Development and Application of Numerical Models of Sediment Transport Associated with Dam Removal

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23.1 INTRODUCTION

Numerous dams have been removed in recent decades in the United States for reasons including economics, safety, and ecological restoration. For example, Edwards Dam, on the Kennebec River, Maine, was removed in 1999 to assist Atlantic salmon recovery efforts. In the Pacific Northwest, proposals to remove or breach dams on the Elwha River, Washington, and the Snake River, Idaho, to resuscitate declining stocks of anadromous salmonids have received national attention.

A key concern in many dam removal proposals is the routing of sediment stored behind reservoirs, including downstream channel response and release of contaminated sediments (e.g., Randle 2003). No studies have been completed to document and quantify channel response to the removal of large dams (Graf 1996), although field observations following the removal of small dams have intensified in recent years (e.g., Pizzuto 2002; Doyle et al. 2003). In addition, development of predictive models to estimate the effects of sediment release following dam removal has been limited until very recently. Decommissioning processes for dams, especially those with relatively large sediment deposits, have been hindered by shortcomings in our capacity to quantitatively predict sediment-transport dynamics following dam removal, and in the face of such uncertainties, costly dredging operations are often proposed before dam removal.

In this chapter we will discuss several issues in developing sediment-transport models following dam removal, including previous numerical modeling efforts relevant to dam removal, coupled modeling of reaches upstream and downstream of dams, reservoir sediment erosion, selection of sediment transport equations, and modeling of pre-dam-removal baseline conditions. We then present the development and application of numerical models for sediment transport following removal of Marmot Dam, a hydroelectric facility on the Sandy River,

Oregon, that is scheduled for decommissioning. The Marmot Dam removal modeling example is used to demonstrate the development and application of numerical modeling of sediment transport following dam removal, thereby illustrating many of the general issues related to dam-removal modeling discussed in the following section.

23.2 DAM REMOVAL AND SEDIMENT-TRANSPORT MODELING

Many of the principles developed for modeling the transport of fluvial sediment are applicable to modeling sediment transport associated with dam removal. Effective numerical models of sediment transport following dam removal should have the capability to route both fine and coarse sediment downstream, account for abrasion of gravel, and simulate transient flows. In developing and applying sediment-transport models for dam removal, modelers must address several unique issues, including the difficulties of coupled modeling of reaches upstream and downstream of dam sites, uncertainties surrounding the channel morphology that will develop within the eroding reservoir sediments, selection of sediment-transport equations that account for the complex nature of reservoir sediment deposits, and the large spatial and temporal scales required for modeling the downstream transport of large volumes of reservoir sediment following dam removal. In the following section, we describe previous numerical modeling efforts relevant to dam removal and discuss special considerations in developing sediment-transport models for dam removal.

23.2.1 Previous Numerical Modeling Efforts Relevant to Dam Removal

Because reservoir sediment deposits behave as large sediment pulses once dams are removed, previous simulations of the evolution of sediment pulses in rivers have provided

a basis for modeling sediment transport associated with dam removal. In the sediment pulse model of Cui and Parker (2005), multiple lithology heterogeneous sediment pulses were routed downstream with full consideration of particle abrasion. The model has been applied successfully to simulate the evolution of a large landslide in the Navarro River, California (Hansler 1999; Sutherland et al. 2002). A simplified version of the Cui and Parker (2005) model has also been used to simulate evolution of gravel pulses in a laboratory flume (Cui et al. 2003).

The first adaptations of the Cui and Parker (2005) model to dam removal projects were applied to the potential removal of two dams in Oregon, Soda Springs Dam on the North Umpqua River and Marmot Dam on the Sandy River. This chapter presents the Marmot Dam removal modeling effort as a case study of the application of sediment-transport modeling to dam removal. Cui et al. (2006a; 2006b) further developed the Dam Removal Express Assessment Models (DREAM): DREAM-1 for simulation of dam removal with the reservoir sediment composed of primarily fine sediment, and DREAM-2 for simulation of dam removal with the top layer of the reservoir sediment composed of primarily coarse sediment (gravel and coarser).

Off-the-shelf sediment-transport models have also been applied to dam removal evaluations. For example, the U.S. Army Corps of Engineers' HEC-6 model was used to simulate sediment release associated with proposed dam removals on the Elwha River, Washington (Bureau of Reclamation 1996a; 1996b). Such models are usually not capable of simulating the upstream and downstream reaches of a dam simultaneously, however, because the models were not originally written for dam removal applications, and the code of the models may not be accessible to users for modification. Modelers may overcome these obstacles without access to and modification of the code in certain cases using two approaches: (1) modeling the upstream and downstream reaches of the dam separately, with the results of the upstream simulation providing input to the downstream reach; and (2) assuming that sediment-transport capacity is controlled at a critical cross section somewhere downstream of the dam, and assuming unlimited sediment supply to that location until all the reservoir sediment is exhausted. Simulating upstream and downstream reaches of the dam separately can be an effective solution in certain cases in which some physical separation between reaches upstream and downstream of the dam site is maintained during or after dam removal. Examples of such cases include dam removal methods in which sediment is metered out by an outlet structure with the dam still in place; early stages of a staged removal, where the remaining portion of the dam separates the two reaches; and a cohesive reservoir sediment deposit with limited potential for deposition immediately downstream of the dam. When the upstream and downstream reaches of the dam are connected and sediment is

deposited downstream of the dam, as will normally be the case in dam removal modeling, such a technique will usually result in erroneous predictions, because the assumption that sediment transport upstream of the dam site is independent of that in the downstream reach becomes invalid. Using a critical cross section further downstream of the dam to meter out sediment may provide useful back-of-the-envelope estimates of suspended-sediment concentration in certain cases. Overall, however, this technique is problematic because sediment deposition following dam removal will inevitably alter the sediment-transport capacity, potentially by orders of magnitude.

Sediment-transport modeling following dam removal is as yet limited to one-dimensional models. One-dimensional models cannot simulate multidimensional effects such as lateral distribution of sediment deposition. This is true even if channel cross sections are used in simulations or if modeling rules are used to distribute sediment deposition and erosion across the cross section. One-dimensional models also cannot simulate local features such as topography generated by alternate bars and pool-riffle sequences and associated fine-scale effects on sediment deposition. As a result of the latter limitation, the best spatial resolution in the results of a one-dimensional model is on the order of several channel widths, i.e., the length of an alternate bar or pool-riffle sequence. Because of the coarse spatial resolution of one-dimensional models, professional judgment and general knowledge of sediment-transport dynamics should be applied to interpretation of one-dimensional model results in order to provide insight into finer-scale effects.

23.2.2 Coupled Modeling of Upstream and Downstream Reaches

A key challenge in any dam removal modeling exercise is the simultaneous modeling of sediment-transport processes upstream of the dam, in the reservoir-influenced reach from which sediment is eroded, and downstream of the dam, in the river reach to which the reservoir sediment is delivered. Simultaneous modeling of reaches upstream and downstream of the dam must address the difficulties in simulating flow over very steep bed slopes, such as would be expected, to characterize the downstream portion of the reservoir sediment wedge immediately following dam removal. In this important transition area between reaches upstream and downstream of the dam, very steep slopes can produce transient flow conditions (Fig. 23-1), potentially resulting in numerical instabilities.

Several techniques can be used in coupled modeling of upstream and downstream river reaches. For example, flow near the dam site can be simulated using a fully coupled model that retains the unsteady terms in the St. Venant shallow-water equations (Eq. (14-1)). Applying a fully coupled model to simulate the transient flow will involve the application of artificial viscosity terms in seeking a solution (e.g., Chaudhry 1993).
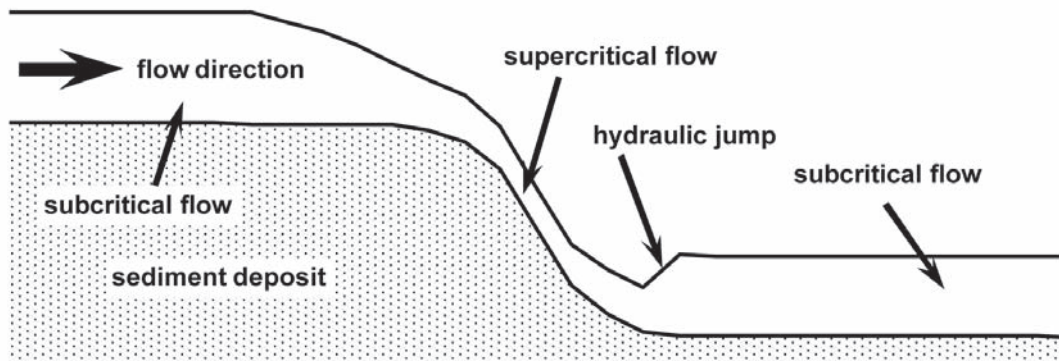
Fig. 23-1. Sketch demonstrating potential transient flow near a dam site following dam removal.

Even with the introduction of artificial viscosity terms, there will still be high-frequency oscillation in the solution for water depth and flow velocity, which, in turn, may result in instability in the solution for bed elevation. Thus, an artificial viscosity term will likely have to be introduced into the Exner equation as well. Cui et al. (2006b) found that applying a viscous term to the Exner equation may introduce artificial waves in bed elevation that can be on the same order of magnitude as the disturbance itself, resulting in an unacceptable solution. Model developers and users developing or applying fully coupled models for sediment-transport simulation following dam removal should therefore be cautious in the treatment of artificial viscosity terms and should be cognizant of the potential for artificial waves on the channel bed during model testing or application. Another method for modeling transient flow is a shock-fitting method, in which the program locates each hydraulic drop or jump and then solves different sections with different methods (e.g., Cui and Parker 1997). This method, however, is unlikely to be successful in application to dam removal simulation because of the complexity of natural rivers.

The U.S. Army Corps of Engineers HEC-6 model can simulate flow with transitions between subcritical and supercritical flow conditions. In the HEC-6 model, flow parameters are calculated with the standard energy conservation equation for subcritical flow conditions, and a quasi-normal assumption is applied for supercritical flow conditions (USACE 1993). The dam removal model presented in this chapter and those of Cui et al. (2006a; 2006b) applied similar principles as those used in HEC-6, whereby the standard backwater equation is applied for low Froude-number flow conditions and a quasi-normal flow assumption is applied for higher Froude-number flow conditions, as described further below in the Marmot Dam case study. In addition, Cui et al. (2006a; 2006b) applied a relatively coarse grid system so as to be compatible with the general resolution of one-dimensional sediment-transport modeling, although they applied an adaptive and much finer subgrid system for flow simulation whenever the channel bed is very steep. This method has been used successfully to simulate sediment-

transport conditions in a laboratory experiment (Cui et al. 2006b).

23.2.3 Reservoir Sediment Erosion

In typical sediment-transport modeling applications, sediment and water discharge tend to be confined within a well-defined channel, whose characteristics can be quantified prior to model implementation. In dam removal modeling, the morphology of the channel that will develop within the reservoir following dam removal is unknown in advance, necessitating assumptions by modelers about how channel morphology will evolve within reservoir reaches. The dynamics of channel incision through a reservoir deposit following dam removal depends on how the dam will be removed, reservoir sediment characteristics (e.g., volume, grain-size distribution, and cohesion), the width of the reservoir sediment deposit relative to stable channel width, and water discharge during and after dam removal.

Dam removal methods will significantly affect subsequent patterns of reservoir erosion. Gradual lowering of the reservoir level (e.g., through notches or lower level outlets) prior to dam removal may produce a channel that is much wider than its stable channel form, as demonstrated in the Lake Mills drawdown experiment on the Elwha River, Washington (Childers et al. 2000). Complete dam removal within a short time span, however, may result in rapid incision into reservoir sediment and creation of a channel that is either similar to or slightly narrower than its stable channel form before the channel begins to migrate laterally when its gradient becomes relatively stable. In cases of cohesive sediment deposits or relatively small discharges, the erosion of reservoir sediment may be characterized by head-cutting or gully-like morphology (Fig. 23-2). In such cases, reservoir erosion is likely to be governed by the rate of head-cut retreat, as has been observed following removal of many small dams (e.g., Pizzuto 2002; Doyle et al. 2003). In contrast, head-cutting or gully-like morphology in reservoir sediment deposits is unlikely where these deposits are not cohesive
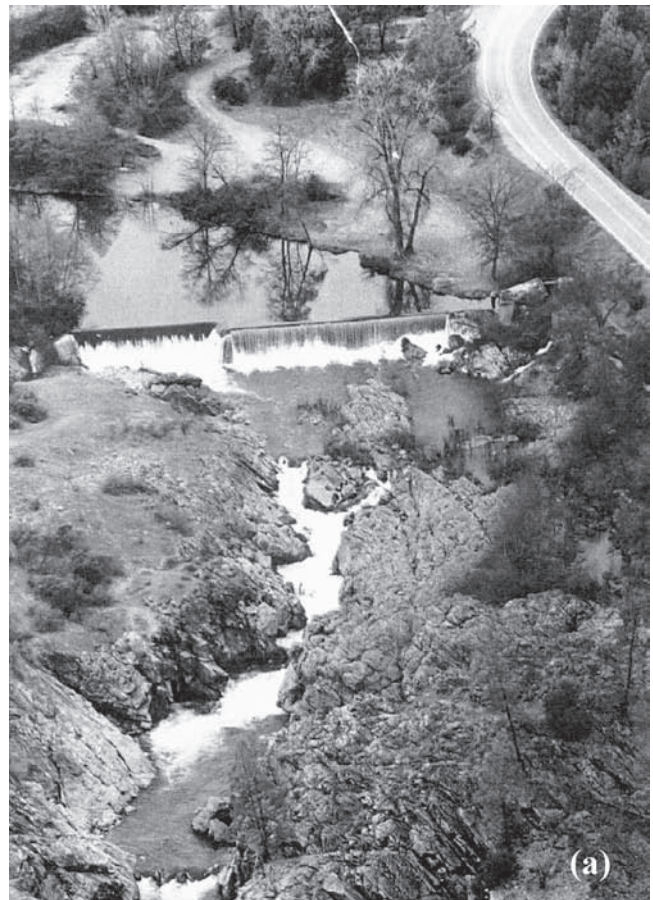
Fig. 23-2. Head cut developed following the removal of the Maple Gulch Dam, Evens Creek, Oregon, courtesy of Greg Stewart. The relatively small discharge before and at the time of the photograph after the dam was removed was probably responsible for the formation of the head cut. The strength from dense tree roots may also have contributed to the formation of the head cut.

Fig. 23-3. (a) Saeltzer Dam on the Clear Creek, California, removed in 2000, courtesy of Geoff Fricker; and (b) former impoundment area of the Saeltzer Dam, photo taken in 2003, courtesy of Peter Miller. No head cut was observed in the reservoir deposit following the removal of the Saeltzer Dam (Matt Brown and Jess Newton, personal communication, 2003).

and where postremoval river discharges are adequate to transport reservoir sediment. For example, head cutting was not observed following removal of Saeltzer Dam on Clear Creek, California, where reservoir sediments were relatively coarse and river discharges were relatively large (Fig. 23-3). The implications of both reservoir-sediment and river-discharge characteristics for reservoir erosion dynamics must therefore be taken into account in modeling sediment transport following dam removal.

Modelers should also be conscious of the inadequacies of current sediment-transport theory for addressing certain reservoir erosion processes. For example, we know of no theory to address the head-cut process as a result of inadequate water discharge, and thus it may be difficult to build a numerical model to accurately simulate the downstream effect in such cases.

23.2.4 Selection of Appropriate Sediment-transport Equations

The complex nature of reservoir sediment deposits can complicate sediment-transport modeling. The size distribution of reservoir sediments is typically wide, ranging from boulders to clay, and reservoir deposits are often stratified, with a coarse top layer and fine bottom layer. Modelers must therefore select sediment-transport equations and

make other assumptions that are appropriate to the particular reservoir sediment characteristics of the case in question. Until recently, no sediment-transport equations were available to handle mixtures of coarse sediment (gravel and coarser) and fine sediment (sand and finer), such as are typical of reservoir sediment deposits; this complicates efforts to model transport of such sediments. The sediment-transport equation of Wilcock and Crowe (2003) provides the first attempt to calculate transport of coarse and fine sediment simultaneously while accounting for the grain-size distribution of the coarse sediment. The equation calculates gravel-transport rate by size fractions and sand transport rate based on known shear stress and surface grain-size distribution, including the fraction of sand on the bed surface. Development of a relation that links the grain-size distribution, including the fraction of fine sediment, in the subsurface to that on the channel surface and to the sediment load would facilitate incorporation of the Wilcock and Crowe (2003) equation into a sediment-transport model.

In lieu of using a sediment-transport equation that simultaneously calculates coarse- and fine-sediment transport, one approach to modeling a wide size range of sediments is to employ separate models of fine- and coarse-sediment transport that calculate coarse- and fine-sediment transport independently. This approach, which was adopted for the Marmot Dam removal study presented below, is based on the assumptions that (1) coarse sediment is transported primarily as bed load during high-flow events, when fine sediment is transported primarily as suspended load, and (2) most fine sediment is transported during the intermediate-flow events, when coarse sediment transport is limited. Observations that suggest that coarse- and fine-sediment transport may be only weakly correlated, and that modeling using independent equations for coarse- and fine-sediment transport is therefore defensible, are suggested by Cui et al. (2006b). These include the observations that (1) the fraction of fine sediment in gravel-bed sediment samples is relatively stable and insensitive to the amount of fine-sediment transport, and (2) the fraction of fine sediment in a clast-supported sediment deposit seems to be inversely correlated with the standard deviation of the particle grain-size distribution of the coarse sediment (Fig. 23-4), indicating that the fraction of fine sediment is dependent on the available space of the coarse-sediment deposit (Cui et al. 2006b). Although applying separate equations for coarse and fine sediment is not a perfect solution because gravel and sand transport likely affect each other, this approach may provide an acceptable approximation.

If the approach of using separate models of coarse- and fine-sediment transport is adopted, modelers must select from the array of published transport equations for sand and gravel. For example, in the modeling of the Marmot Dam removal, we used Parker's surface-based bed-load equation (Parker 1990) to model coarse-sediment transport and
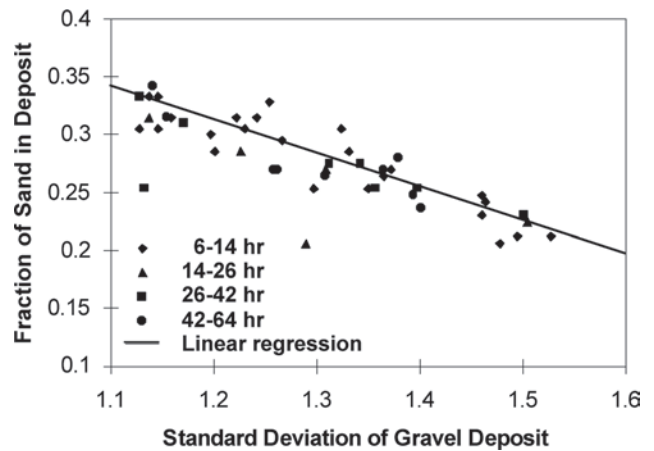
Fig. 23-4. Fraction of sand in gravel/sand deposit as a function of standard deviation of the gravel grain-size distribution in the sediment deposit. Data were derived from a large-scale flume experiment (SAFL downstream fining Run 3) by Toro-Escobar et al. (1996), and the diagram was presented in Cui and Parker (1998).

Brownlie's (1982) bed-material equation for modeling transport of fine sediment, as discussed further in Section 23.3.2.

23.2.5 Reproducing the Pre-dam-removal Longitudinal Profile and Other Background Conditions

Because large volumes of sediment may be released downstream following dam removal, downstream sediment impacts may be spatially and temporally extensive. To predict the nature of these impacts, numerical models therefore must be capable of simulating long river reaches for multiple years, and modelers should be conscious of the potential for propagation of errors for such simulations. For example, the simulation of the Marmot Dam removal presented below was applied to a 50-km river reach for a 10-yr duration following dam removal.

Accurate simulation of a river reach over a long period of time requires that the model be capable of reproducing background conditions in the system of interest. Although reproduction of background conditions is a key task in sediment-transport modeling, this can be difficult to achieve because of a lack of sediment-transport theory, a lack of understanding of the system in question, and/or a lack of field data. In most cases the background condition can be treated as a quasi-equilibrium state, under which the channel bed experiences very limited amounts of aggradation and degradation over time. The process of trying to reproduce this quasi-equilibrium state, which we term the "zero process," provides a frame of reference from which subsequent changes predicted by modeling can be attributed to changes in input or boundary conditions, such as the removal of a dam. The zero process itself also provides model developers and users with an opportunity to test and adjust certain assumptions and input parameters used in modeling.

23.3   NUMERICAL SIMULATION OF SEDIMENT TRANSPORT FOLLOWING THE REMOVAL OF MARMOT DAM, SANDY RIVER, OREGON

The remainder of this chapter will present an application of one-dimensional numerical modeling simulation of sediment transport following dam removal. Our treatment of the issues detailed above, including selection of sediment-transport equations, modeling of reservoir erosion, and reproduction of background conditions (the zero process), will be described, and modeling results from the example application will be presented. The following sections provide background information on Marmot Dam and on the physical setting of the Sandy River basin, descriptions of the numerical models and their governing equations, discussion of the input data used in application of the models to the Sandy River, and results and discussion of the modeling.

23.3.1   Project Background

Marmot Dam is located on the Sandy River approximately 48 km upstream of its confluence with the Columbia River. The dam was originally completed in 1913 as a wood crib rock-filled structure, and it was replaced in 1989 with a 14-m-high, 104-m-wide concrete dam (Fig. 23-5). Approximately 750,000 m^3 of sediment is stored behind Marmot Dam, about two-thirds of which is primarily gravel/pebble and one-third of which is primarily sand (Squier Associates 2000). The Sandy River originates from Mt. Hood on the

Fig. 23-5. Marmot Dam, Sandy River, Oregon, scheduled for removal in 2007 (photo courtesy of Portland General Electric).

western slopes of the Cascade Range and has a drainage area of 1,316 km^2, about half of which is upstream of Marmot Dam (Fig. 23-6). A detailed description of the geology, hydrology, and geomorphology of the Sandy River basin is provided in Stillwater Sciences (2000).

Marmot Dam is scheduled to be voluntarily removed by Portland General Electric (PGE), the holder of the Federal Energy Regulatory Commission (FERC) license for this project. Removal of Marmot Dam will provide unrestricted upstream and downstream passage for anadromous salmonids and other aquatic organisms, restore natural flows in the
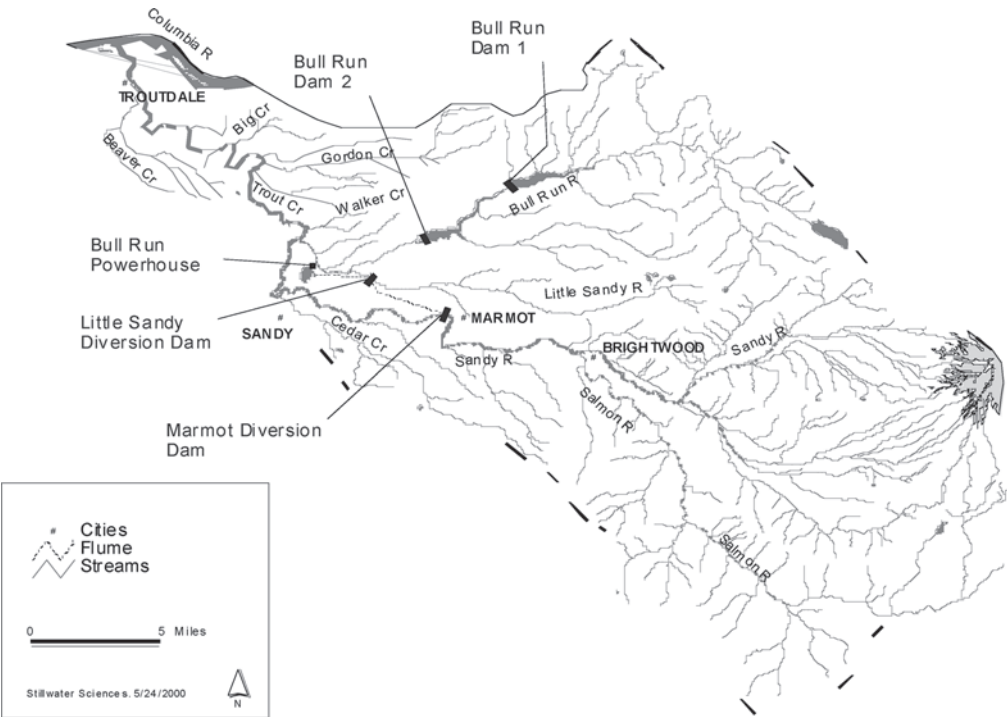

Fig. 23-6. Map of the Sandy River basin.

Sandy River from Marmot Dam to the Bull Run River confluence, and, under some removal alternatives, release sediment stored behind Marmot Dam. Several alternative methods for removal of Marmot Dam have been developed, which differ in the amount of sediment accumulated behind the dam that would be released downstream. These removal alternatives are described in detail in Portland General Electric (2000) and are summarized as follows:

- Single-season dam removal with minimal sediment removal;
- Removal of top of dam in year 1, followed by complete dam removal in year 2 with sand-layer excavation;
- Single-season dam removal after dredging of sediment to 830 m upstream of the dam;
- Single-season dam removal after dredging of 95,600 m³ of sediment;
- Single-season dam removal after dredging of 229,400 m³ of sediment.

The portion of the Sandy River likely to be affected by removal of Marmot Dam extends from the reservoir-influenced reach upstream of Marmot Dam downstream to the Sandy River's confluence with the Columbia River. For purposes of studying the potential geomorphic effects of removing Marmot Dam, the pertinent river reach was delineated into six subreaches (Fig. 23-7) according to their distinctive geomorphic characteristics, as described below and in Table 23-1:

- *Reach 0 (reservoir area):* The Sandy River upstream of the Marmot Dam is affected by the backwater effect of the dam for a distance of approximately 2 to 4 km.

The impoundment formed by the dam has filled to the dam's crest with sediment and now functions as an alluvial river reach. Compared to upstream and downstream reaches, this reach currently has a lower gradient and finer bed substrates as a result of the grade control provided by the dam and the backwater effect of the dam's impoundment. The reservoir is believed to have filled with sediment in the early years following dam closure. Marmot Dam may continue to partially trap coarse sediment, although coarse- and fine-sediment transport over the dam do occur during high-flow events.

- *Reach 1:* Reach 1 extends from Marmot Dam to the mouth of the Sandy River gorge and has moderately pronounced forced pool-riffle morphology. This reach has an armored cobble/boulder bed surface with limited gravel, possibly due to supply reductions caused by Marmot Dam.
- *Reach 2:* Reach 2 is the Sandy River gorge, a steep (0.01 gradient) section of the river that is confined by 20- to 30-m-high bedrock strath terraces with steep hillslopes above. The steep gradient and high confinement in this reach create very high shear stresses, resulting in high sediment-transport capacity. Few deposition areas are therefore present in this reach, and bedrock exposure in the channel bed is common. The reach is characterized by long, deep bedrock pools that are separated by coarse-bedded riffles and boulder rapids, and large (house-sized) boulders are common in the channel.
- *Reach 3:* Reach 3 extends from the downstream end of the Sandy River gorge to the Bull Run River confluence. This reach is considerably wider and lower-gradient than Reaches 1 and 2, reducing sediment-transport capacity and increasing the potential for sediment deposition.
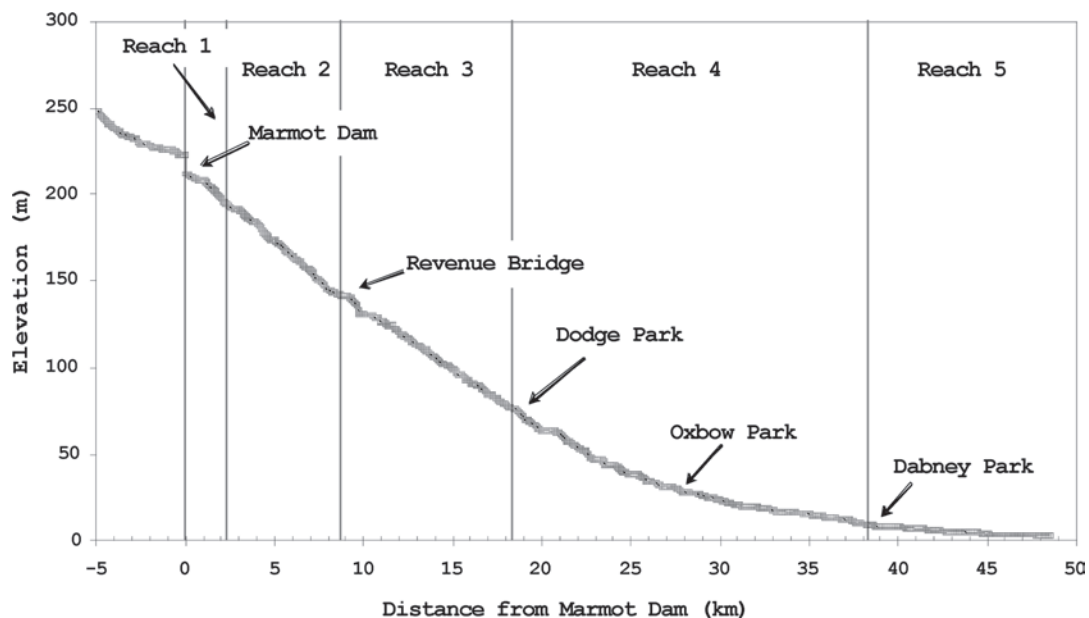

Fig. 23-7.   Sandy River longitudinal profile, based on PGE 1999 photogrammetric data.

- *Reach 4:* Reach 4 extends from the Bull Run River confluence to Dabney State Park. In Reach 4, channel confinement, gradient, and bed particle size decrease further compared to upstream reaches, with these tendencies particularly evident in the lower half of the reach. Large cobble/gravel bars, side channels, and islands are common in Reach 4, which is bounded by high (mostly alluvial) terraces. Sand content in the bed subsurface, on the active bed, and on bars is high in the lower portion of the reach.
- *Reach 5:* Reach 5 extends from Dabney State Park to the confluence with the Columbia River. This reach is characterized by a highly mobile sand and gravel bed surface with large gravel/sand alternate and medial bars. In the Sandy River delta, which forms the downstream-most portion of Reach 5, the channel is sand-bedded and depositional dynamics are strongly influenced by the backwater effect of the Columbia River.

23.3.2 Numerical Model Development for Application to Marmot Dam Removal

One-dimensional numerical models of fine- and coarse-sediment transport were developed to predict the routing of sediment from behind Marmot Dam downstream through the Sandy River. Numerical models were completed to examine a variety of alternatives for removing Marmot Dam. Model results provide estimates of the time required for sediment to be cleared from the reservoir area, time required for sediment to travel out of the Sandy River (including various subreaches), thickness of downstream sediment deposits in various reaches (on a reach-averaged and cross-section-averaged basis), changes in deposition thickness through

time, and total suspended-sediment concentrations through time along the river's longitudinal profile following dam removal. Questions explored with the numerical models for different dam removal alternatives include the following:

- Will substantial bed aggradation occur following dam removal, or is the sediment-transport capacity downstream of the Marmot Dam high enough to minimize aggradation? How long will any aggradational effect persist and in what reaches will it be most prominent?
- How much will suspended-sediment concentrations downstream of Marmot Dam increase following dam removal, and how long will any such increases persist?
- How does transport distance from the dam affect suspended-sediment concentration and coarse- and fine-sediment accumulations following dam removal? Is there a distance downstream of which no detectable changes are expected?
- How will dredging of varying amounts of sediment from Marmot Reservoir prior to dam removal affect downstream sediment deposition and suspended-sediment dynamics?
- How will discharge conditions during and following dam removal affect downstream sediment transport and deposition characteristics?

Because unified theory and transport equations for gravel/sand mixtures are still in a developing stage, as discussed above, two separate models were developed for application to the removal of Marmot Dam: a gravel model for simulation of

Table 23-1   Summary of Geomorphic Characteristics of Sandy River Reaches That Will Be Affected by Removal of Marmot Dam

Reach	Length (km)	Average width (m)	Average gradient	Confinement	Morphology	Dominant grain size
Upstream of Marmot dam (Reach 0)	2–4	50	0.0024	High	Pool-riffle	Gravel-sand
Marmot Dam to gorge (Reach 1)	2.4	45	0.008	Medium	Forced pool riffle/plane bed	Cobble-boulder
Sandy River gorge (Reach 2)	6.4	30	0.01	High	Step pool/ forced pool riffle	Bedrock-boulder
Downstream end of Sandy River gorge to Bull Run River (Reach 3)	9.6	50	0.006	Medium	Forced pool riffle/plane bed	Cobble-gravel
Bull Run River to Dabney Park (Reach 4)	20	70	0.0025	Medium/low	Pool riffle/ plane bed	Gravel-cobble-sand
Dabney Park to mouth (Reach 5)	9.6	100	0.0007	Medium/low	Pool riffle	Sand-gravel

the erosion of the reservoir deposit and downstream deposition of coarse sediment (diameter > 2 mm), and a sand model for simulation of suspended-sediment concentration and downstream deposition of fine sediment (diameter < 2 mm). The use of separate models assumes that (1) as the sediment is released from the reservoir deposit, gravel particles will be transported as bed load and sand will be transported mostly as suspended load because of the steep slope of the Sandy River, and (2) gravel and sand transport occur over different time scales (years versus days; i.e., a gravel particle may take years to travel the same distance that a sand particle travels in several days). In reality, use of separate models may create errors because transport of gravel and sand will each influence the transport rate of the other.

The gravel-transport model was developed based on Parker's surface-based bed load equation (Parker 1990) and is similar to the model of Cui and Parker (2005), with adjustments to accommodate the specific conditions of the Sandy River and Marmot Dam. The Parker equation calculates gravel-transport rate and bed-load grain-size distribution based on the grain-size distribution of the surface layer and the boundary shear stress. The Parker equation was developed to apply to gravel-bed streams (particles larger than 2 mm in diameter) and was not intended for application to sand or for suspended material of any size. Application of the Parker equation to a mixture with a relatively large amount of sand, such as the sediment accumulation behind Marmot Dam, may therefore create some error in predictions of the gravel-transport rate.

The one-dimensional model of sand transport was developed based on Brownlie's (1982) bed-material equation. Brownlie's equation was developed for sand-bedded rivers but is used here because no sediment-transport equations exist to calculate sand transport in a bedrock- or coarse-sediment-dominated river such as the Sandy River. In applying Brownlie's equation of sediment transport and friction, we modified the roughness height to account for the bedrock, boulders, and gravel present along the bed of the Sandy River. Calibration and validation of this approach are required, however, and the error associated with applying Brownlie's equation to a gravel-bed river, even with roughness adjustments, is not known. Our model of sand transport assumes the following: (1) sand transport can be represented as transport over a rough bedrock surface (i.e., the existing gravel bed of the Sandy River remains immobile with respect to sand transport); (2) silt is transported as throughput load that is carried in suspension and cannot be deposited in the channel bed; (3) reservoir sediment is not cohesive; and (4) sand transport is not affected by the amount of coarse-sediment aggradation and degradation downstream of the dam (i.e., the changes in channel gradient resulting from gravel deposition or scour are not accounted for in modeling sand transport). This last assumption may create some errors in reaches where significant coarse-sediment deposition occurs, such as immediately downstream of the dam.

As discussed in Section 23.2.3, simulation of reservoir erosion is a key challenge in dam removal modeling. In the Sandy River model, a number of simplifying assumptions were made to simulate sediment release from Marmot Reservoir. The model assumes laterally uniform sediment transport out of the reservoir, with sediment mobilization and transport derived by the gravel model from Parker's (1990) sediment-transport equation. In the reservoir area, the model assumes that erosion is exclusively dependent on the transport capacity of gravel and the amount of gravel that can be provided through erosion of reservoir sediment deposit. As the gravels within a layer are mobilized, the sand volume within that layer is also mobilized and transported downstream; it is assumed that sand is not available for transport until the gravel within the same layer as the sand is mobilized. Volumetric estimates of sand release from the reservoir deposit that are generated by the gravel model using this method are subsequently used as the upstream boundary condition for the sand model. The model further assumes that, because the reservoir-influenced reach upstream of Marmot Dam (Reach 0) is relatively narrow, all the sediment will be eroded downstream following dam removal (i.e., there will be no long-term storage of reservoir sediment in Reach 0 following dam removal). Sensitivity tests were performed to address uncertainties in modeling of sediment transport from the reservoir and to qualitatively assess the potential effects of incision, as described in Section 23.3.4 below.

The numerical models of fine- and coarse-sediment transport entail equations for calculating downstream changes in flow depth, Exner equations of sediment continuity for sand and gravel, transport-capacity equations, and flow-friction relations. The governing equations used in these models are introduced below; additional details are presented in Stillwater Sciences (2000; 2002).

To calculate downstream changes in flow depth, the standard backwater equation is used for low-Froude-number flows and a quasi-normal assumption is applied for high-Froude-number flows:

$$\frac{dh}{dx} = \frac{S_0 - S_f}{1 - \mathsf{F}^2}, \quad \mathsf{F} < F_c \qquad (23\text{-}1a)$$

$$S_0 = S_f, \quad \mathsf{F} \geq F_c \qquad (23\text{-}1b)$$

where

h = water depth;
x = downstream distance;
S_0 = slope of the channel bed;
S_f = friction slope;
F = local Froude number; and
F_c = a user-defined Froude number that is smaller than and close to unity and that is used to differentiate between low- and high-Froude-number conditions in the application of Eqs. (23-1a) and (23-1b) (see also Cui and Parker 2005).

In the Marmot Dam removal simulation, F_c was set equal to 0.75; below this value, Eq. (23-1a) is used; otherwise Eq. (23-1b) is applicable. The approach of alternating the backwater equation and the quasi-normal flow assumption based on a Froude number threshold has been used in the HEC models (USACE 1993) and in the models of Cui et al. (2003) and Cui and Parker (2005).

Local Froude number is calculated using the equation

$$\mathsf{F}^2 = \frac{Q_w^{\ 2}}{gB^2 h^3} \qquad (23\text{-}2)$$

in which

    Q_w = water discharge;
    g = acceleration of gravity; and
    B = local channel width.

The Exner equations of sediment continuity for gravel used here are variants of those in Parker (1991a; 1991b) and (Chapter 3, Eqs. (3-95a) to (3-95i)) and take the following form:

$$\left(1-\lambda_p\right) f_G\, B\, \frac{\partial \eta}{\partial t} + \frac{\partial Q_G}{\partial x} + \beta Q_G\left(2 + \frac{1}{3\ln(2)}\frac{p_1 + F_1^{'}}{\Delta\psi_1}\right) = 0 \quad (23\text{-}3\text{a})$$

$$\left(1-\lambda_p\right) f_G\, B\left(\frac{\partial\left(L_a F_j\right)}{\partial t} + f_{Ij}\frac{\partial\left(\eta - L_a\right)}{\partial t}\right)$$

$$+ \frac{\partial\left(Q_G\, p_j\right)}{\partial x} + \beta Q_G\left(p_j + F_j^{'}\right)$$

$$+ \frac{1}{3\ln(2)}\beta Q_G\left(\frac{p_j + F_j^{'}}{\Delta\psi_j} - \frac{p_{j+1} + F_{j+1}^{'}}{\Delta\psi_{j+1}}\right) = 0 \quad (23\text{-}3\text{b})$$

where

    λ_p = porosity of the channel-bed deposit;
    f_G = volumetric fraction of gravel in the channel-bed deposit;
    η = deposition thickness above an arbitrary datum;
    t = time;
    Q_G = volumetric transport rate of gravel;
    β = volumetric abrasion coefficient of gravel;
    p_j = volumetric fraction of the j-th size range in bed load;
    F_j = volumetric fraction of the j-th size range in the surface layer;
    $F_j^{'}$ = an adjusted value of F_j providing an estimate of relative surface area exposure of gravel of the jth size range at the surface (Parker 1991a; 1991b);
    f_{Ij} = volumetric fraction of the jth size range in the interface between bed load and the channel-bed deposit;
    L_a = surface layer thickness; and
    ψ = grain size in the ψ-scale, which is the negative of the ϕ scale (also see Chapter 3, Eqs. (3-1a) and (3-1b)).

Equation (23-3a) represents the mass conservation of total gravel, and Eq. (23-3b) represents the mass conservation of the gravel in the j-th size range.

The full grain-size distribution of coarse sediment (gravel and coarser) is discretized into a number of groups, represented by ψ and grain size D in such a way that grain size $\psi_j(D_j)$ and $\psi_{j+1}(D_{j+1})$, from finer to coarser, bound the j-th size group. The average grain size of the j-th range is then

$$\overline{\psi}_j = \frac{\psi_j + \psi_{j+1}}{2}, \quad \overline{D}_j = \sqrt{D_j\, D_{j+1}} \qquad (23\text{-}4\text{a,b})$$

and

$$\Delta\psi_j = \psi_{j+1} - \psi_j \qquad (23\text{-}5)$$

The parameter $F_j^{'}$ in Eqs. (23-3a) and (23-3b) is estimated with the relation provided by Parker (1991a; 1991b):

$$F_j^{'} = \frac{F_j / \sqrt{\overline{D}_j}}{\Sigma\left(F_j / \sqrt{\overline{D}_j}\right)} \qquad (23\text{-}6)$$

The Exner equations of sediment continuity for sand that were used in modeling of sand transport take the forms

$$\frac{1}{B}\frac{\partial \eta_s}{\partial t} + \frac{1}{\left(1-\lambda_s\right)\lambda_g}\frac{\partial Q_s}{\partial x} = 0, \ \ 0 < \eta_s \le k_{s0} \quad (23\text{-}7\text{a})$$

$$\frac{1}{B}\frac{\partial \eta_s}{\partial t} + \frac{1}{1-\lambda_s}\frac{\partial Q_s}{\partial x} = 0, \ \ \eta_s > k_{s0} \quad (23\text{-}7\text{b})$$

in which

    η_s = thickness of the sand deposit;
    λ_s = porosity of the sand deposit;
    λ_g = porosity of the roughness elements;
    Q_s = volumetric transport rate of sand; and
    k_{s0} = height of roughness elements.

Equation (23-7a) applies to cases where the thickness of the sand deposit is less than the height of the roughness elements (in which case sand aggradation fills in the interstices of the roughness elements). Equation (23-7b) is applied when the thickness of the sand deposit is greater than the height of the roughness elements.

As discussed above, two sediment-transport equations were used for calculation of sediment-transport capacity: the surface-based bed-load equation of Parker (1990) for coarse sediment and the bed-material equation of Brownlie (1982) for sand. The surface-based bed-load relation of Parker (1990) is also described in Section 3.7.5 (Chapter 3), and minor adaptations of the bed-material equation of Brownlie (1982) can be found in Stillwater Sciences (2000) and Cui et al. (2006a; 2006b). It is important to note that both

equations are used to calculate sediment-transport capacities rather than sediment-transport rates. Actual sediment-transport rates at any location were evaluated based on upstream sediment supply, local sediment-transport capacity, erodibility of the channel bed, and sediment mass conservation. The application of the sediment-transport equations of Parker (1990), for gravel transport, and Brownlie (1982), for sand transport, requires the use of different friction relations. A Keulegan-type resistance relation (modified from Keulegan 1938) is used for gravel and Brownlie's (1982) friction formulation is used for sand, as detailed in Stillwater Sciences (2000) and Cui et al. (2006a; 2006b).

In addition to evaluating coarse and fine sediment-transport rates, this modeling effort includes estimates of total suspended-sediment (TSS) concentration following dam removal, to assist evaluation of biological impacts. The suspended-sediment concentration is calculated by combining the portion of sand that is transported in suspension with the entire silt and clay load (sediment finer than 62.5 µm) in transport. All of the silt and clay from the reservoir deposit is treated as throughput load that is carried in suspension once it has been mobilized from the reservoir. The criterion set for suspension of sand is given as follows (e.g., van Rijn 1984):

$$\frac{v_s}{\kappa u_*} < 1 \qquad (23\text{-}8)$$

in which

v_s = particle settling velocity calculated with the procedure given by Dietrich (1982);

u_* = shear velocity; and

κ = von Karman constant, with a value of approximately 0.4.

TSS therefore is composed of all the particles finer than 62.5 µm from the reservoir deposit and those satisfying Eq. (23-8).

23.3.3 Input Data and Zero Process

The sediment-transport models developed for the simulation of the removal of Marmot Dam use input data on channel gradients, channel widths, water discharge at each section of the river for the duration of the simulation, grain-size distribution of the sediment deposit in the reservoir and in the downstream channel, and the sediment supply and associated grain-size distribution upstream of the Marmot reservoir. The modeling of total suspended sediment following dam removal also requires an order-of-magnitude estimate of the background average sediment concentration in the Sandy River. These input parameters and their sources are described in the following sections.

23.3.3.1 Channel Gradient and Width Data on channel gradients, and an associated longitudinal profile of the Sandy River from 4.8 km upstream of Marmot Dam downstream to the Columbia River, were derived from 1999 photogrammetric measurements of the Sandy River. The photogrammetric data measure water-surface elevation with an accuracy of ±0.6 m and were averaged over a 0.8-km distance to further smooth the longitudinal profile (Figs. 23-7 and 23-8).

Channel widths were measured from 1:6,000-scale aerial photographs of the Sandy River corridor. Field checking of randomly selected cross sections with a laser distance finder found that channel widths measured from aerial photographs were generally within 10% accuracy. One exception is in Reach 2 (the Sandy River gorge), where widths cannot be measured from aerial photographs due to the narrow channel and valley in this reach. A channel width of 30 m was applied to all of Reach 2 in the model, based on the average of field-measured widths in the Sandy River gorge. In all other reaches of the Sandy River, channel width was varied in the model according to the aerial photographic measurements.

23.3.3.2 Discharge Data and Hydrologic Scenarios Used in Numerical Modeling A daily discharge series spanning the length of model runs was also required as input. Daily discharge data used as input for the modeling are from the USGS Sandy River near the Marmot gauge (Station 1413700), which was assumed to represent the reach from Marmot Dam downstream to the Bull Run River confluence, and the Sandy River below the Bull Run River gauge (Station 14142500), which was assumed to represent discharge from the Bull Run River to the mouth (Fig. 23-6). The Bull Run River is the largest tributary that enters the Sandy River downstream of the Marmot Dam. Other tributaries have small drainage areas, and therefore are likely to create only small increases in water discharge in the Sandy River.

Numerical modeling was performed for three different hydrologic scenarios to evaluate the effects of various flow regimes following dam removal on sediment transport and deposition dynamics. The flows occurring following dam removal, particularly in the first year after removal, will have an important influence on the time required for downstream transport of reservoir sediment, on subsequent deposition patterns, and on the duration of impacts on aquatic organisms. Scenarios for wet, average, and dry hydrologic conditions were developed for input into the numerical modeling, with the flows in the first year after removal varying in each scenario (i.e., hydrologic scenarios were defined according to the discharge conditions in the first year of the model run). The hydrologic scenarios account for both peak flow magnitude and overall water yield, both of which influence sediment-transport dynamics. The peak and annual daily average discharges from the Marmot gauge were fit to a log Pearson III distribution and a normal distribution, respectively, to predict the return period of future discharges. Based on this analysis, daily discharge records were selected as input for Year 1 of model runs from three representative
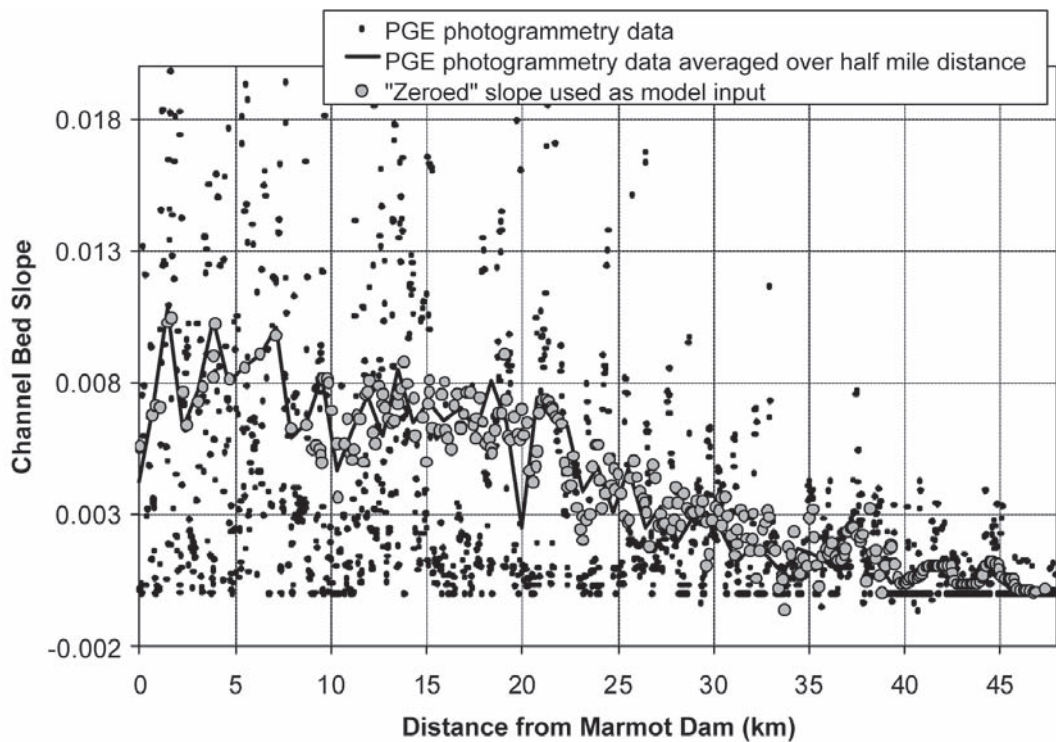
Fig. 23-8.   Sandy River channel slope downstream of Marmot Dam.

water years, with exceedance probabilities for both annual peak discharge and average daily discharge corresponding to wet, average, and dry hydrologic conditions. In the scenarios for dry, average, and wet conditions, flows used as input for Year 1 had both peak flows and average annual discharges with exceedance probabilities of approximately 90% (1.1-yr return period), 50% (2-yr return period), and 10% (10-yr return period), respectively (Table 23-2). The years following the first year were selected randomly from all of the water years in the period of record using a numerical random generator, and the same water years for years 2 through 10 were used in the three different hydrologic scenarios (Table 23-2).

In each model run the simulation starts on the day of the water year (after 1 October) when discharge at the Marmot gauge first exceeds 48 m³/s. This is because removal of Marmot Dam will be carried out with a cofferdam that can hold up to 48 m³/s in place, and the cofferdam will be removed (allowing downstream sediment release) when flow reaches this threshold.

23.3.3.3   Surface Grain-Size Distribution of the Channel Bed and Abrasion of Coarse Sediment   Estimates of the grain-size distribution of the channel-bed surface layer and of abrasion effects are necessary inputs to the gravel model. The surface grain-size distributions were collected at seven locations, shown in Fig. 23-9. The volumetric abrasion coefficient for gravel and coarser material is estimated to be on the order of 0.02/km based on abrasion values reported

by Collins and Dunne (1989) from the Satsop River basin, Washington, for basaltic colluvium, which is geologically similar to river gravels in the Sandy River basin. Detailed input data on surface grain-size distribution are not important for this modeling effort, however, because the model quickly adjusts the grain-size distribution of the channel bed during model simulations.

Effects of abrasion on grain size can be characterized using a modification of Sternberg's (1875) law that can be derived from the Exner equations in Parker (1991a; 1991b), as follows:

$$D_x = D_0 \exp\left(-\frac{2}{3}\beta x\right) \qquad (23\text{-}9)$$

where

D_0 = grain size (diameter) at an upstream section;
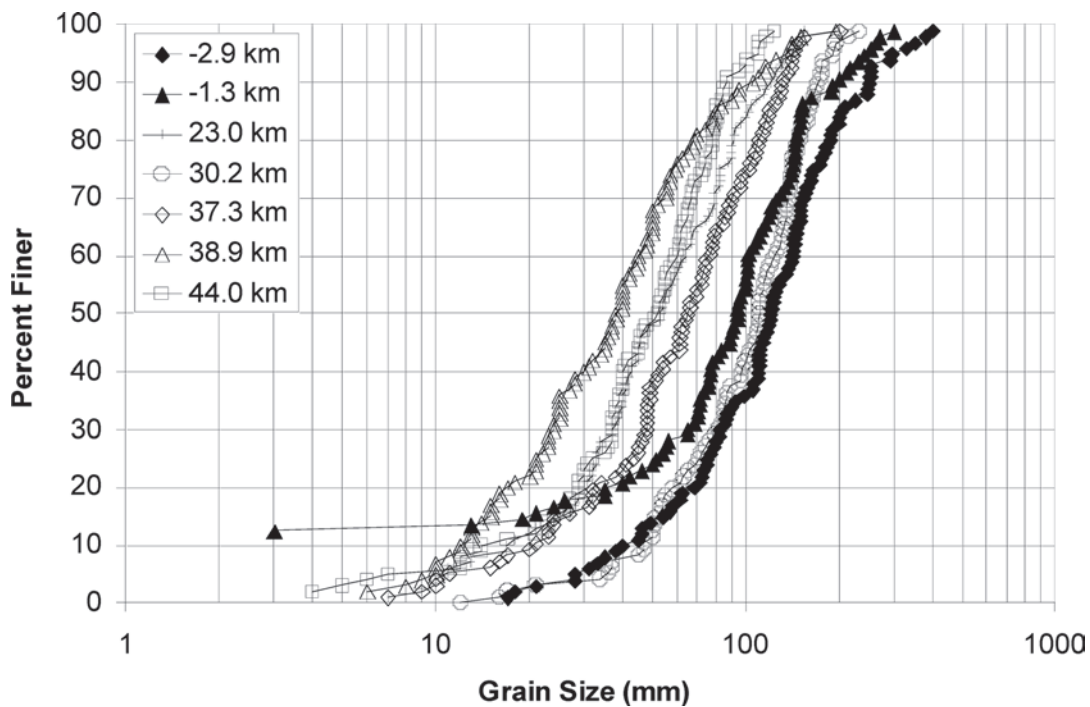D_x = grain size at a downstream section;
β = volumetric abrasion coefficient (fraction of gravel volume lost due to abrasion per unit distance); and
x = distance between the two sections.

The abrasion coefficient used in the model dictates the rate of attrition of gravel released from the reservoir and therefore influences predicted deposition (i.e., if attrition is greater, less deposition will occur because fewer coarse particles will

Table 23-2 Water Year Series Selected for Use in Simulation

Year in model run	Water year	Peak flow (cms)	Exceedance probability of peak flow (%)	Annual average discharge (cms)	Exceedance probability of annual average discharge (%)
1a (Dry)	1987	230	83	28	91
1b (Average)	1991	371	55	37	59
1c (Wet)	1961	778	10	47	14
2	1932	365	56	40	43
3	1951	215	91	46	15
4	1991	371	55	37	59
5	1988	456	38	33	77
6	1949	334	67	43	25
7	1997	393	53	52	4
8	1992	425	48	29	83
9	1932	365	56	40	43
10	1948	546	29	46	15

Fig. 23-9. Surface grain-size distributions in the Sandy River, based on selected pebble counts by stillwater sciences.

be available for deposition). Parker's (1991a; 1991b) modification of Sternberg's law considers the abrasion of both bed load and sediment on the channel surface. This modification is seen in Eqs. (23-3a) and (23-3b), which are the variants of the Exner equations of sediment-transport continuity for

gravel suggested by Parker (1991a; 1991b). Integration of Eq. (23-3a) for the case of equilibrium conditions by ignoring the production of sand (the last term on the right-hand side of the equation) and then converting volume to diameter yield Eq. (23-9).

Because this modeling effort focuses on evaluation of channel aggradation following sediment release from the reservoir deposit (rather than degradation/incision in the downstream channel bed), results are not sensitive to subsurface grain-size distribution in the channel bed downstream of the dam. For simplicity, it is assumed that downstream of the reservoir area, the subsurface grain-size distribution is the same as that of the surface layer.

23.3.3.4 Grain-Size Distribution of the Reservoir Sediment The grain-size distribution of the sediment accumulation stored behind Marmot Dam, which will influence downstream sediment-transport and deposition patterns, was determined based on sampling conducted in October 1999. Sampling of the reservoir sediment consisted of drilling a series of cores within 1 km upstream of the dam and manual and mechanical excavation further upstream (Squier Associates 2000). A summary of the resulting interpretation of grain-size distribution in the reservoir deposit is given in Fig. 23-10. The reservoir sediment consists of two main units, with the predam channel bed representing a third distinct unit (Squier Associates 2000). The uppermost unit (Unit 1) ranges from approximately 2 to 5.5 m in thickness and is composed of sandy gravel with a small amount of cobbles and boulders, becoming thicker toward the dam. The next unit (Unit 2) is predominantly fine sediment (silty sand to sand with a small amount of gravel, ranging from 4 to 11 m thick). Unit 3, the

predam channel, consists primarily of coarse sediment and is 0.8 to 3 m thick. Approximately 750,000 m³ of sediment is stored behind the dam, of which 490,000 m³ is primarily gravel/pebble and 260,000 m³ is primarily sand (Squier Associates 2000).

The grain-size distribution of upstream sediment supply is also required as model input. The grain-size distribution of gravel in upstream sediment supply is assumed to be the same as that of the gravel portion of Unit 1 of the reservoir deposit. This assumption was based on the likelihood that as the reservoir filled in, all or most of the upstream bed load was captured in the reservoir. The grain-size distribution of the sand in sediment supply is assumed to be the same as that of the sand portion of Unit 2 of the reservoir deposit (Fig. 23-10).

The roughness height without sand coverage (k_{s0} in Eqs. (23-7a) and (23-7b)) is assumed to be 0.4 m at Marmot Dam and to decrease exponentially to 0.25 m at the Columbia River confluence. These values are estimates based on field observation and correspond to roughly 4 to 10 times the geometric mean grain size. A model run in which the roughness heights were doubled (i.e., 0.8 m at Marmot Dam and 0.5 m at the Columbia River confluence) was also performed to test the sensitivity of model results to the assumed roughness height. Doubling the roughness heights results in an increased likelihood that sand deposition will be initialized but has only a limited effect on the overall thickness of predicted sand deposition.
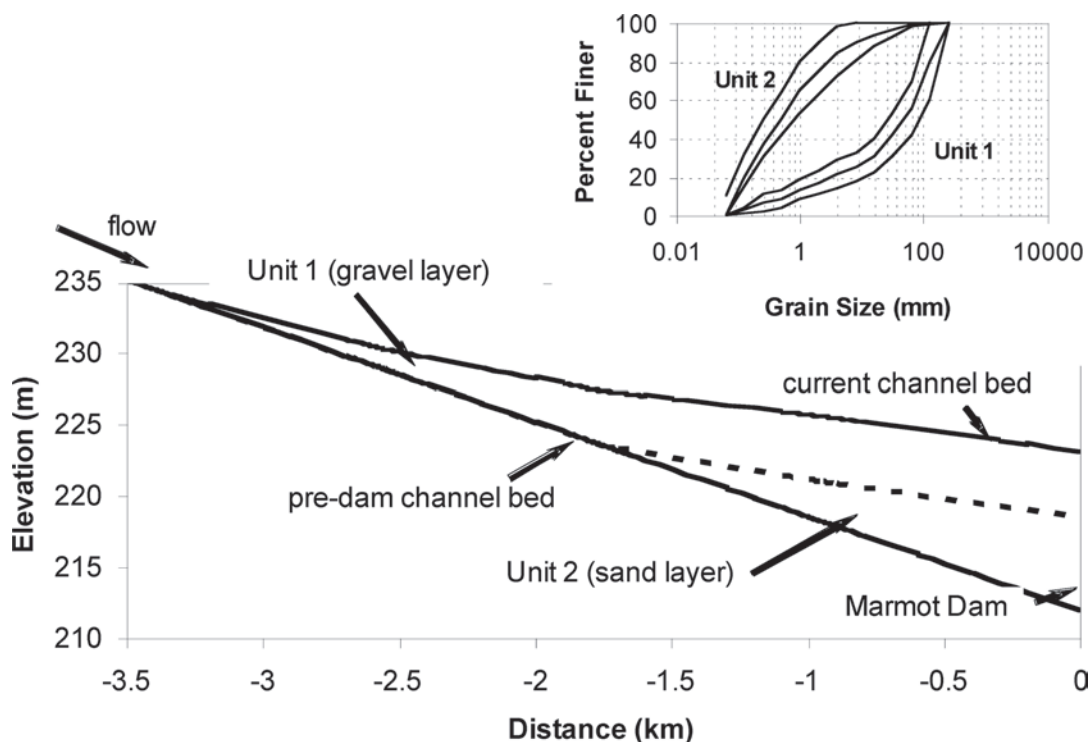
Fig. 23-10. Sediment deposit in Marmot Reservoir. Three grain-size distributions are shown for each unit, representing upper and lower bounds and their average values. Diagram developed based on information provided by Squier Associates (2000).

23.3.3.5 Background Gravel and Sand Transport Rates Background rates of gravel and sand transport in the Sandy River upstream of Marmot Dam are required inputs to the gravel and sand models, but no data are available for reference. To derive a gravel-transport rate, we assumed that the Sandy River's gravel-transport capacity upstream of Marmot Dam exceeds the supply, based on the abundance of bedrock outcrops and boulders in the channel. Thus it is possible to assume that the actual sediment-transport rate upstream of Marmot Dam is some fraction of the transport capacity. This fraction was determined by the model using trial and error as part of the "zero process," whereby various gravel-transport rates were plugged into reference-condition runs so that downstream aggradation and degradation are minimized over the entire river reach. This zero process is discussed in more detail below.

A rough estimate of background suspended-sediment concentration was developed based on an estimate of the long-term average sediment-transport rate and water discharge. For input to the model, the long-term average sediment-transport rate in the Sandy River at Marmot Dam is estimated to be about 250,000 tn/yr (roughly 350 tn/km^2/yr), of which the majority is fine sediment. This is a rough estimate based on review of sediment-yield data from other rivers in Oregon's western Cascade Range, which suggest average sediment yields that range from 100 to 500 tn/km^2/yr for undisturbed and disturbed basins (Curtiss 1975; Swanson and Dyrness 1975; Larsen and Sidle 1980; Swanson et al. 1982; McBain and Trush 1998). In the Sandy River basin, sediment yields may be substantially higher on average than elsewhere in the western Cascades due to Mt. Hood glaciers, the presence of semiconsolidated lahar deposits, steep topography, and land uses. The estimated sediment yield of 350 tn/km^2/yr translates to an average suspended-sediment concentration of about 200 mg/l, which was used as the background suspended-sediment concentration at Marmot Dam in this modeling effort. If the sediment flux from reservoir erosion following removal of Marmot Dam is much higher than the background value, as it is expected to be, model output is not sensitive to the accuracy of the background concentration assumed for model input.

23.3.3.6 Zero Process A "zero process" is generally required for long-term, large-scale sediment-transport simulation. The purpose of the zero process used in this modeling effort is to generate a starting point for the modeling and to evaluate certain input parameters. In the zero process, the model is run repeatedly under a reference condition, in which input data such as discharge are the same as for the simulation of dam removal, but neither Marmot Dam nor any sediment pulse from the reservoir deposit is considered. If the model is fed with raw input data (e.g., channel gradient, width) without modification, it typically will not produce quasi-equilibrium results under reference conditions. The goal of the zero process is to run the model, modifying certain input parameters if necessary, until the model produces quasi-equilibrium results, whereby

the river experiences aggradation and degradation in different reaches over different periods of time and hydrological events, but overall, long-term aggradation or degradation is limited. If a quasi-equilibrium condition is established as the baseline for modeling, changes in the system can be interpreted as a direct result of the introduced disturbances, in this case the release of the sediment pulse from Marmot Dam. Boundary conditions in the model are given by (1) discharge at the upstream end of the modeled reach (4 km upstream of Marmot Dam) and along the Sandy River in a downstream direction, (2) background gravel transport at the upstream end (given as a fraction of the potential gravel-transport rate, as described above), (3) the assumed grain-size distribution of the background gravel load, and (4) a fixed bed elevation at the downstream end of the modeled reach (the confluence of the Sandy River with the Columbia River). The water-surface elevation at the downstream end is acquired by the normal flow assumption.

In the zero process for this modeling effort, channel width is modified in such a way that certain extremely wide sections are reduced to no less than 80% of the original value. The model is then run repeatedly, with the output of the channel bed elevation (slope) as the input of the subsequent run, until the channel bed reaches quasi-equilibrium. The zero process is also used to estimate the background gravel-transport rate upstream of Marmot Dam (which is needed as input to the model). Large-scale deposition (aggradation) will occur if the input sediment-transport rate is too high and large-scale erosion (incision/degradation) will occur if the input sediment-transport rate is too low. The input gravel-transport rates selected for modeling, based on trial and error in the zero process, vary with hydrology and, for the hydrologic conditions shown in Table 23-2, vary from about 7,000 to 72,000 tn/yr at Marmot Dam. These results suggest an average long-term gravel-transport rate of about 25,000 to 30,000 tn/yr (roughly 10% of the total sediment yield estimated above). Assuming a bulk sediment density of 1.7 tn/m^3, this average annual gravel-transport rate would have completely filled Marmot reservoir in about 30 yr following dam closure. The actual length of time required for the reservoir to fill is unknown but 30 yr appears to be a reasonable estimate, based on regional sediment-yield data and on the rapid sedimentation of an area of the reservoir that was excavated to facilitate reconstruction of the dam in 1989.

The "zeroed" bed slope is given in Fig. 23-8 along with the original photogrammetric data. This figure shows that the zero process retains the general overall channel slope but modifies local gradients to convey the background sediment load through all reaches of the Sandy River.

23.3.4 Model Results

Numerical modeling was used to simulate sediment-transport processes both for background conditions in the Sandy River and for the dam removal alternatives listed in Section 23.3.1. Results are presented for background conditions and for the

alternative entailing single-season dam removal with mini-mal sediment removal. Sensitivity tests to evaluate certain model assumptions and approaches are also summarized. Results for modeling of other removal alternatives, as well as additional details on sensitivity testing, are presented in Stillwater Sciences (2000; 2002).

23.3.4.1 Reference Runs of Numerical Models For both the gravel and sand models, model runs were performed for reference conditions assuming that no dam exists and downstream sediment transport is equivalent to estimated background (natural) conditions, with no release of reservoir sediment. Reference runs of the model are a component of the

zero process described above and depict aggradation and deg-radation in the Sandy River in the absence of sediment release from Marmot Dam. Reference runs therefore provide a basis of comparison for interpretation of model predictions of depo-sition patterns following various dam removal alternatives.

For the gravel model, a 10-yr simulation was performed for reference conditions. In the reference run of the gravel model, a small amount of coarse sediment aggradation (and degradation) is indicated in Reaches 3 and 4, even without sediment release from Marmot reservoir (Figs. 23-11 and 23-12). The reference run indicates that up to about 1 m of aggradation would periodically occur in certain reaches.
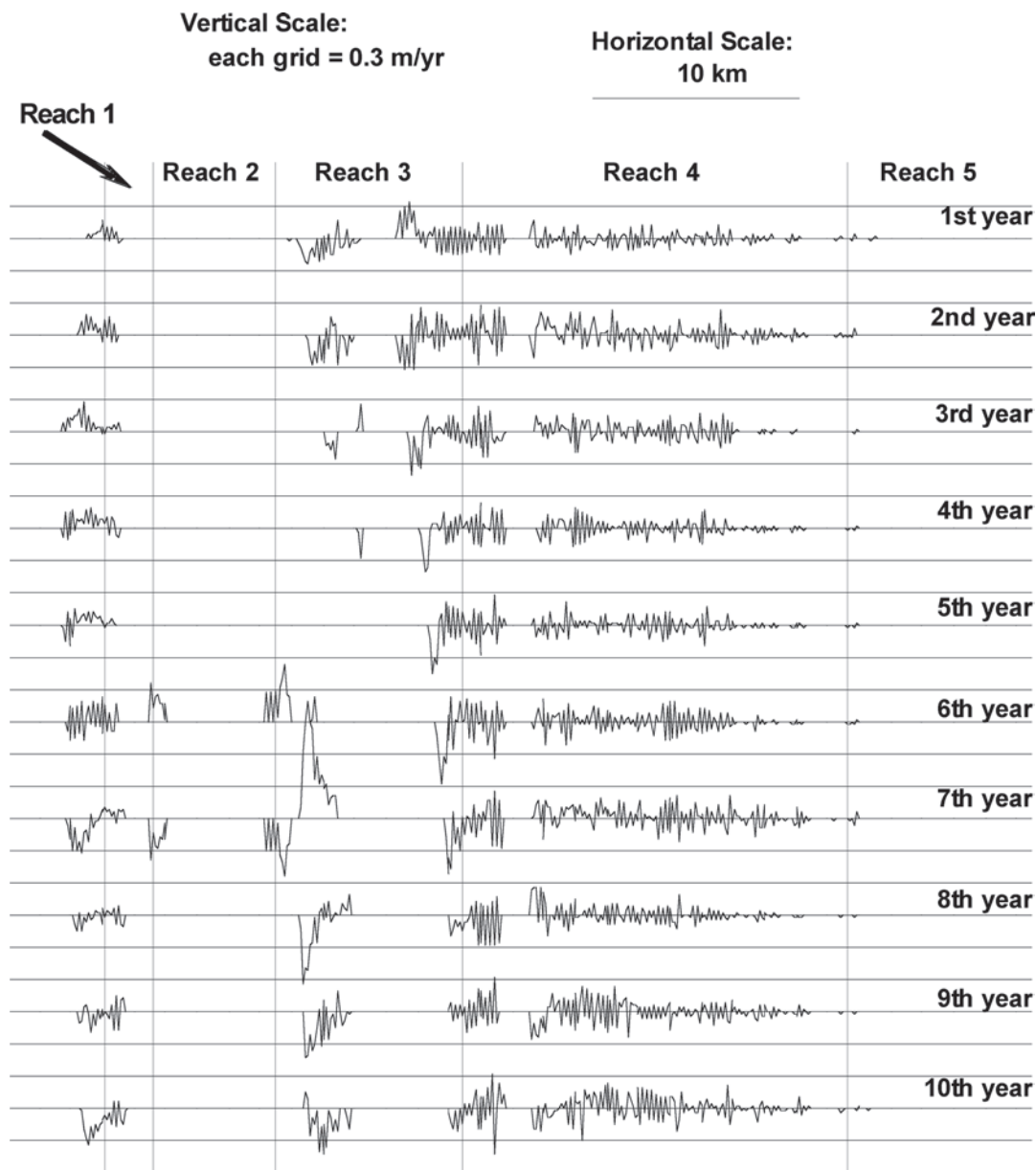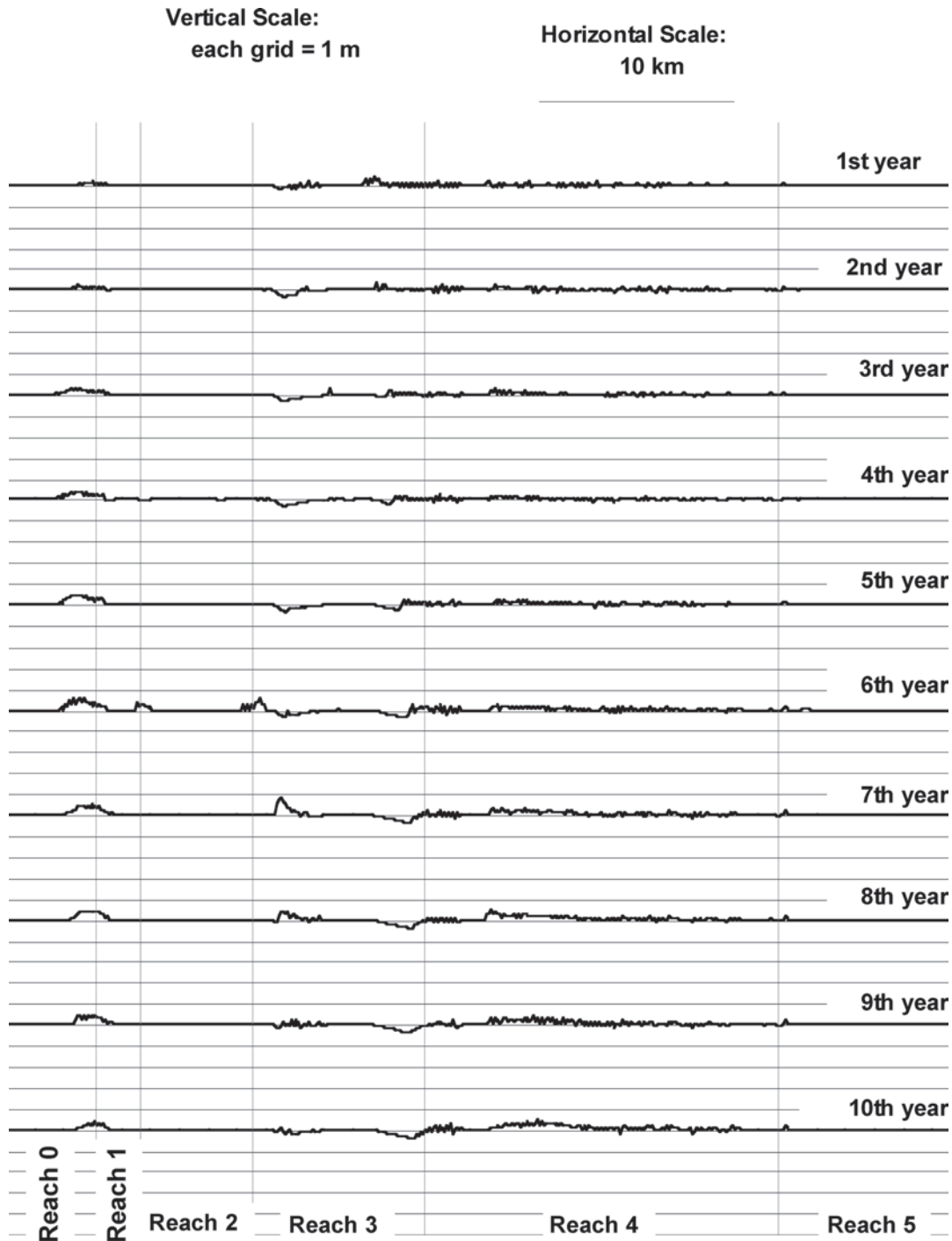

Fig. 23-11. Annual change in bed elevation from gravel erosion and deposition: reference run of the gravel model.

In particular, about 1 m of deposition is observed downstream of the gorge outlet in Year 6 of the model run (which uses water year 1949, a wet year with only moderate peak flow, as input flow data). This result indicates that under certain hydrological conditions, local aggradation or degradation could occur in certain reaches under reference conditions in the Sandy River.

Reference runs of the sand model indicate background suspended-sediment concentrations fluctuating between approximately 90 and 150 ppm at the site of Marmot Dam,

Fig. 23-12. Cumulative change in bed elevation from gravel erosion and deposition: reference run of the gravel model.
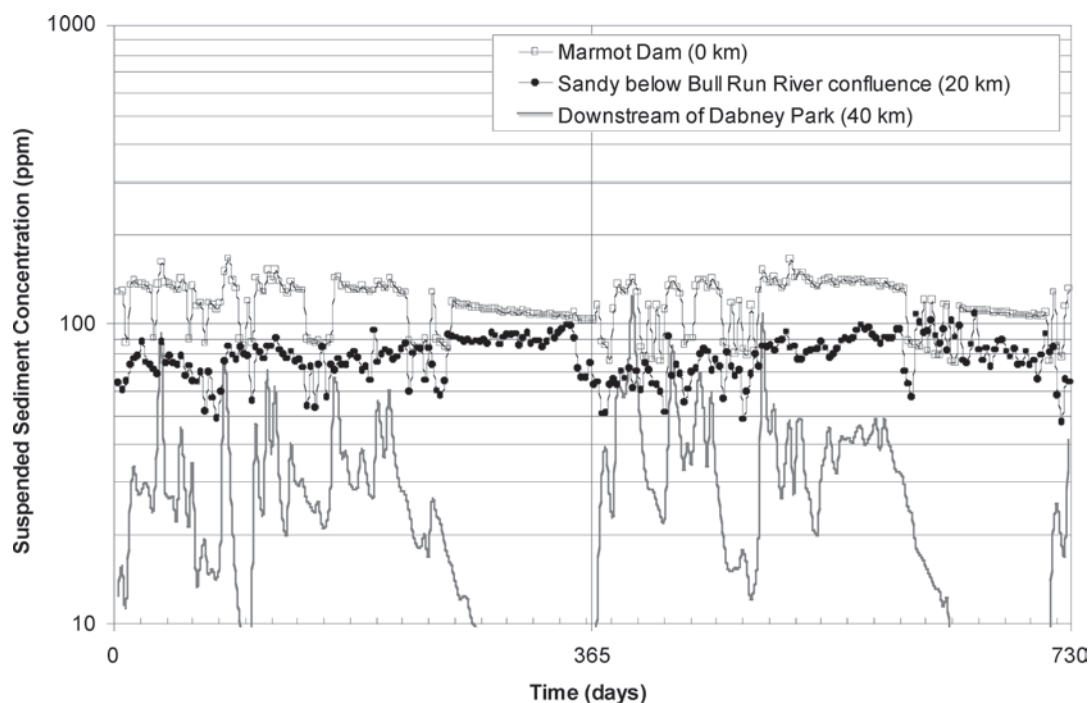
Fig. 23-13. Simulated suspended-sediment concentration downstream of Marmot Dam under reference conditions.

with lower concentrations further downstream (Fig. 23-13), based on the assumed background sediment concentration. Reference runs also show sand aggradation occurring in Reach 5, which is in agreement with field observations of the sand-bedded nature of this reach.

23.3.4.2   Modeling of Sediment Transport Associated with Single-Season Dam Removal and Minimal Sediment Excavation   Under one of the alternatives being considered for removal of Marmot Dam, only a minimal amount of sediment (i.e., enough to facilitate dam removal activities) would be excavated from the reservoir prior to dam removal, which would be accomplished in one season. All of the remaining reservoir sediment would be released downstream following dam removal. Model runs for this alternative assumed that a slightly greater amount of sediment was in the reservoir and would be released downstream (800,000 m³) than the sediment volume of 750,000 m³ suggested by the Marmot reservoir coring study (Squier Associates 2000). This volume difference was arrived at based on review of PGE photogrammetric data (Fig. 23-7), which suggests that the reservoir deposit may extend further upstream than indicated by the coring study (Squier Associates 2000).

Figures 23-14 and 23-15 illustrate model predictions of the downstream movement of coarse sediment out of the reservoir and resulting increases in bed elevation (aggradation) downstream of Marmot Dam, under average hydrologic conditions and over a 10-yr period. These model results indicate that, in the first year following removal, coarse sediment would move downstream into the portion of Reach 1 immediately downstream of the dam, creating

a depositional wedge up to a maximum of about 4 m thick, with small amounts of deposition predicted further downstream in Reach 1 and in Reach 3. In subsequent years, additional sediment would move out of the reservoir, resulting in a gradual increase in deposition thickness in the downstream portion of Reach 1, reaching a maximum of about 1 m on a reach-averaged basis. The aggradational wave is predicted to travel quickly through most of the gorge (Reach 2), with aggradation increasing at the downstream end of the gorge and the upstream end of Reach 3 from Years 1 through 10. Aggradation is predicted to gradually build to a maximum predicted thickness of about 1.5 to 2 m in the upper portion of Reach 3 (9–13 km downstream of the dam), where the channel widens and decreases in gradient (Fig. 23-15). In Reach 1, the greatest amount of aggradation would be expected in the early years following dam removal, whereas in Reach 3, aggradation would be expected to show gradual increases through the first 7 yr. After the first 7 yr, deposition thickness in Reach 3 would gradually decrease as the sediment wave is transported downstream. The model predicts small amounts of aggradation (typically <0.5 m) downstream of the Bull Run River confluence, although this aggradation is similar in magnitude to aggradation predicted in a reference run of the model and is not likely to be distinguishable from natural depositional processes.

Figure 23-16 shows the predicted change in bed elevation in a longitudinal profile view in the reservoir reach and in Reach 1 following dam removal. This figure shows how, following dam removal, the slope in the reservoir reach would gradually flatten out and return to that of the predam channel
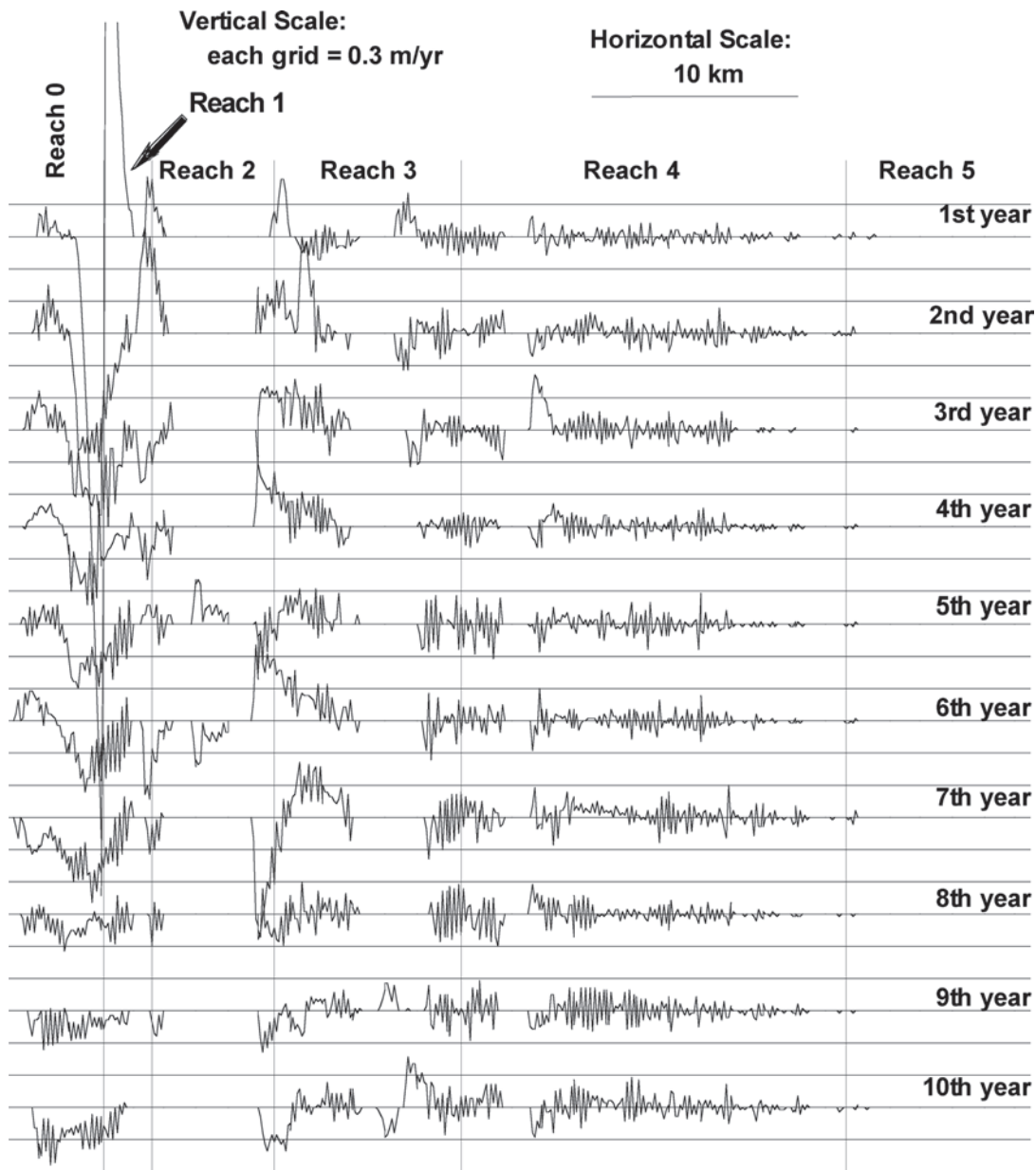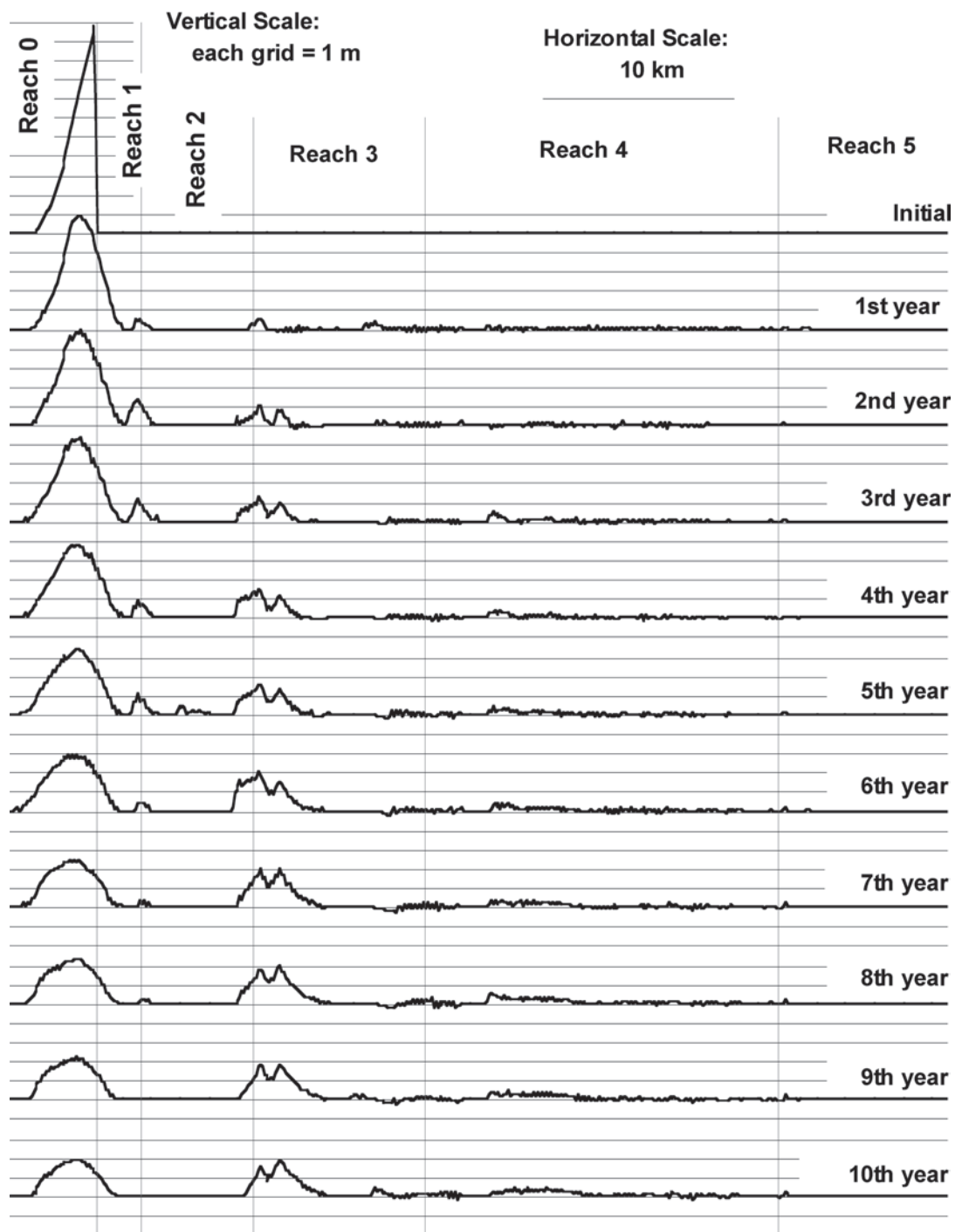
Fig. 23-14.   Annual change in bed elevation following dam removal for single-season dam removal with minimal dredging.

bed. Model results show that under average hydrologic conditions, the depth of the sediment deposit in the reservoir would decrease from about 11 m at the time of dam removal to about 8 m after 30 days, 7 m after 60 days, 6 m after 1 yr, 3 m after 5 yr, and 1 m after 10 yr (Fig. 23-15).

After the dam is removed and the channel begins to incise into the reservoir deposit, sand and finer sediment will be mobilized from the reservoir deposit. The magnitude of sand transport out of the reservoir is predicted to be greatest in the first winter following dam removal, although sand transport out of the reservoir continues for the duration of the model runs. Modeling of sand transport indicates that

sand aggradation is most likely to occur in the lower 10 km of the Sandy River (Reach 5) and that negligible aggradation would occur further upstream. Reach 5 has the lowest transport capacity of any reach in the Sandy River, reflecting its greater width and low gradient, and is currently sand-bedded in its lower portion. The model predicts deposition thicknesses of up to about 0.4 m in Reach 5 (Fig. 23-17), with the greatest aggradation expected to occur in the first year following removal of Marmot Dam. If stages are high enough in the Columbia River to create a backwater effect in the Sandy River during periods of sand transport in the Sandy River, however, the thickness of sand deposition in

Fig. 23-15. Cumulative change in bed elevation following dam removal for single-season dam removal with minimal dredging.

the lower Sandy River could be much greater than predicted here. Because the model does not account for this backwater effect, there is considerable uncertainty in model predictions of deposition thickness in Reach 5.

Figures 23-17 and 23-18 show the pattern of sand deposition at selected locations in Reach 5 during the first 2 yr

following removal of Marmot Dam and indicate that the magnitude of sand aggradation would fluctuate both seasonally and between years. Aggradation in Reach 5 is predicted to occur mainly in the lower 3 km of the Sandy River (with less aggradation in the upper part of the reach), which roughly corresponds to the location of the gravel/sand transition area
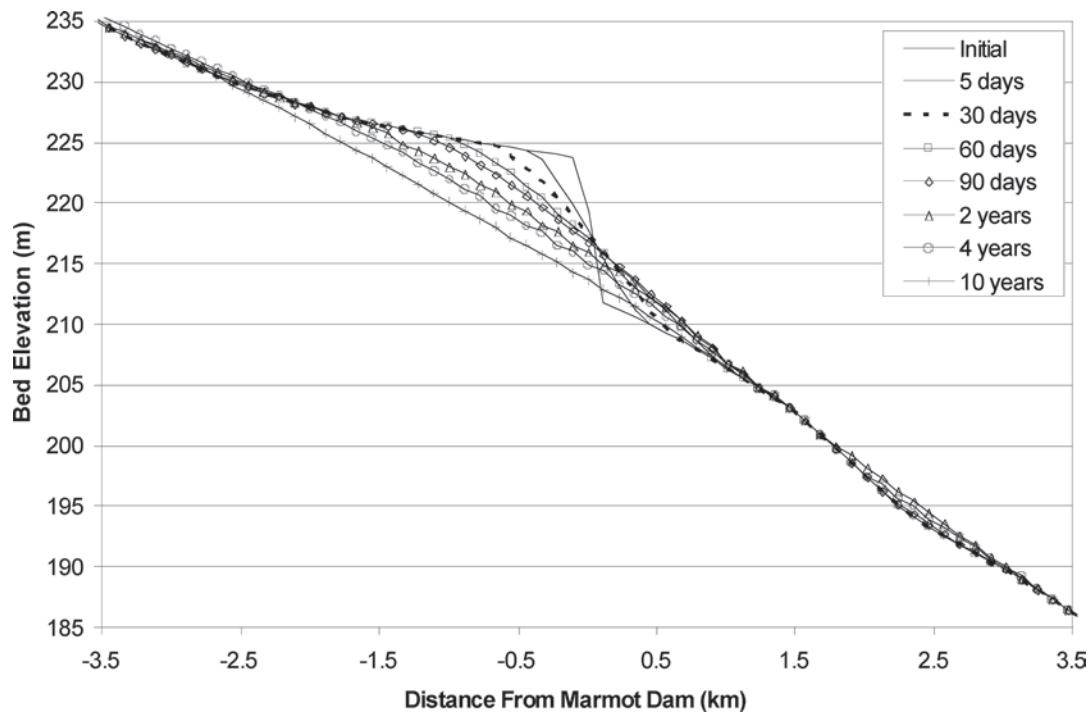
Fig. 23-16. Simulated bed elevation in the vicinity of the reservoir area following dam removal, for single-season dam removal with minimal dredging.
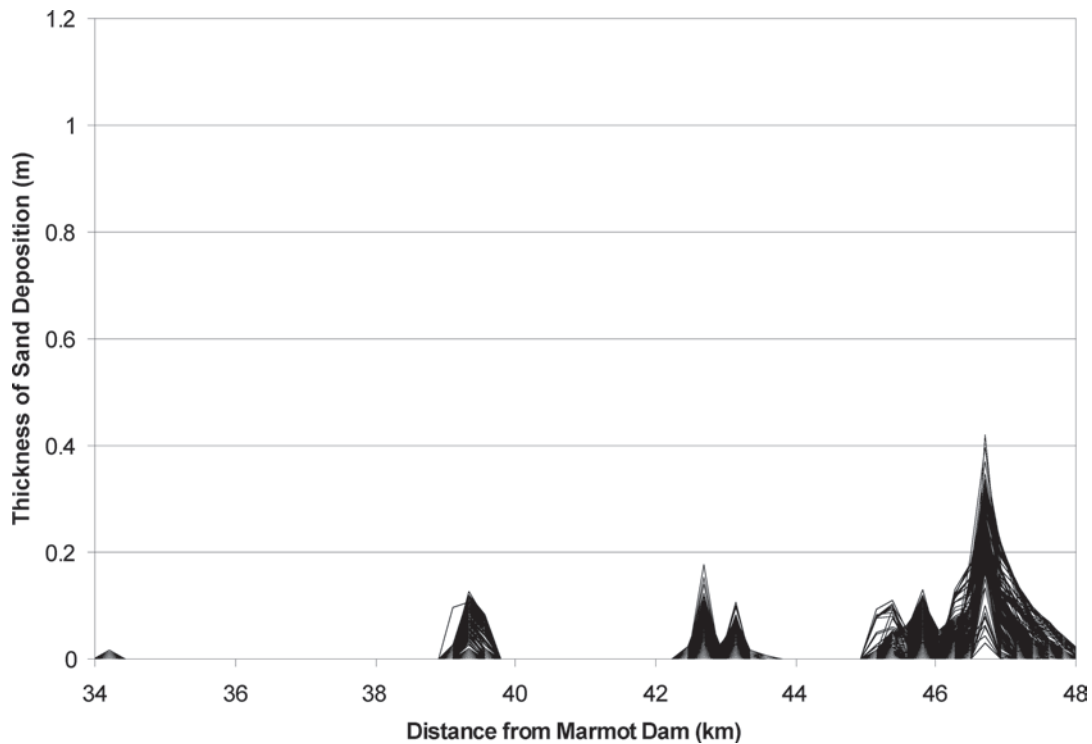
Fig. 23-17. Simulated thickness of sand deposit for single-season dam removal with minimal dredging. The diagram depicts the general areas and magnitudes of sand deposition. No attempt is made to identify individual lines on the diagram.
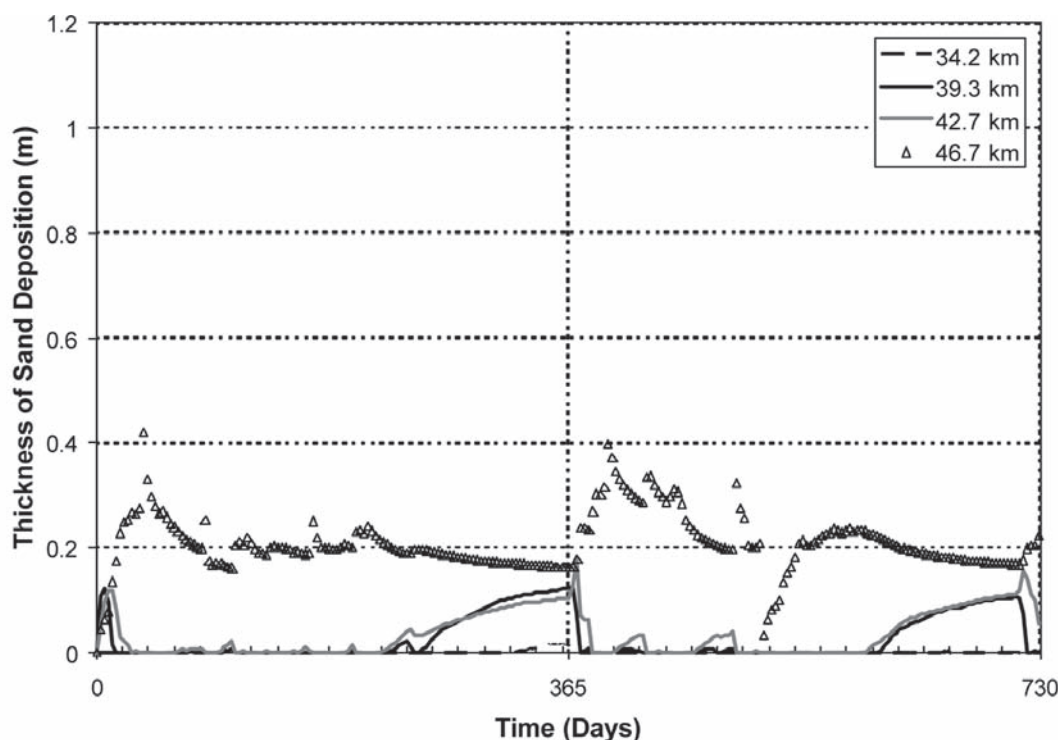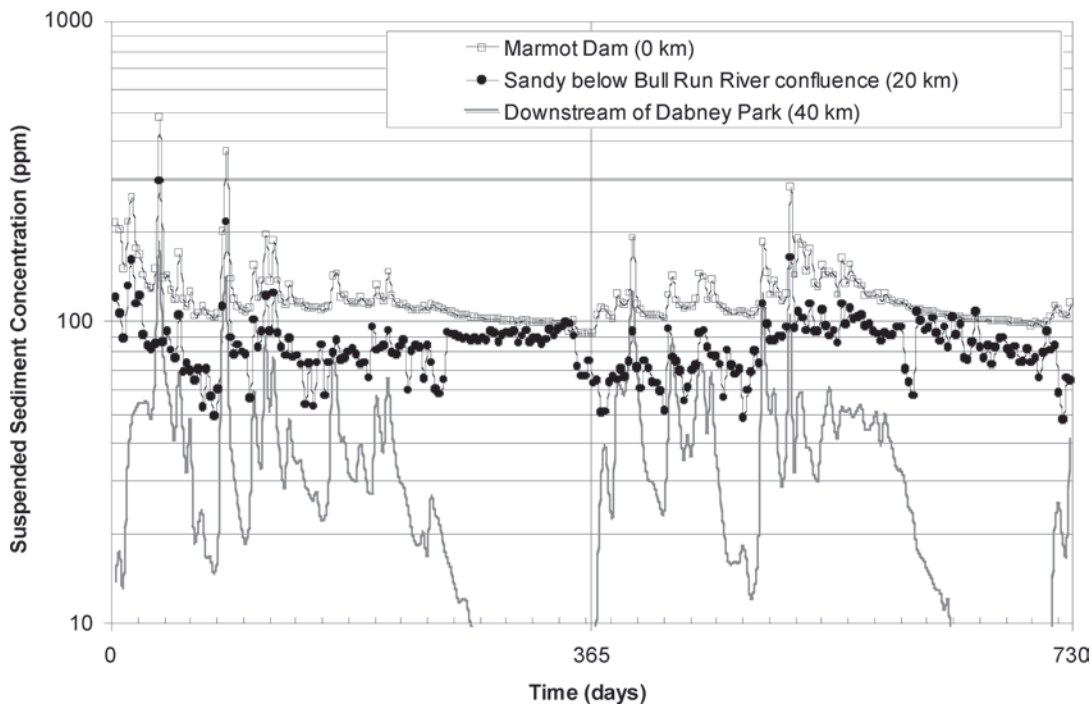
Fig. 23-18. Simulated thickness of sand deposit at four locations for the first two years following dam removal: single-season dam removal with minimum dredging.

in the Sandy River (i.e., very little gravel is found in the channel bed downstream of this portion, whereas upstream the bed contains both sand and gravel). Observations in other river systems suggest that the gravel/sand transition zone is typically an area of active deposition (Dietrich et al. 1999).

Model results also suggest that sand release from the reservoir would produce relatively small increases in total suspended-sediment (TSS) concentrations. Modeling indicates that, between Marmot Dam and the Bull Run River confluence, peak TSS of about 500 ppm would occur in the first winter following dam removal under average hydrologic conditions (Fig. 23-19). Suspended-sediment concentrations would generally remain between 100 and 200 ppm during the first 2 yr after removal, with periodic increases above this level during high flows. Downstream of the Bull Run River, suspended-sediment levels would be lower because of the dilution effect of flows from the Bull Run River. Suspended-sediment levels associated with dam removal are predicted to be relatively low because of the nature of the reservoir sediment deposit, in which fine sediment deposits are armored by a coarser surface layer (Fig. 23-10) and are therefore released gradually, rather than as one large pulse. Background suspended-sediment levels in the Sandy River are not known; modeled results should be considered indicative of potential increases in suspended-sediment concentration above background levels due to sediment release from Marmot Reservoir.

23.3.4.3 Sensitivity Tests Sensitivity tests were also performed to characterize the potential uncertainties in model results as a result of uncertainties either in model input data or in basic assumptions. Sensitivity tests were performed for the Marmot Dam removal simulation to evaluate uncertainties in (1) future hydrologic conditions, (2) grain-size distributions in the reservoir deposit, and (3) erosion rates from Marmot Reservoir. The results of these sensitivity tests are summarized below, and additional details are presented in Stillwater Sciences (2000; 2002). Cui et al. (2006a) present additional sensitivity tests for a hypothetical case study.

Modeling was completed to test the effects of "wet," "average," and "dry" hydrologic conditions in the first year following dam removal on sediment-transport dynamics; descriptions of the input data used for these scenarios are provided in Section 23.3.3. These model runs suggest that varying hydrology in the first year following dam removal strongly affects the rate of sediment transport out of the reservoir reach, with more rapid reservoir erosion under wetter conditions. For example, modeling indicates that after 1 yr, the thickness of the reservoir deposit would be about 3 m based on wet hydrologic conditions, compared to about 6 m based on average hydrology. Compared to average hydrologic conditions (results of which are described above), the more rapid movement of sediment out of the reservoir in Year 1 expected under wet conditions is predicted to slightly

Fig. 23-19.   Simulated suspended-sediment concentration at three locations for the first two years following dam removal: single-season dam removal with minimum dredging.

reduce overall gravel aggradation in Reach 1 in the years following removal, to alter the temporal pattern of aggradation in Reach 3 (with thicker deposition in the first several years after removal, but with similar magnitude of aggradation over a 10-yr scale), and to slightly increase aggradation in Reach 4. Model runs based on dry hydrologic conditions in Year 1 suggest that sediment would initially move more slowly out of the reservoir area compared to average hydrologic conditions, but that after 5 yr, the thickness of the deposit at the dam site would be the same as for average hydrologic conditions. Downstream patterns of predicted aggradation are similar for dry and average hydrologic scenarios, with aggradation concentrated in Reach 1 and Reach 3. The sensitivity of TSS levels to hydrologic conditions was also evaluated: predicted TSS levels are lowest for dry hydrologic conditions in Year 1, generally remaining below 200 ppm, and are similar in average and wet conditions.

In addition to varying the hydrologic input data, we also conducted model runs with different assumed grain-size distributions for the reservoir deposit. The model runs described above assumed an "average" grain-size distribution (Fig. 23-10). Using the "upper bound" (i.e., coarser) and "lower bound" (i.e., finer) grain-size distributions shown in Fig. 23-10 causes only very small changes in the predicted pattern of coarse sediment deposition. Predictions of TSS concentration are somewhat sensitive to the assumed grain-size distribution: TSS levels are highest for the assumed lower-bound distribution and lowest for the assumed upper-bound distribution.

Sensitivity tests were also used to evaluate simplifying assumptions used to simulate reservoir erosion, which is a key uncertainty in this modeling effort. As discussed in Section 23.3.2, basic model runs assume laterally uniform erosion of reservoir sediment from Marmot Reservoir. In reality, however, incision of a channel through the reservoir reach will likely occur to some extent following dam removal. A sensitivity analysis was performed to assess how an increase in the rate of gravel transport out of the reservoir resulting from channel incision could affect downstream deposition patterns. It was assumed that channel incision in the reservoir reach would be most likely when the local channel bed slope was high, as would be the case at the downstream end of the reservoir deposit immediately following dam removal, and that this could result in a gravel-transport rate that was greater than predicted by Parker's bed load transport equation. The increase in sediment-transport rate resulting from downcutting is therefore hypothesized to be an incremental function of bed slope. To simulate this, we applied a multiplier that varied with bed slope to the gravel-transport rate calculated by the Parker equation for channel bed slopes above 0.01. The transport rate out of the reservoir calculated by the Parker equation is thereby increased by a factor of up to 10 in this sensitivity test, depending on local bed slope. The results of this sensitivity test indicate that, if the down-cutting process affects the gravel-transport rate as is assumed in this sensitivity test, there will be only a short term effect on the pattern of gravel erosion from the reservoir and downstream deposition. This is because slopes

will be steepest immediately following dam removal at the downstream end of the sediment deposit, but downstream transport of this material would result in reduced bed slopes (and sediment-transport rates) within a short time, even if channel incision does occur. This sensitivity test does not fully simulate the effects of channel incision on sediment-transport patterns out of the reservoir reach, but it does capture one potential effect of incision (i.e., transport rates that are higher than calculated by the Parker equation when channel incision occurs).

The model also employs simplifying assumptions with respect to the mechanism of sand release from the reservoir, assuming that sand will be metered out of the reservoir in association with transport of gravel, as described in Section 23.3.2. To address the considerable uncertainties in this method, we completed sensitivity tests in which the rate of sand release from the reservoir was increased 5-fold and 10-fold over the rates of sand release predicted by the model based on predicted shear stresses and laterally uniform transport in the reservoir reach. Increasing the rate of sand release by a factor of 5 or 10 would result in complete sand evacuation from the reservoir in about 4 or 2 yr, respectively. The sensitivity analysis for the 10-fold increase indicates that sand release from the reservoir at 10 times the expected rate would result in a peak TSS concentration of approximately 4,000 ppm in the first winter following dam removal (compared with a maximum of about 500 ppm for basic model runs), with other spikes in TSS above 500 ppm during storm events. Otherwise TSS would generally remain between 100 and 400 ppm between Marmot Dam and the Bull Run River confluence, resembling assumed background conditions during late summer and early fall low-flow conditions. Increasing the rate of sand release 10-fold would also result in additional deposition downstream, including sand aggradation of approximately 0.2 to 0.4 m at the downstream end of Reach 4 (where no deposition is predicted for basic model runs), and aggradation predicted throughout Reach 5, with a maximum of about 1 m in this reach (compared to about 0.4 m in basic model runs).

23.3.5 Discussion

The case study presented in this chapter illustrates key considerations in the development of sediment-transport models for dam removal simulations. The model presented here and those of Cui et al. (2006a; 2006b) provide a framework for development of future models, either as a reference or as a starting point for modifications.

Numerical modeling of a process as complex as transport of a large volume of coarse and fine sediment following dam removal contains a number of uncertainties. The modeling approach presented here includes both uncertainties that are specific to the Marmot Dam removal application and those that would likely affect any dam removal modeling effort. Many hypotheses are incorporated in the models, in terms of both theoretical development (i.e., reflecting uncertainties in current scientific understanding about the mechanics of sediment transport) and input data. Key areas of uncertainty in this modeling effort, each of which is discussed further below, include modeling of reservoir erosion processes, selection of appropriate sediment-transport equations, uncertainty arising from the use of one-dimensional modeling, and uncertainty in input parameters.

A key source of uncertainty in this modeling approach arises from simplifying assumptions used to model reservoir erosion. Whereas the model assumes that transport out of the reservoir would be laterally uniform, erosion of reservoir sediment would in fact likely result in incision of a channel within the valley walls, potentially accelerating exposure of the underlying sand layer in the incised area and increasing the time (compared to model predictions) required for sediment on the margins of the reservoir deposit to be eroded downstream. Uncertainties also arise from the use of the Parker equation to model erosion of the mixed sand and gravel layers in the reservoir. The Parker equation is used to predict mobilization of the coarse fraction of various sediment layers in the reservoir, treating those layers as if fine sediments were not present. In fact, although the overall stratification of the reservoir results in a larger proportion of fine sediment in the lower layers of the reservoir and more coarse sediment in the upper layers, each layer in the deposit typically contains a range of grain sizes. The presence of a large amount of fines may create error in the use of the Parker equation because it is not intended for application to particles smaller than 2 mm. The model also assumes that fine sediments within each layer of the reservoir deposit are not transported out of the reservoir until shear stresses are sufficient to mobilize the gravel (>2-mm) component of the layer, as indicated by the Parker equation. Some fraction of the fine sediments in the reservoir, however, will likely be mobilized and transported at discharges lower than those that transport the coarse sediments found in the same layer as the fine sediments, resulting in more rapid transport of sand from a given layer in the reservoir deposit than of the gravel in that layer. In addition, sand following the gravel leaving the reservoir could smooth the bed and increase the mobility of the leading gravel front downstream (T. Lisle, personal communication, 2000). Sensitivity tests to address uncertainties related to reservoir erosion processes are described in Section 23.3.4.

Selection of appropriate sediment-transport equations is an important consideration in sediment-transport modeling of dam removal and, because of the complexities of dam removal modeling and incomplete knowledge of sediment-transport mechanics, the transport equations selected can be a potential source of uncertainty. The Marmot Dam removal case study involves simulation of transport of a mixture of coarse and fine sediment over a primarily coarse existing river bed. Because of the relatively undeveloped nature of transport equations for sand/gravel mixtures, we developed

separate transport models for sand and gravel components in the Marmot case study, rather than simultaneously modeling a sand/gravel mixture. Although sand and gravel transport are treated separately, they do likely affect each other, creating some uncertainty in model results. Moreover, the transport equation used here to model the downstream transport of fine sediment (Brownlie 1982) was developed for sand-bedded channels, and we know of no equations for sand transport over a coarse bed. Because most of the Sandy River has coarse bed materials downstream of Marmot Dam, use of the Brownlie equation (or of a comparable equation for sand transport) creates additional model uncertainty.

One-dimensional numerical modeling, such as the Marmot Dam removal model, provides results that are most applicable on a reach-scale and time-averaged basis, including estimates of sediment-transport rates and cross-section and reach-averaged depths of sediment deposits over the existing channel bed. Current state-of-the-art modeling, however, typically cannot predict complex three-dimensional geomorphic responses over long river reaches and time scales, such as depositional patterns in channel cross section, local changes in sediment particle size distribution, infiltration of sand into the channel bed, or changes in the mobility of the existing channel bed. The Marmot Dam removal model assumes a simplified, rectangular channel, and model predictions do not account for local variations in shear stress caused by features such as deep pools, bedrock outcrops, or large boulders. The modeling of fine sediment transport also does not account for the production of sand and silt from gravel abrasion (i.e., suspended load estimates do not include products of gravel abrasion). The amount of sediment actually deposited may therefore be substantially higher or lower than predicted by the model in localized areas of the channel. Because of the one-dimensional nature of modeling results, professional judgment and field observations of the system being evaluated should be used to interpret model results in terms of expected geomorphic effects.

Numerical models of dam removal, such as the model presented here for the Marmot Dam removal application, require input parameters on a range of physical characteristics that influence sediment transport. Modeling results typically will have varying levels of sensitivity to different types of input data, and input data typically contain varying levels of uncertainty. Modeling accuracy and efficiency will therefore be enhanced if the effort devoted to quantifying input parameters is commensurate with model sensitivity to these parameters. For the Marmot Dam removal application, data were collected specifically for this project or were already available for those input parameters to which the model is most sensitive (i.e., channel gradient, channel width, grain-size distribution of reservoir sediment, and water discharge). In addition, sensitivity analyses were performed to examine the effects of varying certain input data (hydrologic conditions, grain-size distribution of reservoir sediment) on model results, as described above. For other input parameters, such as background gravel- and sand-transport rates, size distribution of bed load, and abrasion rates in the Sandy River, existing data were not available and new data were not collected for this project. For many of these input parameters, only order-of-magnitude estimates are required for the models, and rough assumptions based on field observations of the Sandy River and on published data from elsewhere in the region were therefore used.

Despite the uncertainties in the modeling effort described here, this numerical modeling approach does provide predictions of sediment transport and deposition following dam removal over large temporal and spatial scales and can be used to compare sedimentation impacts associated with various dam-removal alternatives. Modeling efforts such as this one can be improved if field data describing the phenomena being modeled are collected and compared to modeling results. Monitoring of processes such as reservoir erosion, sand and gravel aggradation, and total suspended-sediment concentrations following dam removal is critical to improving upon nascent efforts to simulate sediment-transport dynamics following dam removal.

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