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Sediment Dynamics upon Dam Removal

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PART III: PHYSICAL MODELING

CHAPTER 7

PHYSICAL MODELING OF THE REMOVAL OF GLINES CANYON DAM AND LAKE MILLS FROM THE ELWHA RIVER, WASHINGTON

Chris Bromley, Timothy J. Randle, Gordon Grant, and Colin Thorne

7.1 INTRODUCTION

The U.S. Army Corps of Engineers (USACE) National Inventory of Dams (NID) lists about 80,000 dams in the United States but, including the smaller structures that do not meet the criteria for entry into this database, this number may actually be more than 2 million (Graf 1996). This infrastructure is aging rapidly, leading to problems of obsolescence, safety, high maintenance costs, and loss of functionality (ASCE 1997). Increasingly, these problems are causing dams to be removed; 579 documented removals had occurred by 2003 (AR/FE/TU 1999; see also www.americanrivers.org). The rate of removal is increasing and the large estimated number of dams in the United States suggests that the final number of dams removed could be very large.

While dam removal has the potential to successfully rehabilitate many miles of degraded river channel by re-establishing hydrological, sedimentological, and biological connectivity, it is nevertheless a disturbance to the fluvial system (Stanley and Doyle 2003). As such, it also has the potential to cause a great deal of physical and biological damage through the release of pollutants, the increased mobility of invasive species, and the remobilization of large volumes of reservoir sediment.

An example of the latter is the proposed removal of the Elwha and Glines Canyon dams from the Elwha River on Washington's Olympic Peninsula (Fig. 7-1). Both dams were built without fish passage facilities and they will be removed to achieve "the complete rehabilitation of the Elwha River system and its native anadromous fisheries" (National Park Service 1995), which is called for and authorized by the Elwha River Ecosystem and Fisheries Restoration Act (1992). The two reservoirs

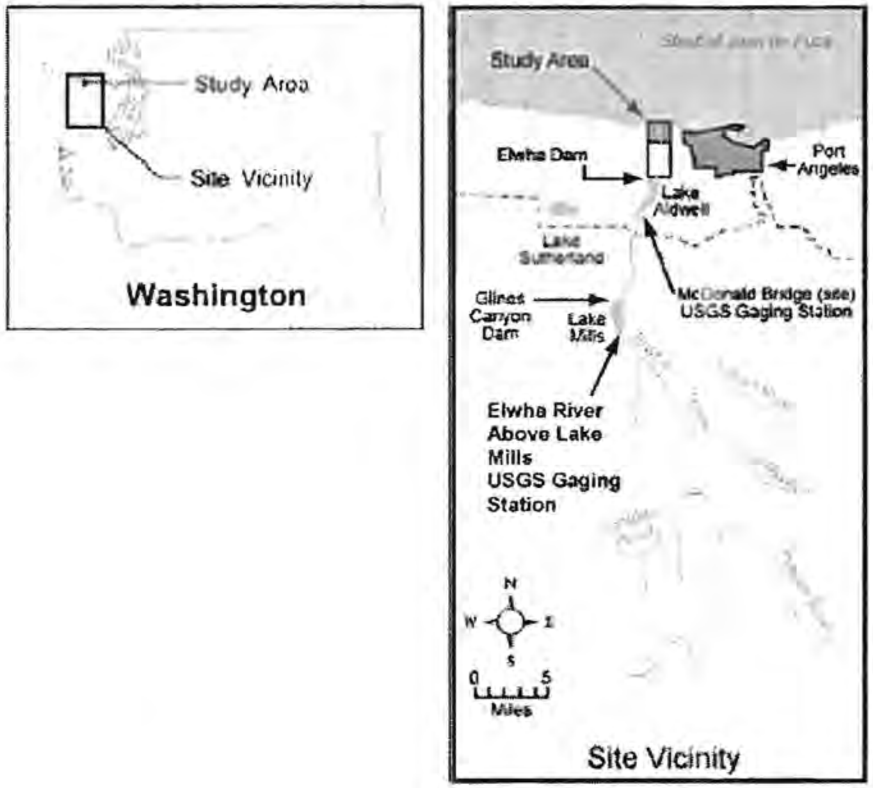


Figure 7-1. Site location. Source: Modified from National Park Service (2005).

impound 14.85 million m^3 of sediment, of which about 11.85 million m^3 is stored in Lake Mills behind Glines Canyon Dam. The sediment management objectives are to erode as much of the original delta as possible, but to distribute throughout and retain within the reservoir area as much of this eroded material as possible so that it can dewater, consolidate, and become stabilized over the medium to long term by recolonizing vegetation.

A series of physical modeling experiments was performed to investigate the morphodynamics of sediment movement through the reservoir area and into the downstream system in response to different magnitudes of drop in water surface elevation (baselevel) during dam removal, and to different initial channel positions on the delta surface. It was hypothesized that the greater the magnitude of drop in baselevel, the greater the volume of the original delta that would be eroded and prograded into the reservoir. In these experiments, the original delta was defined as the body

of sediment enclosed between the topset and foreset[1] delta surfaces and the reservoir boundary prior to the onset of dam removal. It did not include the bottomset deposits produced during the period of accelerated delta growth.

7.2 METHODS

The Lake Mills Basin was shaped using the 1926 pre-dam valley topography (Bureau of Reclamation 1995) and was designed to approximate the Froude and Shields numbers in the upstream delivery channel, according to standard modeling practice (e.g., ASCE 2000). The model was built with a horizontal scale of 1:310 and a vertical scale of 1:81.7, which made it vertically distorted by a factor of 3.79. While vertical distortion is not ideal, it is an accepted practice in physical modeling and the degree of distortion here is well within the maximum upper limits found in the literature, i.e., ≤ 10 (Chanson 1999); ≤ 6 (ASCE 2000). This model had the added benefit of increasing flow depths and therefore the flow's hydraulic roughness, thus reducing the extent to which viscous effects could affect sediment transport.

Glines Canyon Dam is to be removed by cutting it down in 7.5-ft (2.29-m)-high sections, which scales to 0.028 m in the model. The model dam was thus composed of 21 0.028-m-high wooden blocks; each experiment examined the effects of removing the dam in increments of the same number of dam pieces, with the number of dam pieces per increment varying from run to run (Table 7-1, Fig. 7-2).

The delta at the start of each run was grown to the extent of the 2002 prototype[2] delta using an accelerated sediment feed. The silicate sediment mixture used was substantially coarser than required by the scaling calculations (Fig. 7-3) in order to avoid cohesive scale effects and the formation of ripples or dunes on the bed of the model channel, neither of which were present during a drawdown experiment of the prototype Lake Mills in 1994 (USGS 2000). Although lower-density sediments such as coal dust (Cazanacli et al. 2002), crushed walnut shells, or plastic grains (Larsen 1990) could have been used to scale the finer prototype sediments, Whipple et al. (1998) have shown that mixed-density models are subject to scale

[1] The topset surface is the near horizontal surface over which the incising channel flows. The foreset surface slopes steeply downwards from the downstream end of the topset surface to the bed of the reservoir. The bottomset deposits are the finest sediments spread across the reservoir's bed, between the original delta and the dam.

[2] The term "prototype" in modeling parlance refers to the real-world object or phenomenon being modeled.

Table 7-1. Glines Canyon Dam Removal: Experimental Parameters for Selected Model Runs

Run Name	2xR	3xR	1xL	3xL	3xC	6xC[c]	12xC[c]
No. of dam pieces removed per increment of dam removal	2	3	1	3	3	6	12
Delta surface channel position at start of run[a]	Right	Right	Left	Left	Center	Center	Center
Model sediment mixture (mm)	Not sampled	$D_{16} = 0.15$ $D_{50} = 0.42$ $D_{84} = 1.30$	$D_{16} = 0.19$ $D_{50} = 0.40$ $D_{84} = 1.38$	Not sampled	Not sampled	$D_{16} = 0.16$ $D_{50} = 0.43$ $D_{84} = 1.33$	$D_{16} = 0.14$ $D_{50} = 0.43$ $D_{84} = 1.33$
Discharge during dam removal (L/min)	15.57	15.57	15.57	15.57	15.57	15.57	15.57
Recurrence interval of flood flows[b]	No floods	1st flood = 2-yr 2nd flood = 2-yr 3rd flood = 5-yr	1st flood = 2-yr 2nd flood = 2-yr 3rd flood = 5-yr	1st flood = 2-yr	1st flood = 2-yr	No floods	No floods

[a]The channel position is assigned looking downstream from the upstream end of the delta.
[b]Flood flows listed in the order they were run through the model.
[c]Partial runs: a total of 12 dam pieces removed.

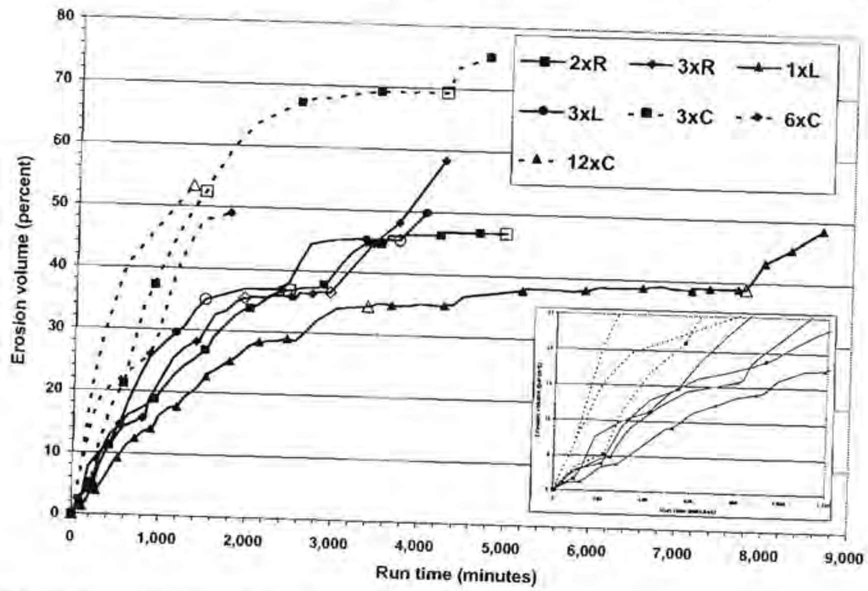


Figure 7-2. Original delta erosion volumes. The solid data markers denote the static equilibrium condition following the removal of one increment of dam, while the first and second empty data markers denote the 12- and 21-piece equilibrium conditions, respectively. The solid markers following the second empty marker denote the static equilibrium following the first two-year, the second two-year, and the five-year flood flows, respectively. The inset graph provides an expanded view of the area of the main graph enclosed between the black lines and the axes. Source: Modified from Bromley (2007; unpublished data).

effects that can complicate the interpretation of the model's results at the prototype scale. Given that the model was already subject to scale effects from the vertical distortion, it was thought prudent to avoid an additional layer of complexity that might further complicate the interpretation of the results. A thin layer of the modeling sediment mixture was stuck to the sides of the basin in order to roughen them prior to performing the experimental runs.

Each run was performed with a constant discharge of 15.57 L/min and a constant baselevel fall rate of 2.8 cm/15 min. Once the dam was completely removed, a series of flood flows were run through the reservoir as indicated in Table 7-1. For each increment of removal, the run was stopped after 1.5, 3.5, 5.5, and 9.5 h of run time, and sometimes at additional intervals in between, in order to scan the delta surface using a Keyence LK-500 laser. A final scan was also made once the system reached

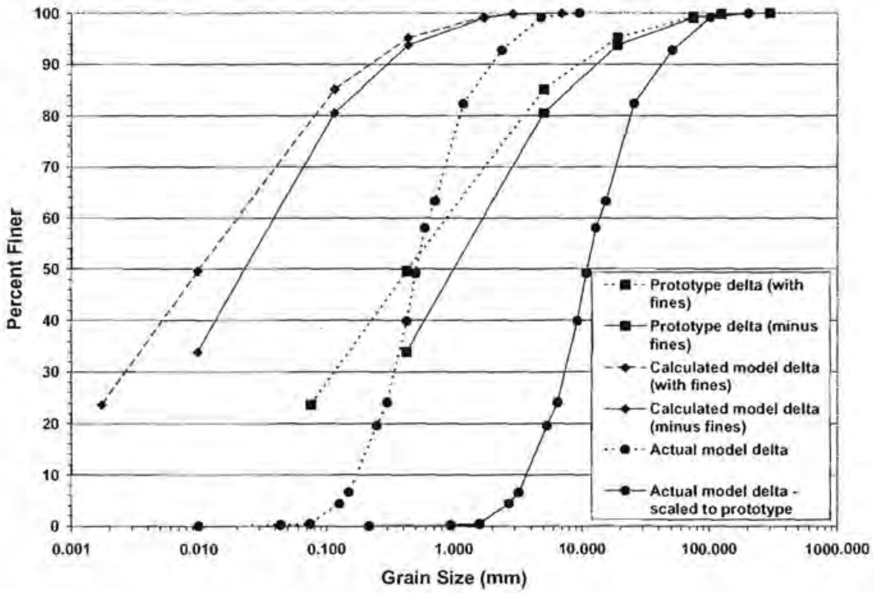


Figure 7-3. Key grain size distributions.

static equilibrium. All runs reported herein were allowed to reach a static equilibrium condition after each increment of dam removal except run 3xC, which was inadvertently performed with an accelerated rate of incremental removal. Cross sections were spaced longitudinally at 5-cm intervals. Delta surface elevation was measured across each section at 0.5-cm intervals and with sub-millimeter vertical accuracy. Additional cross sections were scanned to capture details of breaks in slope and bank line where these fell in between the 5-cm cross sections in order to accurately record the deposit's topography.

7.3 RESULTS AND ANALYSIS

7.3.1 Original Delta Volumes Eroded during Dam Removal

The laser data were used to create digital elevation models (DEMs) of the delta surface for each scan interval (Figs. 7-4 through 7-7). Cut-fill analyses were performed in ArcGIS version 9.0 to estimate the volumes of sediment eroded and deposited during each interval of run time. These estimates were corrected to account as much as possible for errors associated with overhanging banks and terraces and for slight variations in reservoir basin geometry, which were introduced into the DEMs by

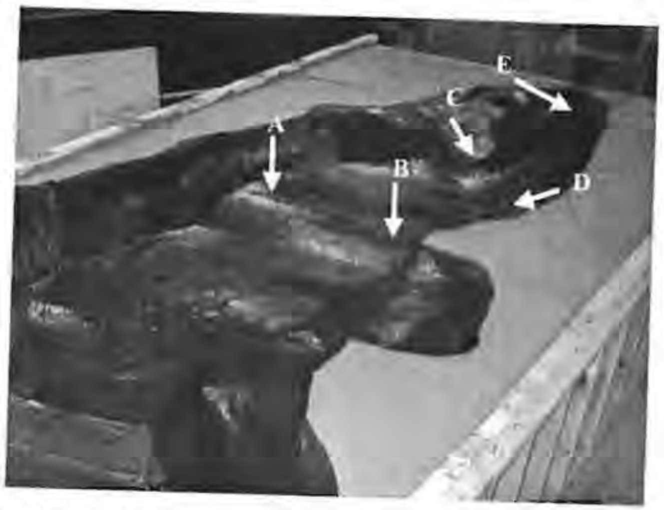


Figure 7-4. View looking upstream at the empty basin in the vicinity of the original delta. Arrows denote important topographical features.

changes in the number and position of the additional cross sections from time step to time step (as discussed in C. Bromley's unpublished Ph.D. dissertation, "The Morphodynamics of Sediment Movement through a Reservoir during Dam Removal," University of Nottingham, Nottingham, UK, 2007, which is hereafter cited as Bromley 2007, unpublished data). In reporting these results, reference is made below to the distal, medial, and proximal original delta areas, which refer to the delta surface sections from 0 to 100 cm, 100 to 200 cm, and 200 to 300 cm, respectively (Fig. 7-5). Reference is also made to central runs, in which the channel at the start of dam removal was located along the center of the original delta topset, and to marginal runs, in which the incising channel started along either the left or right side of the original delta topset.

The results show that, in general, as the position of the incising channel at the onset of dam removal moved from delta left or delta right to delta center, and as the magnitude of the removed dam increment increased from one to three pieces, the percentage of the original delta eroded and prograded into the reservoir increased significantly from 38.9% (run 1xL) to 69.3% (run 3xC) by the time the entire dam had been removed (Fig. 7-2; Table 7-2, Section A).

For runs 2xR, 3xR, and 3xL the pattern of response was not quite so simple. These runs eroded 46.8%, 36.7%, and 45.4%, respectively, of the original delta by the time the entire dam had been removed (Fig. 7-2; Table 7-2, Section A). These variations occurred largely because of the incising

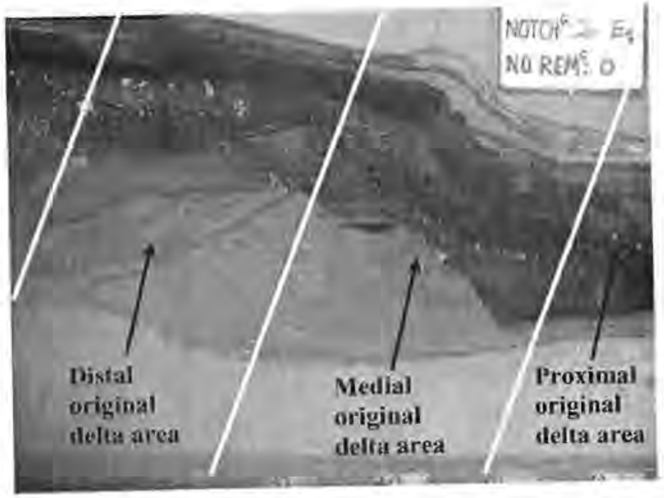


Figure 7-5. View of the original delta area in run 2xR at the static equilibrium following complete dam removal. Flow is from right to left.

channel's interactions with the highly asymmetrical reservoir boundary in the original delta area (Fig. 7-4). By the time the entire dam had been removed in run 2xR, the incising channel had pulled away from the less steeply sloping right reservoir wall (Fig. 7-4, arrow C) and eroded across the full width of the proximal original delta (Fig. 7-5). By the same stage in run 3xR, the incising channel remained against this more gentle slope and was unable to erode the sediment in the left half of the proximal original delta (Fig. 7-6). Although a greater width of the delta appears to have been eroded in run 2xR (Fig. 7-5) than in run 3xL (Fig. 7-7), both runs eroded almost exactly the same volume of original delta (Fig. 7-2; Table 7-2, Section A). This is because the transverse slope from a higher to a lower basin bed elevation (Fig. 7-4, arrows A to B) resulted in a greater depth of sediment through which the channel could incise along the left half of the delta, downstream from about 100 cm (refer to the numbers on the flat model top in Fig. 7-7). Conversely, the left-hand curvature of the left basin boundary (Fig. 7-4, arrow D) tended to guide the incising channel away from the main body of the original delta, thus reducing the amount of lateral original delta erosion.

The pattern of response was also less straightforward among the central runs. Runs 6xC and 12xC were only partial runs but, by the static equilibrium following the removal of the 12th dam piece, at the last point at which runs 3xC, 6xC and 12xC were directly comparable, 52.4%, 49%, and 53.3%, respectively, of the original delta had been eroded (Fig. 7-2; Table 7-2, Section A). This suggests that removing the next dam increment before the system had fully equilibrated to the effects of the previous

Table 7-2. Glines Canyon Dam Removal: Modeled Changes in Reservoir Sediment Volume

(A)	Original Delta Volume Eroded during... (as % of Original Delta Volume)				
Run	Dam Removal	1st 2-Year Flood Flow	2nd 2-Year Flood Flow	5-Year Flood Flow	(C) Total Volume Passing Downstream
2xR	46.8	—	—	—	46.8
3xR	36.7	8.1	3.3	10.3	58.4
1xL	38.9	4.3	2.3	3.1	48.6
3xL	45.4	4.5	—	—	49.9
3xC	69.3	5.8	—	—	75.1

(B)	Volume Passing Downstream during... (as % of Total Reservoir Sediment Volume)				
Run	Dam Removal	1st 2-Year Flood Flow	2nd 2-Year Flood Flow	5-Year Flood Flow	(C) Total Volume Passing Downstream
2xR	13.8	—	—	—	13.8
3xR	2.4	7.6	5.1	9.7	24.8
1xL	7.8	4.3	8.1	5.3	25.3
3xL	13.9	10.8	—	—	24.7
3xC	25.1	9.8	—	—	34.9

Section A: Original delta volume as proportion of initial original delta volume. Section B: Total reservoir sediment. Section C: Sediment volume passing downstream as a proportion of total reservoir sediment volume.

baselevel drop was able to generate a greater amount of original delta erosion than a baselevel drop of twice the magnitude, but in which the system was allowed to fully equilibrate. Furthermore, the relatively small difference in erosion volumes between runs 6xC and 12xC suggests that there may be an exponential decrease in the additional erosion volumes generated by large increases in the magnitude of baselevel drop. In turn, this suggests that there may be an upper limit to the magnitude of baselevel below which very little further increases in erosion volume can be realized. This possibility merits further investigation.

7.3.2 Original Delta Volumes Eroded by Storm Flows Post-Dam Removal

The discrepancy in the volumes eroded by the first 2-year flood flows between run 3xR and the other runs, and between the 5-year flood flows

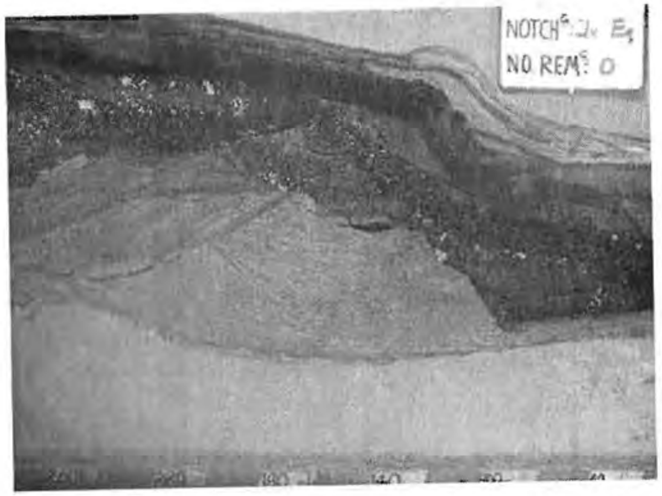


Figure 7-6. View of the original delta area in run 3xR at the static equilibrium following complete dam removal.

Figure 7-7. View of the original delta area in run 3xL at the static equilibrium following complete dam removal.

for runs 1xL and 3xR (Table 7-2, Section A), was probably due to the asymmetry of the reservoir basin. In run 1xL there was only a small amount of mass wasting of the right terrace at the upstream end of the delta after the 5-year flood flow (Fig. 7-8D), while during run 3xR the floods were able to erode large sections of the entire length of the left terrace (Fig. 7-9).

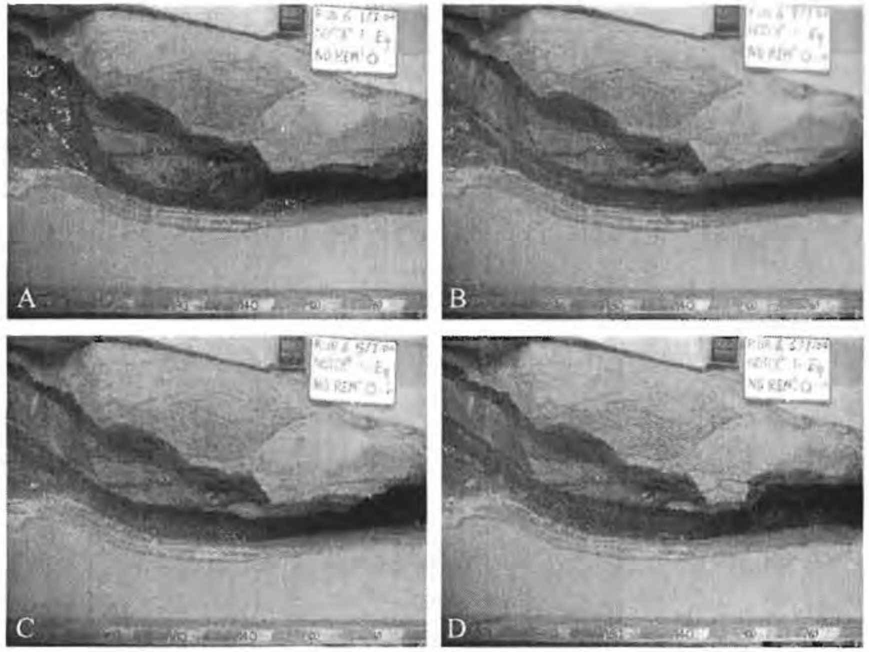


Figure 7-8. Original delta area in run 1xL at static equilibriums after (A) complete dam removal; (B) first 2-year flow; (C) second 2-year flow; (D) 5-year flow.

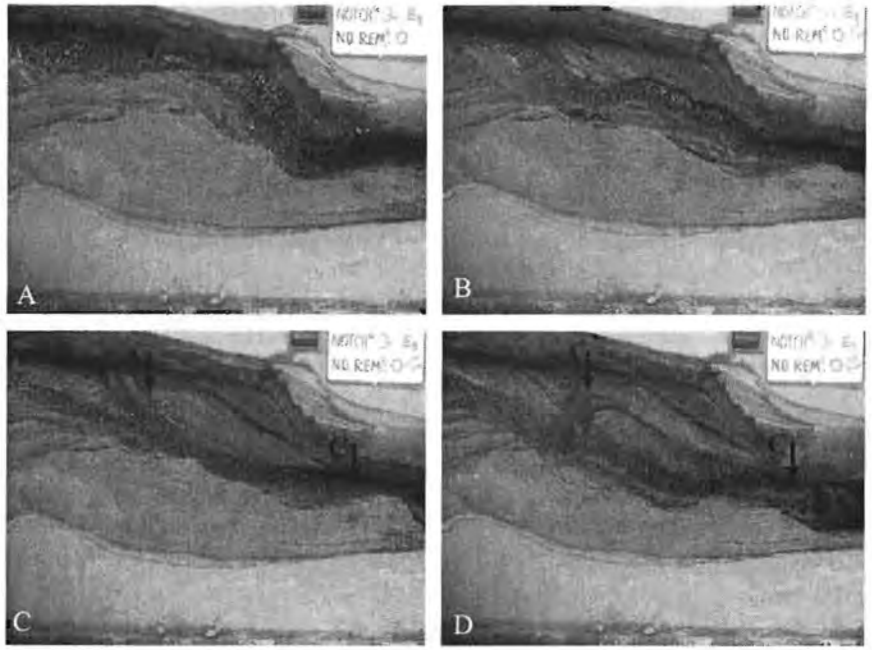


Figure 7-9. Original delta area in run 3xR at static equilibrium after (A) complete dam removal; (B) first 2-year flow; (C) second 2-year flow; (D) 5-year flow.

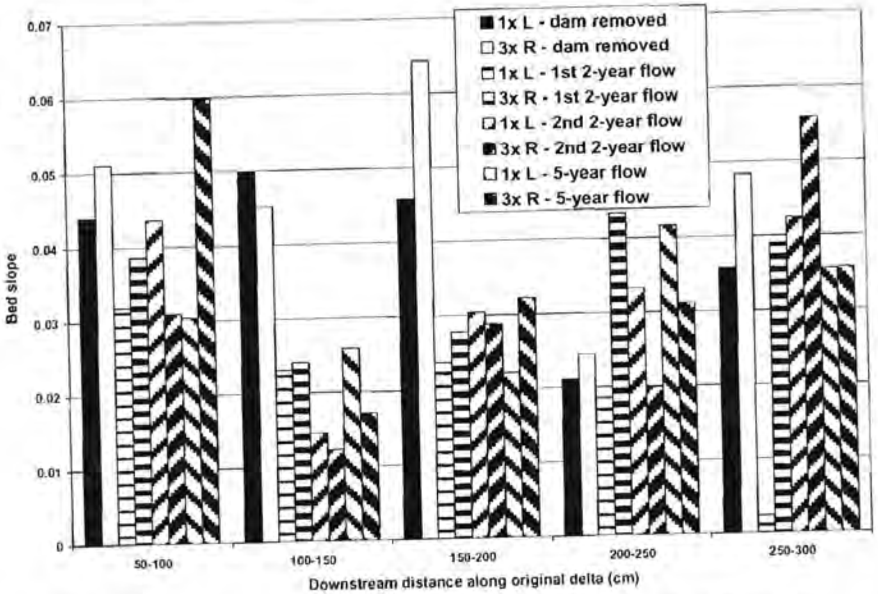


Figure 7-10. Thalweg slopes in the original delta area after flood flows.

While the channel became fixed against the bed of the basin boundary during the dam removal phase in run 3xR (Figs. 7-4 and 7-9, arrows A and C), thus reducing the erosion volume during that period, the higher discharge enabled it to move into the left side of the deposit. In both runs there was a rapid reduction in slope from 50 cm to 200 cm along the delta surface following the first 2-year flood flow (Fig. 7-10). In run 1xL this constituted the bulk of the volumetric adjustment, while in run 3xR the lateral adjustments were responsible for the bulk of the erosion.

7.3.2.1 Sediment Transport into the Downstream System. More sediment was transported through the dam site by the end of the dam removal phase of run 3xC (25.1%) than at any stage of any other run except run 1xL, in which 25.3% was transported by the end of the 5-year flood (Table 7-2, Section B; Fig. 7-11).

Following the 2-year flood in run 3xC, an additional 9.8% of the total reservoir sediment volume was transported through the dam site. The ranking of the runs in order of decreasing total sediment volume transported through the dam site corresponds almost perfectly with their ranking in order of decreasing original delta erosion volume (Table 7-2, Section B), which suggests that as more sediment was eroded from the original delta, more sediment was able to pass downstream once the entire dam had been removed (Bromley 2007; unpublished data).

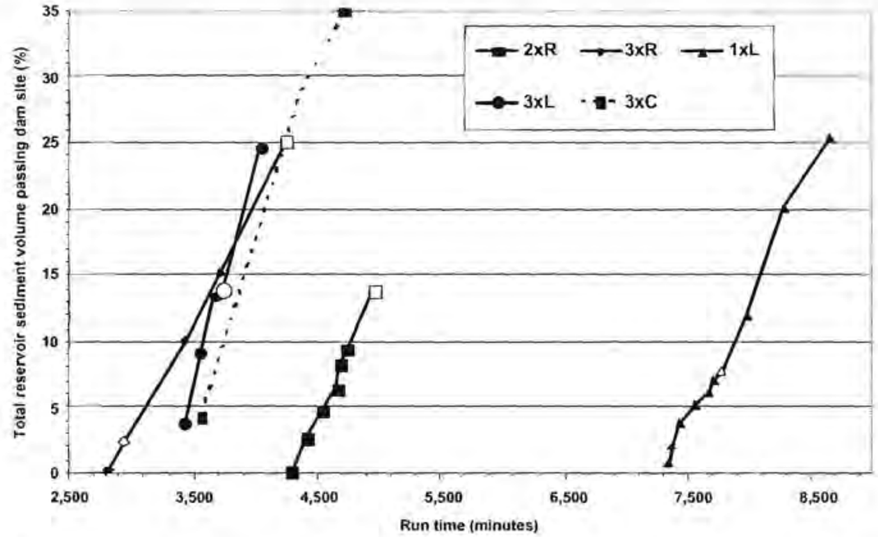


Figure 7-11. Total reservoir sediment passing downstream. The empty markers indicate the static equilibriums at the end of dam removal (Table 7-1).

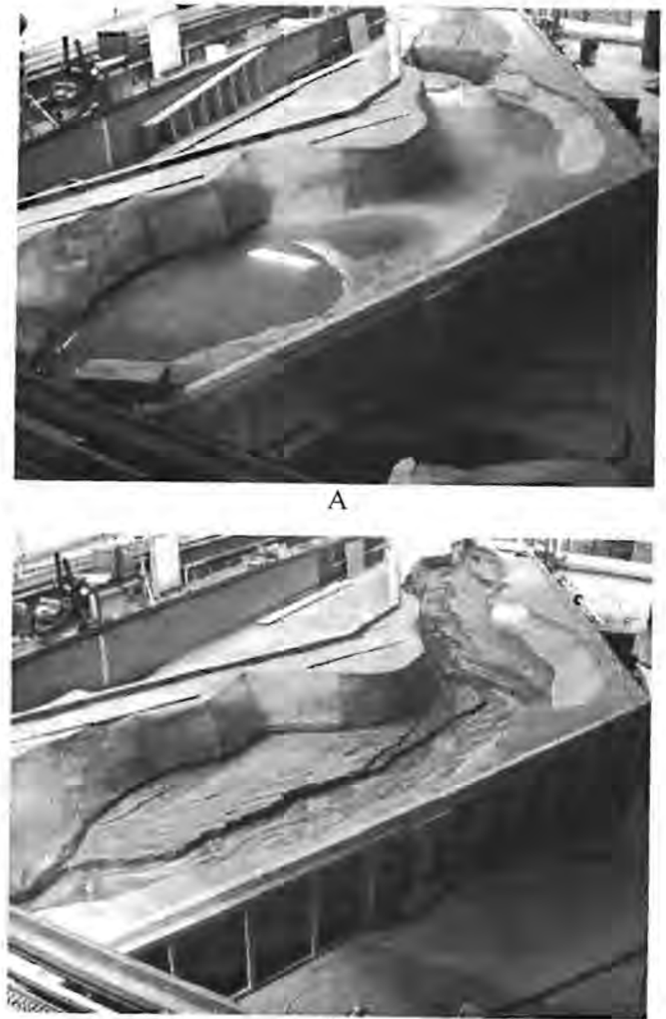
7.4 DISCUSSION

The results show that there was a general tendency for an increase in the magnitude of the drop in baselevel to lead to an increase in the volume of original delta erosion, but only up to a certain magnitude of drop. They also show that this tendency was moderated by the interaction of the incising channel with the reservoir boundary. A noncohesive alluvial channel responding to a drop in baselevel will widen in response to the upstream migration of incision (Schumm et al. 1984; Schumm et al. 1987; Simon 1989; 1992). This widening occurs through a combination of the banks exceeding their critical height for stability due to incision, and the development of sinuous flow paths that lead to channel meandering. Where the reservoir boundary prevented this sinuosity from developing in one direction (e.g., to the left in Fig. 7-8A–D), it also prevented the sinuosity from fully developing in the opposite direction in the next (incipient) bend downstream, thus restricting the extent to which the entire channel could move laterally. In the same way, the reservoir boundary also controlled the extent to which flood flows were able to erode the remaining terrace deposits (Figs. 7-8 and 7-9).

The influence of the reservoir boundary on delta erosion is one specific manifestation of the more general observation that the width of the reservoir sediment deposit relative to that of the river channel will have a significant effect on the proportion of reservoir sediment mobilized during dam removal. In the context of reservoir flushing to recover lost storage capacity, Annandale and Morris (1998) noted that most of the reservoir sediment deposit will be mobilized when it is of a similar width to the river channel. While the sediment management objectives during flushing and dam removal may be quite different, this principle remains the same. The relevant variables to the precise proportion of sediment that will be mobilized will be the deposit's grain size distribution and stratification, the discharge during removal (and specifically the capacity of this discharge to mobilize and transport this grain size distribution), the shape of the basin downstream from the original delta (for cases where the reservoir is not full of sediment); and the magnitude and rate of drop in baselevel. The interactions between some of these variables have been highlighted and discussed by Bromley et al. (2011) and by Bromley (2007; unpublished data).

Runs 3xC, 6xC, and 12xC eroded and redistributed the greatest volumes of original delta sediment throughout the reservoir area (Fig. 7-12). The greatest total reservoir sediment volume passing downstream both at the end of dam removal and after the first 2-year flood flow occurred during run 3xC. If runs 6xC and 12xC had been completed, it is possible that they would have seen similarly large volumes passing downstream. Thus, the central runs were the most effective at redistributing delta sediment throughout the reservoir area (thereby minimizing the ratio of the total reservoir sediment volume to sediment volume within the root zone of recolonizing vegetation). Paradoxically, they were also the most effective at introducing large volumes of sediment into the downstream system in the short-term following dam removal. That the accelerated incremental dam removal in run 3xC was able to generate erosion volumes very similar to those of magnitudes of baselevel drop four times greater is potentially of great practical utility. However, it indicates that the range of erosive behaviors obtained with a wide range of magnitudes of drop can also be obtained with much smaller drops that are more realistically attainable in the field, simply by manipulating the rate of baselevel drop.

These sediment volumes represent many years' worth of natural sediment transport and they will undoubtedly affect the physical and biological fabric of the downstream system. The extent to which they will do so remains unclear, however, and will depend on a number of factors, including the absolute quantities of fine (silt and clay) and coarse (sand and gravel) sediment released; the extent to which the fines are flushed through the system or deposited on and within the bed; the volume of coarse material deposited in pools, channel margins, riffles and, in the case of sand, within the bed; and the extent to which these deposits can be flushed out by higher flows. The adaptive management strategy that has



A

B

Figure 7-12. (A) Original delta at start of run 3xC. (B) Original delta sediment distributed throughout the reservoir by the static equilibrium at the end of dam removal. Compare the extent of original delta erosion here to that at the end of dam removal in the runs whose channels start in left or right delta positions (Figs. 7-5, 7-7, 7-8A, 7-9A).

been developed for sediment management during dam removal reflects this uncertainty (National Park Service 2005).

Over the medium to long term, however, vegetation within the reservoir area will form a well-developed root architecture that will stabilize some or all of the remaining reservoir sediment. If the prototype Glines

Canyon Dam is removed under a central channel removal scenario, the downstream sediment releases may be higher in the short term than under a marginal removal scenario. If the dam is removed under a marginal channel removal scenario, however, it is hypothesized that the sediment releases to the downstream system will be smaller in the short term but will persist at elevated levels over the medium to long term, due to the episodic mass wasting of high, unvegetated, and unstable terrace deposits within the original delta area (Figs. 7-5 through 7-9).

7.5 CONCLUSIONS

The morphodynamic behavior outlined above has not previously been reported for dam removal work. The results presented here do need to be treated with caution, however, since they are based on a limited amount of experimental data. Probably the greatest overall weakness of this study is the lack of replication of any of the experimental runs. This was not possible given the length of time required to complete each run (one month on average), and therefore it is impossible to quantify the natural variability inherent in each removal scenario examined. While such variability is unlikely to invalidate the large erosion volume differences between runs 1xL and 3xC, the same cannot be said for the much smaller erosion volume differences that exist between runs 1xL, 3xL, 2xR, and 3xR, and between 3xC, 6xC, and 12xC.

Also, the model is necessarily a simplification of reality. The bottomset deposits of the prototype were not present; the model was run with a constant discharge; and there was a drop between the mouth of the inlet channel and the channel bed once it began to incise (Fig. 7-4, arrow E). This drop was present because there was insufficient space on the laboratory floor to extend the inlet channel upstream at the correct slope and from the correct elevation on the reservoir base. This drop created an entrance effect in the model that reduced flow velocities at the upstream end of the delta and thus probably decreased the flow's erosivity.

Finally, the model was subject to scale effects from the vertical distortion and the coarse model sediment mixture. The latter may have decreased the erodibility of the original delta, thus leading to potential underestimation of the volume of sediment entering the downstream system.

Despite their shortcomings, the results highlight issues that are of importance to both the Elwha River project and to other dam removal projects. The variables discussed here and those presented in Bromley et al. (2011) merit further field and laboratory investigation in order to more thoroughly understand the dynamics of their interactions. In turn, this will help to clarify the roles of the fundamental factors that control

the morphodynamic response of a mass of sediment impounded in a reservoir to dam removal.

ACKNOWLEDGMENTS

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PART IV: NUMERICAL MODELING

CHAPTER 8

MODELING AND MEASURING BED ADJUSTMENTS FOR RIVER RESTORATION AND DAM REMOVAL: A STEP TOWARD HABITAT MODELING

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8.1 INTRODUCTION

While dams provide many desirable benefits to society, they also are a major hydro-modification to ecosystems, can be safety and boating hazards, and may degrade water quality of the river. In the Great Lakes District, dams that exceed a height of 6 ft (2 m) and a pool volume 50 ac-ft (6.2×10^4 m^3) are inspected and require a state permit to ensure they are properly maintained. For dams that fail inspections, dam owners are faced with four options: (1) do nothing; (2) modify the dam to such an extent that it is not subject to the regulations; (3) rehabilitate the dam to meet the regulatory guidelines of the permit; and (4) remove the dam. The chosen option often depends on the outcome, its economics, and the environmental and political pressures associated with the option. For example, the "do nothing" option may carry a regulatory penalty and liability for a catastrophic failure that causes loss of life and property. If the dam is modified or removed, the fate of changing water levels and sediments loads downstream of the reservoir, immediately after removal and over time, will be a concern to residents along the river. Thus, dam owners need tools to assess the outcomes of the various options applied to their situation.

A cost-effective approach for dam removal planning and decision making is to combine a one-dimensional (1-D) mathematical model of the river hydraulics with a sediment transport model (Cheng and Granata 2007; Doyle and Stanley 2003). Although an extensive body of engineering literature has been amassed on dam failures using models such as