Practical Considerations for Modeling Sediment Transport Dynamics in Rivers

Yantao Cui and Scott R. Dusterhoff

Stillwater Sciences, Berkeley, California, USA

John K. Wooster

National Marine Fisheries Service, Santa Rosa, California, USA

Peter W. Downs

School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth, UK

Sediment transport dynamics are some of the most important aspects to consider in river restoration and management projects. Restoring a river usually involves the manipulation of its flow conditions, channel cross sections, channel alignment, sediment supply, bed material composition, and riparian conditions, all of which directly or indirectly affect sediment transport dynamics. Because a river will be reshaped through sediment transport process following restoration, a lack of or an inadequate consideration of postrestoration sediment transport dynamics may result in poor performance or failure of the project. Here we discuss some practical considerations in sediment transport modeling as a guide for resource managers overseeing river restoration projects as well as sediment transport practitioners. The discussion is not intended as a "how to" guide or a thorough review of the scientific literature pertaining to sediment transport. Instead, the project examples discussed herein are intended to illustrate some of the lessons learned from our experiences in conducting sediment transport analyses for applied projects. The examples are not necessarily river restoration projects, but the practical considerations discussed should generally apply to any sediment transport analysis, including those for river restoration projects.

1. INTRODUCTION

One of the common misunderstandings in sediment transport analysis is the belief that more complicated tools and methodology yield more accurate and more dependable results. While more complicated methods and models usually produce more detailed results, they do not necessarily produce more accurate or reliable results due to limitations of sediment transport theory, the stochastic nature of sediment transport, and often a limited understanding of the system to be analyzed. Moreover, a more complicated methodology or model will inevitably require more input data, which usually introduces additional uncertainty associated with the input data. As a result, it is not uncommon for an excessively complicated model to produce less satisfactory results than a simpler model for conditions where the simpler model can still achieve the project goal. Thus, matching the approach for modeling sediment transport to the project goals is an important first step in an analysis. Two of the project examples

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presented in this chapter are devoted to demonstrate the importance of selecting appropriate methods and models: (1) an analysis of sediment delta progradation in Slab Creek Reservoir as an example where a very simple approach was sufficient and (2) the simulation of fine-sediment dynamics in the gravel-bedded Lagunitas Creek as an example of applying a more complex model. While selecting an appropriate method and tool is the first step toward a successful sediment transport analysis, it is also imperative to have a good understanding of the limitations of different methods and tools. This understanding will help the modeler make the correct decisions during modeling, provide accurate interpretations of modeling results, and recommend appropriate contingency plans to lower the risks associated with the uncertainties. We present the numerical modeling of sediment pulse dynamics in a flume with forced pool-riffle morphology to demonstrate limitations of one-dimensional (1-D) numerical models. We then present a sediment transport study for Marmot Dam removal on the Sandy River, Oregon, to demonstrate some of the important practical considerations in sediment transport modeling, including boundary conditions, the zeroing process as part of model calibration, different approaches to address uncertainties, and to further our discussion on the application of multidimensional numerical and scaled physical models. Finally, we provide a brief discussion of generic flume experiments as a useful but often ignored tool to understand sediment transport dynamics using two examples.

2. SLAB CREEK RESERVOIR DELTA PROGRADATION

2.1. Project Background

Slab Creek Reservoir is located on the South Fork American River in California, impounded by a 71 m dam that raises water levels for power generation. The owner of the reservoir is designing a 400 MW pumped-storage facility as part of a development project that includes the construction of an upper storage reservoir (Iowa Hill storage). Upon completion, water will be pumped from Slab Creek Reservoir into the upper storage reservoir during low power demand periods and released back into Slab Creek Reservoir for power generation during peak energy demand. As part of the permitting process, stakeholders wanted to know whether the repeated water pumping from and releasing into Slab Creek Reservoir would produce persistent high turbidity events. The key to this question is how fast the deltaic front of the sediment deposit in Slab Creek Reservoir will advance during the life-span of the project because pumping-related turbidity will only potentially occur if the Slab Creek deltaic front reaches the vicinity of the pump intake. While stakeholders were interested in developing a 1-D numerical model to answer the question, our examination indicated that a much simpler mass conservation analysis based on basic physical principles would achieve the project goal without the time and expense of additional field data collection. The results are briefly discussed below while a detailed description of the analysis is given by Stillwater Sciences [2008] (accessed 9 July 2010).

2.2. Analysis and Results

Slab Creek Reservoir bathymetry with reasonable resolution is available for 1992 and 2007 (thalweg elevations of the two data sets are presented in Figure 1). The analysis required identification of three deltaic features shown in the longitudinal profile presented in Figure 1 (labeled as “A,” “B,” and “C” in Figure 2). The feature labeled “A” is not a delta deposit but rather an old dam (American River Intake Dam) that was submerged upon the completion of Slab Creek Dam. The deposit upstream of American River Intake Dam indicates that it was completely filled with sediment prior to the construction of Slab Creek Dam, which is reasonable given its relatively small size. The sediment deposited upstream of American River Intake Dam prior to the construction of Slab Creek Dam is indicated in the shaded area in Figure 2, and has a topset slope of 0.0016 (the dashed line labeled “D” in Figure 2), which is identical to the topset slope of the deltaic deposit marked “C” (discussed below). This slope represents the equilibrium slope of the sediment deposit if the reservoir pool level is kept within the normal range of operating conditions (i.e., minimal reservoir drawdown). The deltaic front (i.e., foreset bed) labeled “B” is considerably lower than the normal drawdown pool level. This deltaic deposit was most likely formed during the last week of October 1991 when the

Figure 1. Thalweg elevation within Slab Creek Reservoir, surveyed in 1992 and 2007. Slab Creek Dam, located at 0 km in the diagram, is 71 m tall and was constructed in 1967.
reservoir was lowered to a pool level of 536.9 m due to an outage at an upstream power plant. This represents approximately a 15 to 18 m drawdown from normal operation that presumably mobilized and transported the sediment deposit previously stored further upstream to form the odd-shaped deposit labeled “B.” Because the drawdown did not last long enough for the deposit to reach an equilibrium configuration, the resulting sediment deposit upstream of deltaic front “B” is considerably steeper than the equilibrium slope of 0.0016. The deltaic front “C” is interpreted as the deposit formed after the October 1991 event, as subsequent operational rules were implemented to maintain the Slab Creek Reservoir above 551.7 m at all times.

While topography of the Slab Creek Reservoir area prior to dam construction is not available, a predam thalweg elevation can be reasonably estimated by connecting the bottom of the American River Intake Dam and the upstream end of the current sediment deposit with a straight line (Figure 2). The longitudinal information shown in Figure 2, in combination with a cross-sectional area to depth relation developed based on a typical cross section located approximately 0.8 km upstream of Slab Creek Dam where sediment deposition is minimal, was used to derive Slab Creek Reservoir sedimentation volumes and rates (Table 1).

![Figure 2](image-url)

**Figure 2.** Characteristic features used to estimate long-term sediment supply to Slab Creek Reservoir and to produce a mass conservation model to estimate future advancement of the delta front of the reservoir deposit. Submerged American River Intake Dam is indicated at point A; sediment deposit attributed to the October 1991 drawdown event is indicated at point B; 2007 delta front, with a foreset slope of 0.065 and a topset slope of 0.0016, is shown at point C; and the topset of American River Intake Dam deposit is indicated at point D, which is identical to that of the 2007 deposit shown at point C. Also depicted are the approximate location and elevation of the proposed intake/outlet structure of the Iowa Hill Facility as well as the normal pool elevation of Slab Creek Reservoir.

Note in Table 1 that the Slab Creek sedimentation rate for the period of 1992 to 2007 is significantly higher than the period of 1967 to 1992. This is, in part, attributable to a large landslide that occurred in Mill Creek, a tributary to South Fork American River, on 24 January 1997 that delivered a significant volume of sediment to the main stem [Sydnor, 1997] (accessed July 2010). The majority of this sediment pulse quickly transported into the Slab Creek Reservoir and subsequently elevated the sedimentation rate for the period of 1992 to 2007. An average sedimentation rate of 29,000 m$^3$ yr$^{-1}$ for the period of 1967 to 2007 (includes the high sediment production from the 1997 landslide event) was used to estimate the future advancement of the deltaic front. This analysis was simply accomplished by drawing two straight lines that represent the future topset and foreset locations, then calculating the volume below the two lines and dividing it by the sedimentation rate to obtain the time needed for the sediment deposit to reach this level. Based on the 2007 profile, the sediment deposit in Slab Creek Reservoir has a foreset bed slope of 0.065 and a topset bed slope of 0.0016, and the foreset/topset break point is located approximately 2 m below the normal pool level. The predicted deltaic front advancement using the above information is presented in Figure 3, indicating that the deltaic front will not reach the intake within the facility design life of 100 years, and thus pumping operations within the reservoir are not expected to produce turbidity spikes.

### 2.3. The Alternative: Predicting Deltaic Front Advance With a 1-D Numerical Model

A 1-D numerical model would have accomplished the same goal but with significantly more effort without gaining additional confidence in the results. To estimate the reservoir sedimentation rate for input data to run a 1-D numerical model, one would have conducted the same or similar exercises as discussed above. Additional efforts would have

<table>
<thead>
<tr>
<th>Period</th>
<th>Bulk Volume of Sediment Deposited During the Period (m$^3$)</th>
<th>Sediment Accumulation (Bulk Volume) Rate (m$^3$ yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Slab Creek Dam$^a$</td>
<td>176,000</td>
<td>NA</td>
</tr>
<tr>
<td>1967–1992</td>
<td>577,000</td>
<td>22,000</td>
</tr>
<tr>
<td>1992–2007</td>
<td>593,000</td>
<td>37,000</td>
</tr>
<tr>
<td>1967–2007</td>
<td>1,170,000</td>
<td>29,000</td>
</tr>
</tbody>
</table>

$^a$Amount of sediment accumulated behind American River Intake Dam.
Figure 3. Predicted future delta advancement within Slab Creek Reservoir using a simple mass conservation model. These results indicate that the delta front will not reach the proposed intake in the designed project lifetime of 100 years as the delta front is predicted to be almost 1 km upstream of the intake in 150 years (i.e., year 2157).

included: collection of sediment samples for grain size analysis, analysis of discharge records to select typical hydrologic years for model input, numerical model set up, and a rigorous model calibration to reproduce the observed sediment deposit’s volume and topset and foreset slopes. However, due to limitations in sediment transport theory, it is likely that the observed foreset slope could not have been replicated with a numerical model, and the final calibrated model would only have matched the volume of sediment deposit and the topset slope. Because the derivation of sedimentation rate is similar or identical to the simple method discussed earlier, and model calibration also tries to replicate the observed deposit (i.e., to match topset and foreset slopes), the results of a 1-D numerical model would at best have the same confidence as the simple method. As a result, the simple mass conservation exercise presented earlier is the most appropriate method for this particular project.

3. LAGUNITAS CREEK FINE-SEDIMENT DYNAMICS

3.1. Project Background

Lagunitas Creek, located in Marin County, California, provides regionally important habitat for coho salmon (*Oncorhynchus kisutch*) and steelhead (*Oncorhynchus mykiss*). However, the watershed’s high fine-sediment yield (i.e., sand and finer (<2 mm)) potentially causing excessive fine-sediment deposition that reduces the survival rate of the salmonid eggs is a concern for resource managers. If a numerical model is used to examine how the fraction of fine sediment within spawning gravel deposits will change under various potential measures for fine-sediment reduction, it must have the ability to simulate the transport dynamics of both coarse (i.e., gravel and coarser (>2 mm)) and fine sediment and the interaction between the two size fractions and be able to track the fraction of fine sediment in gravel deposit through time. A 1-D sediment transport numerical model called The Unified Gravel Sand (TUGS) model [Cui, 2007a] has the ability to simulate these criteria and was utilized to predict potential outcomes under different approaches to reduce fine sediment.

In addition to equations that govern the flow of water in river channels and the particle size-based Exner equations of sediment continuity (including the abrasion of gravel during transport), the fundamental components of TUGS model include the surface-based bed load equation of Wilcock and Crowe [2003] that links the local sediment transport capacity to the local boundary shear stress, the gravel transfer function of Hoey and Ferguson [1994] and Toro-Escobar et al. [1996] that links the subsurface and surface gravel grain size distribution with the bed load, a sand transfer function that links the sand fraction in the subsurface to that on the bed surface, and relations for sand entrainment and infiltration into the subsurface bed material. Specific details of TUGS model can be found in the work of Cui [2007a] and case studies demonstrating satisfactory results of TUGS model application in other projects are available in the works of Cui [2007b] and Gomez et al. [2009]. TUGS model is significantly more complicated than computer models developed by the same author and his colleagues used for other purposes (e.g., DREAM-1 and DREAM-2, as presented in the work of Cui et al. [2006a, 2006b]) because it simulates the interaction between coarse and fine sediments. Unsurprisingly, the corollary of this added complexity is that TUGS model is more difficult to set up and requires more input data, some of which is often impractical to obtain (e.g., grain size distribution of sediment supply) and has to be assumed during the model calibration process based on more readily available data (such as surface or subsurface grain size distribution). The increased complexity is necessary for this particular project because without these model capabilities, simulating how the fraction of fine sediment in the bed changes through time would not be possible.

3.2. Analysis and Results

The following data were available and were used either as model input or for model examination/calibration: (1) daily discharge records from two stations, (2) a sediment budget analysis that provided estimated sediment supply at each tributary junction within the study reach. (3) a longitudinal
profile of the river, including locations of nonerodible, geologic, and anthropogenic controls such as bedrock outcrops and concrete weirs, (4) bankfull channel width estimated in the field during the longitudinal profile survey, and (5) surface grain size distributions at various locations obtained through pebble counts and bulk samples.

Of particular note, TUGS requires a comprehensive grain size distribution of the sediment supply, which is impractical to obtain in many projects including this one, and a reasonable estimate of an abrasion coefficient, which predicts how fast gravel particles will break down into finer particles while transported downstream. The grain size distribution of the sediment supply and a gravel abrasion coefficient were derived during a “zeroing process,” where assumptions were made with these unavailable parameters and adjusted iteratively until the model reproduced key parameters observed in the field, including the longitudinal profile and surface grain size distribution. Further discussion of the importance of the zeroing process is provided later in this chapter. A comparison of simulated and observed grain size distributions of the postzeroing model is provided in Figure 4, indicating that predicted surface median size ($D_{50}$) (Figure 4b), surface $D_{84}$ (Figure 4c), surface sand fraction (Figure 4d) generally fell within the measured range, while surface $D_{16}$ (Figure 4a) was underpredicted. The level of agreement between comparisons shown in Figure 4, especially the key sand fraction result (Figure 4d), is generally acceptable in sediment transport modeling exercises, and the model with postzeroing input data was used to simulate fine-sediment fractions in the gravel bed under different measures. Among the measures, the most practical one is to augment clean spawning gravel into one of Lagunitas Creek’s tributaries as a measure.

Figure 4. Simulated surface characteristic grain size and surface sand fraction under current conditions in comparison with field observations: (a) surface $D_{16}$, (b) surface $D_{50}$, (c) surface $D_{84}$, and (d) surface sand fraction. Simulated TUGS model results are depicted with open circles. Solid triangles are pebble count results by M. O’Connor (personal communication, 2006) and Stillwater Sciences staff in 2008. Additional field data are bulk samples from Balance Hydrologics (2008): the solid squares are mean values, the diamonds are the maximum and minimum values, and the large open rectangular boxes represent mean value ±1 standard deviation.
to decrease the fraction of fine sediment in the sediment supply. Simulated surface sand fraction averaged over the study reach downstream of the gravel augmentation point with various rates of gravel augmentation is presented in Figure 5 in comparison with the current condition (0 t yr\(^{-1}\) gravel augmentation), indicating decreased fine-sediment fraction with increasing rate of gravel augmentation. The degree of fine-sediment reduction, however, is rather small for the range of gravel augmentation rates examined. While a final decision as to what action to implement in Lagunitas Creek to reduce the amount of fine sediment on channel bed has not been made, the modeling exercises at least provide some idea to management agencies as to whether the examined measures will be effective, and thus, potentially eliminating some possible trial-and-error actions prevalent in many river management or restoration projects.

4. ONE-DIMENSIONAL MODELING OF SEDIMENT TRANSPORT DYNAMICS IN A FLUME WITH FORCED POOL-RIFFLE MORPHOLOGY

One-dimensional numerical sediment transport models are widely used for sediment transport evaluations in rivers due to their relative simplicity compared to other tools such as multidimensional numerical and scaled physical models. Implicit in their formulation, 1-D numerical sediment transport models are not capable of simulating detailed local topographic features such as pools and riffles in rivers, and their applications generally involve extended river reaches over a long period of time [e.g., Thomas and Chang, 2008; Spasojevic and Holly, 2008; Cui et al., 2008]. As a result, the spatial resolution of 1-D numerical sediment transport models is generally one wave length of the dominant features (e.g., a pool-riffle sequence) or longer, usually implying distances on the order of several channel widths [Cui et al., 2008]. As a consequence, 1-D numerical sediment transport model results pertaining to sediment transport characteristics at a scale smaller than several channel widths should usually be viewed as extrapolations beyond model resolution. Because 1-D numerical models average parameters over the entire cross section, any results describing how a particular cross section changes (e.g., amount of erosion or deposition near a particular bank) should also be viewed as beyond the resolution of the model, even though many 1-D numerical models provide such detailed results in their outputs. Moreover, because of the inherent uncertainties associated with input parameters such as sediment supply and future hydrologic conditions, the temporal resolution of most 1-D model applications is generally on the order of a year or more, unless a model is specifically set up to examine a particular event. Thus, 1-D numerical sediment transport models must be applied and interpreted on a reach-averaged and time-averaged basis. An informative demonstration of the reach-averaged nature of 1-D numerical sediment transport modeling is the numerical simulation of a series of flume experiments given by Cui et al. [2008], summarized below.

![Figure 5](image.png)

**Figure 5.** Simulated surface sand fraction averaged over the study reach downstream of the gravel augmentation point, indicating a slightly decreased surface sand fraction with increasing rate of gravel augmentation.
Figure 6. Experimental flume Richmond Field Station, the University of California, Berkeley, used for two generic experiments: (1) sediment pulse dynamics in rivers with pool-riffle morphology and (2) fine-sediment infiltration into gravel deposit. (a) Sketch of the flume and its associated facilities. (b) Plan view of the setup for sediment pulse experiments. (c) Plan view of the setup for fine-sediment infiltration experiments. (d) Photograph showing sediment pulse experiment, looking upstream.

Figure 7. Comparison of measured and simulated change in reach-averaged bed elevation relative to the initial reach-averaged bed profile for run 7 (large fine-sediment pulse run). Time steps in the diagrams reference time relative to the start of sediment pulse feed, in hours:minutes:seconds. DREAM-1 was used for numerical simulation. Diagram adapted from the work of Cui et al. [2008], reprinted with permission from ASCE.
to determine whether large fine- and coarse-sediment pulses in rivers would result in an oversimplified channel bed (i.e., a less complex channel with flatter bed), presented in more detail later in this chapter where generic flume experiments are discussed.

The data were also used by Cui et al. [2008] to examine the performance of two 1-D numerical models, DREAM-1 and DREAM-2 [Cui et al., 2006a, 2006b], for simulation of sand-sized and gravel-sized sediment transport, respectively, focusing on how the models performed with respect to the pool-riffle morphology. First, due to the reach averaged nature of 1-D sediment transport numerical models, Cui et al. [2008] did not use the surveyed initial bed profile, which is rather undulating due to the presence of pool-riffle sequences, as the initial condition but instead used a planer bed with a slope identical to the surveyed slope averaged over five channel widths (one wavelength of the pool-riffle morphology). This practice produced a good match between numerical simulation and experimental data for both models even though DREAM-1 was uncalibrated, and DREAM-2 was calibrated simply by adjusting one coefficient within the model so that it reproduced the observed bed slope under 40 kg h\(^{-1}\) sediment feed rate and 20 L s\(^{-1}\) discharge. Comparisons of numerical modeling results and flume observations for two runs, one each for DREAM-1 and DREAM-2, are presented in Figures 7 and 8, respectively, both indicating good agreement between observations and predictions. Then, to demonstrate that trying to use 1-D numerical models to produce results at a scale finer than a reach-averaged resolution would produce undesirable if not completely invalid results, Cui et al. [2008] also simulated the same two runs using the surveyed thalweg profiles as the initial profile input to the models (Figures 9 and 10). Results in Figures 9 and 10 indicate that the models poorly reproduced the channel aggradation and degradation at most locations, especially in the area of pools, although the simulated general patterns of sediment pulse movement are visible and bear some similarities with the observations. Further analysis of the simulation results indicate that the median errors in bed elevation for DREAM-1 and DREAM-2 simulations are approximately 8 and 2 times higher, respectively, for runs where the observed thalweg elevations were used directly as model initial conditions compared to using a planer bed, which represents the reach average of the observed bed elevation.

![Figure 8](image-url). Comparison of measured and simulated change in reach-averaged bed elevation relative to the initial reach-averaged bed profile for run 8 (the large coarse pulse run). Time steps in the diagrams reference time relative to the start of sediment pulse feed, in hours:minutes:seconds. DREAM-2 was used for numerical simulation. Diagram adapted from the work of Cui et al. [2008], reprinted with permission from ASCE.
5. MARMOT DAM REMOVAL SEDIMENT TRANSPORT STUDY, SANDY RIVER, OREGON

5.1. Project Background

The 14 m tall Marmot Dam was located on the Sandy River, Oregon approximately 48 km upstream of its confluence with Columbia River. Based on economic and environmental considerations, Portland General Electric (PGE), the owner of the dam, decided to remove the dam and decommission the associated hydropower project, which reestablished continuity for physical and biological processes throughout the system including fish passage for three listed species of anadromous salmonids. In order to obtain a permit for dam removal and select an appropriate removal alternative, a pair of 1-D numerical sediment transport models was developed in 1999 to understand the fate of approximately 750,000 m$^3$ of gravel and sand deposited upstream of Marmot Dam during its 80+ years of operation (see Stillwater Sciences [2000] (accessed May 2010) and Cui and Wilcox [2008]). In 2002, stakeholders agreed on the alternative that removed the dam in a single season with minimal sediment excavation, at least in part based on the modeling results. This option, referred to as “blow-and-go” alternative hereafter, involved releasing almost all of the sediment stored upstream of the dam to downstream reaches, making it the most economical removal alternative considered as well as the one with the highest potential for causing downstream impacts. Downstream concerns included potential burial of spawning habitat, blockage of secondary channels, and simplification of channel geometry that could potentially hamper upstream

Figure 9. Comparison of measured and simulated change in bed elevation for run 7 (the large fine-sediment pulse run) without reach averaging, demonstrating decreased model performance following mishandling of the initial condition relative to the reach-averaged results presented in Figure 7. Numerical simulation used the initial thalweg elevation without averaging as model input, and the measured change in bed elevation is calculated based on the surveyed thalweg elevation data. Time steps in the diagrams reference time relative to the start of sediment pulse feed in hours:minutes:seconds. DREAM-1 model was used for simulation. Diagram adapted from the work of Cui et al. [2008], reprinted with permission from ASCE.

Figure 10. Comparison of measured and simulated change in bed elevation for run 8 (the large coarse-sediment pulse run) without reach averaging, demonstrating decreased model performance following mishandling of the initial condition relative to the reach-averaged results presented in Figure 8. Numerical simulation used the initial thalweg elevation without averaging as model input, and the measured change in bed elevation is calculated based on the surveyed thalweg elevation data. Time steps in the diagrams reference time relative to the start of sediment pulse feed in hours:minutes:seconds. DREAM-2 model was used for simulation. Diagram adapted from the work of Cui et al. [2008], reprinted with permission from ASCE.
migration of adult salmonids, fine-sediment deposition in spawning habitat, and sediment deposition in the delta area (Sandy River confluence with Columbia River) that might block adult salmonids from entering the Sandy River.

Modeling results, however, indicated that major coarse-sediment deposition would occur only within the first few kilometers downstream of the dam and within a short distance downstream of the Sandy Gorge approximately 8 km downstream of the dam, and fine sediment would pass through most of the Sandy River with little deposition except within a few kilometers of the confluence with the Columbia River where the river is already sand bedded under current conditions. In addition, modeling results indicated that multiple-year staged removal would provide no advantage over the blow-and-go alternative and that dredging a portion of the stored sediment during one dry season would provide only minimal benefit over the blow-and-go alternative (i.e., minimal reduction in the thickness of sediment deposition downstream of the dam).

As a result, the blow-and-go option was implemented in the summer of 2007, and the cofferdam protecting the working area and preventing erosion of the sediment deposit was breached in the fall following the first storm event of the season. Figure 11 details simulated erosion and deposition processes in the Sandy River upstream and downstream of Marmot Dam following dam removal in comparison with field data collected after dam removal, indicating that field observations generally fall within the range of numerical model predictions. The model also predicted a low daily-observations generally fall within the range of numerical model predictions. The model also predicted a low daily-

5.3. Sediment Supply

Based on a review of pertinent sediment production literature from the same region with similar geological and climatic conditions, Stillwater Sciences geologists estimated a sediment production rate in the Sandy River basin upstream of Marmot Dam between 100 and 600 t km⁻² yr⁻¹, which translates to approximately 70,000 to 300,000 t yr⁻¹ sediment supply at the Marmot Dam site that has a catchment area of approximately 680 km² [Stillwater Sciences, 2000] (accessed May 2010). The coring results of the impoundment deposit (Squier Associates 2000, as discussed above) provided an excellent approximation of the grain size distribution of the sediment supply. The volume estimate of the impoundment deposit, however, was not beneficial for calculating the sediment supply rate in the Sandy River because the duration that completely filled Marmot Dam impoundment was unknown (e.g., the reservoir was completely full of sediment and when this occurred was unknown). Although the 70,000 to 300,000 t yr⁻¹ sediment supply was a rough estimate, a more accurate assessment was determined neither practical nor necessary, and the rough supply estimate would be adequate to conduct sediment transport modeling, especially with the grain size distribution information provided through the coring exercise. Because most of the reach of interest (i.e., Sandy River downstream of Marmot Dam) is gravel bedded, the gravel supply rate is the primary consideration for modeling. Using the assumption that 5% to 10% of the sediment supply is gravel, the 490,000 m³ of gravel deposited within the Marmot Dam impoundment would represent at least 15 times more than the long-term averaged gravel supply in the Sandy River. As a result, the sediment supply used as model input was not expected to significantly affect the simulated sediment transport dynamics following Marmot Dam removal. Nevertheless, the assumed sediment supply rate is important because an imbalance between the sediment supply rate (and the associated grain size distribution) with the channel geometry, slope, and hydrology would result in persistent channel aggradation or degradation for long-term simulations such as those following dam removal. A sediment supply rate that is in balance with sediment transport capacity in the Sandy River was determined as part of the zeroing process discussed later in this section.
5.4. Simulating Discharge

Hydrologic conditions vary considerably from year to year in the Sandy River, and using different hydrologic conditions will influence modeling results. While some practitioners advocate using a Monte Carlo method to simulate sediment transport dynamics (e.g., treating discharge and sediment supply as stochastic parameters in the model using random
functions following predetermined distributions), simulations for Marmot Dam removal project used a much simpler method that provided confident predictions with far less effort. Recognizing that postdam-removal sediment transport would become less active through time, three model runs were conducted for each removal alternative, each run using a different hydrologic condition to represent the first year following dam removal, while the hydrologic conditions starting in year 2 after dam removal were selected randomly from the existing record and were consistent for all runs. The three hydrologic conditions were represented by three typical years selected from the daily discharge record based on exceedance probabilities for the annual peak series and annual runoff: a wet year with exceedance probability of approximately 0.1, an average year of approximately 0.5, and a dry year of approximately 0.9. Three sets of results were provided for each alternative, with the sediment transport characteristics expected to fall within the envelope of values included in the three scenarios. This practice proved to be effective, as evidenced by the comparison between pre-removal modeling results and postremoval field data shown in Figure 11. A Monte Carlo simulation would likely have achieved similar results, but the number of runs for each alternative would need to be several hundreds, if not thousands, in order to achieve meaningful statistics for the simulated results.

5.5. Determining Downstream Boundary Conditions

The downstream boundary of the simulation was set at the Sandy River-Columbia River confluence approximately 48 km downstream of Marmot Dam as a fixed bed elevation and a normal flow condition. A mathematically correct downstream boundary condition would involve using a series of water surface elevations in the Columbia River at the confluence, but this is impractical because future water surface elevations are unknown and have no direct relation with the discharge in the Sandy River. The downstream boundary condition was not expected to have any impact to the modeling results near Marmot Dam, where significant erosion (in the impoundment) and deposition (downstream of the dam) would occur. Because there was considerable amount of sand in the Marmot Dam deposit, and sand was expected to transport rapidly downstream following dam removal, however, it was unclear whether the approximate nature or uncertainty in downstream boundary condition would have some influence on predicted sand deposition near the confluence. This uncertainty could have potential impacts for local fish passage if greater amounts of sand were deposited than predicted, especially during critically dry flow conditions. The intractability of this concern was addressed with a contingency plan (discussed later) instead of trying to increase the confidence and precision of the modeling, which was likely not possible to achieve.
5.6. Setting the Initial Channel Geometry

Marmot Dam removal sediment transport modeling was unique in that channel geometry and longitudinal profile for modeling input were all obtained through remote techniques: channel geometry was assumed to be rectangle, and the width of the channel was measured from a set of 1:6000 scale aerial photos; longitudinal profile was measured through photogrammetry analysis based on aerial photographs obtained during low flow periods. Only limited field data were collected, which was used only for validation purposes.

We used rectangles to approximate detailed channel geometry because the width to depth ratio of a natural river is usually large during high flow events when there is active sediment transport, and a rectangle usually provides a good approximation of the cross section if floodplains are neglected. Neglecting floodplains is often acceptable because (1) overbank flow events usually occur only for a small fraction of time, and thus, the cumulative sediment transport during overbank flow periods usually accounts for only a small part of the total sediment transport despite the fact that overbank flow events are always associated with significant sediment transport and (2) potential simulation errors introduced by omitting floodplain are usually collectively accounted for with other modeling uncertainties (e.g., hydrology and sediment supply) in the calibration process that includes a period of time with different flow events, including overbank flow events [Cui et al., 2008].

We did not subtract water depth from the longitudinal profile obtained through photogrammetry analysis that are more representative of the water surface elevation instead of the thalweg elevation. Adjusting the longitudinal profile by subtracting water depth would have required on-the-ground cross-section surveys that are expensive and time consuming. More importantly, such adjustment would have provided no additional value for the modeling because the longitudinal profile of the river had to be adjusted during a zeroing process in order to serve as the initial condition for the modeling of sediment transport dynamics following dam removal.

5.7. Simulating the Baseline Condition: The Zeroing Process

The objective of a zeroing process is to adjust the model input parameters so that they approximately reproduce the existing quasi-equilibrium long profile under the assumed background conditions. One assumption, therefore, is that the modeled reach is in a quasi-equilibrium condition, in which some aggradation or degradation may occur following flood events, but the long-term cumulative channel aggradation or degradation is minimal. The zeroing process

Figure 13. Comparison of the Sandy River photogrammetry-derived longitudinal profile to the post-zeroing profile (i.e., the initial profile for Marmot Dam removal used for sediment transport modeling). (a) Longitudinal profile, showing reasonable agreement at least at the scale presented. (b) Net difference between the two profiles, showing up to 3.7 m differences at certain locations. (c) Channel gradient, which serves as the driving force for sediment transport. Figure 13c is from the work of Cui and Wilcox [2008], reprinted with permission from ASCE.
involves running the model repeatedly with the surveyed longitudinal profile as the initial condition and the recorded hydrologic condition and best estimate of sediment supply rate and grain size distribution as boundary conditions. During this process, certain input data such as channel width, sediment supply rate, and/or grain size distribution are adjusted iteratively until the model reproduces a quasi-equilibrium profile similar to that observed. The reproduced quasi-equilibrium longitudinal profile is then used as the initial profile for modeling future conditions such as evaluating sediment transport dynamics following dam removal herein or following channel reconstruction for restoration. Because this initial profile is in quasi-equilibrium state within the model, any deviations from this condition in the subsequent simulations are considered to result from the perturbation injected into the model input (e.g., the release of the sediment deposit in the impoundment area in case of dam removal).

During the zeroing process for Marmot Dam removal sediment transport study, the following adjustments were made: channel width was adjusted by narrowing some of the excessively wide cross sections, long-term averaged sediment supply rate was adjusted within the range found during the literature review, and the abrasion coefficient of gravel particles was also adjusted based on published range so that the predicted grain size distribution and longitudinal profile under the current conditions were similar to observations. The resulting postzeroing equilibrium profile and channel gradient are shown in Figure 13 in comparison with the surveyed data, and the simulated annual and cumulative changes in bed elevation postzeroing process are shown in Figures 14 and 15, respectively. Note in Figure 13a that the

![Diagram](image)

**Figure 14.** Simulated annual change in bed elevation under the assumed background condition, showing up to 0.6 m of annual aggradation or degradation due to sediment deposition or erosion at certain locations. Flow is from left to right; Marmot Dam was located at the upstream end of reach 1; and the Columbia River confluence is at the downstream end of reach 5. From the work of Cui and Wilcox [2008], reprinted with permission from ASCE.
postzeroing profile is very similar to the photogrammetry data, at least at the scale shown, and the channel gradient is also similar between the two sets of profiles, as shown in Figure 13c. However, there was actually up to 3.7 m of elevation difference between the two profiles, as shown in Figure 13b. The simulated channel aggradation and degradation under background conditions using the postzeroing profile as initial condition indicated that although there is annual aggradation or degradation up to 0.6 m at certain locations (Figure 14), the cumulative change in bed elevation is minimal (Figure 15). As such, any changes simulated following dam removal would indeed be the consequences of the release of stored sediment.

It should be noted that there are professional judgment to be made during the zeroing process, and the experience of the modeler may play an important role in successfully conducting the zeroing process.

5.8. Interpreting Model Results

Running a sediment transport model is only part of the process of analyzing sediment transport dynamics for river

![Figure 15](image-url)

**Figure 15.** Simulated cumulative change in bed elevation under the assumed background condition, showing minimal cumulative change in the 10 year period of simulation. Flow is from left to right; Marmot Dam was located between reaches 0 and 1, and the Columbia River confluence is at the downstream end of reach 5. From the work of Cui and Wilcox [2008], reprinted with permission from ASCE.
Critically, model results need interpretation by experienced professionals for any number of reasons, of which three are highlighted here. First, there is a need to identify whether all the model results are explainable and, if not, whether there are potential errors in the model and/or input data. During the Marmot Dam removal sediment transport modeling, for example, the first set of results showed an unlikely scenario of more sediment deposition in the narrow and steep Sandy Gorge (reach 2 in Figures 14 and 15), than in neighboring reaches. This led to the discovery and correction of an error in the model, a single line error within thousands of lines of FORTRAN code that would not have been discovered otherwise. Figure 16 illustrates the results from one run of the corrected model showing minimal change in bed elevation within the Sandy Gorge following dam removal, far more consistent with an understanding of how sediment behaves in similar conditions. Second, there is a need to ensure that results are interpreted by those with sufficient experience in sediment transport processes and sediment transport modeling, and with a good understanding of the river system to be modeled. Bed elevation and thickness of sediment deposition as a function of distance, for example, can easily be interpreted inaccurately because results are often presented (by necessity) on plots with very
compressed longitudinal scales and measured from arbitrary datum. Using the results presented in Figure 16 as an example, it is very easy to think that there would be substantial amount of reservoir sediment left in the impoundment area (reach 0) and downstream even 10 years after dam removal, evidenced by the “bumps” in reaches 0 and 3, raising concerns about potential long-term impact to spawning habitat in the river. However, for those with knowledge of the river and modeling practice, at least part of the bump in the impoundment area was to involve predam topography rather than the reservoir deposit because the thickness of sediment deposit in that reach was measured from arbitrary bench values (i.e., if the thickness is measured from a higher elevation in that area, the bump would have been smaller). In addition to cumulative thickness of sediment deposition presented in Figure 16, an experienced modeler would also examine the annual change in bed elevation (Figure 17). Results in Figure 17 show that annual change in bed elevation for reaches 2, 3, 4, and 5 is only slightly higher than background conditions (shown in Figure 14) at all times, and reach 0 and 1 becomes similar to background conditions (i.e., similar to downstream reaches) after approximately year 2, indicating that the potential impact to spawning habitat would be minimal except in the reach immediately upstream and downstream of the dam (i.e., the downstream portion of reach 0 and upstream portion of reach 1), where the impact was expected to last for a couple of years at maximum. Third, river projects often involve multidisciplinary issues so requiring a team of experienced experts to understand and interpret the issues related to sediment transport. In the Marmot Dam removal project,

**Figure 17.** Simulated annual change in bed elevation following Marmot Dam removal for the “blow-and-go” scenario under the average hydrologic condition. Flow is from left to right; Marmot Dam was located between reaches 0 and 1, and the Columbia River confluence is at the downstream end of reach 5. From the work of Cui and Wilcox [2008], reprinted with permission from ASCE.
for example, a team of geomorphologists, engineers, fisheries biologists, and riparian biologists were required to help interpret the modeling results. The team of scientists not only provided interpretations of modeling results, but also identified sensitive issues and, in association with uncertainties of the model, designed contingency plans (discussed below) to ensure that the project would be successful even if certain aspects of sediment transport dynamics were predicted less accurately or incorrectly.

5.9. Accommodating Uncertainties

Numerical sediment transport models are far from perfect representations of the prototype rivers, and there are always uncertainties associated with their predictions. In addition to unknown future hydrologic conditions, the most common sources of uncertainties include the following: (1) model resolution lower than what is required for a particular project, (2) areas of concern not represented or inadequately represented by the model, and (3) uncertainties associated with upstream and downstream boundary conditions. These uncertainties must be identified by the modeler and the team of professionals that provide interpretations to modeling results. Several techniques can make the numerical modeling results useful despite the uncertainties associated with the modeling results: (1) to conduct sensitivity test runs and provide a potential range of outcomes rather than providing a single set of prediction so that the “true results” will be most likely within the predicted range, (2) to use the model results comparatively between different alternatives, (3) to better understand the specific concern and potential outcome through more in-depth research, and (4) to provide appropriate contingency plans to address the concerns. These techniques are discussed below.

5.10. Conducting Sensitivity Test Runs

As discussed earlier, sediment transport modeling for Marmot Dam removal project used discharge record from three different hydrologic years to serve as input data during the first year following dam removal and, thus, providing three sets of results for each scenario. This practice proved to be effective, evidenced by the comparison of observed and predicted channel aggradation and degradation shown in Figure 11, where observations generally fell within the predicted range. In addition to considerations of uncertainties in future discharge, the modeling also conducted other sensitivity test runs, including (1) potential errors in estimated grain size distributions of the reservoir deposits (assumed coarser- and finer-grain sizes as sensitivity test runs) and (2) potential errors in sediment transport equations in case of steep slopes (applied slope adjustment to predicted sediment transport capacity as sensitivity test runs). Detailed descriptions of Marmot Dam removal study sensitivity test runs can be found in Stillwater Sciences [2000] and the work of Cui and Wilcox [2008], and sensitivity runs that examined a variety of parameters for dam removal sediment transport modeling can be found in the work of Cui et al. [2006b].

5.11. Using Modeling Results Comparatively

Despite the many uncertainties, modeling results are generally much more reliable if used for comparisons of different alternatives. For example, modeling results shown in Figure 16 indicated that there would be increasing sediment deposition near the upstream end of reach 3 in the first few years following dam removal, reaching a maximum value of approximately 0.6 m in year 6. This result could only be interpreted as that there would likely be sediment deposition in that area, with relatively low confidence level in the predicted value of 0.6 m. If, however, a second dam removal alternative was simulated under the same assumptions, and the results indicated that there would be only up to 0.3 m of sediment deposition in the same area, then we would be able to say confidently that the second dam removal alternative would result in lower sediment deposition in reach 3, although the level of confidence toward the predicted value of 0.3 m was equally low. The concept of using modeling results comparatively was fully utilized during Marmot Dam removal sediment transport study, and the model was used to examine several dam removal alternatives, providing important information for the stakeholders to select a preferred alternative confidently based on comparisons of modeling results between the alternatives. For example, modeling results indicated that a 2 year staged removal would produce no benefit in terms of reducing the amount of downstream sediment deposition, and dredging sediment during one dry season (summer and fall) prior to dam removal would produce minimal benefit compared to the most cost-effective “blow-and-go” alternative. Had these results not been available at the time, it was most likely that regulating agencies would have demanded dredging prior to dam removal or a removal alternative that releases sediment gradually, and PGE might have chosen to abandon the dam for some other interested parties to continue to operate instead of dam removal due to the high cost.

5.12. Detailed Research for Specific Questions

Although none of the concerns raised during Marmot Dam removal study was addressed through in-depth research during the project, a couple of follow-up research projects that
benefit dam removal project, in general, were inspired by Marmot Dam removal project. These studies are (1) flume experiments investigating sediment pulse dynamics in a channel with pool-riffle morphology, inspired by the need to understand whether a large pulse of sediment release following dam removal project would result in reduced channel complexity (i.e., filled pools and flattening of channel bed) and (2) flume experiments investigating fine-sediment infiltration into a gravel deposit, inspired by the need to understand the impact to salmonid spawning habitat due to fine-sediment release following dam removal. These two studies are briefly discussed as examples of generic flume experiments later in this chapter.

5.13. Contingency Plans

Instead of trying to answer each concern with greater confidence, appropriate contingency plans can often be used as a relatively economical way to address the uncertainties associated with sediment transport numerical modeling. Three contingency plans were developed by PGE to address the concerns where numerical modeling and professional judgment were unable to provide adequate resolution to the issues: (1) PGE would dredge the channel and/or install large woody debris if postremoval monitoring indicated upstream passage difficulties for adult salmonid in the vicinity of the dam, (2) PGE would dredge open the entrances to secondary channels if they were blocked by sediment deposition, and (3) PGE would contract a local miner to dredge a channel to facilitate upstream migration of adult salmon if monitoring indicated fish passage difficulty in the Sandy River delta. The concern for upstream fish passage near the Marmot Dam site was caused by the fact that numerical modeling was unable to answer the question as to whether the channel bed will become less complex following rapid sediment deposition, which in turn, could result in relatively shallow water depths. Similarly, numerical modeling was unable to provide information as to whether the sediment deposition at a specific location such as the entrance to a side channel will occur after dam removal. The fish passage concern near Sandy River delta was largely prompted by the fact that there was a historical upstream fish passage blockage during an extremely dry year, compounded with the fact that it is the downstream end boundary of the numerical modeling, and thus, there is relatively low confidence in modeling results in that specific area. Postremoval monitoring indicated none of the concerns were realized, and as a result, no contingency plan was put into action. The Marmot Dam removal project shows that providing contingency plans can be an efficient and economic way of addressing some of the uncertainties in numerical sediment transport modeling or other sediment transport analysis, especially where potential consequences are serious, and modeling results were unable to answer questions beyond a reasonable doubt.


Because 1-D numerical sediment transport models can only reliably predict sediment transport dynamics on a reach-averaged basis, as demonstrated earlier, it is intuitive to think that multiple dimensional numerical models or scaled physical models should be used in place of a 1-D model when more detailed results are desired. The objective of producing more detailed and reliable results using multidimensional numerical models or scaled physical models, however, may not always be achievable due to their respective limitations. A comprehensive description of multidimensional numerical sediment transport models can be found in Spasojevic and Holly [2008], where the authors summarized capability requirements of different numerical models, discussed modeling techniques, and provided model examples. Here we briefly discuss some of more important limitations facing the use of multidimensional models.

There are three main limitations for multidimensional numerical models. First, while multidimensional modeling can usually realistically reproduce the flow field, the detailed relation between sediment transport and movement of sediment particles is not fully understood, and all the current sediment transport equations were developed based on data collected on a cross-section averaged basis. As such, topography predicted as a direct result of flow field (such as scour due to river bend) can often be realistically modeled, but the topography associated with complex sediment transport dynamics, such as the formation and development of alternative bars in a straight channel, may not be realistically reproduced. Second, attempting to model sediment transport dynamics in detail requires the collection of detailed field data, some of which are critical to the modeling but impractical to obtain in many situations or at a large scale. For example, simulating detailed topography in an area subject to channel erosion will require the knowledge of detailed grain size distributions and information with regard to where nonerodible material (such as bedrock and large boulders) is located and how deep it is beneath the surface. While it is possible to make some generalized assumptions about grain size distributions based on observations of the surface or bulk samples, it is impractical to know the locations and depth of the bedrock and large boulders, and without such information, the modeling results with regard to future topography would not have the desired resolution. Third, limitations in available computer resources will set upper bounds on the number of nodes permissible in a
multidimensional model simulation, and because computational meshes cannot be overly distorted (i.e., the longitudinal dimension of the meshes cannot be too much larger than the lateral dimension), there are practical limits on the length of the river that can be simulated. This latter issue can introduce a further problem in that modeling short reaches may make the entire simulation domain dependent on boundary (especially downstream boundary) conditions, making the simulation results unreliable. This is generally not an issue in 1-D modeling because a 1-D model can be set to a significantly longer reach so that the interested area is beyond the influence of the model boundary.

Multidimensional numerical modeling was not proposed during the Marmot Dam decommission process, although there was some interest from academicians to test run a 2-D model in a short reach up- and downstream of the dam. The primary reason that multidimensional numerical modeling was not proposed at the time was that 1-D numerical modeling had satisfactorily answered all the important questions that the stakeholders and regulating agencies needed to know, with a few uncertainties addressed with contingency plans discussed earlier, allowing the stakeholders to reach an agreement. In addition, multidimensional simulations would have been limited to only a short period of time following dam removal, which was not the primary interest of the stakeholders. Technically, setting up a 2-D model a short distance up- and downstream of the dam will face the difficulty of correctly assigning the downstream end boundary conditions because there would potentially be channel aggradation and subsequent degradation that was not known prior to modeling. As discussed earlier, modeling results in a short river reach will be dictated by boundary conditions, especially the downstream boundary condition. As a result, an independent 2-D numerical sediment transport model would not have been feasible, and 1-D modeling results would have to be used to serve as the downstream boundary condition for a 2-D model. If a 2-D numerical sediment transport modeling simulation was conducted using 1-D model results as downstream boundary condition, it may have yielded results of some interest that the 1-D model did not offer, but it should be noted that the 2-D modeling results would not have been more reliable than that of the 1-D model due to its dependence on 1-D modeling results. That is, seeking more reliable modeling results should not have been the reason to conduct a 2-D modeling under these circumstances.

5.15. Scaled Physical Model of Marmot Dam Removal Sediment Transport

Scaled physical models, which provide powerful visualizations for the modeled projects and events, are subject to similar limitations as multidimensional numerical sediment transport models. Because a scaled physical model usually cannot be constructed to represent a long river reach, for example, project managers and professionals using scaled physical models for river restoration and other river projects should pay particular attention to impact of possible errors introduced through the setup of boundary conditions and treat the results cautiously, as discussed below.

Prior to Marmot Dam removal, a physical model was constructed at St. Anthony Falls Laboratory (SAFL), the University of Minnesota by Marr et al. [2007] to provide direct observations of sediment transport dynamics following dam removal and to examine how to best breach the cofferdam following dam removal. The experiment provided powerful visualization effect as to how sediment would likely be eroded from the Marmot impoundment following cofferdam breaching and suggested that the cofferdam should be artificially breached near its left bank to allow for more efficient erosion of the reservoir deposit, which was adapted by the engineers in the field. The model also demonstrated the major limitations for scaled physical models in that it cannot cover an adequately long reach, and thus, modeling results are likely significantly affected by the downstream boundary set up, making a direct scale up of modeling results rather difficult. The SAFL’s Marmot Dam removal model scaled approximately 305 m (1000 feet) of the impoundment area [Marr et al., 2007] and an even shorter reach downstream of the dam, and as a result, the downstream boundary was located in a reach that received rapid and substantial deposition following dam removal (Figure 11). The experiment, however, could only use a fixed water surface elevation as downstream boundary condition. As a result, the model likely overpredicted the rate of sediment erosion from the impoundment, evidenced by a quick evacuation of all the reservoir deposit in the model. This notwithstanding, scaled models such as this are very useful to answer some of the specific questions, as long as their limitations are fully considered, and model results are not overinterpreted.

6. PRACTICAL USES OF GENERIC PHYSICAL MODELS

One of the most powerful but often ignored tools for understanding of sediment transport issues is generic physical/flume modeling (i.e., modeling not scaled according to a prototype). Generic flume experiments are usually not designed to solve a site-specific sediment transport problem. Instead, they most often attempt to answer fundamental sediment transport questions and therefore are used to develop universal theories and validate numerical models that can be
applied to other projects in similar fluvial environments. Because of their wide-ranging applicability, generic flume experiments are probably one of the most economic ways for addressing sediment transport issues on a per project basis, even though conducting a successful generic flume experiment can be expensive.

The flume experiments conducted for sediment pulse evolution in rivers [e.g., Lisle et al., 1997, 2001; Cui et al., 2003a; Sklar et al., 2009], for example, are typical generic experiments that established that sediment pulses in rivers evolve by a combination of dispersion and translation, with dispersion always being the dominant process. The research established theories and provided insight between the evolution of sediment pulses, the flow parameters, and the relative grain size distributions of bed material and pulse sediment; the measurements collected during the experiments became a critical data set for the examination and validation of numerical models developed thereafter [e.g., Cui et al., 2003b], which were the predecessors of the 1-D sediment transport model used both for the Marmot Dam removal project [Stillwater Sciences, 2000; Cui and Wilcox, 2008] and, subsequently, the DREAM and TUGS models [Cui et al., 2006a, 2006b; Cui, 2007a].

Two generic model experiments conducted at RFS inspired by Marmot and other dam removal projects can provide some insights with regard to the considerations and values of flume experiments. During the Marmot Dam removal project, it was not well understood if the rapid sediment deposition following dam removal would result in an oversimplified channel that would potentially impair holding, rearing, and spawning habitat for native salmonids. Although, from a project perspective, this concern was addressed satisfactorily through development of a contingency plan (discussed earlier in this chapter) during the project’s permitting process, several flume experiments were conducted to better understand this issue because its potential impact on downstream biological processes is of interest in most dam removal projects. The key experimental results, illustrating the potential change in channel complexity following the introduction of sediment pulses, were briefly discussed in the work of Downs et al. [2009] and are presented in Figure 18. Experimental observations indicated that pools did not ubiquitously fill with sediment and maintained water depths similar to their initial depths in areas of higher shear stress while contracting in aerial extent as sediment accumulated in areas of lower shear stress areas. These data suggest that pool filling and topographic simplification of the channel bed are likely not issues of concern when considering the impact of the large amount of sediment release after dam removal, provided there is enough flow to transport the released sediment. This conclusion was also confirmed by field observations following the removal of Marmot Dam, where it was found that there was no substantial change in channel complexity index, defined here as the standard deviation of bed elevation [Stillwater Sciences, 2010] (accessed May 2010) (Figure 19). Lateral variations in channel bed elevation persisted following the dam removal, thus preserving a reasonable water depth even under low flow conditions.

In addition to bed burial, fine sediment (sand and finer) infiltrating into downstream gravel deposits and impacting habitat conditions and biological processes (e.g., salmonid spawning) has also been a concern associated with dam removal projects. To address these issues, a series of intensive flume experiments were conducted at the RFS to test...
ideas about the interaction between infiltrating sediment and the bed sediment framework [Wooster et al., 2008]. Prior to the experiments, it was hypothesized that the amount of fine-sediment infiltration and the vertical profile of fine-sediment concentration in a gravel deposit following infiltration are functions of the grain size distributions of the gravel deposit and the infiltrating fine sediment. To examine this hypothesis, the flume was set at a moderate slope, divided into 10 zones (Figures 6a and 6c), and filled with gravel of nine different grain size distributions (two zones were filled with gravel of identical grain size distribution for comparison purposes). Water was then released into the flume at a constant discharge, and sand was fed from the upstream until the 10 zones appeared to be saturated with fine sediment (i.e., no more fine sediment could be infiltrated into the deposit).

Upon termination of the experiment, multiple sediment samples were collected from each of the 10 zones at different depths, and grain size distribution of each sample was analyzed. Corroborating the experimental data with basic geometric relations, Wooster et al. [2008] were able to derive semiempirical relations linking the amount of fine sediment in a gravel deposit due to infiltration with grain size distributions of the gravel deposit and the infiltrating fine sediment. The experiments showed that fine-sediment concentration decreases exponentially in depth for the case of fine sediment infiltrating a gravel bed initially devoid of fine sediment, confirming observations that fine-sediment infiltration into gravel deposit is generally shallow. The implication of these results is that impact from fine-sediment release on a gravel bed following dam removal will be mostly on the channel.

**Figure 19.** Selected cross sections in the Sandy River before (2005, 2006, and 2007) and after (2008 and 2009) Marmot Dam removal, showing persistent lateral variations in topography following substantial channel aggradation postdam removal. All four cross sections are located within 600 m downstream of the dam. Field data were collected by PGE.
surface, which can be helpful for the design of future dam removal projects. For example, in some dam removals, it may be comparatively beneficial to encourage the quick release of all impounded fine sediments prior to winter high flows (or a planned high flow release from upstream dams). The high flow will act to remove much of the fine sediment accumulated on channel surface and in the shallow depth of the deposit so limiting the duration of the impact from fine-sediment deposition. Figure 20 provides a comparison of the experimental data with the relations derived by Wooster et al. [2008], which also contains an account of experimental details.

7. SUMMARY AND CONCLUSIONS

In this chapter, we have discussed several practical issues that are important for sediment transport evaluations, including the importance of selecting appropriate methods and tools, the importance of understanding the limitations of the tools to be used for the analysis, consideration of issues relating to data use, setting baseline conditions, interpreting the results and accommodating uncertainties in numerical models, and the potential utility of physical models. Because sediment transport is inherently complex and contingent on boundary conditions specific to each project, and because the discussions are drawn mostly from our past experiences, the information presented here is far from comprehensive. As such, this chapter is intended as a vehicle to promote critical thinking before, during, and after sediment transport evaluations rather than as a specific guide for sediment transport modeling. The key experiences that we recommend are as follows:

1. Select appropriate methods and tools and avoid the one-tool-fits-all practice that we see often. This is usually the first step to ensure that the analysis achieves the project goal.
2. Understand the limitations of the tools utilized for the analysis, reduce uncertainties through appropriate techniques, and if necessary, provide contingency plans to safeguard the success of the project. None of the tools used in sediment transport analysis are perfect, but modeling results are very useful if their limitations are realized and appreciated in interpreting the results.

Set up models using the correct techniques. Tools for sediment transport analyses, particularly numerical models, require the modeler to have extensive modeling experience, comprehensive knowledge of sediment transport theories and principles, and an analytical understanding of specific geomorphic conditions of the river in order to make certain critical decisions. Important steps in the modeling process include (1) determining the appropriate input data and the level of accuracy of input data; (2) adjusting the model and input data through model calibration and/or other techniques (such as the zeroing process discussed in this chapter); and (3) simplifying the model inputs as much as is feasible (e.g., approximating channel cross-section dimensions using a simple rectangular channel form can often be sufficient).

3. Assemble a team of experienced professionals to guide the sediment transport analysis and to help the modeler correctly interpret the results. This is especially important given that numerical tools are becoming more user-friendly, and users without adequate experience or knowledge can easily abuse them to generate outputs that may be inappropriate or incorrect. An incorrect modeling approach or an incorrect interpretation of model results will ultimately do more harm than good.

4. In addition to evaluating sediment transport dynamics on a project by project basis, generic flume experiments can be used to develop generalized theories related to sediment transport and habitat condition that can be used in a variety of restoration projects and fluvial settings. Despite the possible...
relatively high expense to conduct a successful generic flume experiment, it is almost always more cost effective on a per project basis compared to dealing with the same issue in all the projects due to the fact that results obtained through a successful generic analysis are general in nature and can be applied to subsequent projects.

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Y. Cui and S. R. Dusterhoff, Stillwater Sciences, 2855 Telegraph Avenue, Suite 400, Berkeley, CA 94705, USA. (yantao@stillwatersci.com)

P. W. Downs, School of Geography, Earth and Environmental Sciences, University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK.

J. K. Wooster, National Marine Fisheries Service, 777 Sonoma Avenue, Santa Rosa, CA 95404, USA.