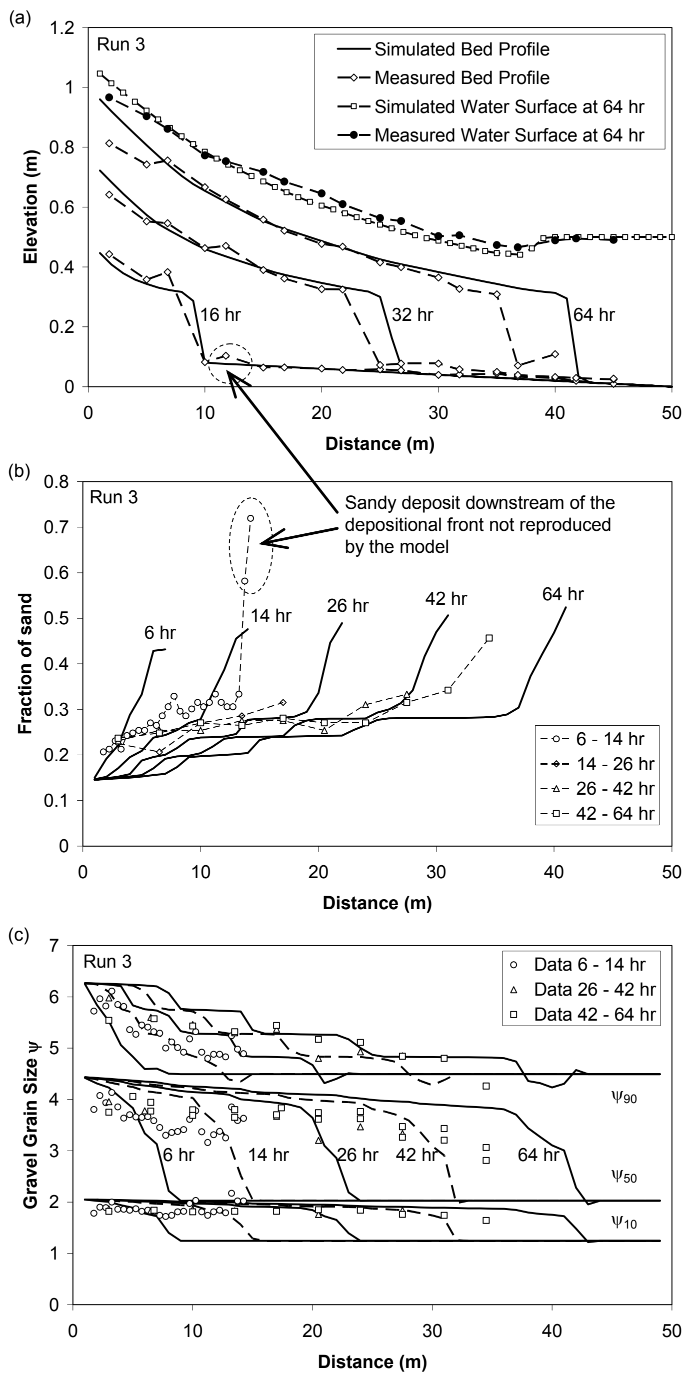


Figure 1. Examination of TUGS model performance with SAFL experimental Run 3 data: (a) longitudinal channel bed profile, (b) sand fraction in the deposit; and (c) characteristic gravel grain size in the deposit. Simulation was conducted with minor adjustment to Wilcock and Crowe's (2003) sediment transport equation. Diagram is adapted from Cui et al. (2007a).

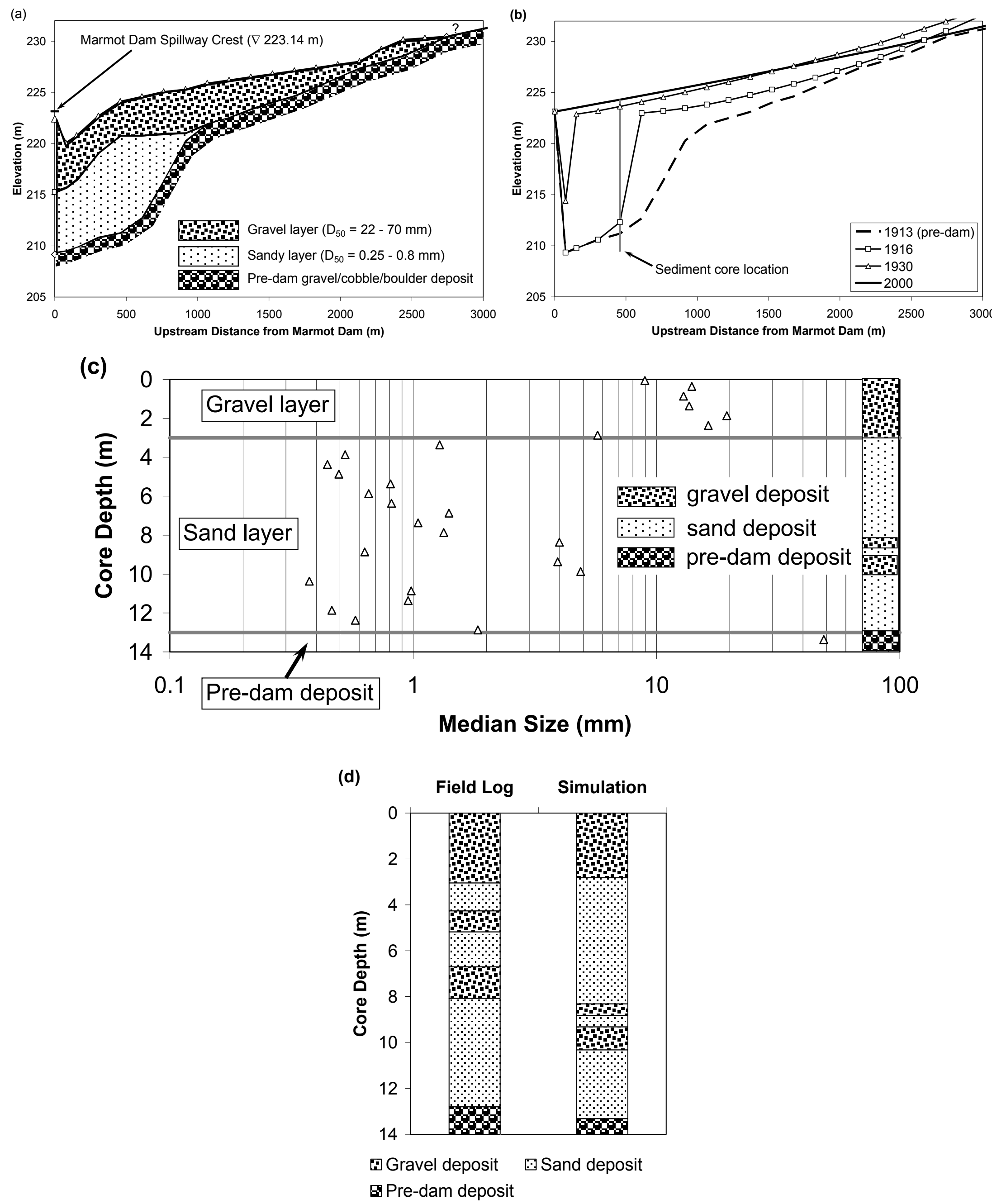


Figure 2. Examination of TUGS model performance with Marmot Reservoir sedimentation process, Sandy River, Oregon. (a) Measured bed profile and the stratification of the sediment deposit; (b) simulated bed profile; (c) Simulated stratification of the sediment deposit; and (d) comparison of the stratification of the sediment deposit between a field log and numerical simulation. Note in (d) that the model even produced two gravel lenses, much like the ones indicated in the drilling log, despite differences in depth and thickness which most likely reflect the absence of detailed event-by-event sediment supply information in the numerical simulation. Diagrams are adapted from Cui et al. (2007b).

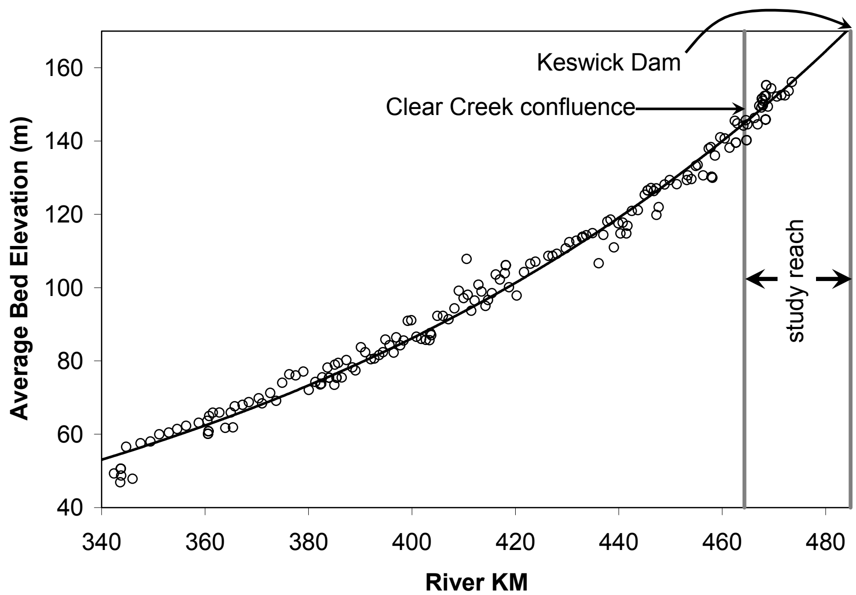


Figure 3. Longitudinal profile of the upper Sacramento River. Circles represent cross-sectionally averaged bed elevations, based on cross sections from CDWR and USACE HEC-RAS modeling (unpublished data collected in 2001). The solid line is a regression to the data. The reach-averaged regression slope for the study reach is 0.0011, which was used as an initial pre-dam condition throughout the TUGS simulations.

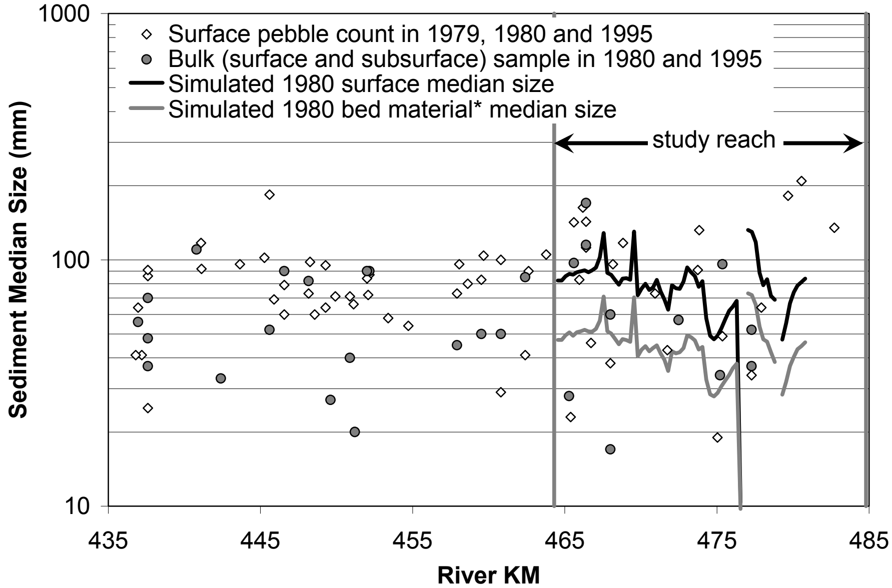


Figure 4. Median grain size ($D_{50}$) from pebble counts and bulk samples of the surface in the upper Sacramento River. Data source: CDWR (1994), Buer (1995). The simulated bed material for 1980 is composed of 50% surface material and 50% subsurface material, for compatibility with the bulk sampling data. Areas with no simulated median sizes (i.e., the gaps) reflect bedrock exposure in the simulation.

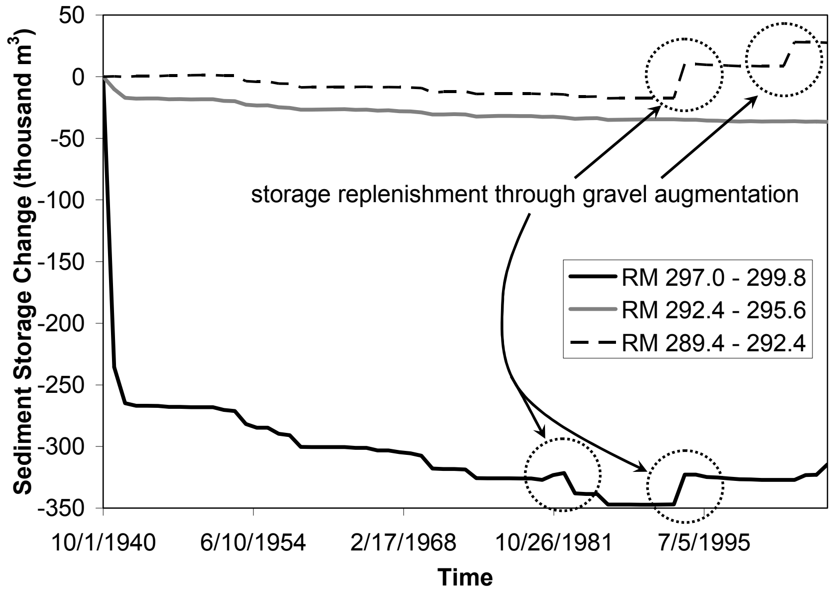


Figure 5. Simulated change in sediment storage for three sub-reaches, indicating progressive decreases in sediment storage, except after episodes of gravel augmentation.

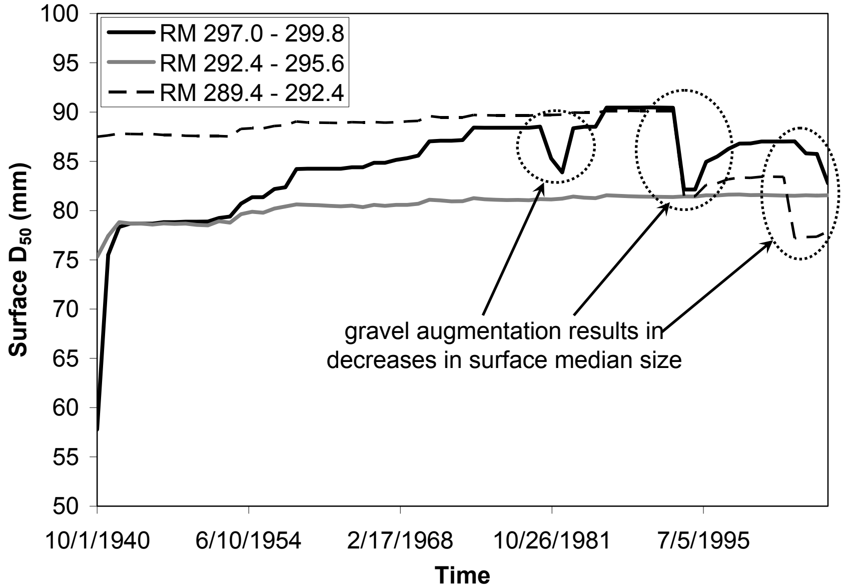


Figure 6. Simulated change in median size of the surface for the three sub-reaches, indicating progressive coarsening of surface, except after episodes of gravel augmentation.

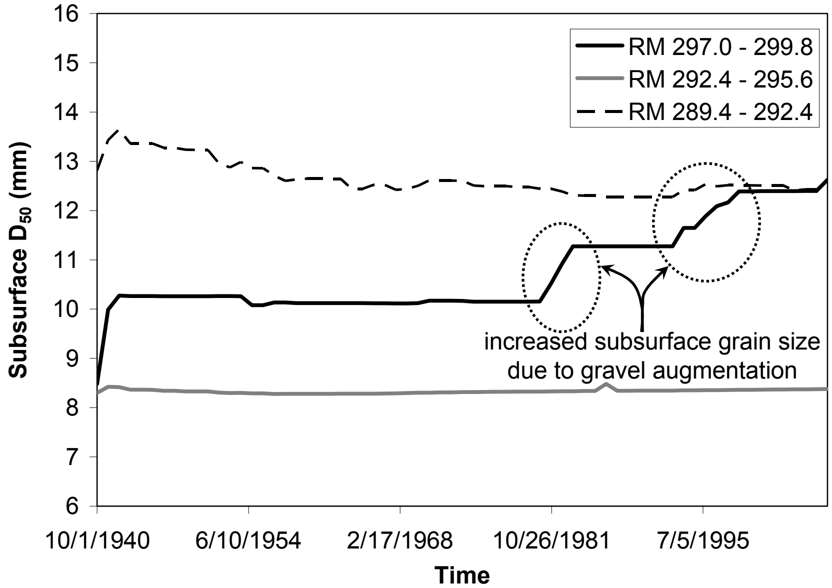


Figure 7. Simulated change in subsurface median size for three sub-reaches, showing relatively little change in subsurface grain size (compared to what we observe in the surface; Figure 6). The two circles indicate subsurface coarsening due to gravel augmentation.

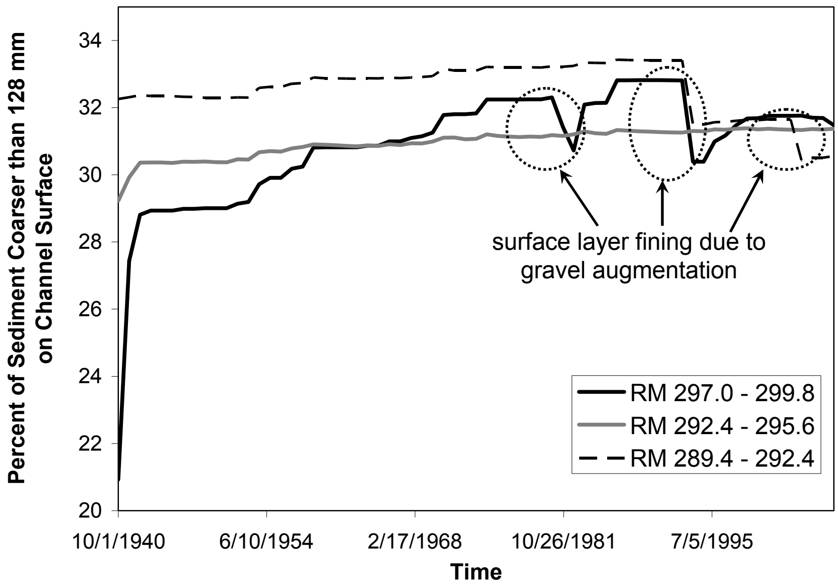


Figure 8. Simulated change in the fraction of particles coarser than 128 mm in the surface for the three sub-reaches, indicating progressive coarsening of surface, except after episodes of gravel augmentation.

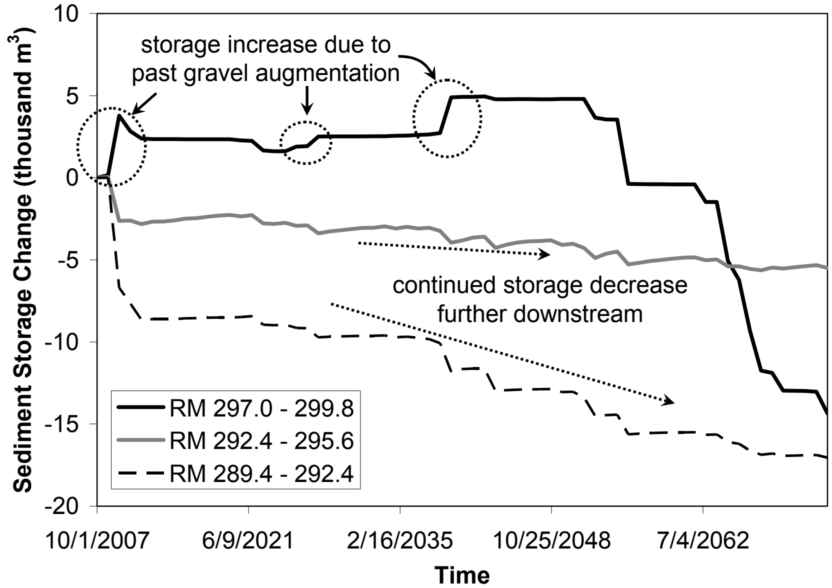


Figure 9. Simulated sediment storage in the three sub-reaches for Run 1: extrapolation of current hydrologic conditions without gravel augmentation. Sediment storage will increase for the next 40+ years in sub-reach RM 297.0–299.8 due to downstream migrating benefits of past gravel augmentation projects at Salt Creek (RM 301) and Keswick Dam (RM 302). Sub-reach of RM 292.4–295.6 will continue to progressively lose small amounts of sediment storage, while the sub-reach farther downstream (i.e., RM 289.4–292.4) will lose a more significant volume of sediment storage over the simulated interval.

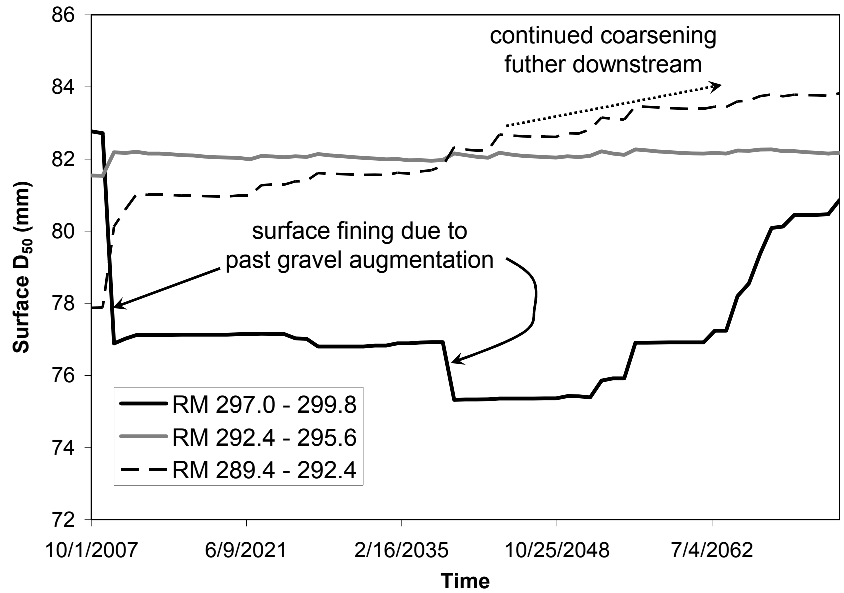


Figure 10. Simulated surface median size in the three sub-reaches for Run 1: extrapolation of current hydrologic conditions without gravel augmentation. Surface sediment in sub-reach RM 297.0–299.8 is predicted to become finer on average, due to downstream migrating benefits of past gravel augmentation projects at Salt Creek (RM 301) and Keswick Dam (RM 302). Surface grain size in sub-reach RM 292.4–295.6 will become stabilized on average, while the surface in sub-reach RM 289.4–292.4 will become significantly coarser over the simulated interval.

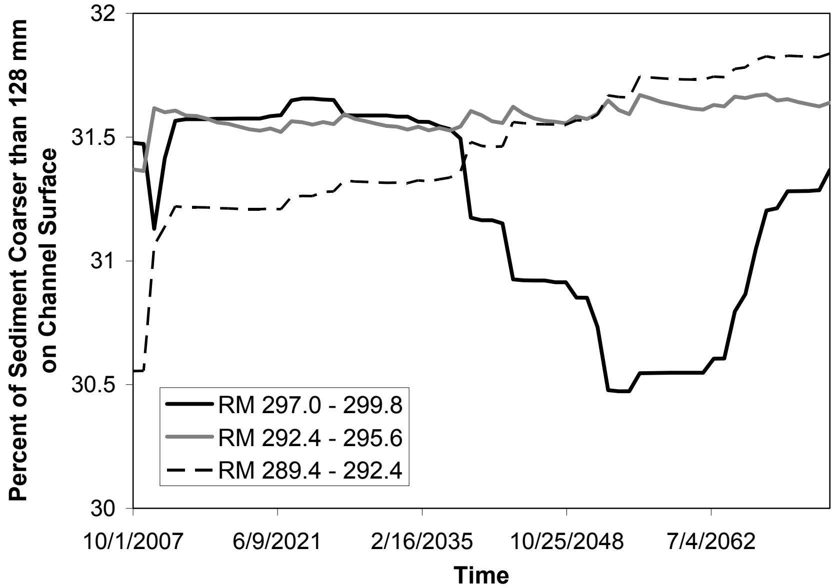


Figure 11. Simulated fraction of sediment coarser than 128 mm on channel surface for the three sub-reaches: extrapolation of current hydrologic conditions without gravel augmentation. This plot complements the patterns of changes in sediment storage (Figure 9) and $D_{50}$ (Figure 10).

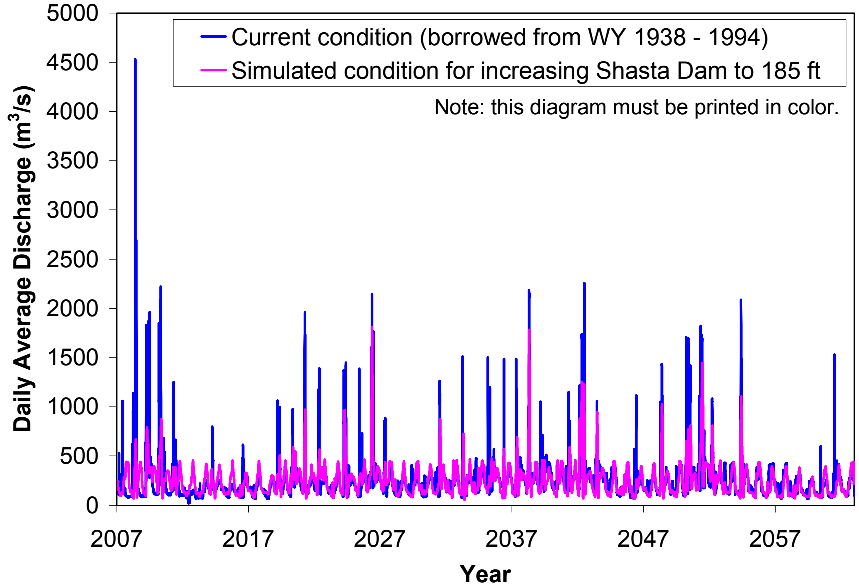


Figure 12. Predicted future daily average discharge from CALSIM for a 56-m (185-ft) increase in Shasta Dam height based on hydrologic records from WY 1939–2004 (purple line), in comparison with future daily average discharge estimated by extrapolation from the Keswick Dam (USGS #11370500) discharge record for the WY 1939–2004 period (blue line).

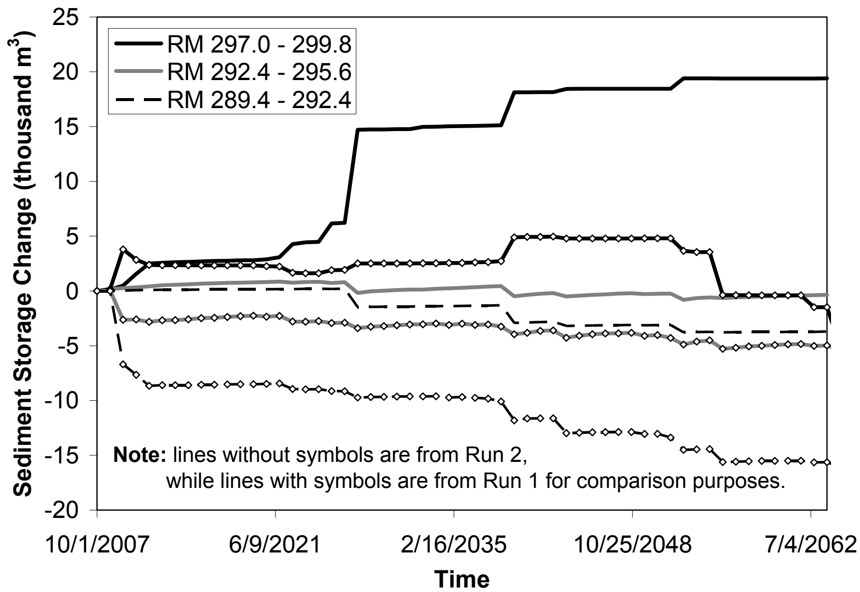


Figure 13. Simulated sediment storage in the three sub-reaches for 56-m (185-ft) increase in Shasta Dam height without gravel augmentation (Run 2), in comparison with results from Run 1 (extrapolated hydrologic condition without gravel augmentation). Results indicate that increasing the height of Shasta Dam will result in relatively higher sediment storage in all three sub-reaches due to the decreases in peak flows shown in Figure 12.

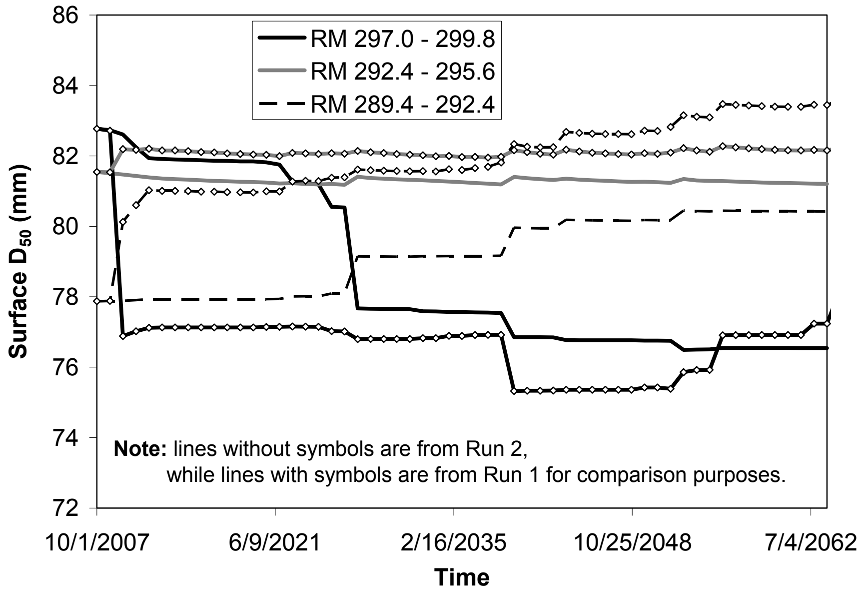


Figure 14. Simulated changes in the reach-averaged $D_{50}$ of the surface in the three sub-reaches for 56-m (185-ft) increase in Shasta Dam height without gravel augmentation (Run 2), in comparison with results from Run 1 (extrapolated hydrologic condition without gravel augmentation). Results indicate that increasing the height of Shasta Dam will result in slightly coarser $D_{50}$ values in sub-reach RM 297.0-299.8 due to the reduced peak flow that reduced the amount of gravel augmented in the upstream sub-reach to transport into the sub-reach. The other two sub-reaches for the option of increasing the height of Shasta Dam have slightly finer bed than Run 1 due to the decreases in peak flow shown in Figure 12.

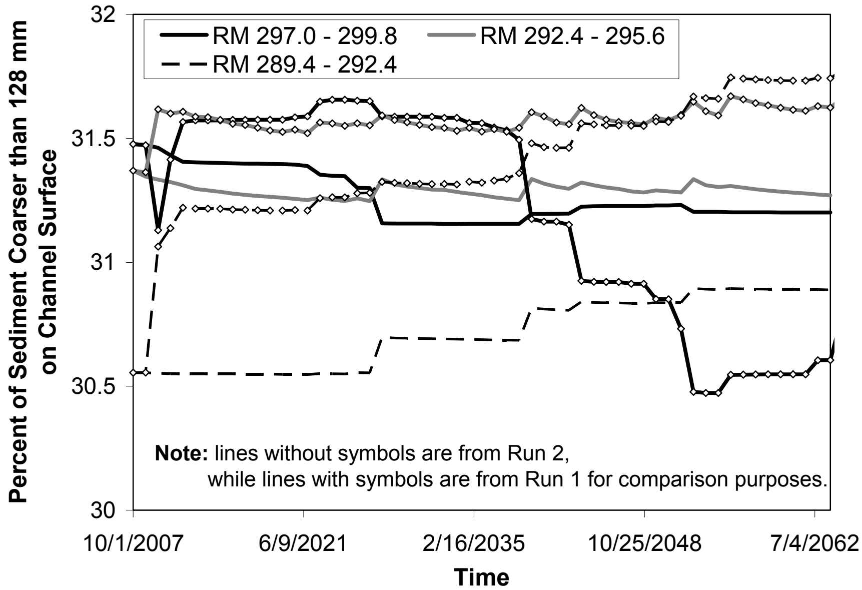


Figure 15. Simulated fraction of surface particles coarser than 128 mm in the three sub-reaches for 56-m (185-ft) increase in Shasta Dam height without gravel augmentation (Run 2), in comparison with results from Run 1 (extrapolated hydrologic condition without gravel augmentation), compliment the results shown in Figures 13 and 14.

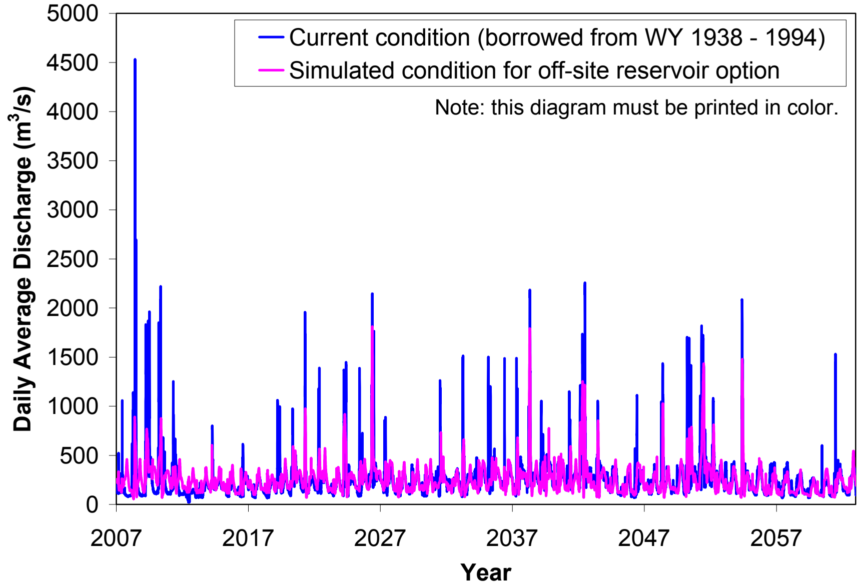


Figure 16. Predicted future daily average discharge from CALSIM for the proposed off-site storage reservoir based on hydrologic records from WY 1939–2004 (purple line), in comparison with future daily average discharge estimated by extrapolation from the Keswick Dam (USGS #11370500) discharge record for the WY 1939–2004 period (blue line).

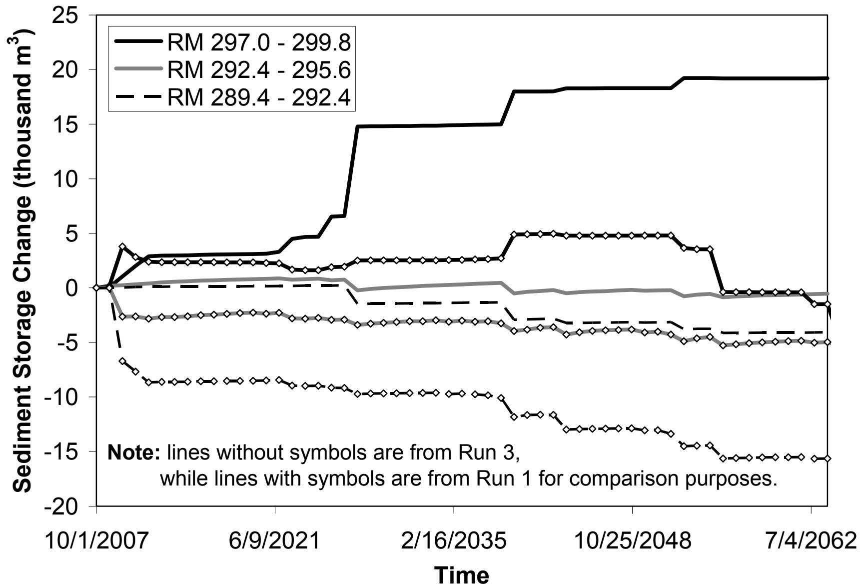


Figure 17. Simulated sediment storage in the three sub-reaches for the off-site reservoir without gravel augmentation (Run 3), in comparison with results from Run 1 (extrapolated hydrologic condition without gravel augmentation). Results indicate that the off-site reservoir option results in higher sediment storage in all the three sub-reaches due to the decreases in peak flow shown in Figure 16.

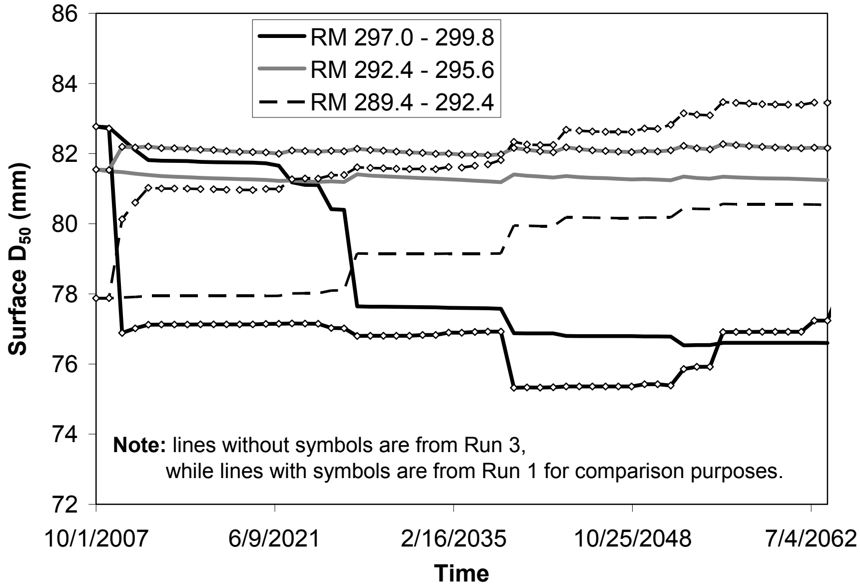


Figure 18. Simulated surface median size in the three sub-reaches for the off-site reservoir without gravel augmentation (Run 3), in comparison with results from Run 1 (extrapolated hydrologic condition without gravel augmentation). Results indicate that increasing the height of Shasta Dam will result in slightly coarser $D_{50}$ values in sub-reach RM 297.0-299.8 due to the reduced peak flow that reduced the amount of gravel augmented in the upstream sub-reach to transport into the sub-reach. The other two sub-reaches for the off-site reservoir option have slightly finer bed than Run 1 due to the decreases in peak flow shown in Figure 16.

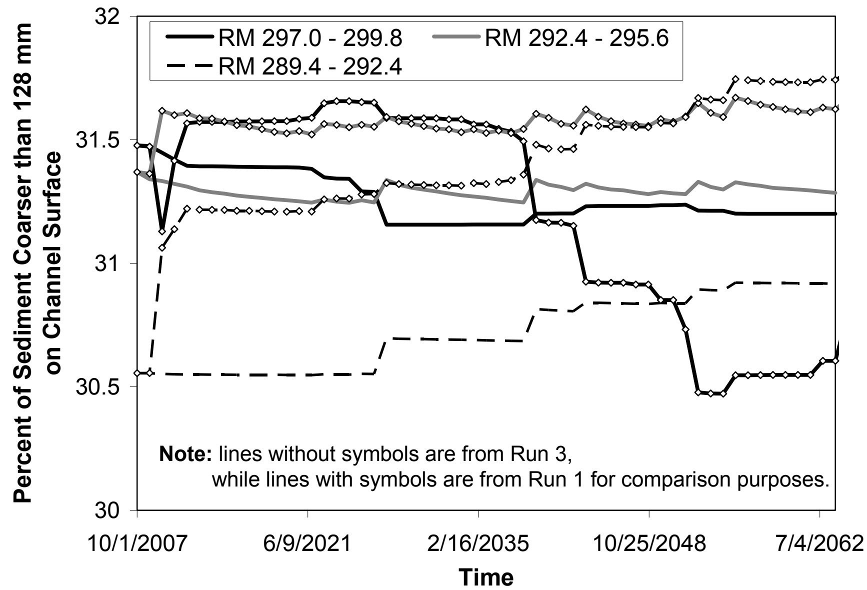


Figure 19. Simulated fraction of surface particles coarser than 128 mm in the three sub-reaches for off-site reservoir option without gravel augmentation (Run 3), in comparison with results from Run 1 (extrapolated hydrologic condition without gravel augmentation), compliment the results shown in Figures 17 and 18.

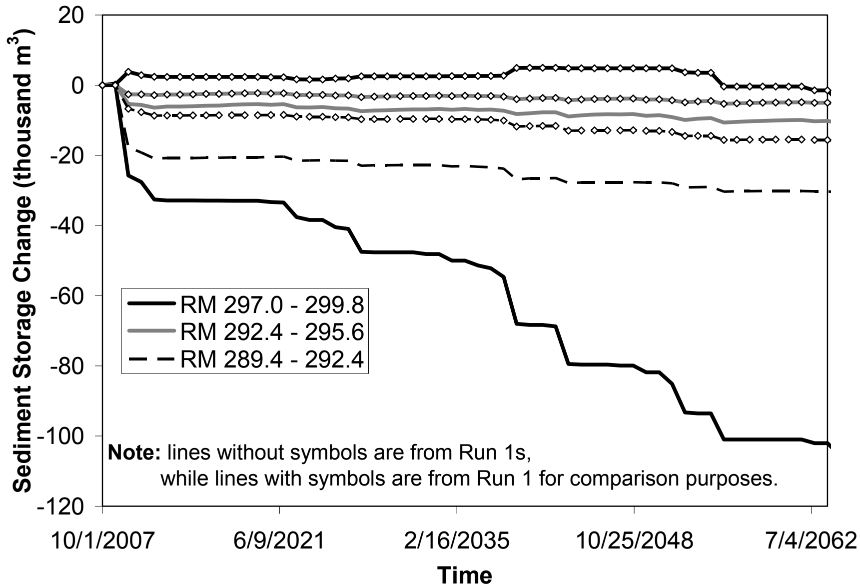


Figure 20. Simulated change in sediment storage in the three sub-reaches for sensitivity test (Run 1s, with bedload transport rate increased by a factor of 3), in comparison with results from Run 1. Results indicate that there will be more storage losses in all the three sub-reaches.

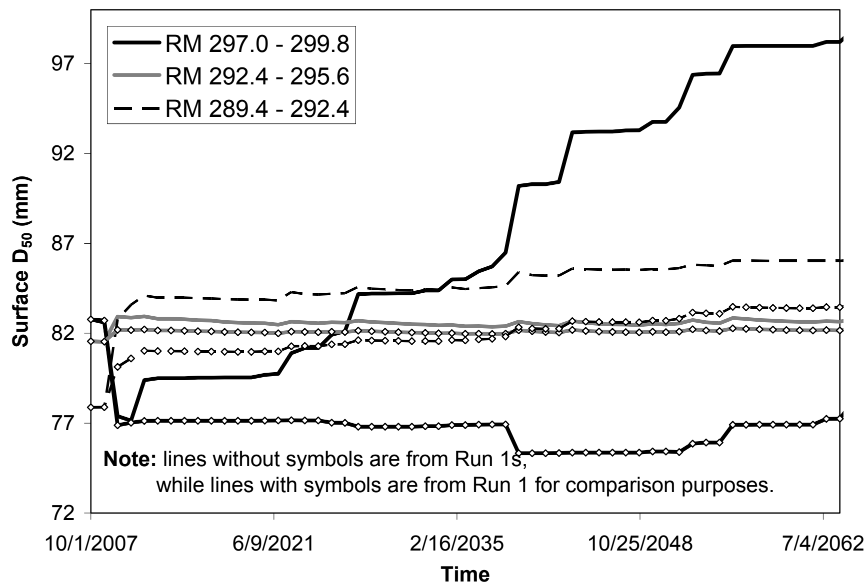


Figure 21. Simulated surface $D_{50}$ in the three sub-reaches for sensitivity test (Run 1s, with bedload transport rate increased by a factor of 3), in comparison with results from Run 1. Results indicate that there will be more bed coarsening in all three sub-reaches.

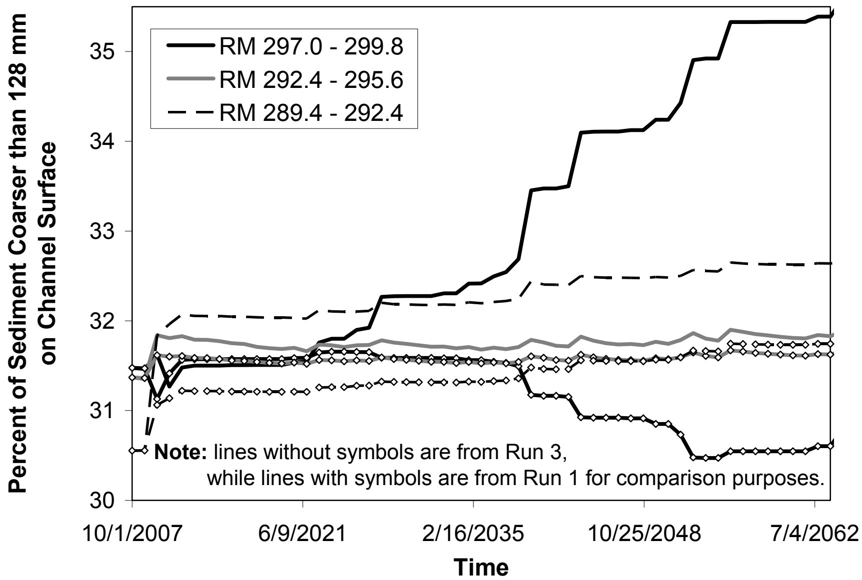


Figure 22. Simulated percent coverage by coarse material in the three sub-reaches for sensitivity test (Run 1s, with bedload transport rate increased by a factor of 3), in comparison with results from Run 1. Results indicate that there will be more bed coarsening in all three sub-reaches.

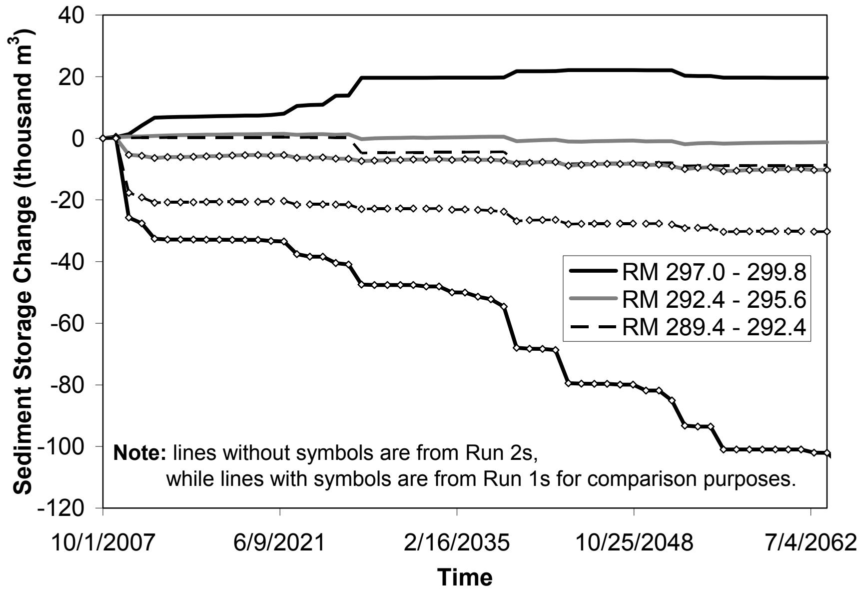


Figure 23. Simulated change in sediment storage in the three sub-reaches for sensitivity test (Run 2s, with bedload transport rate increased by a factor of 3), in comparison with results from Run 1s. Results indicate that there will be less storage depletion in all three sub-reaches for an increase in Shasta Dam height relative to extrapolated current hydrologic conditions.

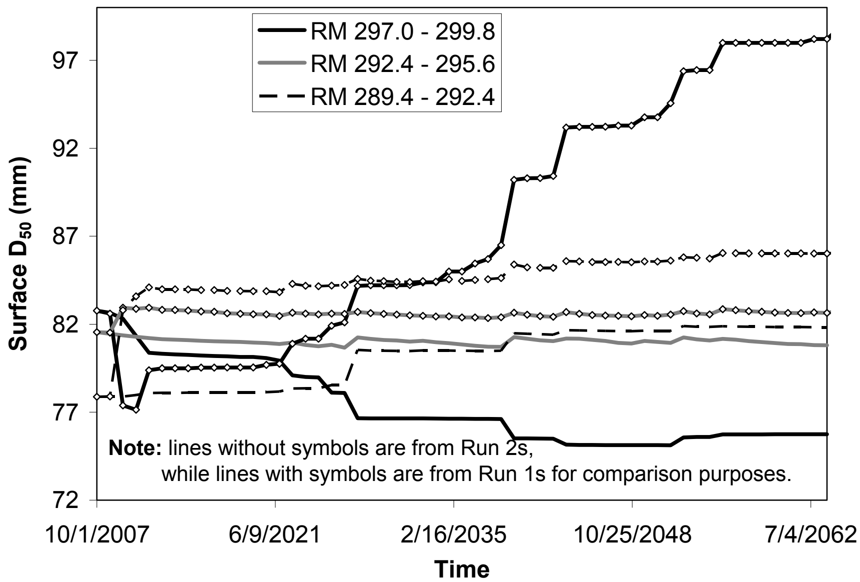


Figure 24. Simulated surface $D_{50}$ in the three sub-reaches for sensitivity test (Run 2s, with bedload transport rate increased by a factor of 3), in comparison with results from Run 1s. Results indicate that increasing the height of Shasta Dam will result in a slightly finer channel surface compared to what we predict would occur if current hydrologic conditions were maintained.

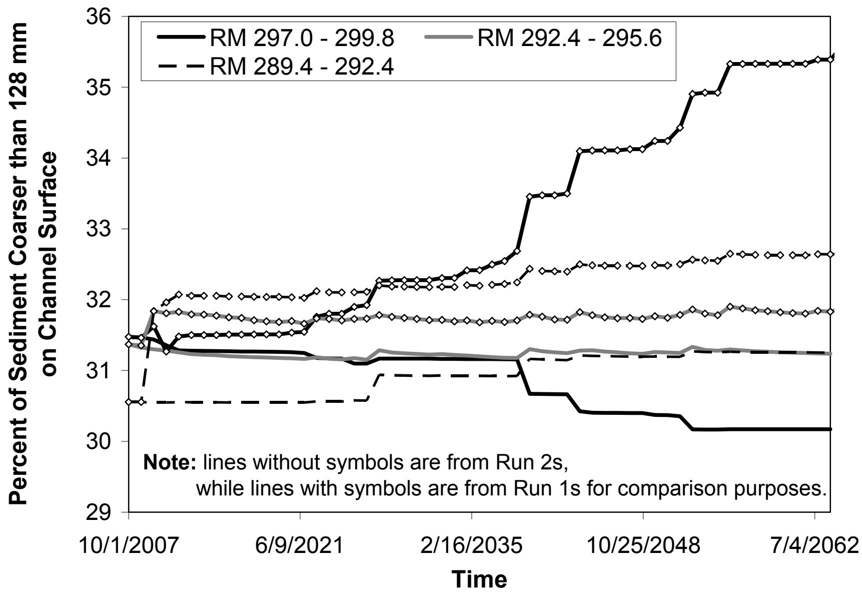


Figure 25. Simulated percent coverage by coarse material in the three sub-reaches for sensitivity test (Run 2s, with bedload transport rate increased by a factor of 3), in comparison with results from Run 1s. Results indicate that increasing the height of Shasta Dam will result in a slightly finer channel surface compared to what we predict would occur if current hydrologic conditions were maintained.

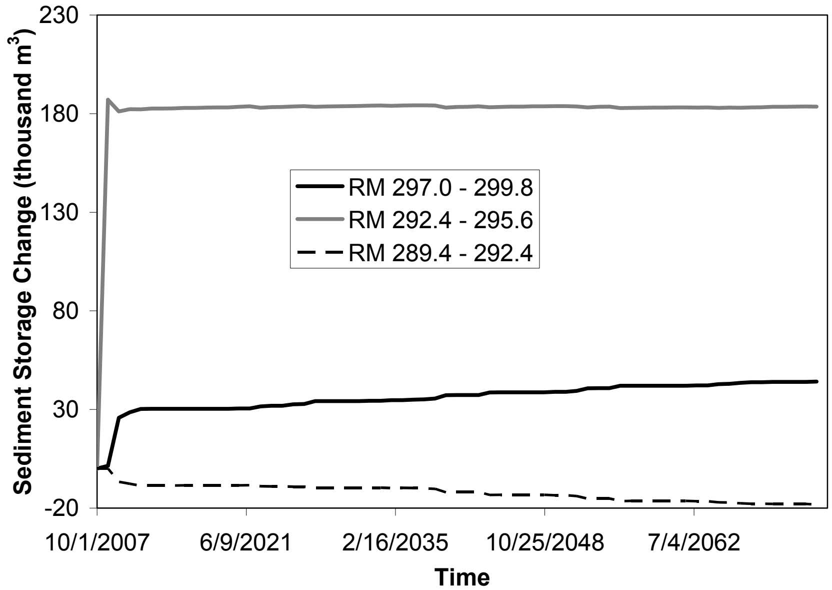


Figure 26. Simulated change in sediment storage in the three sub-reaches for Run 1g, which simulates sediment transport dynamics using current hydrologic condition and gravel injection in year 1.

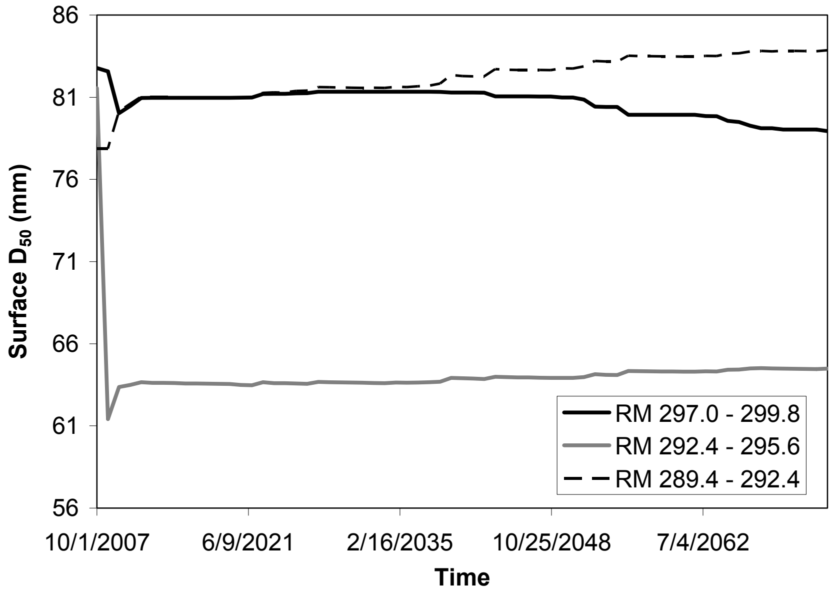


Figure 27. Simulated change in surface $D_{50}$ in the three sub-reaches for Run 1g, which simulates sediment transport dynamics using current hydrologic condition and gravel injection in year 1.

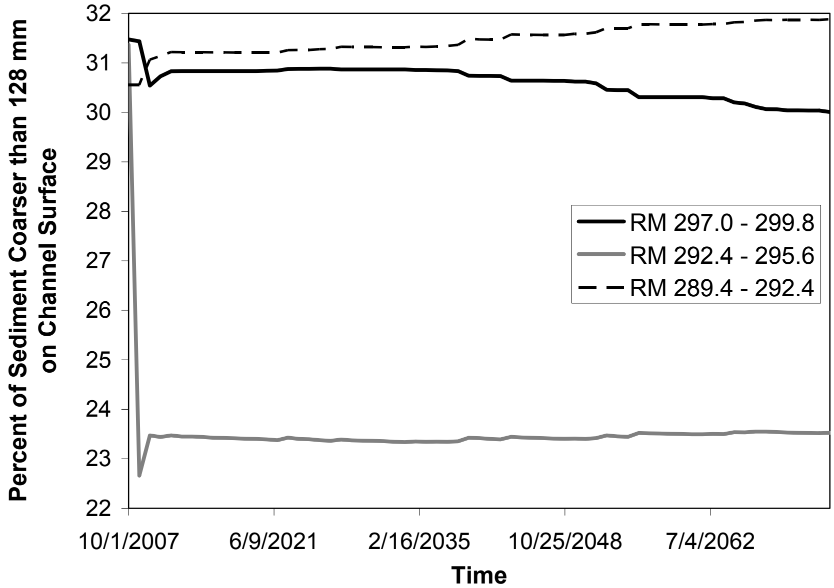


Figure 28. Simulated change in the percent coverage by coarse material in the three sub-reaches for Run 1g, which simulates sediment transport dynamics using current hydrologic condition and gravel injection in year 1.

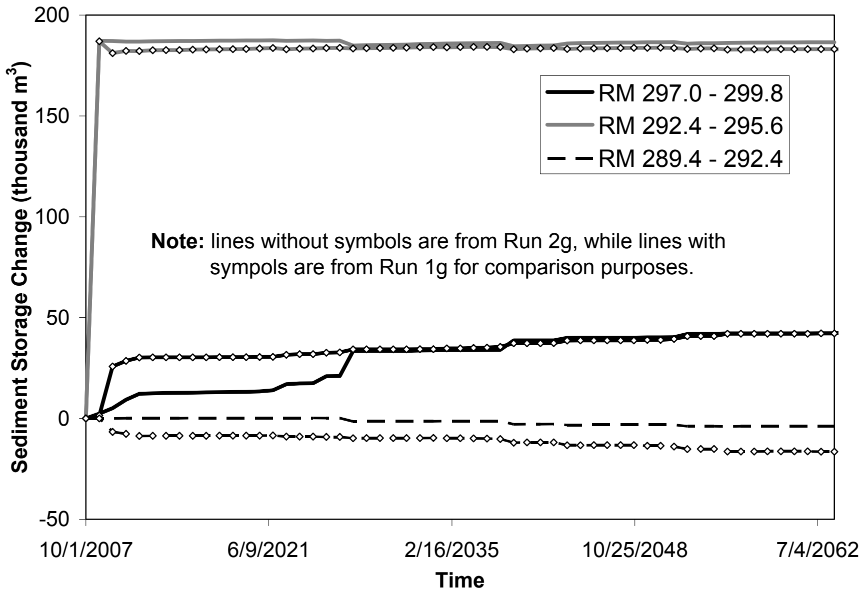


Figure 29. Simulated change in sediment storage in the three sub-reaches for Run 2g, which simulates sediment transport dynamics using under the assumption that Shasta Dam has been raised by 56 m (185 ft) and with a large gravel injection in year 1. Results from Run 1g are also plotted for comparison.

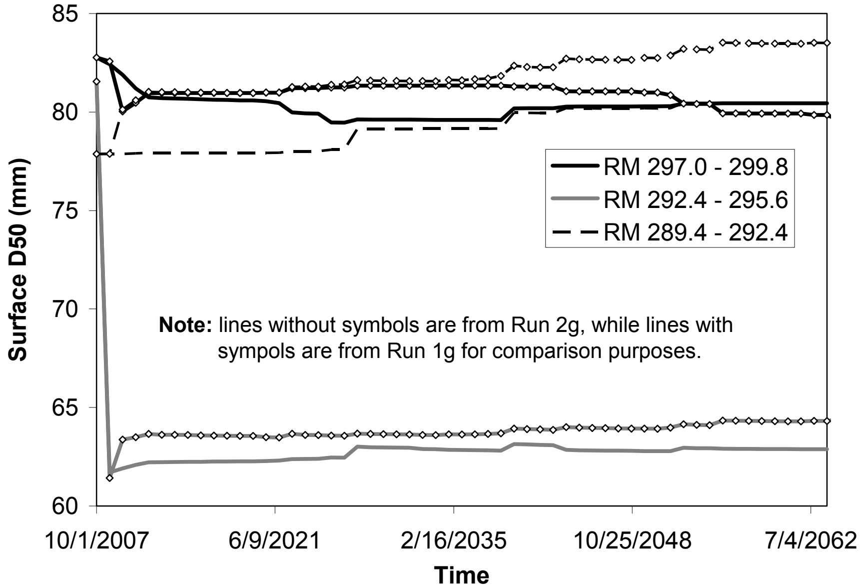


Figure 30. Simulated change in $D_{50}$ in the three sub-reaches for Run 2g, which simulates sediment transport dynamics under the assumption that Shasta Dam has been raised by 56 m (185 ft) and with a large gravel injection in year 1. Results from Run 1g are also plotted for comparison.

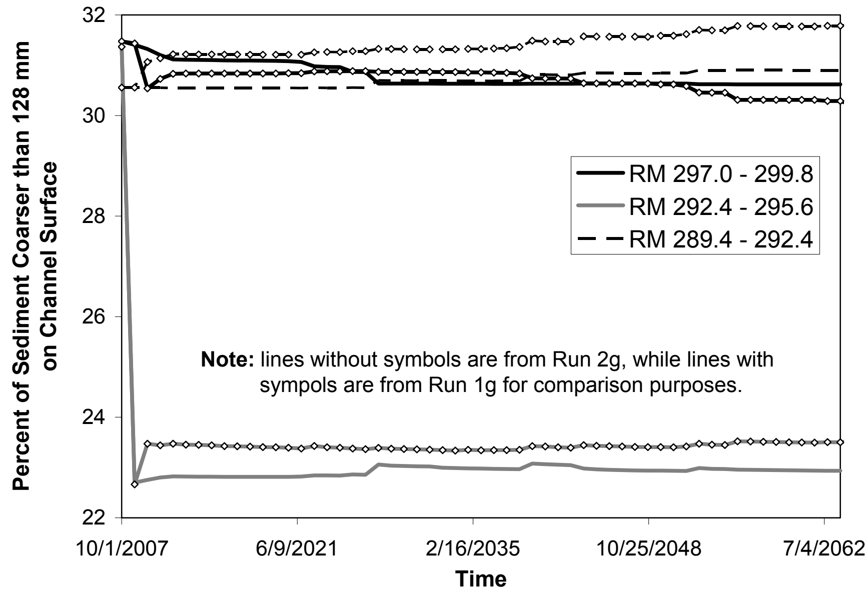


Figure 31. Simulated change in percent coverage by coarse material in the three sub-reaches for Run 2g, which simulates sediment transport dynamics using under the assumption that Shasta Dam has been raised by 56 m (185 ft) and with a large gravel injection in year 1. Results from Run 1g are also plotted for comparison.

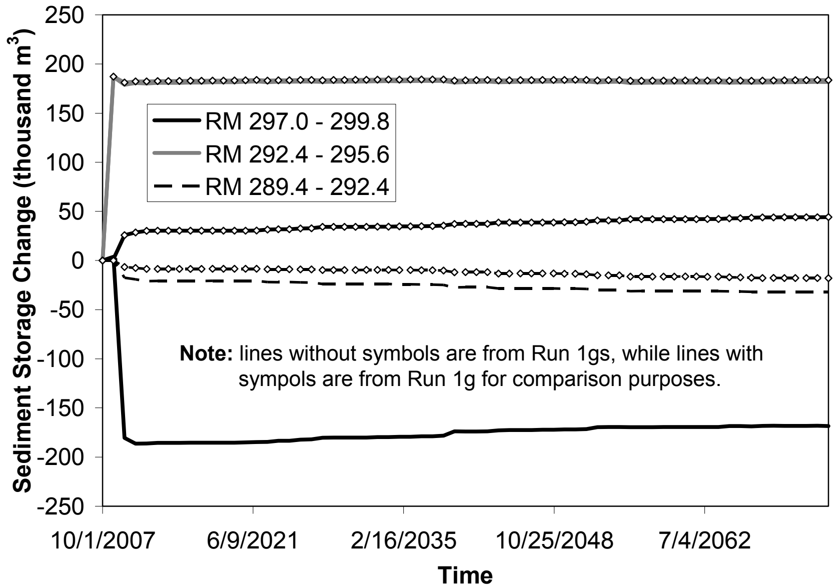


Figure 32. Simulated sediment storage in the three sub-reaches for Run 1gs, which simulates effects of current hydrologic regime, an initial gravel injection, and a bedload transport rate that is three times higher than what was used in the baseline simulations. Results from Run 1g are also presented for comparison.

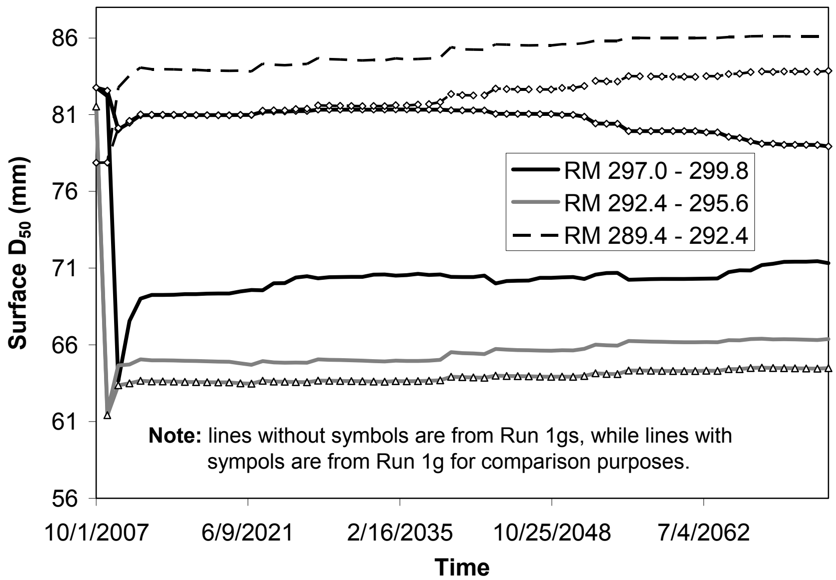


Figure 33. Simulated change in $D_{50}$ in the three sub-reaches for Run 1gs, which simulates effects of current hydrologic regime, an initial gravel injection, and a bedload transport rate that is three times higher than what was used in the baseline simulations. Results from Run 1g are also presented for comparison.

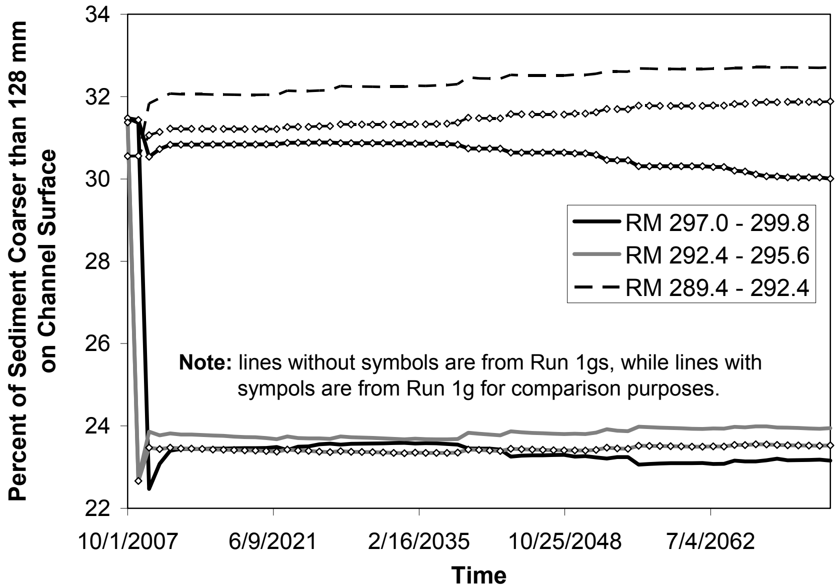


Figure 34. Simulated fractional coverage by coarse material in the three sub-reaches for Run 1gs, which simulates effects of current hydrologic regime, an initial gravel injection, and a bedload transport rate that is three times higher than what was used in the baseline simulations. Results from Run 1g are also presented for comparison.

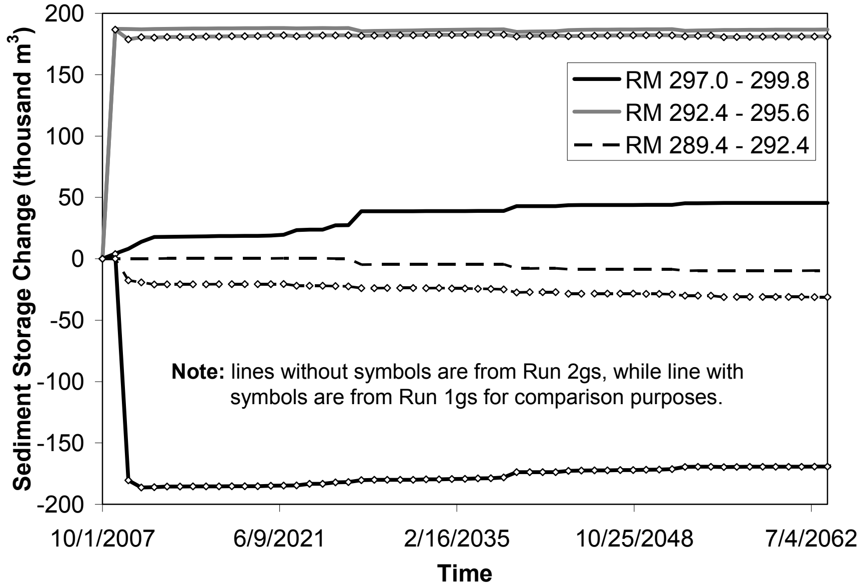


Figure 35. Simulated sediment storage in the three sub-reaches for Run 2gs, which simulates sediment transport dynamics under the assumption that Shasta Dam has been raised by 56 m (185 ft) with a large gravel injection in year 1 and assuming bedload transport is three times higher than predicted with bedload equation in TUGS model. Results from Run 1gs are also presented for comparison purposes.

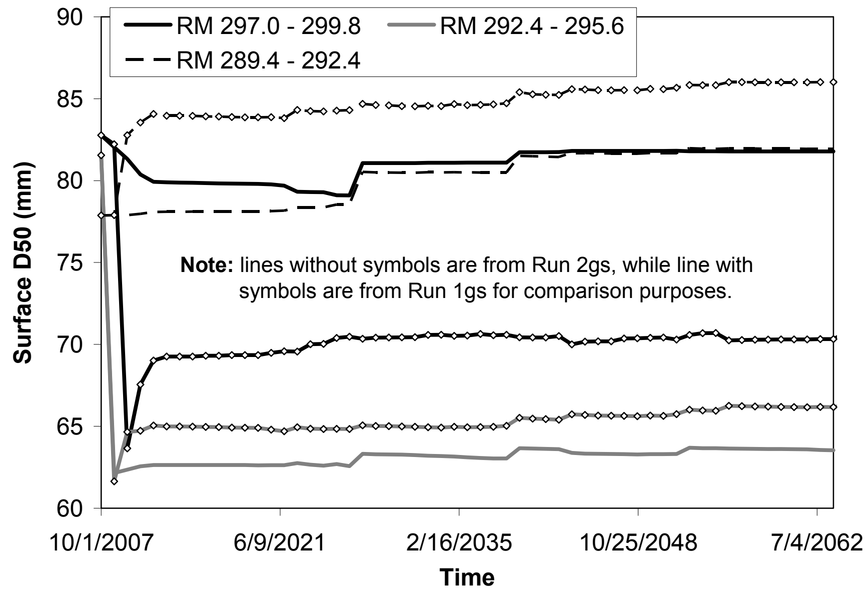


Figure 36. Simulated change in $D_{50}$ in the three sub-reaches for Run 2gs, which simulates sediment transport dynamics under the assumption that Shasta Dam has been raised by 56 m (185 ft) with a large gravel injection in year 1 and assuming bedload transport is three times higher than predicted with bedload equation in TUGS model. Results from Run 1gs are also presented for comparison purposes.

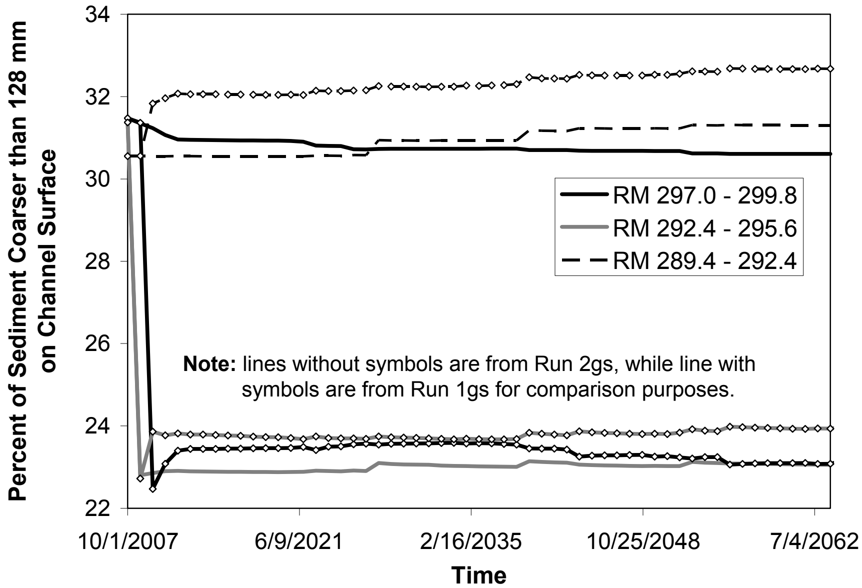


Figure 37. Simulated fractional coverage by coarse material in the three sub-reaches for Run 2gs, which simulates sediment transport dynamics under the assumption that Shasta Dam has been raised by 56 m (185 ft) with a large gravel injection in year 1 and assuming bedload transport is three times higher than predicted with bedload equation in TUGS model. Results from Run 1gs are also presented for comparison purposes.