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EXAMINING THE DYNAMICS OF GRAIN SIZE DISTRIBUTIONS OF GRAVEL/SAND DEPOSITS IN THE SANDY RIVER, OREGON WITH A NUMERICAL MODEL

YANTAO CUI*

Stillwater Sciences, 2855 Telegraph Ave., Suite 400, Berkeley, CA 94705, USA

ABSTRACT

This paper describes the application of The Unified Gravel-Sand (TUGS) model for the simulation of the Sandy River, Oregon. TUGS model employs Wilcock and Crowe's (2003) bedload transport equation for simulation of gravel and sand transport, and is capable of simulating the dynamics of bed material grain size distributions, including the fractions of sand in the deposits. The model has been examined with three large-scale flume experiments and a flushing flow flume experiment with good agreements in bed profiles, gravel characteristic grain sizes and fractions of sand in the deposits. These examinations, along with descriptions of model development, are presented in a manuscript submitted concomitantly elsewhere (Cui, 2007), and this paper expands model examinations to a natural river. Eight runs are conducted with the Sandy River, Oregon as the prototype river, focusing on the responses of bed material grain size distributions under different hydrologic and sediment supply conditions. Simulation with the recorded discharge and the best understanding of sediment supply in the Sandy River produced good agreement in river longitudinal profile. This simulation also produced decreased median grain size and increased sand fraction in the downstream direction that match well with the general observations in the field. Examinations with varied sand supply indicate that bed material sand fractions are positively correlated with sand supply. Examinations with varied water discharge indicate that increased discharge under the same sediment supply conditions results in decreased bed material sand fraction. Examination of a hypothetical backwater effect from the Columbia River indicates that backwater effect results in increases in bed material sand fractions. Simulation of the sedimentation process upstream of a 14-m tall dam during dam operation produced similar current bed profile and a stratified sediment deposit very similar to those observed in the field. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: numerical model; gravel-bedded river; channel morphology; grain size distribution; sediment deposit; sand fraction; reservoir sedimentation

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INTRODUCTION

Understanding the dynamics of grain size distributions, the fraction of sand in particular, of sediment deposits in gravel-bedded rivers is one of the most challenging tasks in fluvial geomorphology. Such understandings are important to fish biologists and aquatic ecologists, who need to understand the dynamics of grain size distributions of the sediment deposit in order to better understand biological issues such as spawning habitat quality, egg mortality, and invertebrate production. The fine sediment fraction in the gravel-dominated sediment deposit of salmon bearing rivers, for example, is one of the most important indicators of salmonid spawning habitat quality (e.g. Cooper, 1965). It can be expected that sediment supply (including its rate and grain size distribution) and hydrologic conditions in a river are the two major contributors in determining the amount of fine sediment in the deposit. In this paper, I simulate the fine sediment dynamics in responses to changes in sand supply and hydrologic conditions in the Sandy River, Oregon for a 50-km reach between Marmot Dam and its confluence with the Columbia River (Figure 1). In addition, I also simulate the sedimentation process upstream of the Marmot Dam during its more than 90 years operation and compare the simulated texture of sediment deposit with field coring

*Correspondence to: Yantao Cui, Stillwater Sciences, 2855 Telegraph Ave., Suite 400, Berkeley, CA 94705, USA.
E-mail: yantao@stillwatersci.com

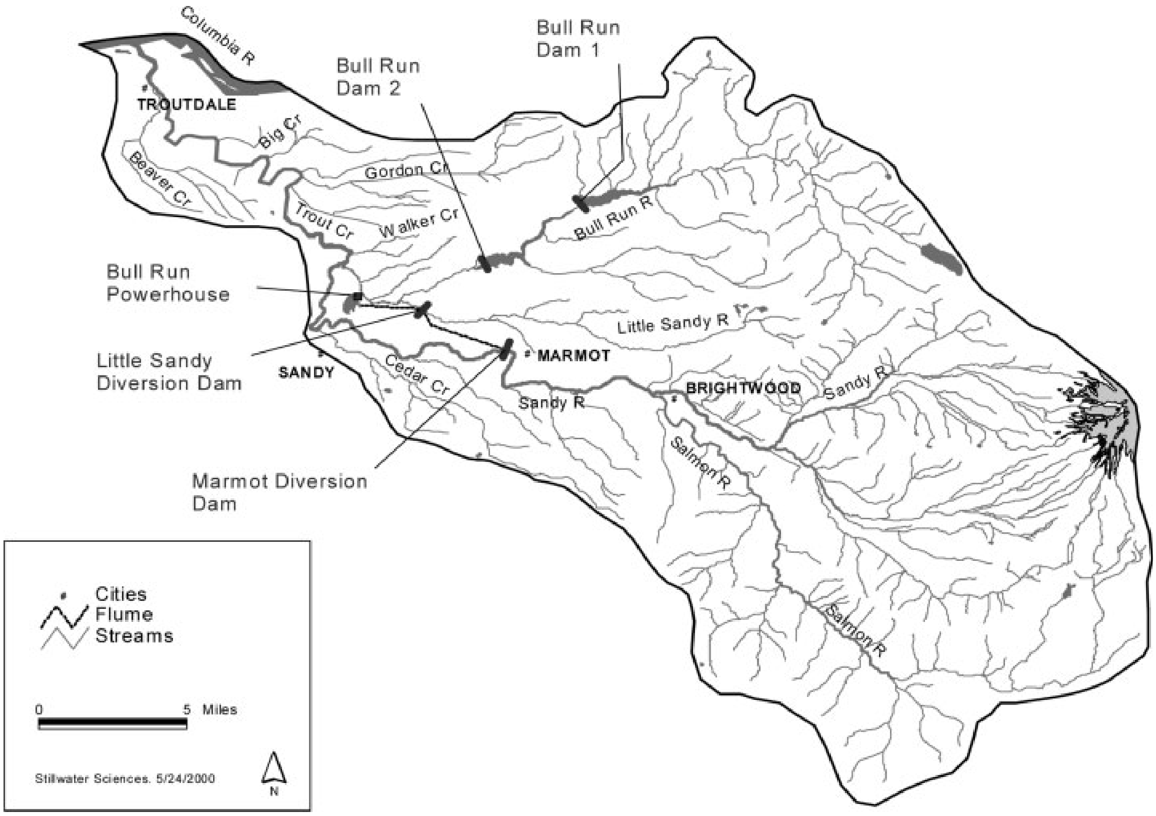

Figure 1. Sandy River watershed, Oregon. The studies presented in this paper include the sedimentation process upstream of Marmot Dam and the fine sediment dynamics in the Sandy River between Marmot Dam and its confluence with the Columbia River

data. The simulations are conducted with the recently developed The Unified Gravel-Sand (TUGS) model, which is presented elsewhere (Cui, 2007). A brief overview of TUGS model is provided below.

OVERVIEW OF TUGS MODEL

The key components of TUGS model include: (a) the surface-based bedload equation of Wilcock and Crowe (2003) that links local sediment transport capacity to local shear stress; (b) the gravel transfer function of Hoey and Ferguson (1994) and Toro-Escobar *et al*. (1996) that links the gravel grain size distributions in subsurface and surface deposits with bedload; (c) a hypothetical sand transfer function that links the sand fraction in subsurface deposit to that on channel surface developed in Cui (2007) based on available field and laboratory data; (d) hypothetical relations for sand entrainment and infiltration that allows for sand entrainment from and infiltration into the subsurface deposit; (e) the grain-size-based Exner equations of sediment continuity, including the abrasion of gravel during transport as proposed by Parker (1991a,b) and used in many sediment transport models of gravel-bedded rivers (e.g. Cui and Parker, 1998; Cui *et al*., 2003; Cui and Parker, 2005; Cui *et al*., 2006a,b; Cui and Wilcox, 2007); and (f) equations for open channel flow that provides local shear stress for sediment transport capacity calculation. Among the above components, the gravel transfer function, the grain-size-based Exner equation, the abrasion formulation for gravel, and the equations for open channel flow are either identical or very similar to those presented in previous Parker family of models (e.g. Parker, 1991a,b; Cui *et al*., 1996; Cui and Parker, 1997; Cui and Parker, 1998; Cui *et al*., 2003; Cui and Parker, 2005; Cui *et al*., 2006a,b; and Cui and Wilcox, 2007), and thus will not be discussed any further in this paper. The sand entrainment and infiltration functions were proposed in Cui (2007) to accommodate for strongly non-equilibrium short-term events such as managed flushing

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flow events. Such short-term events, however, are not the subject of interest of this paper, and thus, the sand entrainment and infiltration functions are not discussed further, and the functions are disabled in the modelling exercises presented in this paper. The application of Wilcock and Crowe's (2003) equation and sand transfer functions are unique in TUGS model and a brief discussion is provided below.

The surface-based bedload equation of Wilcock and Crowe (2003) is developed based on their experimental data and is unique in that the mobility of the sediment particles increases with the increase in sand fraction on channel surface, which represents the state-of-the-science in sediment transport capacity prediction, and TUGS model is the first numerical model that implements this equation to simulate the dynamic responses in gravel-bedded rivers. Wilcock and Crowe's (2003) equation was implemented in TUGS model with the three-layer conceptual model (e.g. Hirano, 1971; Parker, 1991a,b) as shown in Figure 2. This three-layer conceptual model is adapted directly from Parker (1991a,b), in which sediment deposit is classified as a coarser surface layer lying on top of a subsurface layer. The sediment transported as bedload over the surface layer constitutes the third layer of the three-layer model. In addition to the surface, subsurface and bedload layers, a fourth interface layer is also used in the formulation. The interface layer is defined as the sediment deposited in the subsurface layer while channel aggrades, or the eroded subsurface sediment during degradation. This interface layer, however, exists only conceptually because its thickness $\rightarrow 0$ for a time interval $\Delta t \rightarrow 0$, and thus the conceptual model is conventionally named as a three-layer model instead of a four-layer model. With the application of existing gravel transfer functions (e.g. Hoey and Ferguson, 1994; Toro-Escobar *et al*., 1996) that links interface gravel grain size distribution to gravel grain size distributions in the surface layer and the bedload, a sand transfer function was needed to link the amount of sand in the interface to that in the surface and/or the bedload layers in order to implement Wilcock and Crowe's (2003) equation into a dynamic sediment transport model. In case of channel degradation, the flow mines the subsurface sediment, and thus, TUGS model assumes that the interface sand fraction is identical to the sand fraction in the subsurface. The sand transfer function used in TUGS model for the case of channel aggradation was proposed in Cui (2007) based on available paired surface/subsurface grain size distribution data and the principle that (a) interface sediment sand fraction should increase as the surface sand fraction increases; (b) the interface sediment sand fraction should increase with the decrease in the standard deviation of the gravel class of the interface sediment because well-sorted gravel deposits provide more pore space for sand to settle in; (c) the sand fraction in the interface should be equal to or higher than surface sand fraction because subsurface sediment is generally finer than surface sediment; and (d) the calculated range of interface sand fraction should generally fall within the same range as the subsurface sand fractions measured in the field. The exact formulation for sand transfer function, together with approximately 30 other equations used in TUGS model, can be found in Cui (2007) and is not presented here.

TUGS model was examined in Cui (2007) with data from three large-scale flume experiments conducted at St. Anthony Falls Laboratory (SAFL) and reported in Paola *et al*. (1992), Seal *et al*. (1995), Toro-Escobar *et al*. (1996)

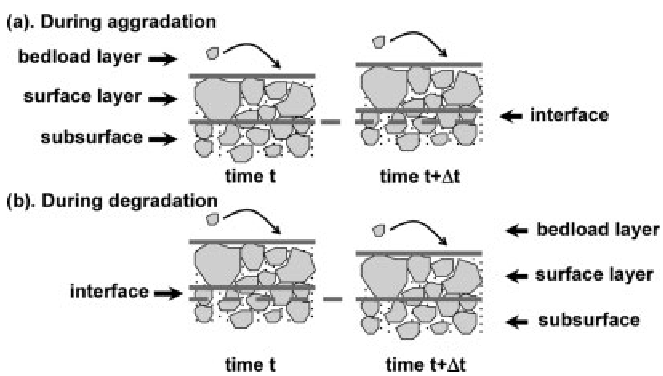

Figure 2. The three-layer conceptual model, adapted from Parker (1991a,b), used in TUGS model, showing the bedload, surface and subsurface layers. A fourth layer, the interface layer, exists only conceptually because its thickness $\rightarrow 0$ when time interval $\Delta t \rightarrow 0$. A hypothetical sand transfer function was used in TUGS model, linking interface layer sand fraction to surface layer sand fraction for sand exchange during channel aggradation

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and Seal *et al*. (1997). Model examination indicates that there are excellent agreements in bed profile, gravel characteristic grain sizes in the deposits, and sand fractions in the deposits between TUGS model prediction and experimental data. Details of the model examination with SAFL flume data can be found in Cui (2007), and results for Run 3, one of the three SAFL runs, are provided in Figure 3. Below I further examine TUGS model by simulating the fine sediment dynamics in a natural river.

HYDRO AND GEOMORPHIC CONDITIONS OF THE STUDY REACH IN THE SANDY RIVER, OREGON, USA

The Sandy River is a tributary of the Columbia River that drains the western slopes of the Cascade Range in Oregon, USA. The study reach extends between the Marmot Dam and its confluence with the Columbia River for a total length of approximately 48 km. Marmot Dam is scheduled for removal in 2007, and all the field data used in this study were collected during the dam removal study between 1999 and 2003 (Stillwater Sciences, 2000a,b; Cui *et al*., 2006a; Cui and Wilcox, 2007). Constructed in 1913 as the only dam on the Sandy River, the impoundment upstream of Marmot Dam was completely filled with sediment sometime before 1989, when the original wood crib dam was replaced with a concrete dam, and thus there has been very little trapping of sediment within the reservoir at least for the past 17 years. The drainage area of the Sandy River at Marmot Dam site is approximately 680 km^2, which increases to approximately 1316 km^2 at its confluence with the Columbia River, an increase of approximately 636 km^2. Downstream of Marmot Dam there is only one major tributary, the Bull Run River, that joins the Sandy River approximately 20.5 km downstream of Marmot Dam. Downstream of Bull Run River confluence, the Sandy River average annual runoff increased by approximately 69% compared to at the Marmot Dam site based on analysis of USGS daily discharge record between water year (denoted as WY hereafter, defined as between October 1 of the previous calendar year to September 30 of the calendar year) 1931 and WY 2004, with most of the additional runoff contribution originating from the Bull Run River. Despite the large contribution in runoff, the Bull Run River contributes virtually no coarse sediment (gravel) and only a small amount of sand to the Sandy River due to the sediment trapping by large dams located at the upper Bull Run River watershed. In the upstream portion of the study reach, the Sandy River is predominantly a bedrock/boulder controlled channel with isolated gravel deposits. Further downstream, the Sandy River gradually translates into an alluvial river with abundant of gravel and sand deposits typified with frequent large gravel bars and occasional sand bars. Field observations indicate that sand content on the bed surface increases in the downstream direction, and part of the channel bed is often covered completely with sand in the reach within a short distance of its confluence with the Columbia River. The longitudinal profile of the Sandy River in the study reach shows the typical upward concavity with a bed slope of approximately 0.008 near Marmot Dam, which decreases to under 0.001 near its confluence with the Columbia River (Cui *et al*., 2006a; Cui and Wilcox, 2007). The longitudinal profile of the study reach in the Sandy River is shown in Figure 4 (shown as photogrammetry data). The simple geomorphic setting and readily available field data from previous studies makes the Sandy River downstream of Marmot Dam an ideal river reach for application of sediment transport numerical models. Cui *et al*. (2006a), for example, applied Dam Removal Express Assessment Models (DREAM-1 and -2) on the same river reach to examine the sensitivity of the input parameters used in DREAM-1 and -2. Here TUGS model is applied to this reach to qualitatively examine model performance under field scale.

There are two USGS hydrologic stations on the Sandy River in or near the study reach, one is located a short distance upstream of Marmot Dam with daily discharge record since WY 1911, and the other is located a short distance downstream of Bull Run River confluence with daily discharge record since WY 1930. Annual peak series also exists for each of the two USGS stations. Table I shows the peak flow magnitudes for selected recurrence intervals at the two stations that can be useful for understanding of the general flow magnitude in the river. For modelling purposes, daily discharge is used to represent the hydrologic conditions of the study reach, with the USGS above Marmot Dam station record representing the reach between Marmot Dam and the Bull Run confluence, and USGS below the Bull Run confluence station record representing the reach between the Bull Run confluence and the Sandy River confluence with the Columbia River. Instead of applying all the available discharge record in TUGS simulation, only 10 years of data, selected randomly from the available USGS

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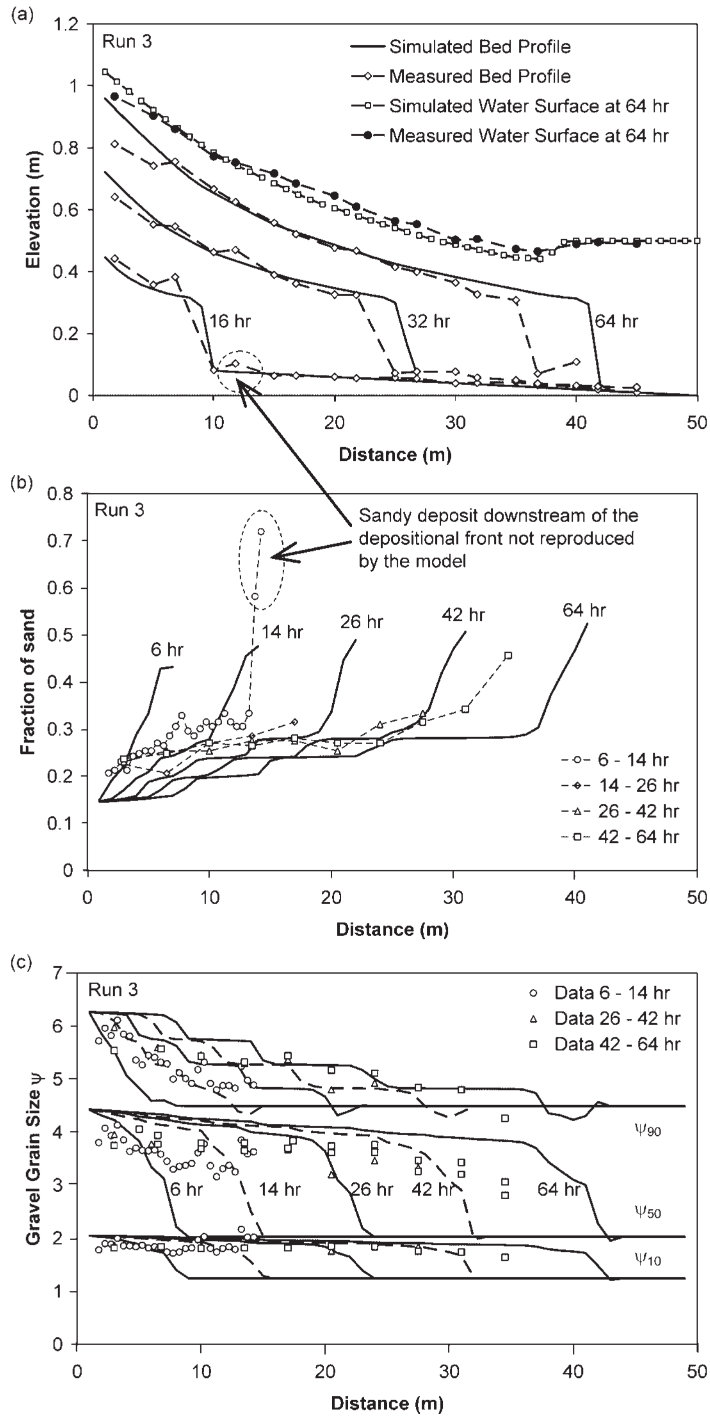

Figure 3. Comparison of TUGS model simulation with experimental data for SAFL Run 3, showing good agreement in bed slope (a), sand fraction in the deposit (b), and characteristic gravel grain size. In Figure 3(c) grain size ψ is defined as $\psi = \log_2(D)$, in which D is grain size in mm. The simulated volumes of sediment deposit in Figure 3(a) seem to be larger than flume data. This discrepancy is most likely caused by the fact that a small amount of fine sediment passed the depositional front and deposited in the deeper pond downstream, while TUGS model cannot pass any fine sediment through the depositional front, that is, TUGS model under predicted sand transport rate under extremely low shear stress conditions (i.e. in the ponded area). This shortcoming is likely unimportant in most of the geomorphic simulations because sediment transport in natural rivers occurs mostly during high flow events when shear stress is high. More detailed discussions about the comparisons can be found in Cui (2007)

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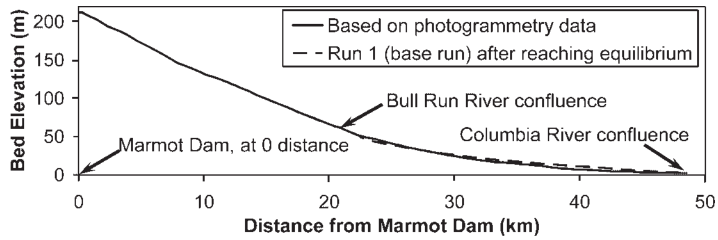

Figure 4. Longitudinal profile of the Sandy River downstream of Marmot Dam, compared with TUGS model simulation, Run 1

Table I. Peak flow for typical recurrence intervals on the Sandy River, Oregon, USA

Return period (year)	Discharge ($m^3 s^{-1}$)	
	Above Marmot Dam[a]	Below the Bull Run confluence[b]
1.2	240	400
1.5	320	590
2	410	620
5	630	960
10	790	1190
50	1180	2180
100	1350	N/A

[a]Based on USGS peak flow record for the period of WY 1912–2005 and a log-Pearson III fitting.
[b]Based on USGS peak flow record for the period of WY 1911–2005 and Weibull plotting position.

records by Cui and Wilcox (2007) for dam removal studies, are used for the simulation. For simulations longer than 10 years, the 10-year series was run repeatedly until the last year of simulation is reached. The main reason for Cui and Wilcox (2007) to use a 10-year series for simulation is that their study needs only to be simulated for a 10-year period and this study inherited the same 10-year hydraulic series. Applying a longer hydrologic series does not change the general behaviour of the simulated results. The 10 years selected for simulation, along with the relative magnitude of the annual peak flow and annual runoff of each year, are shown in Table II.

A detailed sediment budget for the Sandy River is not available. A coarse level sediment budget based on regional geology and literature review was conducted by Stillwater Sciences geologists and presented in Stillwater Sciences (2000b), according to which, sediment production in the Sandy River watershed is roughly between 100 and 600 mt km^{-1} $year^{-1}$, or approximately 68–408 mt $year^{-1}$ (or roughly 25 000–150 000 m^3 $year^{-1}$) sediment transport

Table II. Water year series selected for TUGS simulation, after Cui and Wilcox (2007)

Year number in simulation	Water year	Peak flow ($m^3 s^{-1}$)	Exceedance probability of peak (%)	Annual runoff ($\times 10^6 m^3$)	Exceedance probability of annual runoff (%)
1	1991	371	55	1163	57
2	1932	365	56	1262	42
3	1951	215	91	1458	15
4	1991	371	55	1136	57
5	1988	456	38	1049	71
6	1949	334	67	1355	27
7	1997	393	53	1650	5
8	1992	425	48	916	85
9	1932	365	56	1262	42
10	1948	546	29	1455	16

Peak flow and annual runoff in the table are based on USGS above Marmot Dam station record.

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Table III. Assumed sediment supply rates[a] (in $m^3\,year^{-1}$) for the TUGS model simulation base run

	Sandy River upstream of Marmot Dam	Bull Run River
Washload supply[b] (<0.0625 mm)	50 000	30 000
Sand supply (0.0625–2 mm)	3000	700
Gravel supply (>2 mm)	10 000	0

[a]The sediment supply rates given here are for sensitivity tests only and may not represent the actual sediment supply rates in the Sandy River.
[b]Washload is assumed to pass through the river without deposition in a TUGS simulation.

at Marmot Dam site. Based on this coarse level sediment budget, coring data from Marmot Reservoir (Squier Associates, 2000), and the understanding of sediment trapping in the reservoirs in the Bull Run River, Cui *et al.* (2006a) applied long-term average sediment supply values as shown in Table III for the simulation of the study reach with DREAM-2 and produced good agreement for river longitudinal profile. The sediment supply assumptions given in Table III are also applied to the TUGS model simulation in this paper. Grain size distributions of the gravel and sand supply are derived based on reservoir sediment coring data (Squier Associates, 2000) and are shown in Figure 5. The combined gravel and sand supply grain size distribution is shown in Figure 6 (labelled as Run 1).

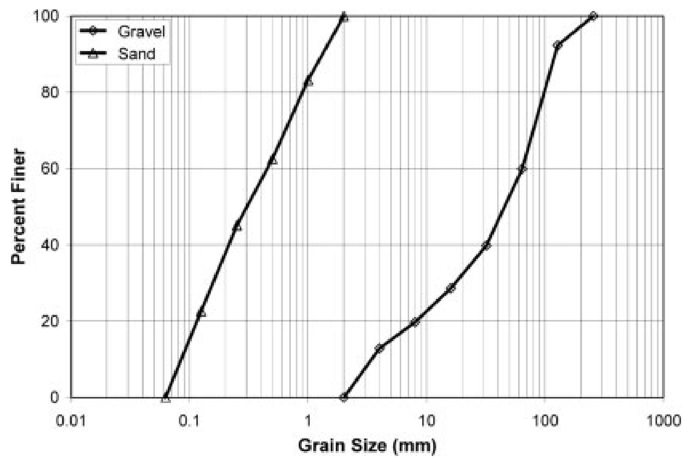

Figure 5. Estimated gravel and sand grain size distributions in sediment supply, based on coring data of Marmot Reservoir sediment deposit

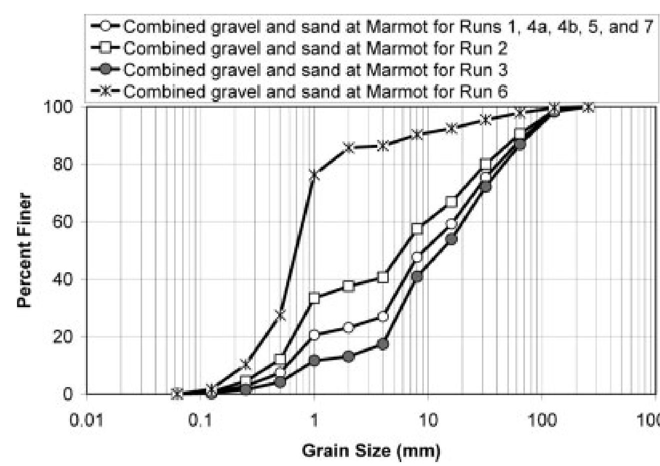

Figure 6. Assumed grain size distributions for combined gravel and sand in sediment supply for all the runs

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No abrasion experiments were conducted for the Sandy River gravel particles. The modelling exercises of Cui and Wilcox (2007) and Cui *et al*. (2006a) assumed a volumetric abrasion coefficient (i.e. fraction of volume lost for a gravel particle to transport a unit distance) of 0.02 km^{-1} and produced reasonable river longitudinal profile. This abrasion coefficient is also employed in the TUGS modelling exercises described below for all the runs.

TUGS model also include functions for simulation of short-term sand infiltration into and entrainment from subsurface deposits. Those functions were not mechanistically-based and not fully examined, and thus, coefficients for the functions need to be calibrated. Because there are no data for such calibrations, the functions for sand infiltration into and entrainment from subsurface deposit are disabled for the modelling exercises presented here. The inherent assumption is that fine sediment infiltration into and entrainment from subsurface deposit are short-term dynamics and can act to negate each other in the long-term. This assumption is probably not entirely true under the conditions when actions that deviate strongly from the quasi-equilibrium sediment supply and hydrologic conditions (such as release of fine sediment following dam removal, flushing flow that sends down a large pulse flow with very little sediment) are taken, it is, however, a very reasonable assumption under the quasi-equilibrium conditions on which this paper is focusing.

EXPLORATORY SIMULATION OF THE SANDY RIVER DOWNSTREAM OF MARMOT DAM

Seven exploratory runs were conducted for the study reach: Runs 1, 2, 3, 4a, 4b, 5 and 6. Run 1, which serves as the base run against which the other runs can be compared, was conducted under the recorded hydrologic conditions and the best understanding of sediment supply conditions as outlined earlier. Six more runs (Runs 2, 3, 4a, 4b, 5 and 6) explored the potential Sandy River geomorphic conditions if the hydrologic or sediment supply conditions were different, and the results are compared with that of Run 1. In addition to these exploratory runs, an eighth run, Run 7, was conducted at the reach upstream of the Marmot Dam within the current Marmot Reservoir impoundment to simulate the sedimentation process. The combined gravel and sand supply grain size distribution of sediment supply from upstream of the Sandy River for each run is shown in Figure 6, and a brief description of all the runs are given in Table IV. More detailed descriptions of the runs are discussed below.

Run 1 (base run)

Run 1 establishes the quasi-equilibrium condition in the Sandy River under the recorded hydrologic and the best estimate of sediment supply conditions. This run, as well as Runs 2, 3, 4a, 4b, 5 and 6 are conducted in the identical procedure of the zeroing process described in Cui and Wilcox (2007) and Cui *et al*. (2006a,b). The zeroing process is based on the assumption that the current river is at quasi-equilibrium state and it experiences only minimal aggradation and degradation at a long-term average basis, although aggradation and degradation do occur at different reaches at different hydrologic events. To reach this quasi-equilibrium state, TUGS model was run with the input parameters described earlier repeatedly until a quasi-equilibrium state is realized, by which there is little long-term aggradation or degradation anywhere in the study reach. The simulated river longitudinal profile is shown in Figure 4 in comparison with the measured river longitudinal profile. Comparison of the two longitudinal profiles in Figure 4 indicates that the model closely reproduced the slope in the study reach. It is useful to point out that the simulated longitudinal profile is also very similar to that simulated with DREAM-2 (Cui *et al*., 2006a), which is not shown in Figure 4 in order to reduce clutter in the figure. Once the simulated channel reached quasi-equilibrium, an additional 10-year simulation was conducted to document the general dynamics of channel bed elevation, grain size distribution, and surface and subsurface sand fractions. To demonstrate that the river experiences minimal aggradation and degradation following the zeroing process, Figure 7a shows the maximum annual aggradation and degradation within the 10-year period simulated, and Figure 7b shows the cumulative change in bed elevation over the 10-year period simulated. Figure 7a indicates that maximum annual aggradation and degradation occur approximately 10 km upstream of its confluence with the Columbia River with a maximum rate of less than 0.2 m $year^{-1}$. Figure 7b indicates that the cumulative change in bed elevation over a 10-year period is within $\pm$0.02 m. The cumulative volume of gravel and sand transported over the simulated 10-year period is shown in Figure 8. The gravel transport rate decreases and sand transport rate slightly increases in the downstream direction due to the abrasion of gravel which produces a large fraction of silt and a very small fraction of sand. Due

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Table IV. Brief summary of the numerical runs conducted for the Sandy River

Run #	Description
1	Background run, ignoring the backwater effect from the Columbia River. Results from all the other runs will be compared to this run.
2	Identical to Run 1, except that sand supply rates at Marmot Dam site and from the Bull Run River are doubled under the hypothetical scenario of watershed development.
3	Identical to Run 1, except that sand supply rates at Marmot Dam site and from the Bull Run River are halved under the hypothetical scenario of better erosion control and reforestation in the watershed.
4a	Identical to Run 1, except that water discharge is reduced by 20% and up to 56.6 $m^3 s^{-1}$ (2000 cfs) at the Marmot Dam site under the hypothetical scenario of water diversion.
4b	Identical to Run 1, except that water discharge is increased by 20% and up to 56.6 $m^3 s^{-1}$ (2000 cfs) at the Marmot Dam site under the scenario that hypothetical previous diversion water is back to the river due to changes in water usage.
5	Identical to Run 1, except that backwater effect from the Columbia River is included by increasing water surface elevation during some flood events at the downstream end of the study reach.
6	Identical to Run 1, except that sand supply rates at Marmot Dam site and from the Bull Run River are increased by a factor of 20 to examine model performance under extremely high sand supply conditions.
7	Sediment input is identical to Run 1; initial bed profile is set to be the pre-dam bed profile upstream of Marmot Dam; discharge is set to be the post-dam discharge at USGS above Marmot Dam between dam construction and sediment coring (WY 1913–2000); water surface is raised at the Marmot Dam site to simulate the effect of Marmot Dam construction and continued operation.

to the continued fining of gravel particles as they are transported, the rate of gravel loss to abrasion increases in the downstream direction, resulting in rapidly decreasing volume of transported gravel in the downstream direction. The simulated long-term average sand fraction $\pm$ one standard deviation in the surface and subsurface layers is presented in Figures 9a and 9b, and the simulated surface and subsurface median grain sizes are shown in Figure 9c, along with six surface median size collected through surface pebble counts in the summer of 1999. In Figure 9, locations without mean sand fraction and median grain size values are bedrock reaches throughout the run, and in Figure 9a,b, locations with mean sand fraction values but without error bars indicate less than 10 samples (one sample was taken at each grid point on each day of simulation because the simulation used daily average discharge for input) are available over the simulated 10-year period due to frequent bedrock exposure. Here the thickness of subsurface samples vary between 0 and 0.5 m at different locations and at different times, because sediment deposits are stored in 0.5-m thick layers, and the samples are taken from the top layer, which is usually thinner then the full thickness of 0.5 m. Results in Figure 9 indicate that the surface sand fraction is relatively stable in time in the steep upper reach and has more variations further downstream (i.e. larger standard deviations). The subsurface sand fraction seems to be more stable in time than the surface sand fraction except within a short distance downstream of the Bull Run confluence at about 21 km. Figure 9b also indicates that a significant decrease in subsurface sand fraction occurred downstream of Bull Run River confluence. This decrease in subsurface sand fraction is most likely due to the significant contribution of flow from the Bull Run River (approximately 69% increase in runoff in the Sandy River downstream of the Bull Run conference) and a relatively small increase in sand supply (Table III). Further downstream, both the surface and subsurface sand fractions increase rapidly in the downstream direction. Although no field data are available to validate the model results in surface and subsurface sand fractions in the study reach, the predicted trend in surface sand fraction matches well with author's visual observations made during reconnaissance trips to the study site. In comprehending the comparisons of the surface median size in Figure 9c, the pebble counts included particles that may have been derived from non-alluvial events such as debris flow events or local slope failures that cannot be transported through fluvial transport, while the simulated results represent only particles that are transported by flow. With that, the simulated surface median size is reasonable and is better than shown in the comparison with pebble counts in Figure 9c. Figure 10a,b show the simulated surface and subsurface sand fractions at five locations, all located downstream of Bull Run River confluence, in comparison with discharge record downstream of Bull Run River confluence. The subsurface sand fraction is relatively stable and is only slightly affected by hydrologic conditions. The surface layer sand fraction,

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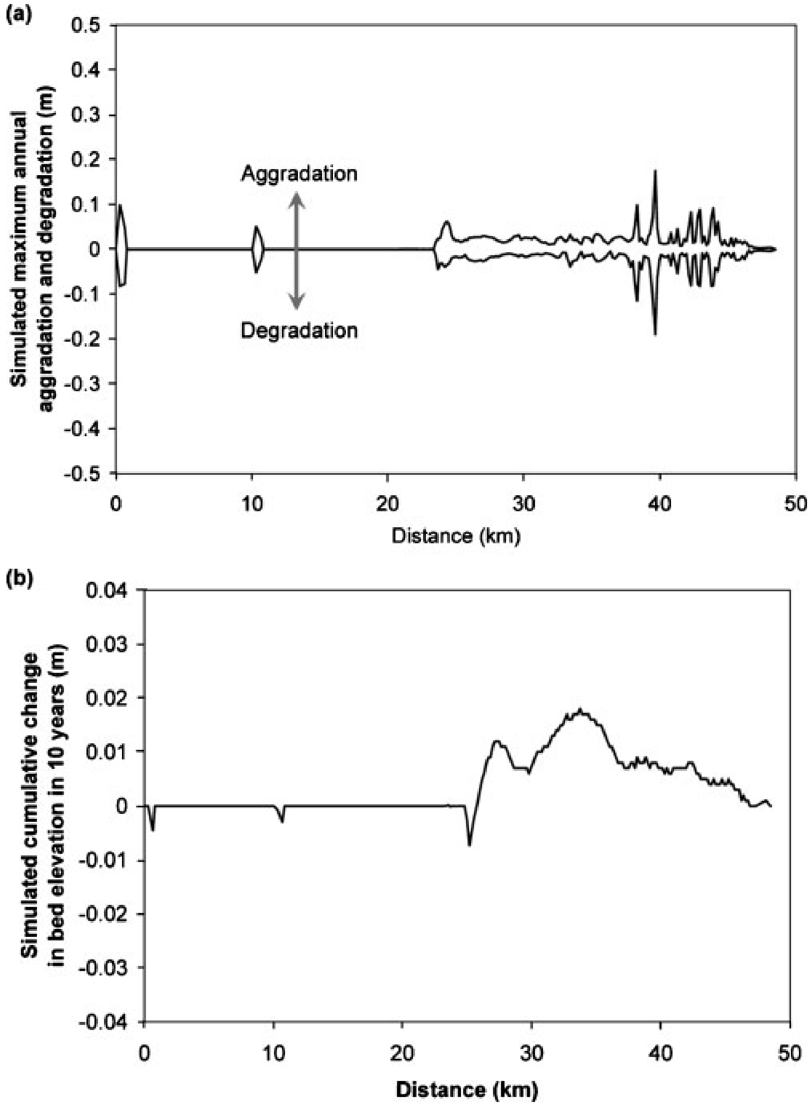

Figure 7. Simulated 10-year period channel bed variation for Run 1: (a) maximum annual aggradation and degradation; and (b) cumulative change in bed elevation in a 10-year period

however, varies significantly in time with changes in hydrologic conditions (Figure 10a). The correlation between the surface sand fraction and discharge is not clear from the simulation results, as the surface sand fraction at one location seems to be negatively correlated to the discharge (e.g. at 39.65 km) while at other stations the surface sand fractions seem to be somewhat positively correlated to discharge. The author does not have an intuitive explanation for the coexistence of both positive and negative correlations between discharge and the surface sand fraction. Despite the relatively large variations in surface sand fractions, it is interesting to note that the surface layer median size is relatively stable if sand is excluded (Figure 10c), which supports the argument of Wilcock and DeTemple (2005) that the armour layers in gravel-bedded rivers may be persistent during floods.

The comparative runs, Runs 2, 3, 4a, 4b, 5 and 6 were conducted with the identical procedure as Run 1. With adjustment to input parameters such as sediment supply, hydrologic series, or downstream water surface elevation, the model was run repeatedly until a new quasi-equilibrium state is reached. While it may take up to several hundred years simulation before a new quasi-equilibrium state is achieved, the actual number of years for this

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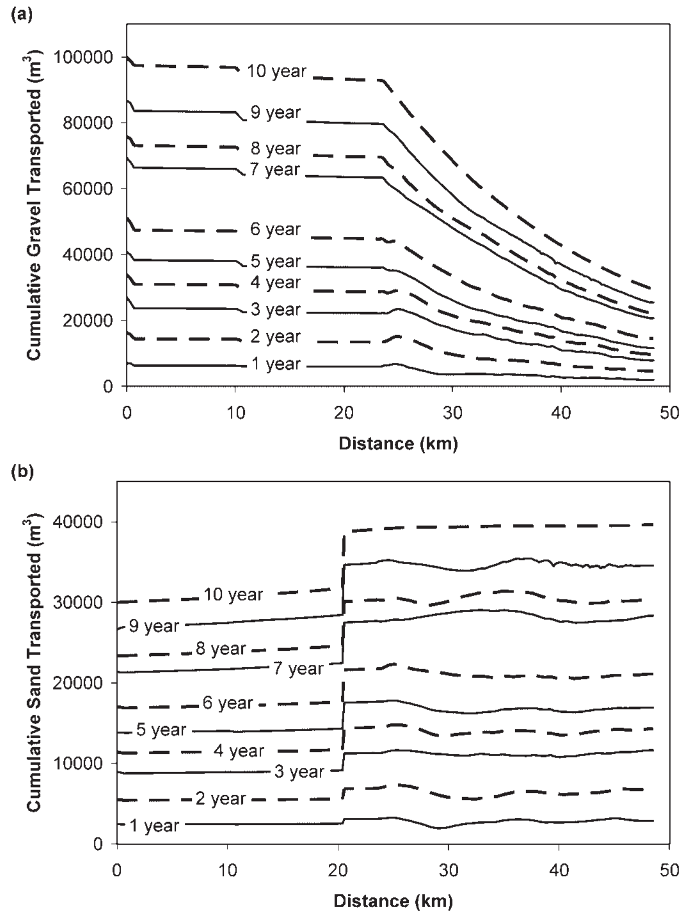

Figure 8. Simulated (a) cumulative gravel transport and (b) cumulative sand transport, Run 1. The decreasing volume of gravel transport in the downstream direction is due to the abrasion of gravel and the lack of tributary input, and the increasing volume of sand transport in the downstream direction is due to gravel abrasion, which produces a small fraction of sand and a large fraction of silt and clay, and the contribution from the Bull Run River at 20.5 km

simulation was not documented due to the techniques used to accelerate the process for the system to reach an equilibrium state. Upon realization of the new quasi-equilibrium, a 10-year simulation was conducted and the results were compared with those of Run 1. The discussions below focus on the dynamics of fine sediment fractions in subsurface deposit and on channel surface.

Runs 2, 3 and 6 (the effect of increased or decreased sand supply)

Runs 2, 3 and 6 examine the potential effects of different sand supply conditions by adjusting sand supply at Marmot Dam site and from the Bull Run River by a factor of 2, 0.5 and 20, respectively. The grain size distributions of the combined gravel and sand supply at the Marmot Dam site for the three runs are given in Figure 6. In addition to comparing results under different sand supply conditions, Run 6 also examines the potential model limitations under extremely high sand supply conditions. To focus on fine sediment in the deposits, Figure 11 presents changes in surface and subsurface sand fractions from Run 1 for Runs 2, 3 and 6. Comparison in Figure 11 indicates that surface and subsurface sand fractions are positively correlated to sand supply as can be expected. Results in Figure 11 also show that changes in the surface sand fractions are generally higher than that in the subsurface, indicating that the surface sand fraction is more sensitive to changes in sediment supply than the subsurface. Results

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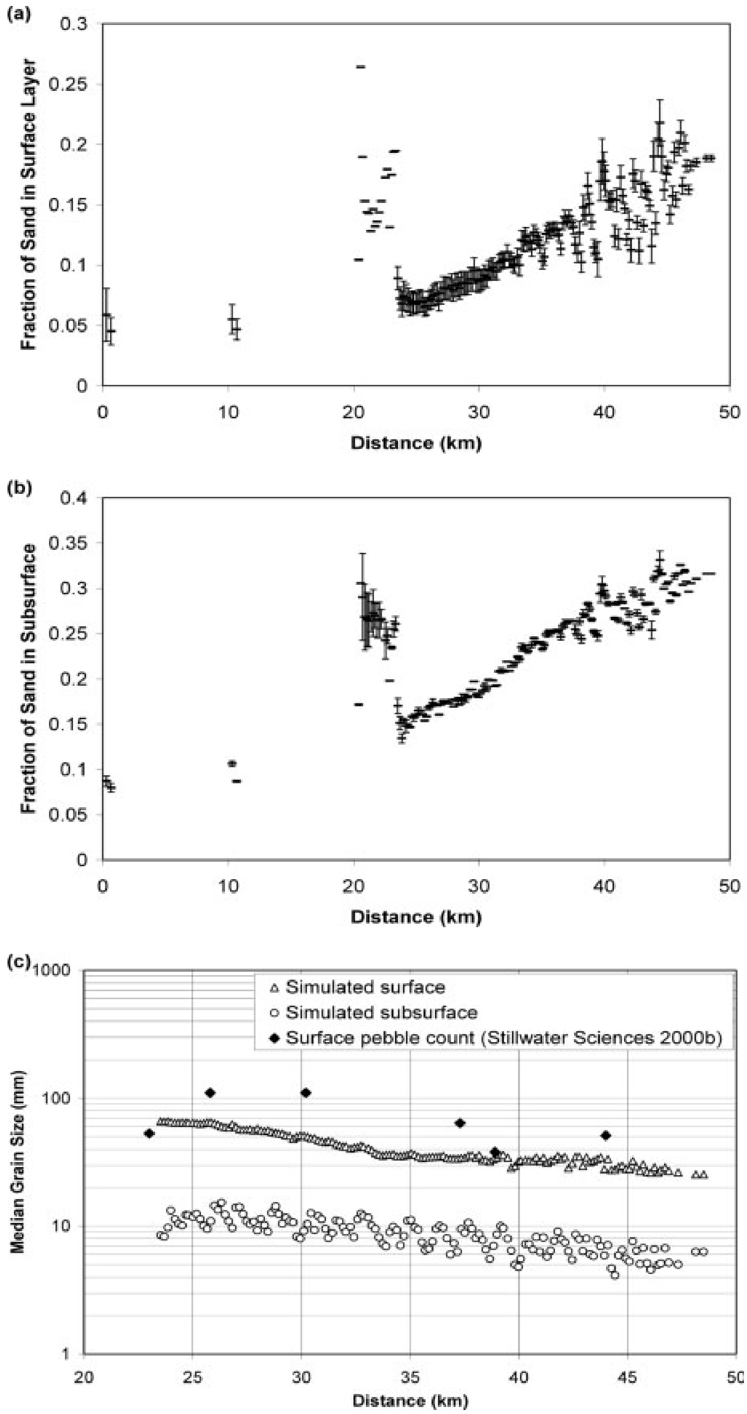

Figure 9. Simulated surface and subsurface sediment characteristics for Run 1: (a) average surface sand fraction ± one standard deviation; (b) average subsurface sand fraction ± one standard deviation; and (c) surface and subsurface median size, in comparison with field pebble counts. The reaches without sand fraction data are bed rock reaches or reaches with shallow coarse bed. Surface median size is presented as excluding particles finer than 2 mm in accordance with pebble count practices, while subsurface median size includes both gravel and sand

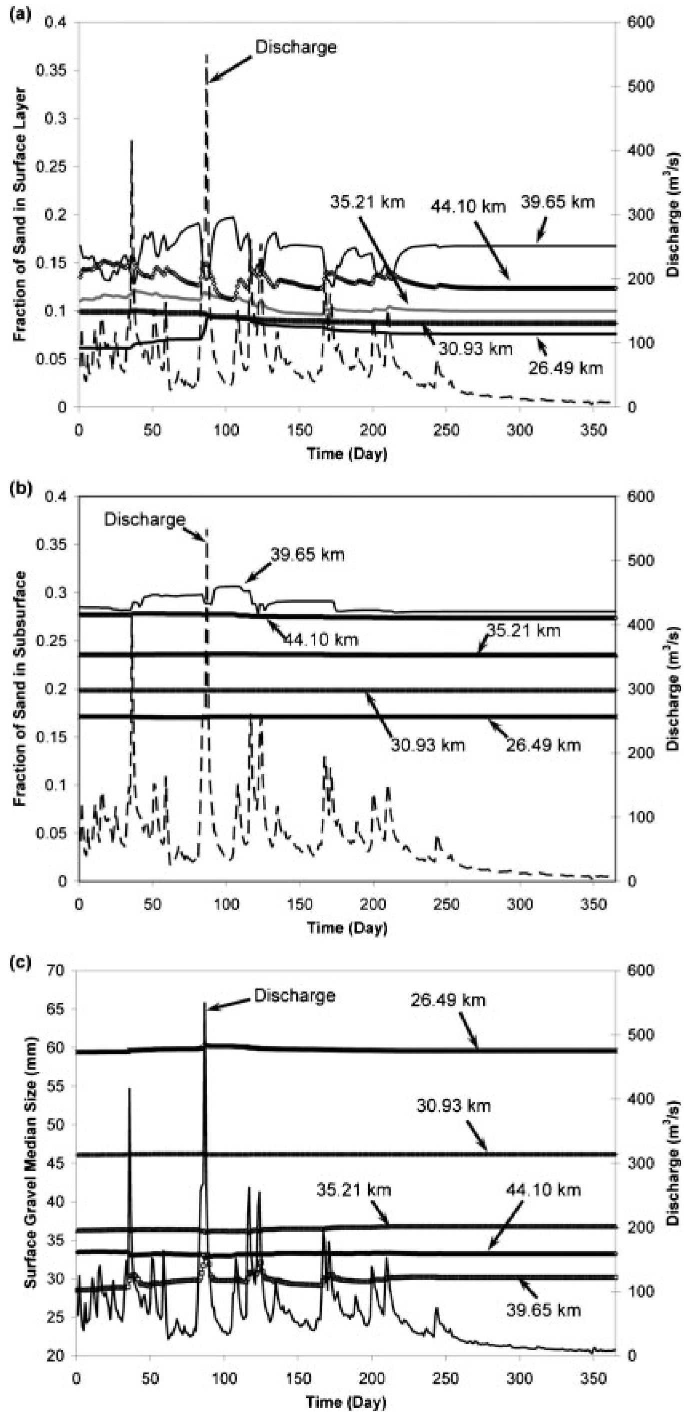

Figure 10. Predicted evolution of grain size characteristics at five locations: (a) surface sand fraction; (b) subsurface sand fraction; and (c) surface median size (excluding sand)

for Run 6 are also presented in Figure 12 as 10-year average surface and subsurface sand fractions. It is interesting to note that with sand dominating the sediment supply, the surface sand fractions become almost identical to that in the subsurface deposit, and the river becomes predominantly a sand-bedded river, as indicated by the higher than 50% sand fractions in the surface layer and subsurface deposits.

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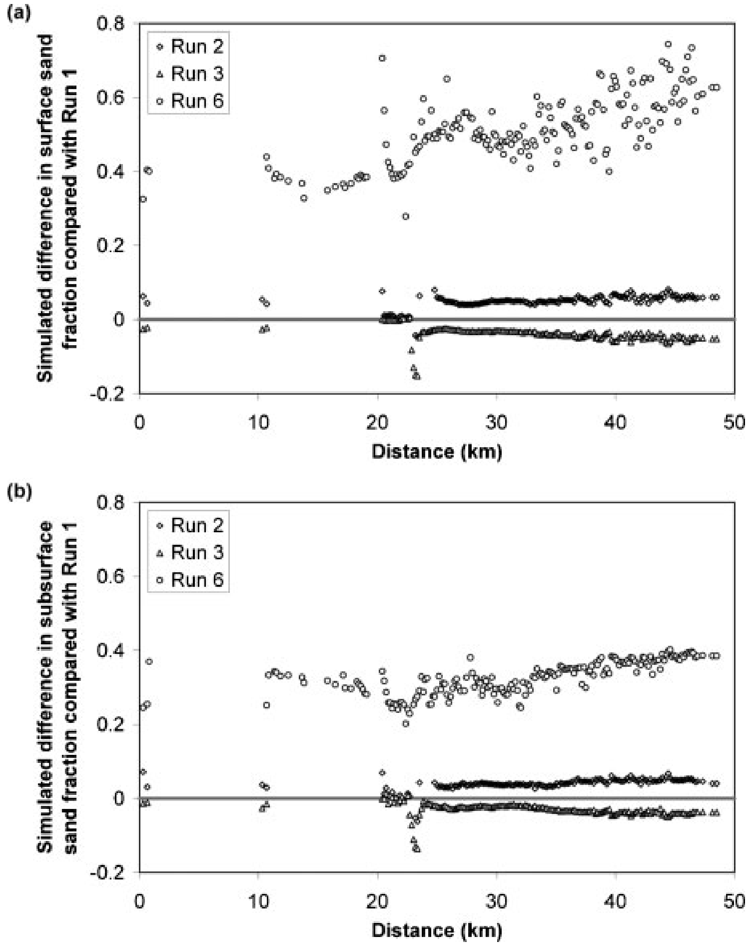

Figure 11. Simulated (a) surface sand fraction; and (b) subsurface sand fraction for Runs 2, 3 and 6, presented as differences from that of Run 1

Runs 4a and 4b (the effect of decreased or increased discharge)

Runs 4a and 4b examine the potential impact from increased and decreased discharge as specified in Table IV. Results for Runs 4a and 4b are presented in Figure 13 as differences in 10-year average surface and subsurface sand fractions from Run 1. Results in Figure 13 indicate that higher discharge under the same sand and gravel supply conditions will normally result in less sand deposition. Contrary to the reaction to changed sand supply conditions, Figure 13 shows that changes in hydrologic conditions resulted in slightly stronger reactions in the subsurface deposit sand fraction than sand fraction on channel surface. This result seems to contradict the observation in Figure 10 that there are more variations in sand fractions on channel surface than in subsurface when discharge changes. The results in Figure 10, however, represent a time series of changes in the surface and subsurface sand fractions while results of Runs 4a and 4b shown in Figure 13 represent the long-term changes in the average sand fractions in the surface layer and subsurface in response to a permanent change in hydrologic regime. The results are reasonable given that the equilibrium subsurface sand fraction is generally larger than or equal to the surface sand fraction, as discussed earlier in the section on Overview of TUGS Model.

Run 5 (the effect of downstream base level control, i.e. backwater effect)

The purpose of Run 5 is to explore whether assuming a normal flow condition at the downstream boundary and neglecting the backwater effect from the Columbia River produced significant errors for the previous runs (e.g. Runs 1, 2, 3, 4a, 4b and 6). Because a water surface elevation record at the Columbia River near its confluence with

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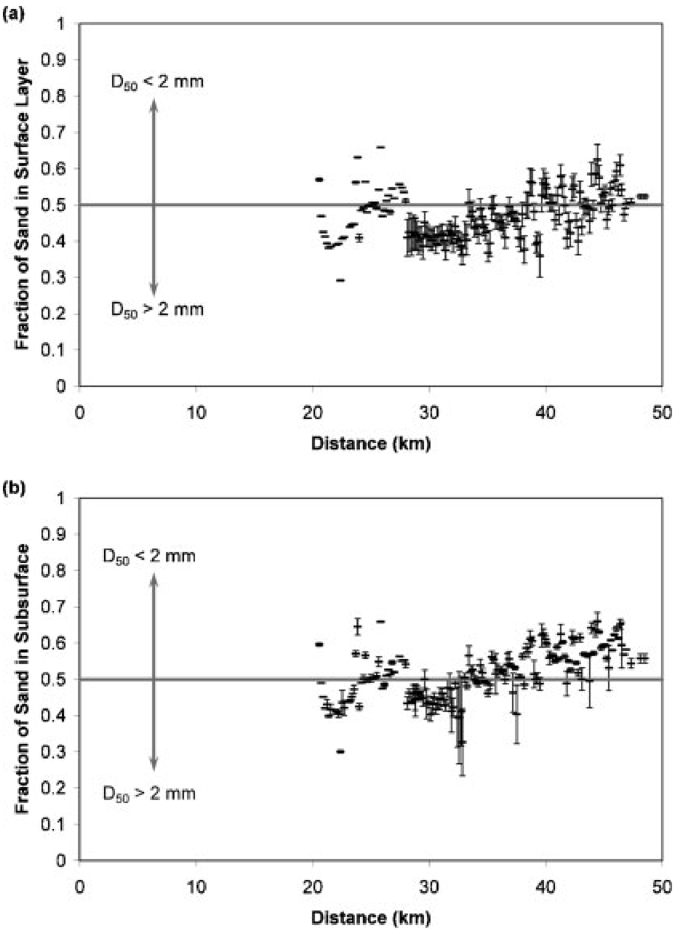

Figure 12. Simulated (a) surface and (b) subsurface sand fraction for Run 6

the Sandy River does not exist, the following procedure was used to generate a water surface series to test the potential backwater effect. During any given water year, the flood season (assumed to be the first 200 days of the water year for the Columbia River near its confluence with the Sandy River) were divided into twenty 10-day periods. Within each of the 20 periods, a uniformly distributed random number between 0 and 5 was generated. This random number, assumed to be depth in metres, was added to the downstream end water surface elevation calculated with normal flow assumption to serve as downstream end boundary condition. That is, the assumed backwater effect was between 0 and 5 m above normal flow conditions, as shown in Figure 14 for the first year of simulation. Results for Run 5 are shown in Figure 15 as the difference in the 10-year average sand fractions between Run 5 and Run 1 for both the surface layer and subsurface deposit. It is seen from Figure 15 that, by assuming a maximum increase of 5 m in downstream water surface elevation, the surface sand fractions increase in approximately a 15-km reach, while subsurface sand fraction would increase only in approximately a 5-km reach.

Run 7 (Marmot Reservoir sedimentation process)

Run 7 differs from the previous runs in that it simulated the sedimentation process upstream of the 15-m tall Marmot Dam. The simulation was conducted by setting the simulation domain to the reach between Marmot Dam and 30 km upstream. Starting with the pre-Marmot Dam longitudinal profile, bed elevation at the Marmot Dam site was set to the Marmot Dam crest elevation, which was not allowed to change during simulation, to imitate Marmot Dam construction and continued operation. Water depth over the Marmot Dam crest was then set to the critical depth for a given discharge, providing the downstream base level control for the simulation. Marmot Dam was

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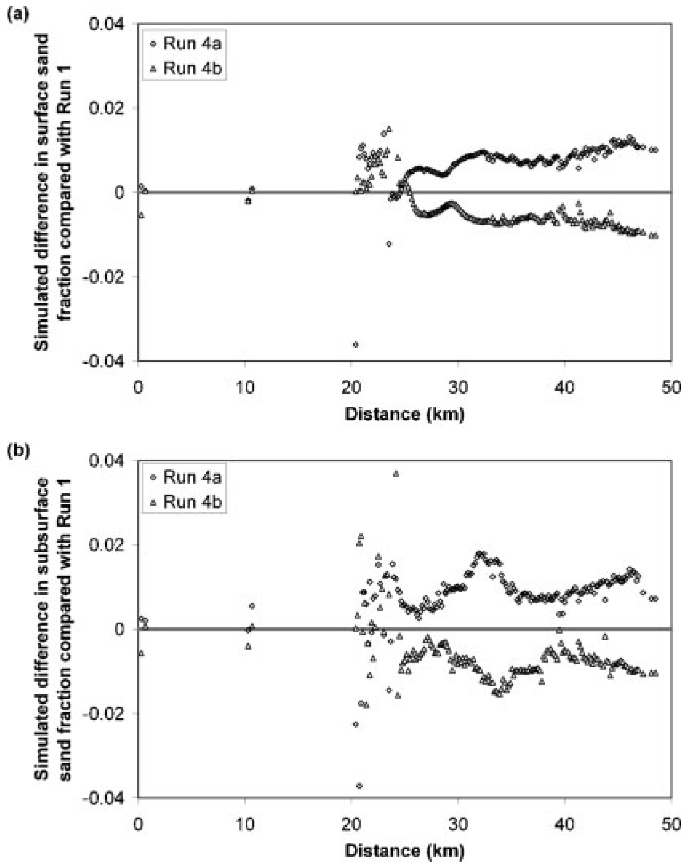

Figure 13. Simulated (a) surface sand fraction; and (b) subsurface sand fraction for Runs 4a and 4b, presented as differences from that of Run 1

constructed in 1913, and water discharge recorded at the USGS upstream of Marmot Dam station exists for the entire duration of Marmot Dam operation. With that, the actual discharge record between WY 1913 and WY 2000 was applied in this run. Sediment supply into the reservoir was assumed to be the same as Run 1. The field survey and coring results conducted in 2000 (Squier Associates, 2000) are shown in Figure 16a. The simulated bed profile

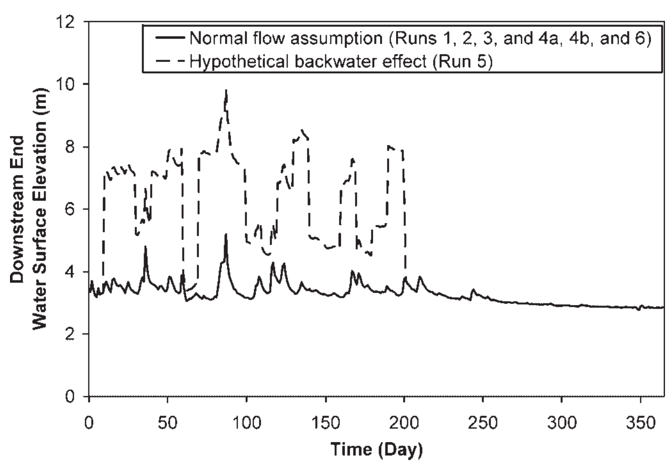

Figure 14. Assumed backwater effect at the Sandy River–Columbia River confluence (i.e. downstream end of the study reach) for Run 5

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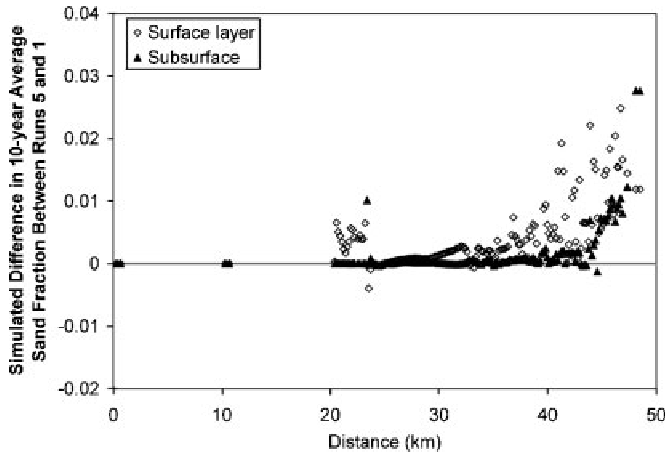

Figure 15. Simulated surface and subsurface sand fraction for Run 5, presented as changes from that of Run 1

for year 1913 (pre-Marmot), 1916, 1930 and 2000 are shown in Figure 16b, and simulated median sizes at a core indicated in Figure 16b are shown in Figure 16c. Results in Figure 16 indicate that there is a close similarity between simulated and observed current (i.e. year 2000) bed profile and grain sizes in the sediment deposit. For example, reservoir coring data by Squier Associates (2000) suggested that the reservoir sediment deposit is stratified with the top layer as predominantly gravel, beneath it is a sand dominated layer that lies above the pre-Marmot Dam coarse Sandy River deposit as shown in Figure 16a, and the simulated results indicate the same pattern, as shown in Figure 16c. It is interesting to note that the simulated sediment deposit has two gravel lenses within the sandy layer (Figure 16c), which are not shown in the Squier Associates (2000) interpretation of the sediment deposit (Figure 16a). A closer examination of the field log of sediment cores located at the proximity of the simulated core also indicated two similar gravel lenses, and a comparison of the sediment textures from one field log and the simulated core is presented in Figure 17. Comparison in Figure 17 indicates that other than the difference in vertical locations, the two gravel lenses predicted in the simulation are very similar to those shown in the field log. It can be expected that the two gravel lenses are the results of two high flow events, and their vertical locations depend mostly on the amount of sediment supply prior and during the two events. The sediment supply data used in the model simulation presented in this paper, however, were derived from a coarse level sediment budget based on regional geology and literature review with potentially very large relative error, especially when it is considered on an event by event basis. With that, the differences in the vertical locations of the gravel lenses between model simulation and field core are not surprising.

CONCLUSIONS

This paper applied TUGS model to the Sandy River downstream of the Marmot Dam for qualitative examinations of model performances and potential channel morphology under different sediment supply and hydrologic conditions, which compliment the more quantitative examinations conducted with laboratory experimental data as presented in Cui (2007). In addition, the model was also applied to simulate the sedimentation process upstream of Marmot Dam following its construction. The model closely reproduced the Sandy River longitudinal profile by applying input parameters based on the best understanding of its current hydrologic and sediment supply conditions. With only some general observations of surface sediment grain size and a few pebble counts available to examine the modals performance, simulated grain size distributions can only be compared with field data qualitatively, and the comparison is reasonable. In particular, simulated surface median size is somewhat finer than pebble count data but it is understood that pebble counts may have included non-alluvial particles that cannot be mobilized by the flow; simulated surface and subsurface median size decrease in the downstream direction, and simulated sand fractions on channel surface and in subsurface deposits increase in the downstream direction, both

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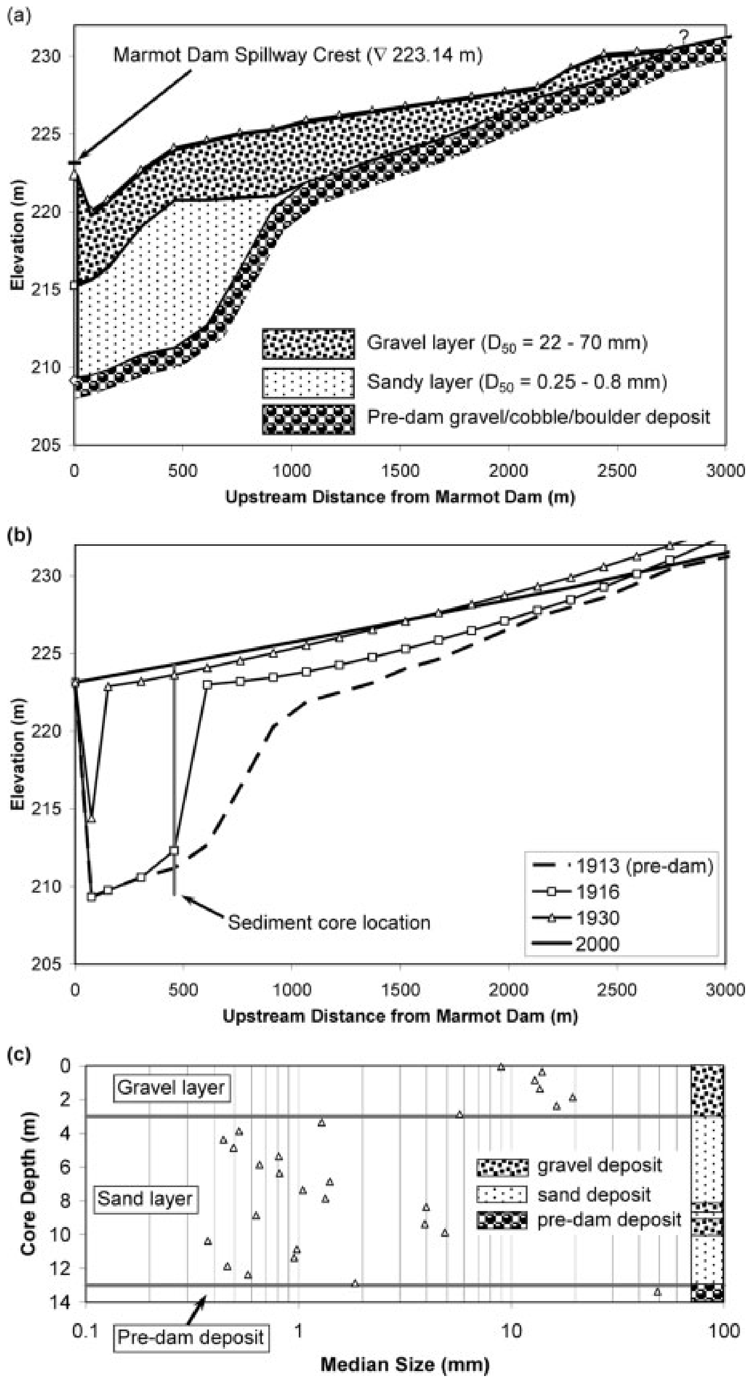

Figure 16. Sediment deposit in Marmot Dam impoundment, Sandy River, Oregon: (a) field measurement of channel profile and grain size in 2000, showing the stratified deposit with a gravel layer on top of a sand layer, and a pre-Marmot coarse sediment layer is yet beneath the sand layer, not shown in the figure, adapted from Squier Associates (2000); (b) simulated channel profile in 2000, showing the migration of the depositional delta, and the location of a sediment core at which median grain size is reported in (c); and (c) simulated median size in the sediment core located at approximately 460 m upstream of Marmot Dam as indicated in (b), showing stratified deposit with (from top to bottom) a gravel layer; a sand layer with gravel lenses, and the pre-Marmot coarse sediment deposit

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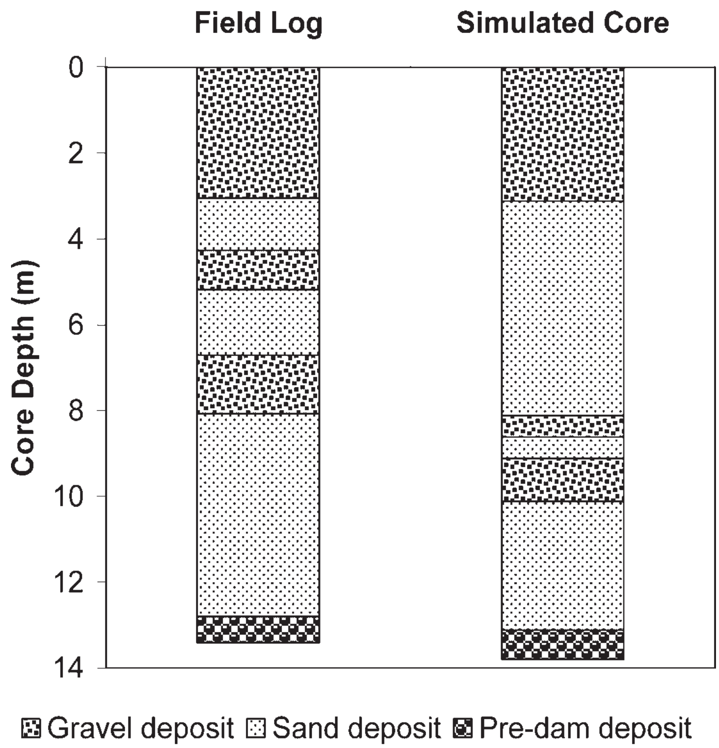

Figure 17. Comparison of simulated sediment texture in the core indicated in Figure 16(b) with field log from a core located at proximity of the simulated core. The differences in the vertical location of the gravel lenses are most likely due to the fact that there was no event-by-event sediment supply information available for the modelling exercise

agree with general observations in the study reach and general understandings about grain sizes in gravel-bedded rivers. Examinations with changes in sand supply indicate that surface and subsurface sand fractions are positively correlated to sand supply as expected. The responses to changes in sand supply on channel surface seems to be stronger than that in the subsurface. The examinations also indicate that the channel can change to predominantly sand-bedded in both the surface layer and the subsurface if sand supply becomes high enough. Examinations with changes in hydrologic regime indicate that, under the same sediment supply conditions, increasing discharge would result in decreased sand fractions in the surface layer and the subsurface, while decreasing discharge would result in increased sand fractions in the surface layer and the subsurface. Under the case examined, the subsurface sand fraction experienced slightly more change, then that in the surface layer when changes in hydrologic regime are applied. Examination of the backwater effect from the Columbia River indicates that backwater effect results in increased sand fraction in the surface layer and the subsurface. Under the assumed backwater conditions (i.e. a backwater that is up to 5 m deeper than the normal flow depth), the affected reach with increasing sand fraction is approximately 15 km upstream into the river for the surface layer and approximately 5 km upstream into the river for the subsurface deposit. Simulation of the sedimentation process upstream of Marmot Dam indicates that the simulation closely reproduced the bed profile and the stratified sediment deposit within the reservoir. The results above should provide useful information to river managers on potential geomorphic reactions in a river in response to certain management actions such as water diversion and watershed development that may result in increased fine sediment supply.

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