UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS LABORATORY
Engineering, Environmental and Geophysical Fluid Dynamics

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Physical Model Study of Marmot Dam Removal: Cofferdam Notch Location and Resulting Fluvial Responses

By

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Summary and Recommendations

This report summarizes observations made for a set of experiments conducted using the physical model of the Sandy River and Marmot Dam constructed for Portland General Electric (PGE). The experiments focused on the location of the cofferdam notch and its impact on the immediate sediment remobilization, knickpoint location and trajectory, volume of removal, and location of stranded sediment. The motivation for the study was to provide insights on how and if the position of a cofferdam notch will have an impact on how the site fails and how the reservoir sediments are remobilized. Based on early experiments with the model, PGE expressed concern that some failure scenarios resulted in abandonment of large terraces of sediment near the dam site, posing potential public safety issues. One goal of these experiments was to determine if cofferdam notch location could be positioned to minimize the volume of sediment stranded in terraces.

Eight model scenarios were completed for this study. Seven of the scenarios examined a failure discharge of 2500 cfs (cubic feet per second), the minimum failure design discharge. Within these seven scenarios, we examined three notch positions; river right (north bank of river), center, and river left (south bank of river). In an eighth scenario we examined a river right notch location and failure at a high discharge of 5500 cfs. Sediment mixtures used in the model were scaled to sediment core data of the Sandy River reservoir sediment.

The data and observations indicate that at the minimum design failure discharge of 2500 cfs, notch position does impact the location of cofferdam failure as well as the location of the first major knickpoint and its trajectory. The data suggest that a river left notch position minimizes the extent of stranded sediment terraces and a river right notch tends to result in larger terraces. A center notch position yielded similar results to the river right notch. At a discharge of 5500 cfs, results suggest that notch position is less important than at lower discharge rates, as the knickpoint is more or less bank to bank and is able to mobilize sediment more effectively.

Recommendations:

1. If one of the objectives accompanying dam removal is to maximize the volume and rate of sediment evacuated from the reservoir, then the cofferdam should be encouraged to breach in a river left position by construction of a shallow notch. Forcing the initial breach to occur at river left will tend to force lateral migration to the right bank of the channel in the period immediately following breaching, thereby increasing the volume of sediment evacuated from the near dam site area. A shallow notch is preferred because this permits a greater head to develop prior to initiation of the breach.

2. For purposes of removing the maximum volume of sediment quickly, breaching the cofferdam should occur at the highest flow that the structure can reasonably be expected to withstand. Breaching at a higher versus a lower flow will tend to result in formation of a more energetic knickpoint, promoting greater sediment evacuation.

3. Most evacuation of sediment in the near dam site area will occur very quickly following breaching. The strategy should therefore be to maximize the sediment evacuated in the period immediately following breaching of the cofferdam. Once the knickpoint has migrated into the bedrock canyon several hundred meters above the dam site, the outcome will be less influenced by notch position and discharge at time of breaching.

Introduction

The final removal of Marmot Dam and failure of the Marmot site will occur in the fall of 2007. The failure of the site will begin major sediment remobilization in the upstream reservoir and a grade adjustment that will involve erosion upstream of the dam and deposition downstream of the dam. Portland General Electric (PGE) has contracted St. Anthony Falls Laboratory (SAFL) to construct a physical model of the Sandy River and the Marmot Dam to gain insight on what the site failure and grade adjustments may involve.

At the field site, preparations for dam removal were made during 2007 summer low flows. The preparations included construction of upstream and downstream earthen cofferdams to bypass river flow around the removal site; installation of multiple dewatering wells to allow control of groundwater seepage; and removal of the main concrete dam structure and ~30,000 cubic yards of sediment between the upstream cofferdam and the Marmot Dam. The actual failure of the Marmot dam site and the onset of major sediment remobilization will occur after the first large rainfalls and associated high flows in the Sandy River in fall 2007. The historic hydrologic record suggests this could occur anytime after late September. The final steps needed to prepare the site for failure include shutdown and removal of the dewatering system, possible notching or lowering of the cofferdam in a specified location, removal of the upstream access bridge, and blockage of the bypass channel. At this point, the bypass will be cut-off, and the upstream pool level will rise until it reaches and overtops the cofferdam notch, initiating the failure process.

A distorted geometrically scaled physical model of the Marmot Dam, including the adjacent upstream and downstream reaches of the Sandy River, was constructed at SAFL. The model was used to test various scenarios of failure location in the upstream cofferdam and the impact this location had on the pattern and volume of material eroded from a zone extending from the dam site to approximately 1000 ft upstream of the site. We have attempted to follow the same removal protocols that will be employed in the field, i.e. cofferdam alignment and dimensions, groundwater dewatering, notch geometry, and bypass blockage. This report summarizes the observations and measurements made during these simulations.

The simulations involved consideration of two failure discharges: 2500 cfs and 5500 cfs. Based on 95 years of flow data recorded at the USGS gaging no. 14137000 (Sandy River near Marmot, OR), a 2500 cfs discharge has a probability of occurrence of more than 99% at any given year, and a 5500 cfs discharge has a probability of occurrence of 96%. Therefore, the chance that a flood with a magnitude of 5500 cfs occurs once every year is very high. These discharges were scaled to model flows (details on scaling are provided in Appendix A). At the 2500 cfs discharge, the reported minimum failure design discharge, we examined three cofferdam notch positions and resulting patterns of fluvial adjustment. Below we provide a summary of these observations.

The Physical Model

The physical model of the Sandy River and Marmot Dam is a distorted geometrically scaled model of the real system. The model is called “distorted” because the horizontal length scale and the vertical length scale are different. By defining the horizontal and vertical scaling, and using two dimensionless numbers that characterize open channel flow and sediment transport, we are able to scale many of the physical processes in the model. The size and shape of the model, flow rates, grain size distributions and time are all scaled to the field based on modeling similarity in two dimensionless numbers, the Froude number and the Shields number. A more thorough discussion of the scaling procedure is given in Appendix A of this report.

The scaling factors for this concrete and wood model are 1:150 in the horizontal and 1:70 in the vertical. These factors were chosen to maximize the use of space and complement the scaling of the accompanying sediment. Topographic data used to shape the model came from a 2006 airborne LIDAR survey provided by Portland General Electric and PGE endpoint surveys. From these data, the locations of twenty-nine cross sections were strategically chosen to capture important geometric characteristics of the river basin. Once converted into model scale, templates of these cross sections were placed in the model basin creating a form that was then filled with lightweight concrete, sealed and then painted to complete the model. Mississippi

River water was routed through the model and water discharge was monitored with a Signet 8550-1 flow meter with a paddle-wheel sensor.

Model Sediment

The Sandy River transports a mixed-load of sediment during high flow events that ranges from silt up to large boulders. The reservoir fill is comprised mostly of sandy and coarse materials (gravel – boulders) and is most likely vertically and horizontally sorted. A small number of core samples were taken of the reservoir sediments and analyzed for grain size distribution. These data, collected by PGE, were the basis for determining the grain size distribution in the model. From this field data, we determine the D90, D50 and D10 particles sizes. The scaling factor for grain size was applied to these characteristic sizes yielding target D90, D50 and D10 sizes for the model. We then determined a mixture of available aggregates that most closely matched the target grain size. The sediment was introduced into the experiment with mechanical volumetric sediment feeders. Sediment was fed at a constant rate for all discharges from a single location at the upstream end of the model.

Experimental Methods

Data Collection

Data collected from several sources were used to analyze characteristics of the dam removal and cofferdam failure. Eight sheet lasers were mounted parallel to each other directly above the model with 120 ft (prototype scale units) spacing and were used to document elevation changes post-removal (figure 1). Laser topographic images were taken using a high resolution Nikon D70 digital camera mounted at an oblique angle to the dam and upstream river section. Topographic images for each removal scenario were taken before cofferdam failure, after knickpoint migration to a position just upstream of topographic profile H (figure 1), and at the end of each removal scenario.

Three high resolution Olympus 770Z digital cameras were mounted overhead, capturing timelapse images at 30 second intervals during both the filling and removal stages of each scenario. In addition to these photos, a digital video recorder (DVR) was mounted above the dam and recorded cofferdam failure and upstream knickpoint migration during the initial stages of each run.

Data Analysis

Data analysis involved both qualitative and quantitative methods. DVR videos and timelapse images were used to qualitatively describe cofferdam failure, knickpoint migration, and channel characteristics for each removal scenario. Topographic images taken before cofferdam failure, after knickpoint migration to a position just upstream of topographic profile H (figure 1), and at the end of each removal scenario were combined with bedrock valley wall topography to understand erosive patterns and quantify estimates of sediment volumes and percent valley fill eroded during each removal scenario (table 2).

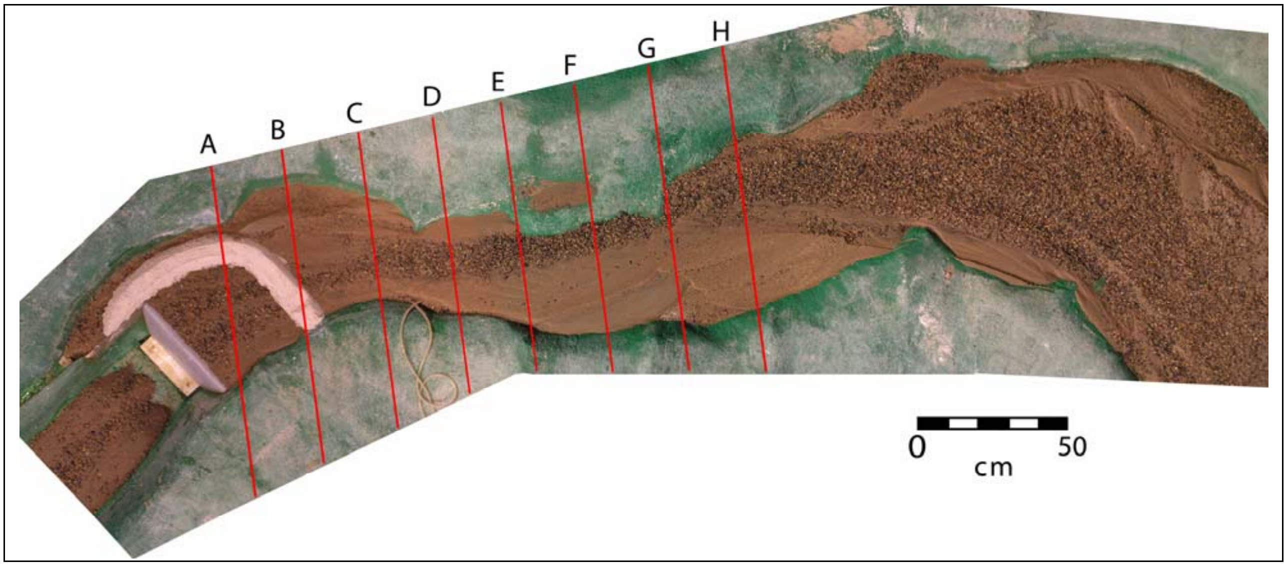


Figure 1. Overhead composite image showing Marmot Dam, cofferdam, and locations of eight topographic profiles (A-H).

Procedure:

Eight dam removal scenarios were modeled during this study (table 1). Each individual removal scenario began by naturally filling the basin (right side of figure 1, approximately 500 ft upstream of topographic profile H, to dam structure at left in figure 1) over approximately 4.5 days (prototype equivalent time). Sediment and water were supplied approximately 1500 ft upstream of figure 1. During this period, overhead timelapse images were taken at nine minute (prototype equivalent time) intervals. After the basin had filled completely, the cofferdam was constructed by scaling specifications outlined in the engineering design plans to model units (figure 2). During cofferdam construction, drain tiles were activated, simulating the dewatering of reservoir deposits. The dam structure was then removed. Flow was introduced at the laboratory discharge representing 2500 cfs in the field (or 5500 cfs for removal run #5). See appendix A1 for an explanation of discharge scaling. This discharge remained constant throughout the removal scenario. Immediately after flow reached the cofferdam and was diverted down the side canal, a plug was placed in the canal, thereby blocking flow, forcing upstream pool elevations to rise, and forcing flow through the notch in the cofferdam. After cofferdam failure, the knickpoint was allowed to erode and migrate to a position just upstream of topographic profile H, at which point flow was stopped and a mid-removal topographic image was taken for analysis. Flow was immediately brought back to the desired discharge and held constant for an additional 9 hours (prototype equivalent time), at which point another topographic image was taken.

Removal Run #	Modeled Discharge	Cofferdam Notch Position
1	2500 cfs	river right
2	2500 cfs	river right
3	2500 cfs	river left
4	2500 cfs	river left
5	5500 cfs	river right
6	2500 cfs	center
7	2500 cfs	river left
8	2500 cfs	river right

Table 1. Summary of eight dam removal scenarios during this study. See figure 2 for notch locations on cofferdam.

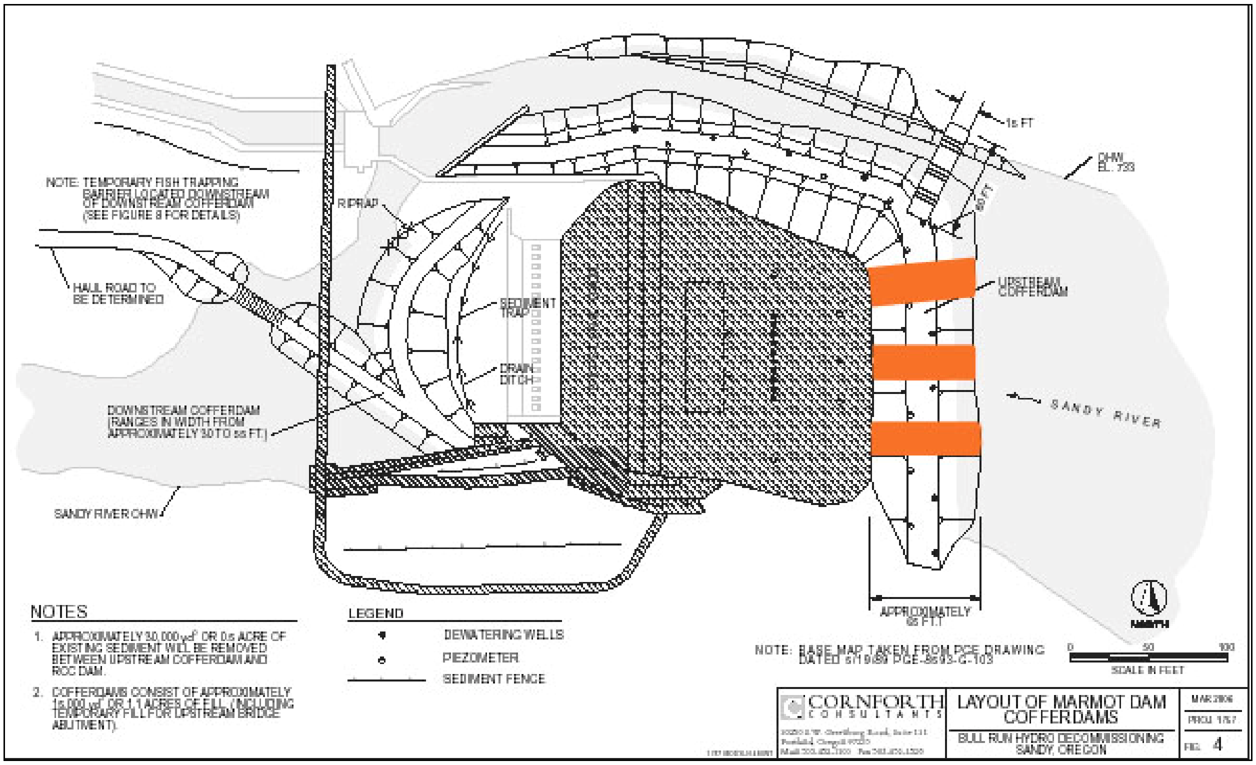


Figure 2. Engineering design plans for cofferdam. Additions include approximate notch positions used during model studies at St. Anthony Falls Laboratory. River left notch located 55 ft (prototype units) at center from river left river bank when looking downstream. Center notch located 112 ft (prototype units) at center from river left bank. River right notch located 168 ft (prototype units) at center from river left bank.

Observations:

The results of the model simulations suggest that, at a sustained failure discharge of 2500 cfs, the location of cofferdam failure, the location of the initial knickpoint, and the path of the knickpoint migration through the reservoir sediments depend largely on the position of the notch in the cofferdam. The data also suggest that sediment terraces formed and ultimately abandoned by the down-cutting river are larger and higher for a river right notch location than a river left notch position. We discuss these results further below.

Knickpoint Trajectory

The failure of the cofferdam through a notch focuses flow and sediment scour in the excavation work zone of the Marmot Dam site and quickly leads to the formation of an upstream migrating waterfall or knickpoint. A knickpoint is a zone of intense hydraulics (hydraulic jumps and standing waves) and sediment scour, which migrates upstream by eroding sediment. The data collected in this study suggest that the first knickpoint forms at the location of the cofferdam notch. This is not a surprising result. What is surprising however is the significant difference in knickpoint trajectory observed between a river right notch and river left notch position, which is due to the unique river valley (bedrock) alignment immediately upstream of the Marmot Dam site.

Figure 3 is a shaded relief image of the Sandy River upstream of the Marmot Dam. As the river approaches the Marmot Dam it encounters a sinuous bedrock reach. The river bends to the left at 1, to the right at 2, and then back to the left just upstream of the dam at 3. It is important to recognize that the river valley is actually narrower than the current water surface width at the dam. In actuality, the length of the north-south dam crest is the width of the valley and the east-west wing wall crest is the approximate alignment of the northern bedrock river bank that extends to the east from the dam crest and attaches to the bank upstream of the dam (indicated in figure 3 with a dashed line). Once failure occurs at this site and river incision begins, the river will quickly drop back inside this narrow bedrock valley.

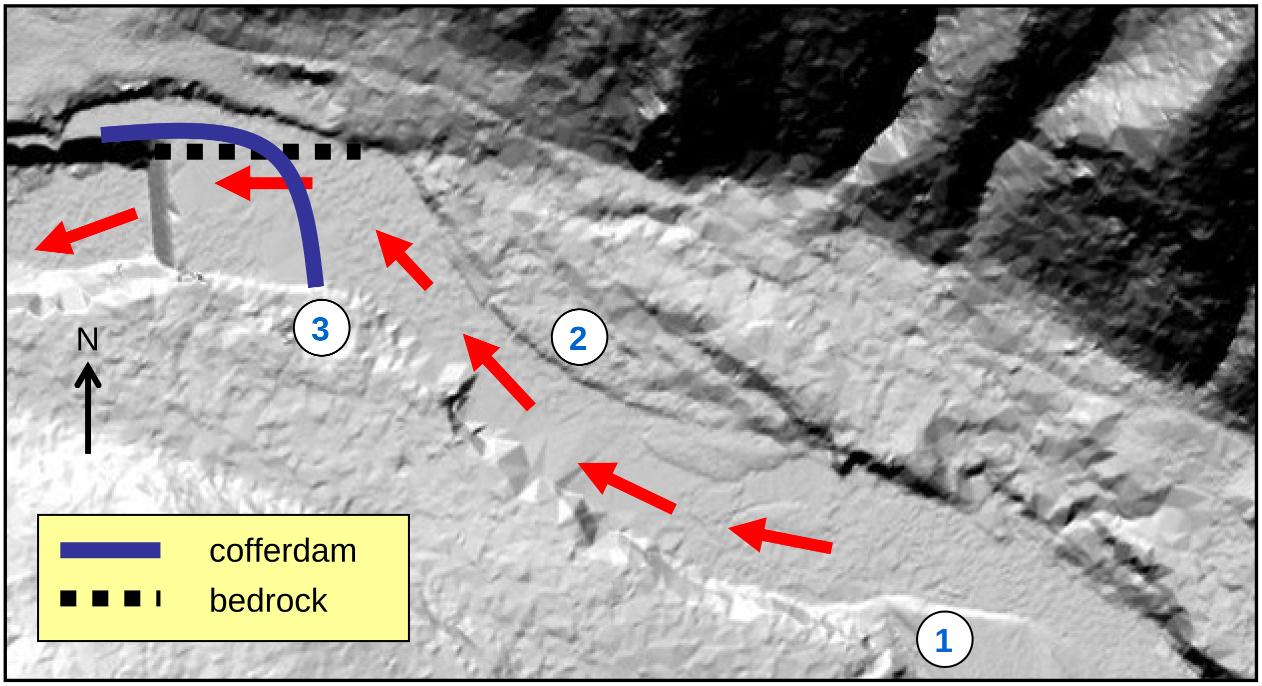


Figure 3. Shaded relief map of the Sandy River upstream of Marmot Dam with annotation.

The model simulations suggest that the notch position determines where the knickpoint begins, but after it passes into the narrow bedrock reach, it is directed by the sinuous bedrock walls. The post removal primary flow path of the Sandy River is against the outsides of bends and against the north valley wall indicated by the dashed line in figure 3. A common characteristic of laterally migrating alluvial rivers is that they become "hung up" when they become impinged on their bedrock valley wall and no longer avulse laterally toward the river center. This is the case in the simulations; for a river right cofferdam notch, the knickpoint forms near the north bedrock river bank and, because of the unique flow alignment entering this reach, the river sticks against this wall. The effect is a narrower, yet deeper incision, with minimal lateral migration of the flow. The simulations of river left cofferdam notching differ in that it forces the failure at the south bedrock bank and, because of the high sinuosity and the desire for the river to push to the outside bank, we observe much more lateral migration. This results in a more uniform grade adjustment across the valley width.

Appendix B shows a series of timelapse photographs from a right notch experiment (removal run 1) and a left notch experiment (removal run 3) at various intervals after the collapse of the cofferdam. Note the initial and final trajectories of the main channel of flow. At the end of each experiment, the final flow trajectory flows along the river left inside bend of the river in the upstream section until the cofferdam position, at which point it deviates from that bank and proceeds to the outside bank along river right (figure 4). Flow then returns to the river left bank. A river right cofferdam notch position orients the flow trajectory in this position immediately after collapse. Since this is the naturally stable position, the flow remains in this path and proceeds to incise into the deposit, leaving other parts of the deposit untouched. A clear example is the river left section of the cofferdam that remains attached to the wall—the flow is never able to avulse and clear this area out. When the cofferdam is notched along the river left side, the flow initially follows a route that erodes much of the river left portion of the deposit. Through time, the flow migrates toward its stable flow path as described above, and during this process it sweeps the river valley, thereby removing a more laterally uniform depth of sediment.

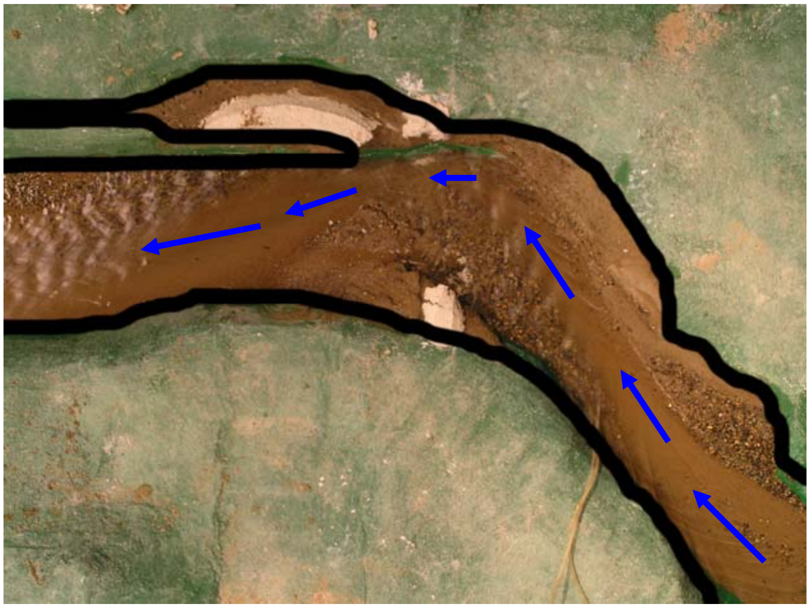


Figure 4: Generalized illustration of final flow trajectory for all cofferdam notch positions. Background image taken from removal Run 1.

Abandoned Sediment Terraces

A primary concern related to the dam removal is the abandonment of sediment terraces that would result from rapid down cutting through the sediment after the collapse of the cofferdam. Once the river stage is lowered due to upstream knickpoint migration and grade adjustment, it will be difficult for the river to clear away abandoned terraces. In addition, the erosion that does occur will be in the form of undercutting and could result in unstable cliffs and cause high banks to slough off into the river. Because of this concern, we focused our observations on these terraces and the surrounding valley morphology after each removal configuration.

Analysis of pre-removal and post-removal topographic profiles provided quantitative estimates of volumes eroded during model studies (table 2). Volume estimates indicate that a river left notch placement, on average, eroded larger quantities of reservoir sediments, both in terms of volumes and percent valley fill. A river right or river center notch placement typically failed to erode large volumes. Due to a higher shear stress resulting from a much larger discharge, the removal scenario simulating 5500 cfs resulted in the highest quantity of sediment removal and redistribution. Only one scenario was simulated with this high discharge, so we were not able to speculate if a river left notch position would again be more efficient than a river right or center notch position; however, the high discharge proved to spread the knickpoint across the entire width of the basin and should therefore be repeatable for any of the three notch locations. If an excessively large discharge (e.g. 5500 cfs) is expected following fall storm events, cofferdam notch positioning will not influence future morphology as much as during a lower failure discharge.

Removal Run #	**Estimate volumes eroded: cm^3 (model)**	**Normalized volumes: cm^3 (model)***	**% valley fill eroded (model)**
1 (RR)	29699	29699	30.8
2 (RR)	31880	29186	34.4
3 (RL)	33911	31046	36.5
4 (RL)	31066	27662	34.3
5 (RR)**	37557	34875	40.2
6 (RC)	29901	25574	33.1
7 (RL)	35103	31256	38.9
8 (RR)	29259	26415	30.9

Table 2: Summary of estimated volumes of sediment eroded from upstream reservoir.
*Volumes are adjusted to a constant time duration to allow comparison.
(** simulated 5500 cfs; RR – river right; RL – river left; RC – river center)

Topographic profiles from two experiments are shown in Appendix C (removal run 3: river left notch placement; removal run 8: river right notch placement). During experiments, rapid incision occurs as the knickpoint migrates upstream and redistributes reservoir sediments. Depending on the efficiency of redistributing sediment and adjusting fluvial grade across the entire valley width, occasionally patches of perched sediment and terraces remain at the end of removal scenarios. Topographic profiles show possibilities for large abandoned terraces to remain intact after incision of the river. Examples of this are seen in profiles B and C from removal run 8. Converting to prototype units shows that abandoned terraces have potential to range in sizes up to several meters tall. Projected prototypical abandoned terrace heights range from 1 to 4 meters (3 to 13 feet) following river left notch position scenarios and 3 to 6 meters (10 to

20 feet) following river right notch position scenarios. These could potentially produce high risk situations to the area and its surroundings.

References:

Stillwater Sciences. 2000. Numerical Modeling of Sediment Transport in the Sandy River, OR Following Removal of Marmot Dam. Technical Report prepared for Portland General Electric, Portland, Oregon.

Portland General Electric Company. 2005. Bull Run Decommissioning Contract No. 1 Marmot Dam Removal, Sandy, Oregon.

Appendix A: Distorted Geometric Scaling

Introduction

The physical characteristics of the model constructed for this study were computed from well tested procedures developed in the hydraulic and aerospace fields that strive to achieve similarity in geometry and kinematics between the model and the prototype system. This section describes the methods used for the Marmot model study and we summarize the scaling relationships.

The Marmot model is a distorted geometrically scaled model. It is described as distorted because the horizontal scaling is different from the vertical. The procedure for scaling involved defining the vertical and horizontal length scales and using these relationships with three dimensionless numbers that describe the dynamics of the flow and sediment transport. The model has similarity if these dimensionless numbers are the same in both the model and the field. In the following discussion we refer to the field system (i.e. Sandy River) as the “prototype” and the physical model as the “model”. We will use the subscripts p and m to refer to prototype and model parameters, respectively.

Geometry

The length scales for the models were chosen to maximize the extent of the model river in the horizontal and vertical space available in the laboratory. The horizontal scale, α_h, and the vertical scale, α_v, were defined as follows:

$$\frac{L_p}{L_m} = \alpha_h = 150 \tag{1}$$

$$\frac{H_p}{H_m} = \alpha_v = 70 \tag{2}$$

Using equation 1 and 2 we are able to scale all horizontal lengths, L, and vertical heights, H, from the prototype to the model such as river width and alignment, dam width and vertical height, and slopes.

Slope

Slope or gradient is dimensionless and measured as rise over run or $\Delta H/\Delta L$ and can be written as:

$$S = \frac{H}{L} \tag{3}$$

$$\frac{S_p}{S_m} = \frac{H_p L_m}{H_m L_p} \tag{4}$$

Slope is therefore scaled as:

$$\frac{S_p}{S_m} = \alpha_v (\alpha_h)^{-1} = 0.467 \tag{5}$$

Water Discharge

Water discharge, Q, is an important component to the Sandy River and the removal of the Marmot dam. The dimensionless number that best characterizes the flow of water in open channel flow is the Froude number, Fr.

$$Fr = \frac{U}{\sqrt{Hg}} \tag{6}$$

Where U is the mean flow velocity, H is the flow depth, and g is the gravitational acceleration constant. Notice that the Froude number has no dimensions. To have similarity between the model and prototype we seek equality in the Froude number in both systems. It follows that:

$$Fr_m = Fr_p \tag{7}$$

$$\frac{U_m}{\sqrt{H_m g}} = \frac{U_p}{\sqrt{H_p g}} \tag{8}$$

Continuity in flow suggests

$$Q = U * A \tag{9}$$

Where A is the cross-sectional area of flow and is the product of a width (L) and depth (H) allowing (9) to be rewritten as:

$$Q = U * L * H \tag{10}$$

Substituting (10) into (8) gives:

$$\frac{Q_m}{L_m \sqrt{H_m{}^3 g}} = \frac{Q_p}{L_p \sqrt{H_p{}^3 g}} \tag{11}$$

Rearranging and substituting in (1) and (2) gives the scaling for discharge as:

$$\frac{Q_p}{Q_m} = \alpha_h * \alpha_v{}^{1.5} = 87849.3 \tag{12}$$

Grain size

The size and distribution of grains is an important model parameter. The scaling relationships utilize a second dimensionless number that characterize the dimensionless bed stress relative to resistance of the grains to motion. Our goal is to have similarity in the Shields Stress between the field and the model. The Shields stress, τ^*, is written as follows:

$$\tau^* = \frac{\tau_0}{(\gamma_s - \gamma_w) D} = \frac{\gamma_w HS}{(\gamma_s - \gamma_w) D} = \frac{HS}{1.65D} \tag{13}$$

Where H is the flow depth, γ_s and γ_w are specific weights of sediment and water, respectively, τ_0 is the bed shear stress, S is slope, and D is particle size. We seek to have similarity in Shields stress between the model and the prototype such that:

$$\tau_m^* = \tau_p^* \tag{14}$$

$$\frac{H_m S_m}{1.65 D_m} = \frac{H_p S_p}{1.65 D_p} \tag{15}$$

$$\frac{D_p}{D_m} = \frac{H_p}{H_m}\frac{S_p}{S_m} \tag{16}$$

Substitution of equation 2 and 5 into 16 gives the scaling relationship for grain size:

$$\frac{D_p}{D_m} = {\alpha_v}^2 (\alpha_h)^{-1} = 32.6 \tag{17}$$

Time

The derivation of the time scaling is done here by considering the units of velocity *U* as a length, *L*, over time *T*, such that:

$$U = \frac{L}{T} \tag{18}$$

Using continuity, $Q=U*L*H$, and rearranging 18 we can get the following general expression for time:

$$T = \frac{L^2 H}{Q} \tag{19}$$

Writing 19 for both the prototype and the model we derive the following scaling relationship for time:

$$\frac{T_p}{T_m} = \frac{\alpha_h}{\sqrt{\alpha_v}} = 17.9 \tag{20}$$

For the Marmot model the time scale is such that about 1.3 hrs in the model is equivalent to 24 hrs in the field.

Appendix B: Overhead timelapse image photo sequence.

At collapse

After 5 minutes

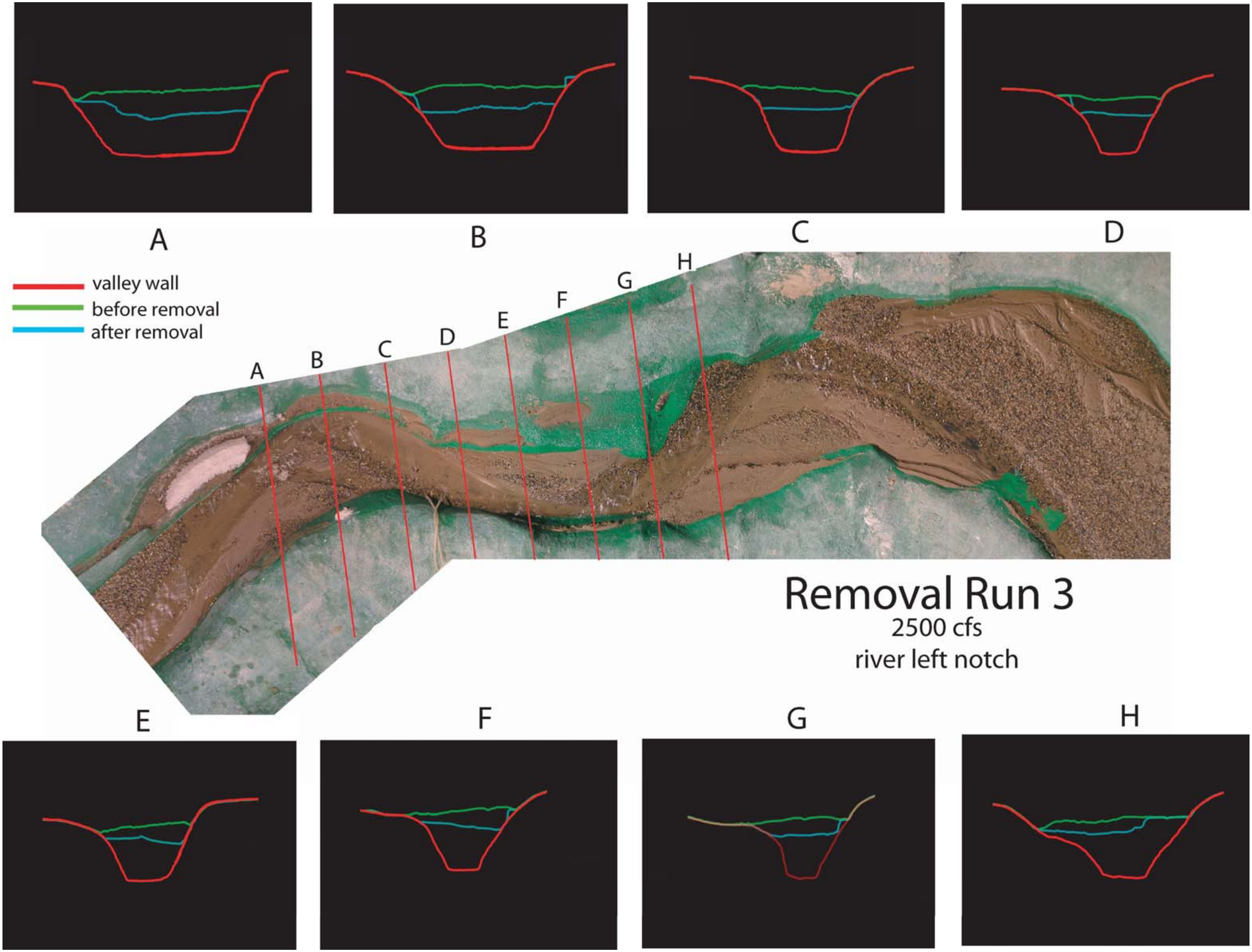
After 10 minutes

After 15 minutes

After 20 minutes

After 30 minutes

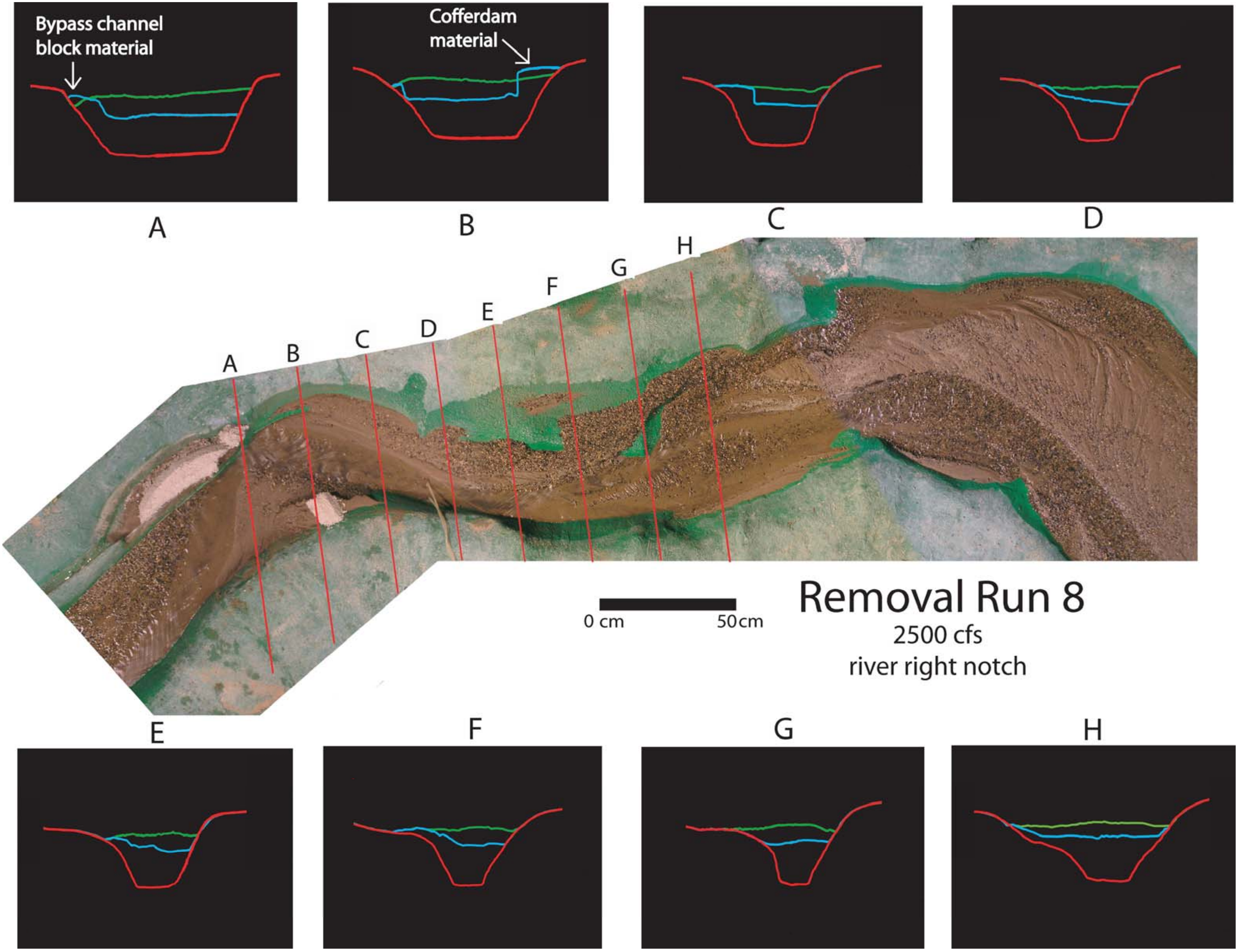
Appendix C (following 2 pages):
Topographic profile comparisons; pre-removal, post-removal, and bedrock valley.



Removal Run 3

2500 cfs

river left notch



Removal Run 8

2500 cfs

river right notch