Understanding River Sediment in the Virtual World[a]

By Yantao Cui, Ph.D., Hydraulic Engineer, Stillwater Sciences, Berkeley, California, USA

ABSTRACT

Better understanding of sediment transport issues associated with the development, operation, and decommissioning of hydroprojects is becoming increasingly important, and computer simulation is by far the most powerful tool for achieving such an understanding. Four computer models designed to minimize costly field data collection were developed to address unique and important sediment transport questions related to hydroprojects. GAP (Gravel Augmentation Processor) predicts the effectiveness of gravel augmentation, which is often required downstream of hydroprojects because dams and reservoirs trap sediment and reduce gravel supply to downstream reaches; TUGS (The Unified Gravel-Sand) model predicts the impacts of the project construction and/or operation on surface and subsurface grain size distributions, which are important to aquatic biota (invertebrates, spawning salmonid, etc.); and DREAM-1 and DREAM-2 (Dam Removal Express Assessment Models) predict sedimentation processes following the removal of dams, which often determine the suitable alternative and project cost of a dam decommissioning project. All four models are one-dimensional and are based on the principles of open channel hydraulics, conservation of sediment mass on a fractional basis, and sediment transport equations. GAP applies the surface-based bedload equation of Parker (1990); TUGS applies the surface-based bedload equation of Wilcock and Crowe (2003); DREAM-1 applies Brownlie's (1982) bed material equation; and DREAM-2 applies both Parker's (1990) surface-based bedload equation and Brownlie's (1982) bed material equation. All four models have been tested on the Sandy River, Oregon using a combination of field and hypothetical data with reasonable and interesting results. The predecessor of DREAM-1 was used to predict sediment transport issues following the proposed removal of Soda Springs Dam, North Umpqua River, Oregon, and the predecessor of DREAM-2 was used to predict sediment transport issues following the proposed removal of the Marmot Dam on the Sandy River, Oregon and Saeltzer Dam on Clear Creek, California. Marmot Dam is scheduled for removal in 2007, and its removal alternative was selected based on the simulation results. Saeltzer Dam was removed in 2000, and simulation results compare favorably with post-dam-removal field observations. The redesigned DREAM-1 was also used to estimate potential sediment deposition in the Klamath River following the removal of four dams with more than 15 million cubic yards of reservoir sediment deposit under an assumed worst-case-scenario based on limited resources and field data.

Introduction

Four numerical models (*GAP*, *TUGS*, *DREAM*-1 and *DREAM*-2) were developed to deal with different sediment transport issues that are commonly related to hydroeletric project planning, operation, and decommission. The primary purpose of this paper is to briefly introduce the basic principles used in the four models and to provide results of selected applications to demonstrate their potential utility. The paper also provides references that describe the models in more details. Table 1 provides brief descriptions of the four models.

[a] **Citation:** Cui, Y. 2006. Understand river sediment in the virtual world. *Proceedings*, HydroVision 2006, Portland, Oregon.

Table 1. Brief descriptions of the numerical models introduced in this paper

Model	Description
Gravel Augmentation Processor (*GAP*)	*GAP* is a general gravel transport model that can be used to predict the effectiveness of gravel augmentation projects. *GAP* is adapted from the gravel pulse model of Cui and Parker (2005), modified to include flows over floodplains.
The Unified Gravel-Sand (*TUGS*) Model	*TUGS* is a general gravel/sand transport model that can be used to predict the long-term variations in surface and subsurface grain size distributions of gravel-bedded rivers. The model is especially useful in predicting spawning gravel quality because of its ability to describe sand content in gravel deposits. *TUGS* model is described in detail in a manuscript (Cui, unpublished manuscript) available at *http://www.stillwatersci.com/publications.*
Dam Removal Express Assessment Models-1 (*DREAM*-1)	*DREAM*-1 predicts the impact of sediment release from the removal of a dam under the situation that the reservoir deposit is composed primarily of non-cohesive fine sediment (sand and finer). *DREAM*-1 is described in detail in Cui et al. (2006a,b).
Dam Removal Express Assessment Models-2 (*DREAM*-2)	*DREAM*-2 is developed to predict the impact of sediment release from the removal of a dam under the situation that the top layer of the reservoir deposit is composed primarily of coarse sediment (gravel and coarser). *DREAM*-2 is described in detail in Cui et al. (2006a,b).

Gravel Augmentation Processor (*GAP*)

GAP was adapted from the sediment pulse model of Cui and Parker (2005), modified to include flow over floodplains. To solve for flow parameters, the one-dimensional numerical model solves the backwater equation in case of subcritical flow and applies the quasi-normal flow assumption in case of supercritical flow. This same technique is also employed in the other numerical models described in this paper. Sediment is discretized by grain size into several bins, and thus its grain size distribution can be described by the model. By combining the equations for water flow with the surface-based bedload equation of Parker (1990) that links the flow parameters to sediment transport and sediment mass continuity equations that conserve mass for different sediment size bins, the equations are solved by marching forward from an initial condition to acquire different parameters (*e.g.*, thickness of sediment deposit, grain size distributions of sediment deposit and channel surface, water depth) at different times. The results of model simulations provide valuable nformation for choosing the most effective gravel augmentation measures for a specific project. An example of the application of *GAP* is to the Dredger Tailings Reach (DTR) of the Merced River (Stillwater Sciences 2004b). The 11-km river reach was simulated as part of the Merced River Corridor Restoration Plan Phase IV. Detailed model results are provided in Stillwater Sciences (2004b) and described briefly below.

The Merced River DTR begins downstream of Crocker-Huffman Dam, which is the downstream most dam in the Merced River. From approximately a century ago and through the 1950s, gold miners exploited the DTR by excavating the channel and floodplains to bedrock and re-depositing the dredger tailings in large roles stretching for miles. As a result, the current DTR channel is completely different from the historical Merced River channel. In addition to gold mining, construction of large reservoirs upstream of the reach had greatly altered its hydrology and practically eliminated all coarse and fine sediment supply to the reach. Typical peak flow events (*e.g.*, two-, five-, ten-year recurrence flows), for example, are now reduced to approximately 20% of its pre-hydro development values. The combination of alterations to channel and hydrologic conditions and the elimination of sediment supply had greatly decreased spawning habitat for Chinook salmon. Preliminary modeling was conducted with *GAP* to evaluate the current sediment transport conditions and the potential benefits of channel restoration and/or gravel augmentation (Stillwater Sciences 2004b). As an example, Figure 1 illustrates the simulated channel mobility represented with bed Shields stress, indicating that the current channel is static, with surface particle mobilizing at only at a few isolated locations. Those locations are primarily associated with current gravel augmentation projects and/or the construction of gravel wing dams that reduce bed material grain size and increase local channel slope.

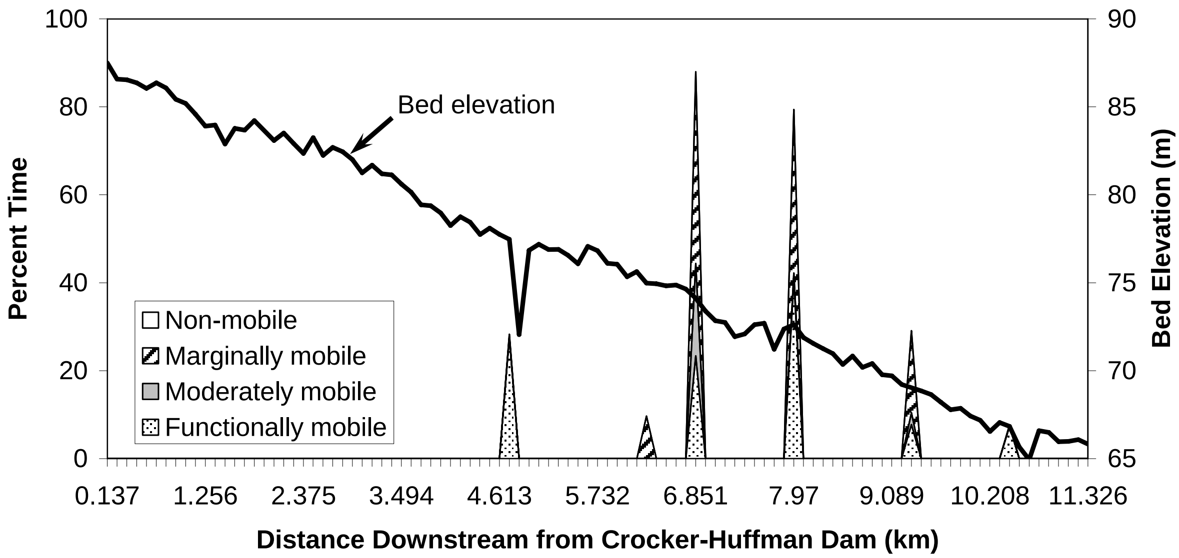

Figure 1. Simulated channel mobility of the Merced River Dredger Tailings Reach for water year 1983, where functionally mobile, moderately mobile, marginally mobile, and non-mobile are defined as $\tau_g^* < 0.0386$, $0.0386 \le \tau_g^* < 0.0502$, $0.0502 \le \tau_g^* < 0.0618$, and $\tau_g^* \ge 0.0618$, respectively. τ_g^* denotes surface-geometric-mean-based Shields stress. Water year 1983 was one of the wettest years of the post hydro development period and thus, the average bed mobility was lower than predicted.

Simulation of augmentation with gravel of sizes suitable for Chinook salmon spawning indicates that the benefits would be limited to the area that directly receives the gravel because of the limited sediment transport capacity of the reach. Figure 2 shows the reach-averaged bed elevation and surface median grain size, indicating the slightly increase in gravel thickness (as reflected in bed elevation) and slight decrease of surface median size. No changes in bed elevation or surface grain size are observed a short distance away from the gravel augmentation site. These results concur with the design of the current gravel augmentation program in the DTR that involves creating suitable spawning areas in a few selected locations rather than depositing gravel in one location and relying on flow to distribute it to downstream areas. The results also indicate that it would be necessary to reconstruct the channel with appropriate bed material and channel dimensions in order to fully restore sediment transport processes and the ecological benefits dependent on them.

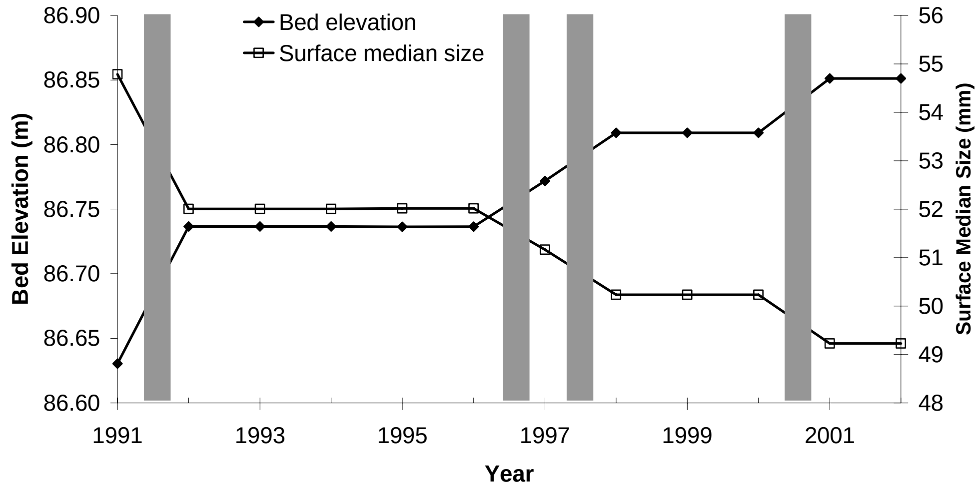

Figure 2. Simulated reach-average bed elevation and surface median size at a location (~1.0 km on Figure 1) where gravel was augmented on four occasions (indicated by bars in the figure).

The Unified Gravel-Sand (*TUGS*) Model

TUGS model is similar to *GAP* in many ways. The major difference between them is that *GAP* applies the surface-based bedload equation of Parker (1990) that excludes sand in the simulation, while *TUGS* employs the surface-based bedload equation of Wilcock and Crowe (2003) that includes sand. Details of the model and its application can be found in Cui (unpublished manuscript, available at *http://www.stillwatersci.com/publications*) and example applications are presented below.

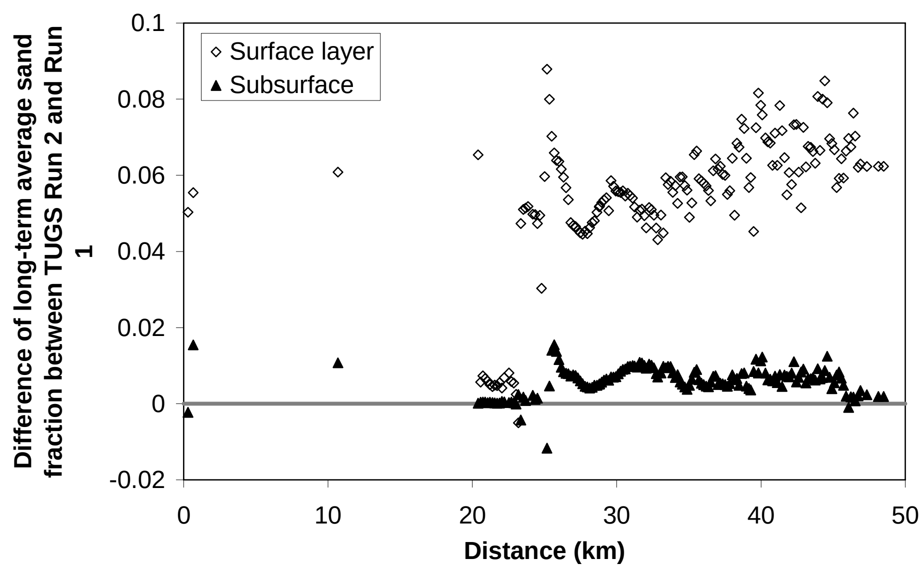

Figure 4. Simulated increase in sand fraction in a 50-km river reach if sediment supply is doubled. Areas without data points (*i.e.*, upstream of 20 km) are bedrock reaches where there were no sediment deposits during the period of simulation.

Figure 4 compares the simulated surface/subsurface sand fractions in a gravel-bedded river for two model runs with the sand supply for Run 2 double that for Run 1. Results in Figure 4 indicate that doubling sand supply to the river increases sand fractions both in the surface layer and in subsurface. The increase in subsurface sand fraction in this particular case is relatively mild (< 0.02) while the increase in surface sand fraction is much higher (mostly > 0.04) than that in the subsurface. Results such as shown in Figure 4 are useful for better understanding of the consequences land management activities that result in different sediment supply conditions. Simulations were also conducted to examine the effect of water diversion and other land and water management activities. Figure 5 illustrates the simulated sediment deposition process following the construction of a large dam, showing the proceeding delta migration into the reservoir behind the dam and the stratified sediment deposit. It should be noted that the stratified sediment deposit predicted with the model is very similar to that observed in the field under similar geomorphic and hydrologic conditions (e.g., Cui and Wilcox 2006). Results in Figure 5 are useful for understanding of the reservoir sedimentation process during the planning stage of a hydro project and are especially useful in understanding of the sediment composition in an existing reservoir when a dam is to be decommissioned.

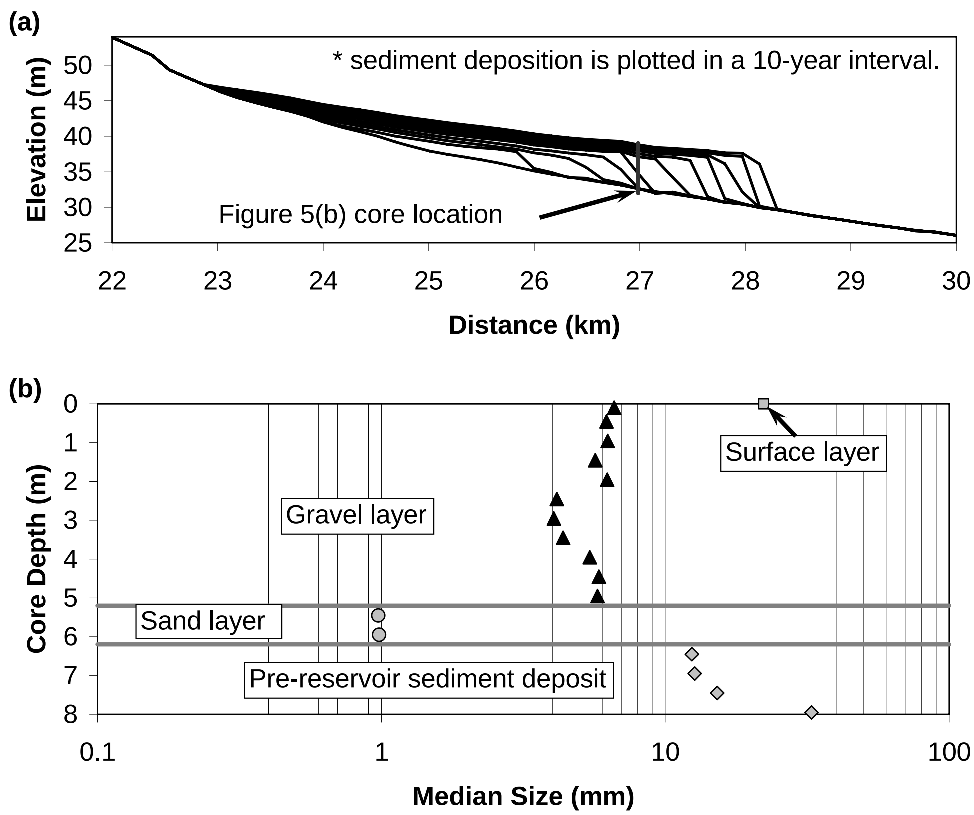

Figure 5. Simulated sediment deposition process in a reservoir, indicating delta formation and migration (a) and stratification of sediment deposition (b). The hypothetical dam is located at 50 km (outside of Figure 5a) with a crest elevation of 40 m.

Dam Removal Express Assessment Models (*DREAM*-1 and *DREAM*-2)

Moving to the dynamics of sediment transport following the removal of a dam, the two Dam Removal Express Assessment Models (*DREAM*-1 and 2) apply to situations characterized by different types of reservoir sediment deposits: *DREAM*-1 applies to dams with reservoir sediment deposits composed primarily of non-cohesive fine sediment (sand and finer), and *DREAM*-2 applies to dams with reservoir deposits in which the top layer consist mainly of coarse sediment (gravel and coarser), such as shown in Figure 5. Technical details for the two models can be found in Cui et al. (2006a,b) and application of *DREAM*-1 to the Klamath River for evaluation of the potential removal of Irongate, Copco (1 and 2), and J.C. Boyle dams can be found in Stillwater Sciences (2004a) and Cui et al. (2005). Prior to the development of the two models, a predecessor of *DREAM*-1 was used to evaluate the potential removal of the Soda Springs Dam on the North Umpqua River, Oregon, and a predecessor of *DREAM*-2 was applied to evaluate the sediment transport processes following the potential removal of the Marmot Dam on the Sandy River, Oregon (Stillwater Sciences 2000, 2002; Cui and Wilcox 2006), and the Saeltzer Dam on the Clear Creek, California. Examples of some of the simulation results with *DREAM*-1 and 2 are provided below.

The initial model evaluations of *DREAM*-1 and *DREAM*-2 presented here were conducted on the lower 60 km of the Sandy River, Oregon. Details of the Sandy River can be found in Stillwater Sciences (2000) and Cui and Wilcox (2006). Of relevance here is that the lower 60 km of the Sandy River is cobble/gravel-bedded. The reach has a typical concave profile with channel gradient of approximately 0.007 at the upstream end that decreases to less than 0.0001 near its confluence with the Columbia River. The reach is confined by high terraces except at a few isolated locations, and there is only one major tributary that enters the river approximately 20 km downstream of the Marmot Dam site. Marmot Dam is a 15-m high diversion dam located approximately 48 km upstream of the confluence of the Sandy and Columbia rivers. The reservoir behind Marmot Dam is completely filled with a mixture of gravel and sand and was studied for potential removal between 1990 and 2002. Detailed studies of the potential effects of Marmot Dam removal on sediment transport in the Sandy River can be found in Stillwater Sciences (2000, 2002) and Cui and Wilcox (2006). The results presented here, however, assumed a dam and reservoir conditions completely different from the Marmot Dam (*i.e.*, different compositions and larger volume of sediment deposit) in order to demonstrate the capabilities of the two dam removal models.

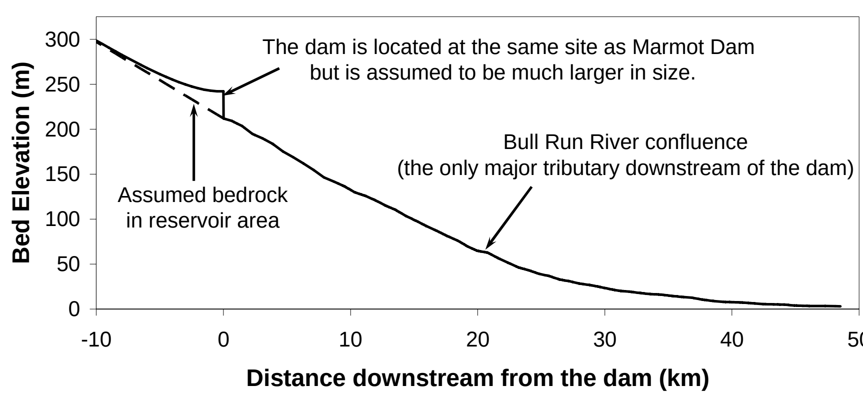

Figure 6. The lower 50-km of the Sandy River, Oregon and the hypothetical dam at the current Marmot Dam site to be used for *DREAM*-1 and *DREAM*-2 simulations.

For *DREAM*-1 runs, the dam was assumed to be 30 m high and its reservoir filled with approximately 4.8 million m^3 of sand, with a geometric mean grain size of 0.5 mm and a geometric standard deviation of 2.55 (by contrast, there is approximately 750,000 m^3 of gravel and sand deposit in Marmot Reservoir). The hypothetical dam and the Sandy River are shown in Figure 6.

Two *DREAM*-1 runs are presented here, the first run assumes that the dam is removed completely before any sediment transport event will occur (*i.e.*, the blow-and-go scenario), and the second run assumes that the dam will be removed in five stages with 26 weeks between the stages. Results of the simulation are presented in Figure 7 for the blow-and-go scenario and in Figure 8 for the staged removal. Comparing results in Figures 7 and 8 indicates that a staged removal would reduce sediment deposition within 30-km downstream of the dam over a period of about 30 weeks and would reduce suspended sediment concentration by almost an order of magnitude for the selected events.

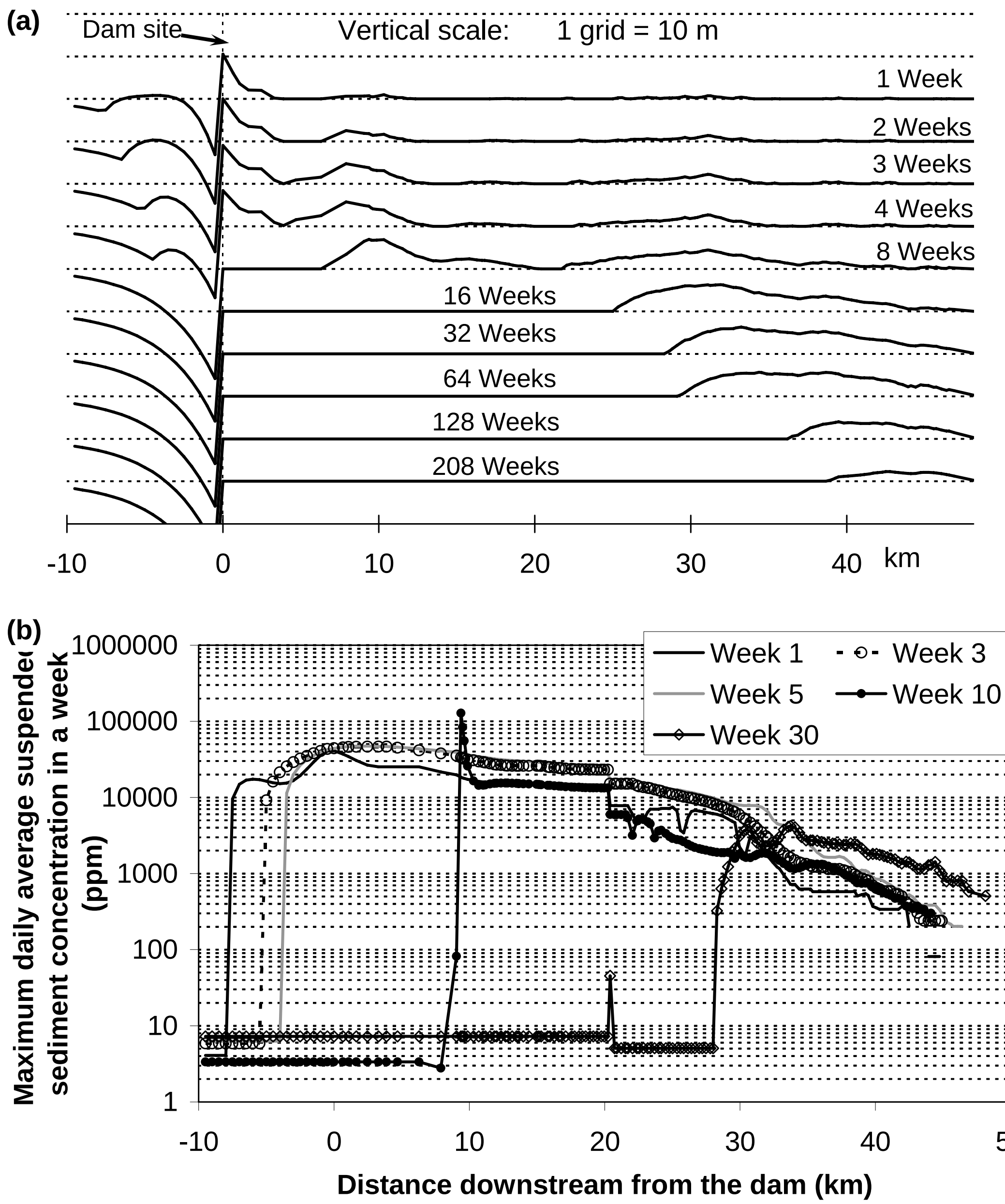

Figure 7. *DREAM*-1 simulation results for the case the reservoir deposit is composed of 0.5-mm sand under the blow-and-go scenario: (a) cumulative aggradation/degradation following dam removal; and (b) weekly maximum daily average suspended sediment concentration following dam removal.

The same 30-m tall dam is assumed for the *DREAM*-2 runs, except that the sediment deposit is assumed to be a stratified gravel/sand deposit similar to that shown in Figure 5. The top layer of the reservoir deposit is assumed to be composed of a gravel/pebble/sand mixture, and the bottom layer is assumed to be primarily sand. The amount of sediment deposit in the reservoir is assumed to be the same as the *DREAM*-1 runs, i.e., approximately 4.8 million m^3.

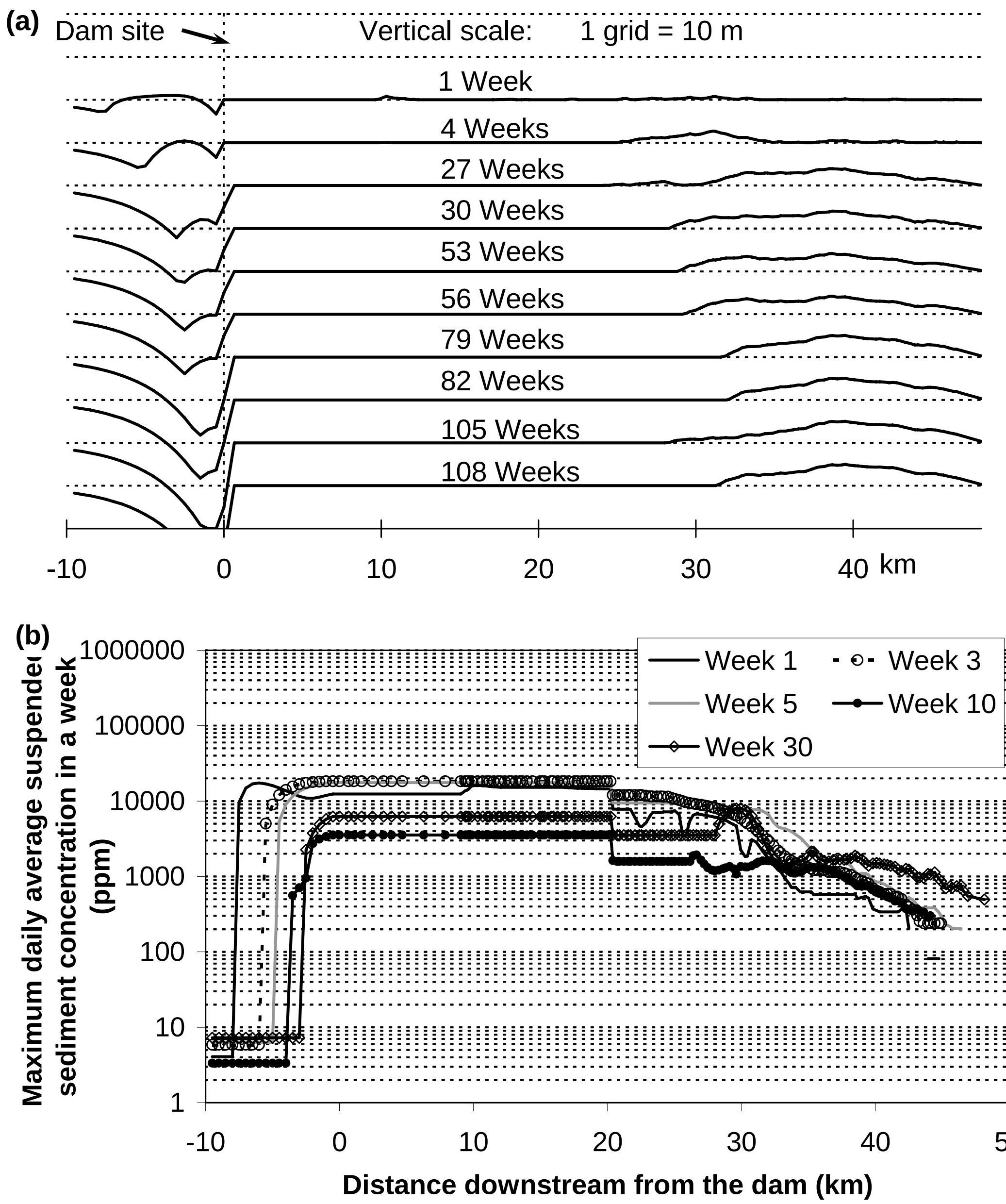

Figure 8. *DREAM*-1 simulation results for the case the reservoir deposit is composed of 0.5-mm sand under the staged removal scenario: (a) cumulative aggradation/degradation following dam removal; and (b) weekly maximum daily average suspended sediment concentration following dam removal.

Three *DREAM*-2 runs are presented here: the first run assumes a blow-and-go scenario, the second run assumes that the dam will be removed in five stages, one each year for five consecutive years, and the third run assumes partial dredging of reservoir sediment deposits before the removal of the dam. Results of the DREAM-2 runs are shown in Figure 9 for the blow-and-go scenario, in Figure 10 for the staged removal, and in Figure 11 for partial dredging scenario. In the dredging run, it is assumed that the sediment deposit within the 3-km reach immediately upstream of the dam is mechanically removed prior to the removal of the dam, resulting in a sediment deposit prior to dam removal that is slightly less than half of the total sediment deposit before dredging.

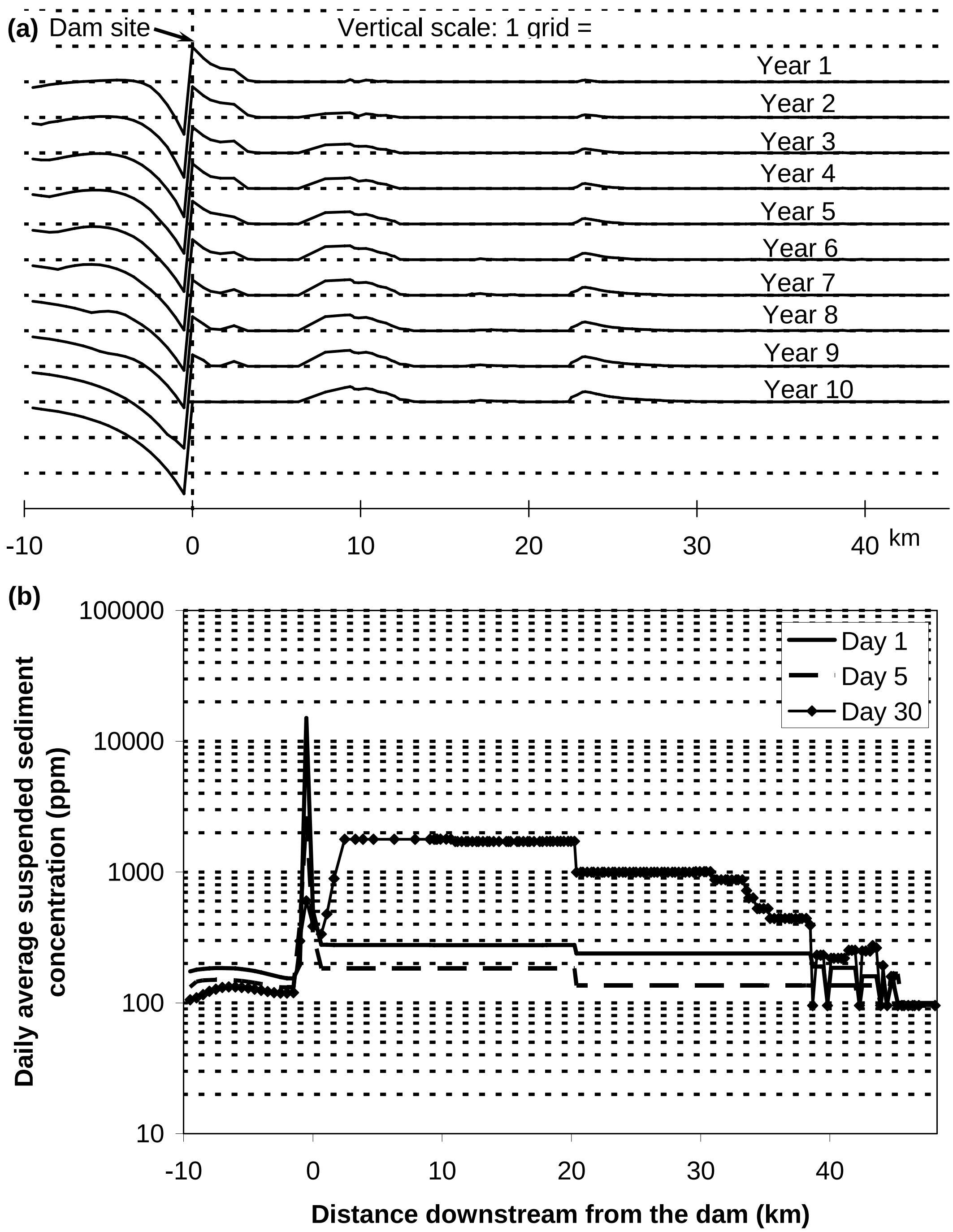

Figure 9. *DREAM*-2 simulation results for the case the reservoir deposit is composed of mixtures of gravel/pebble and sand under the blow-and-go scenario: (a) cumulative aggradation/degradation following dam removal; and (b) weekly maximum daily average suspended sediment concentration following dam removal.

Comparing results in Figures 9 and 7 indicates that differences in the composition of reservoir sediment deposits results in vastly different responses in both channel aggradation/degradation and suspended sediment concentration. If the reservoir sediment is composed of fine sediment (sand), the erosion and transport of reservoir sediment is much faster than if the reservoir sediment deposit is coarser. The amount of sediment deposition, however, is higher for the fine sediment reservoir deposit. The fine reservoir sediment deposit also caused more extensive downstream sediment deposition and much higher suspended sediment concentration.

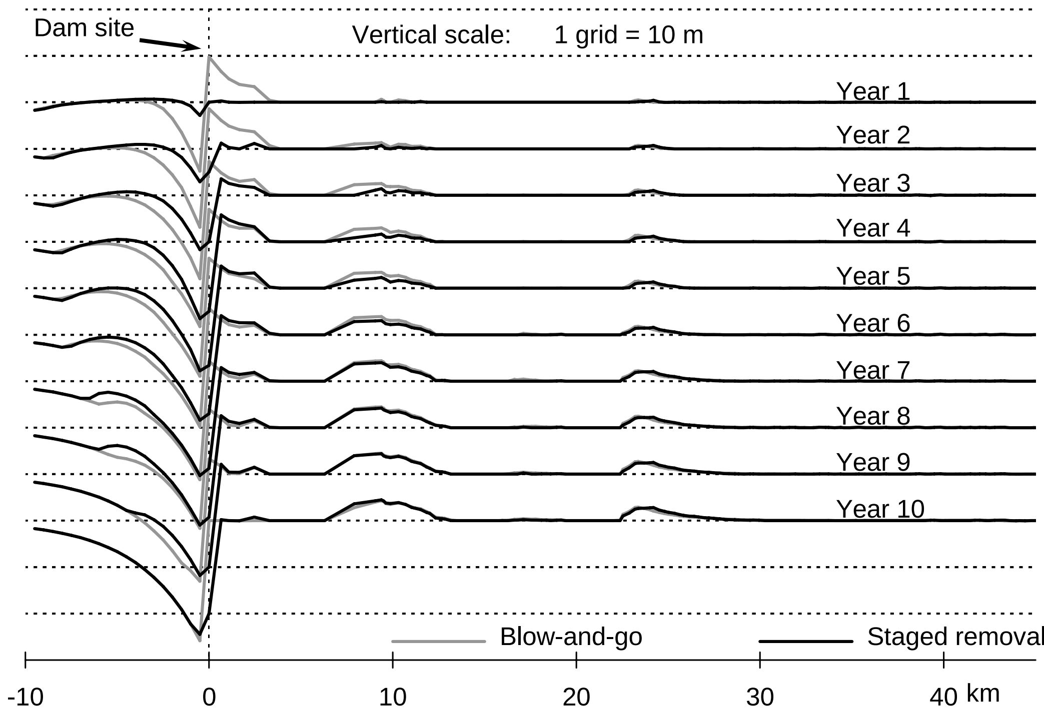

Figure 10. *DREAM*-2 simulation results for the case the reservoir deposit is composed of a mixture of gravel/pebble and sand under the staged removal scenario: cumulative aggradation/degradation following dam removal. Results for the blow-and-go scenario are also presented for comparison purposes.

Comparing results in Figures 9 and 10 indicates that staged removal resulted in similar magnitudes and patterns of sediment deposition downstream for the case reservoir sediment deposit is composed of mixture of coarse and fine sediment. This comparison is completely different from the comparison of blow-and-go versus staged removal scenarios for fine-grained reservoir deposits (*i.e.*, the comparison between Figures 7 and 8), indicating the importance of the composition of the reservoir sediment deposit when selecting a dam removal alternative. In addition to the simulations presented in this paper, Cui et al. (2006b) conducted several more runs to test the sensitivity of various parameters, and their results indicated that accurately estimating the sediment composition of the reservoir deposit is the most important task for evaluating potential sediment transport following dam removal. It can be expected that a good understanding of the composition of reservoir sediment deposit can be accomplished either by extensive coring exercises or by a combination of a relatively less extensive coring exercise and a numerical simulation with TUGS, as demonstrated in Figure 5.

Comparing the model results shown in Figures 9 and 11 indicates that dredging approximately half of the sediment deposit resulted in a significant reduction in downstream sediment deposition following dam removal. In most of dam removal projects, however, dredging 50% of the sediment from a reservoir deposit would be technically difficult and financially prohibitive. During the Marmot Dam removal study, for example, it was determined that the maximum possible dredging volume was approximately 230,000 m^3 (300,000 cubic yards), which constitutes approximately 30% of the 750,000 m^3 of reservoir sediment deposit. Numerical simulations conducted for the project (Stillwater Sciences 2002) indicated that dredging 230,000 m^3 of sediment prior to the removal of Marmot Dam would result in only very small decreases in downstream sediment deposition. As a result of the simulation, it was decided that the dam would be removed without any dredging prior to dam removal.

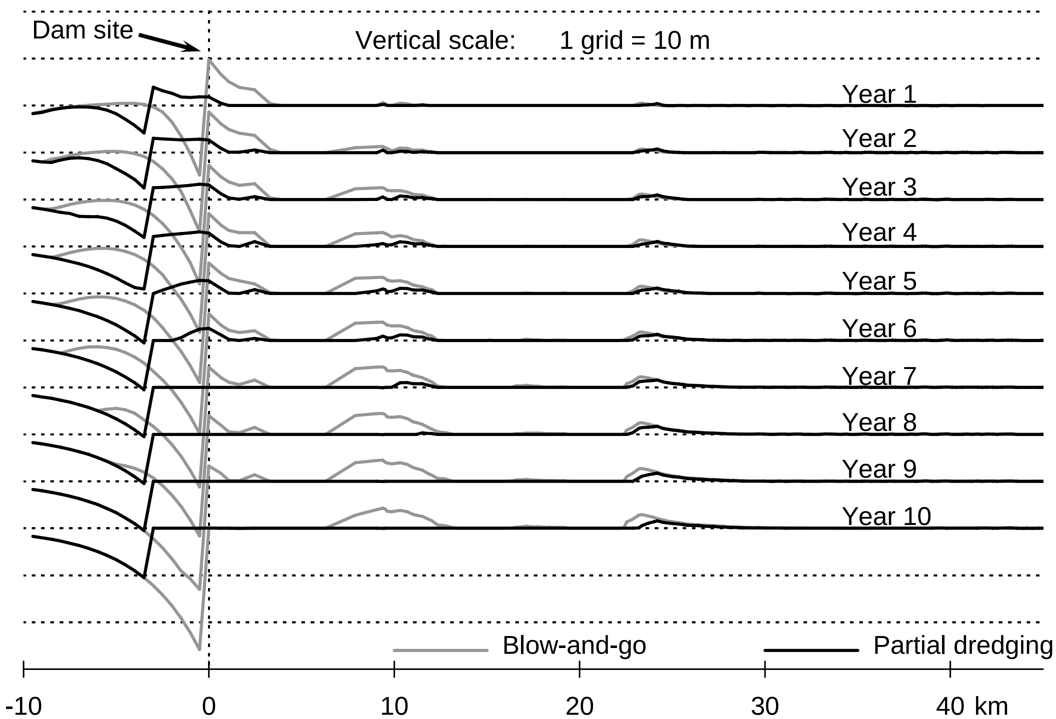

Figure 11. *DREAM*-2 simulation results for the case the reservoir deposit is composed of a mixture of gravel/pebble and sand with partial dredging prior to dam removal: cumulative aggradation/degradation following dam removal. Results for the blow-and-go scenario are also presented for comparison purposes.

Conclusions

Four sediment transport numerical models (*GAP*, *TUGS*, *DREAM*-1, and *DREAM*-2) are introduced in this paper. Tests of the four numerical models demonstrate how applying the appropriate numerical model would help managers make informed decisions at all stages (*e.g.*, planning, operation, and decommissioning) of a hydroelectric project. Correct application of appropriate numerical models not only helps the project owners and regulating agencies to understand the consequences of certain management actions, it also helps select the best alternative that maximizes ecological benefits and minimizes cost, as demonstrated in the Marmot Dam removal study (Stillwater Sciences 2000, 2002; Cui and Wilcox 2006).

Acknowledgement

Many people contributed to the development of the numerical models described in this paper. Here I can provide only an incomplete list of major technical contributors: Christian Braudrick, Brian Cluer, William Dietrich, Peter Downs, Thomas Lisle, Gary Parker, and Jim Pizzuto. I thank the California Bay-Delta Authority (CALFED), National Marine Fisheries Services, Ok Tedi Mining Ltd., PacifiCorp, Portland General Electric, and The Nature Conservancy for financial support that aided in developing the models. I also thank the National Science Foundation and Environmental Protection Agency for providing the funding to Professor Gary Parker that supported my graduate and post-doctorial research that laid the foundation for the four models described in this paper. I thank Peter Downs and Angela Percival for their careful review, edit, and suggestions.

References

Brownlie, W.R. (1982) Prediction of flow depth and sediment discharge in open channels, Ph.D. Thesis, California Institute of Technology, Pasadena, California.

Cui, Y. and Parker, G. (2005) Numerical model of sediment pulses and sediment-supply disturbances in mountain rivers. *Journal of Hydraulic Engineering*, 131(8), 646-656. doi: 10.1061/(ASCE)0733-9429(2005)131:8(646).

Cui, Y., Braudrick, C., and Rothert, S. (2005) Preliminary assessment of sediment transport processes following dam removal: a case study. *Proceedings* in CD-ROM, EWRI 2005 Conference, Williamsburg, Va, July 19-22.

Cui, Y., and Wilcox, A.C. (2006) Numerical modeling of sediment transport upon dam removal: application to Marmot Dam in Sandy River, Oregon, In *Sedimentation Engineering*, ASCE Manual 54, Vol. 2, Garcia, M.H. ed., in press.

Cui, Y., Parker, G., Braudrick C., Dietrich, W.E., and Cluer, B. (2006a) Dam Removal Express Assessment Models (*DREAM*). Part 1: Model development and validation. *Journal of Hydraulic Research*, in press.

Cui, Y., Braudrick, C., Dietrich, W.E., Cluer, B., and Parker, G. (2006b) Dam Removal Express Assessment Models (*DREAM*). Part 2: Sample runs/sensitivity tests. *Journal of Hydraulic Research*, in press.

Parker, G. (1990) Surface-based bedload transport relation for gravel rivers, *Journal of Hydraulic Research*, 28(4), 417-436.

Stillwater Sciences (2000) Numerical modeling of sediment transport in the Sandy River, OR following removal of Marmot Dam. *Technical Report* prepared for Portland General Electric, Portland, Oregon. March 2000.

Stillwater Sciences (2002) Sediment transport modeling following the removal of Marmot Dam with 125,000 and 300,000 cubic yards of dredging prior to dam removal. *Technical Memorandum* to Portland General Electric, Portland, Oregon.

Stillwater Sciences (2004a) A preliminary evaluation of the potential downstream sediment deposition following the removal of Iron Gate, Copco, and J.C. Boyle Dams, Klamath River, CA. *Technical Report*, prepared for American Rivers by Stillwater Sciences, Berkeley, CA, 34p (including figures), March.

Stillwater Sciences (2004b) Sediment transport model of the Merced River Dredger Tailings Reach, *Technical Memorandum #3*, prepared for CALFED by Stillwater Sciences, Berkeley, California, 31p + figures, May.

Wilcock, P.R., and Crowe, J.C. (2003) Surface-based transport model for mixed-size sediment, *Journal of Hydraulic Engineering*, 129(2), 120-128.

Author

Yantao Cui is a senior scientist at Stillwater Sciences, Berkeley, California. His primary responsibilities at Stillwater Sciences are providing inputs on sediment-related issues in rivers, including developing site-specific sediment transport numerical models and applying numerical models to real world problems.