RECLAMATION
Managing Water in the West

Analysis of Sediment Transport Following Removal of the Sandy River Delta Dam

Troutdale, Oregon

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
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Analysis of Sediment Transport Following Removal of the Sandy River Delta Dam

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I. Executive Summary

Project Background and Objectives

The Sandy River Delta Dam (SRD Dam) is located near the confluence of the Sandy and Columbia Rivers, east of Portland, Oregon. As a result of its closure in 1938 to improve fish passage through the Sandy River, flow has been redirected from the east (upstream) distributary to the west (downstream) distributary of the delta. The east distributary has since partially filled with sediment and supports dense riparian vegetation, including aged cottonwoods (Figure 1.3). Although once the main distributary channel, the east distributary is currently only activated under high flow conditions on the Sandy or Columbia Rivers.

Increased understanding of the ecological functions of the natural channel configuration and requirements of anadromous fish has initiated a reassessment of the role of the SRD Dam in improving fish passage. Recent efforts to improve aquatic habitat conditions have considered the removal of the SRD Dam. A hydraulic and sediment model of the system was proposed to more effectively evaluate possible effects related to removal of the SRD Dam

Objectives of the present study were to develop and apply a numerical model of the hydraulics and sediment transport of the delta system to assess potential impacts to (a) a mining operation on the Columbia River, just downstream of the confluence of the Sandy and Columbia Rivers, and (b) channel scour at a railroad bridge and two freeway bridges upstream of the Sandy River Delta, following the removal of the SRD Dam. Additional analyses were performed to (1) qualitatively evaluate how the planned removal of the Marmot Dam, located approximately 48 kilometers (km) upstream of the confluence with the Columbia River, might affect the accuracy of the numerical model, and (2) assess the impact of the removal of the SRD Dam on bank erosion along the right bank of the west distributary channel.

Development and Results of Numerical Model

In this study, several scenarios were created to evaluate impacts to sediment delivery to the mining area and channel scour near the upstream bridges if the SRD Dam is removed. The Existing Condition scenario was developed to represent the current conditions within the Sandy River Delta system. This scenario served as a benchmark with which other scenarios might be compared. The Removed Dam scenario was created such that only the SRD Dam and the sediment plug west of the dam were removed relative to the Existing Condition scenario. This scenario may represent conditions immediately following the dam removal. The Eroded East Channel scenario was based on estimated erosion along the east distributary channel and deposition in the west distributary channel several years after dam removal. This scenario was intended to reflect likely adjustments in channel morphology a number of years after the SRD Dam removal. Finally, the Complete Blockage scenario was developed to study the worst-case (or extreme case) scenario for which the entire Sandy River flowed to the east channel under all flow events.

A quantitative analysis with the 2D hydraulic and sediment model, GSTAR-W, reached the following conclusions:

(1) The impact on sand (sizes from 0.0625 to 2.0 mm) delivery to the mining area was estimated based on the numerical analysis, and it is summarized in Table I.1 below. The range in percentage represents simulated results at different cross sections: lower numbers correspond to a cross section in the west distributary channel while the higher numbers indicate reductions to an area just downstream of the confluence of the west distributary of the Sandy River and the Columbia River (see Figure 5.33). Note that higher percentage reductions were predicted for smaller floods. Therefore, the percentage of sand reduction to the mining area could be higher than the 2-year values for flows less than the 2-year flood. However, flows of smaller magnitude generally transport small quantities of sediment relative to the quantities transported under flood flows. Only those at and above the 2-year flood, therefore, were meaningful.

Table I.1. Model estimated percentage of reduction in sand delivery to the mining area for different scenarios and under varying Sandy River floods.

Sandy River Flow	% Reduction in Sand Delivery to the Mining Area		
	Removed Dam	Eroded East Channel	Complete Blockage
2-Year	12 ~ 15 %	31 ~ 39 %	~ 100 %
5-Year	8 ~ 13 %	24 ~ 32 %	~ 100 %
10-Year	7 ~ 10 %	20 ~ 27 %	~ 100 %

(2) Results from the worst-case scenario analysis based on the Complete Blockage scenario, along with other hydraulic results analyzed, indicate that the sediment source of the mining area was primarily the west distributary channel of the Sandy River. Sand contributions to the mining area from the Columbia River were estimated to be small. Therefore, sand delivery to the mining area would be reduced significantly, if not completely, if the Sandy River flow is directed completely towards the east distributary channel (Table I.1).

(3) More Sandy River sediments would be deposited on the east delta, located at the mouth of the east distributary channel of the Sandy River, if more flow is directed toward the east channel. These deposits were not transported to the mining area under the conditions simulated, i.e., when the Columbia River was at about 160 thousand cubic feet per second (kcfs) and the Sandy River was at flood flows. A question then arises as to whether the east delta sediments may be transported to the mining area when the Columbia River is at flood conditions. Based on the hydraulic analysis, it appears that the east delta sediments would not be a major source to the mining area, even if the Columbia River is at a flood stage.

(4) The channel morphology in the east and west distributary channels would change if the SRD Dam was removed. The flow split between the two channels is the key parameter in determining the sediment impact to the mining area. If the flow split is known, the sand delivery reduction may be estimated using the results in Table I.1 through interpolation.

(5) The current analysis did not show a noticeable impact to the flow hydraulics or sediment transport at the interstate highway and railroad bridges due to the SRD Dam removal. Note that the conclusion was based on results within a few years after the dam removal. If, over a longer time period, much more water flows through the east distributary channel, changes in bed elevation could result in noticeable hydraulic and geomorphic impacts at the bridges. When the west distributary channel was completely blocked, model results indicated that local scour at the bridge area was expected to be reduced. Under the Complete Blockage scenario, velocities at the bridge locations decreased from 14 percent to 30 percent.

(6) Note that the above conclusion concerning the bridges upstream of the fork of the east and west distributary channels reflects local scour at the bridges during flood events. Impacts to the bridge area due to larger-scale geomorphic changes were not considered.

(7) Despite various uncertainties, we have confidence in the percentage change in sediment delivery to the mining area predicted in this study (Table I.1), as well as the qualitative trends predicted. Caution has to be exercised concerning the absolute values of sediment transport rate and quantities of deposition reported. Reported absolute values may contain a high degree of uncertainty and should be used primarily as a means to compare alternatives.

Qualitative Analysis of the Removal of the Marmot Dam

Numerical modeling of sediment transport following the removal of Marmot Dam performed by Stillwater Sciences (2000a) determined that up to 0.4 meters (m) of sand aggradation may occur within the region of the current study. To analyze the impact of the removal of Marmot Dam on the model results, two possible scenarios were considered: (1) sediment from Marmot Dam would only accumulate in the west distributary channel and (2) sediment from Marmot Dam would accumulate in both the east and west distributary channels. Scenario 1 is most likely to occur if the SRD Dam is removed following arrival of reservoir sediments from the Marmot Dam, while scenario 2 is expected to occur if the SRD Dam and sediment plug are removed prior to removal of the Marmot Dam.

Scenario 1 would result in greater flow conveyance through the east channel and could potentially impact the results of the model, the extent to which can not be evaluated without further modeling. Under scenario 2, the predicted distribution of flow through each channel and sand transported to the mining operation would be minimally affected.

Without a numerical model of these scenarios, the only qualitative conclusion is that the addition of sediment to the system following removal of Marmot Dam will provide a short-term increase in the volume of sediment delivered to the mining operation. Additional modeling could provide greater insight as to the degree to which sediments from removal of Marmot Dam, in conjunction with removal of the SRD Dam, impact sand delivery to the mining area and scour at the bridges sites. Reclamation recommends that a monitoring program following removal of both Marmot Dam and the SRD Dam be initiated to test the hypotheses proposed in this study.

Assessment of Bank Erosion in the West Distributary Channel

Under the present conditions of the Sandy River, the right bank of the west distributary channel is actively eroding downstream of the fork of the east and west distributary channels. The eroded right bank is located on the outside bend of the river. Rip rap and wooden piles protect approximately 800 feet (ft) of the right bank of the west distributary. Downstream from the rip rap, the current channel bank is eroding.

Due to hydraulic processes acting near the bank, depth-averaged velocities and bed shear stress values at points near the bank should be correlated to the bank erosion and can be used to compare expected rates of bank erosion. Depth-averaged velocities and bed shear stresses for 5 points near the right bank of the west distributary were quantitatively compared for the Existing Condition scenario, the Removed Dam scenario, and the Eroded East Channel scenario. Results of the comparison generally indicate small reductions (typically less than 10 percent) in the velocities and shear stress values following removal of the SRD Dam. Accordingly, the erosion rate of the right bank will slightly decrease under the 2-, 5-, and 10-year flows after dam removal. Under the extreme case of the Complete Blockage scenario, bank erosion due to hydraulic processes of the river at the locations of concern would cease completely.

In summary, the removal of the SRD Dam is not anticipated to accelerate bank erosion along right bank of the west distributary channel; conversely, it may marginally allay erosion of the west distributary channel. Following removal of the SRD Dam, bank erosion without protection is likely to continue, but at a reduced rate.

1.0 Project Background

The Sandy River is a tributary to the Columbia River, located east of Portland, Oregon. Headwaters of the Sandy River originate from glacial slopes of Mount Hood, and flows of the main stem travel northwest until meeting the Columbia River in Troutdale, Oregon. The watershed of the Sandy River encompasses approximately 1,316 km^2, and the river is regulated by several small- to medium-sized dams, including the Bull Run Dams, the Little Sandy Dam, and the Marmot Dam (Stillwater Sciences, 2000a).

Basin geology indicates the occurrence of Tertiary and Quaternary volcanic events and Pleistocene glaciations (Stillwater Sciences, 2000b). The most recent eruptive period of Mount Hood, the Old Maid episodes, occurred approximately 200 years ago. During this period, a single, large lahar, a mixture of volcanic debris and water, triggered between 10 to 20 meters of sediment aggradation in the Sandy River valley (Rapp, 2005; Stillwater Sciences, 2000b). The Sandy River has since eroded through much of this deposited material, resulting in high terraces and actively eroding banks (Figure 1.1). Complete characterizations of the geological setting of the Sandy River are provided by Rapp (2005) and Stillwater Sciences (2000b).

Figure 1.1. Geologic evidence of fine sediment deposition and subsequent bank erosion following Old Maid volcanic episodes nearly 200 years ago.

Located at the confluence of the Columbia and Sandy Rivers, the Sandy River Delta is a relic delta originally formed from volcanic lahars following Mt. Hood eruptions (Rapp, 2005). Large debris flows accompanying the Bonneville

Landslides and ensuing floods on the Columbia River have reworked the delta since its original formation (Montgomery, Watson & Harza, 2001). The present-day Sandy River Delta functions as a Columbia River Island-Slough System under high flow conditions on the Columbia River, in which Columbia River flows enter the east distributary channel of the Sandy River and force water upstream and into the west distributary channel.

Prior to 1931, the delta divided flow from the Sandy River into two distributary channels approximately 1.8 miles apart at their mouths. The east (upstream) distributary channel transported most of the flow to the Columbia River, while the west (downstream) channel acted as a secondary flow path that was primarily active under high flow conditions on the Sandy and Columbia Rivers. A high flow event in 1904 caused a large volume of sediment aggradation at the mouth of the west distributary channel, which may have completely blocked fish passage under low flow conditions (Craig and Suomela, 1940).

To improve fish passage, the SRD Dam was constructed across the east distributary channel. The original dam, built between 1931 and 1932, consisted of a 750-foot-wide, 5-foot-high dam constructed of two rows of pilings (Brockmann, 1946). In 1938, additional funding was used to improve the dam to an 8- to 10-foot-high wooden structure filled with riprap-sized rock (Craig and Suomela, 1940; Brockmann, 1946; Maben, 1993). Installation of the dam resulted in a redirection of flow to the west distributary of the delta, providing year-round fish passage (Figure 1.2). The east distributary has since partially filled with sediment and supports dense riparian vegetation, including aged cottonwoods (Figure 1.3). A sediment plug has accumulated on the west side of the dam.

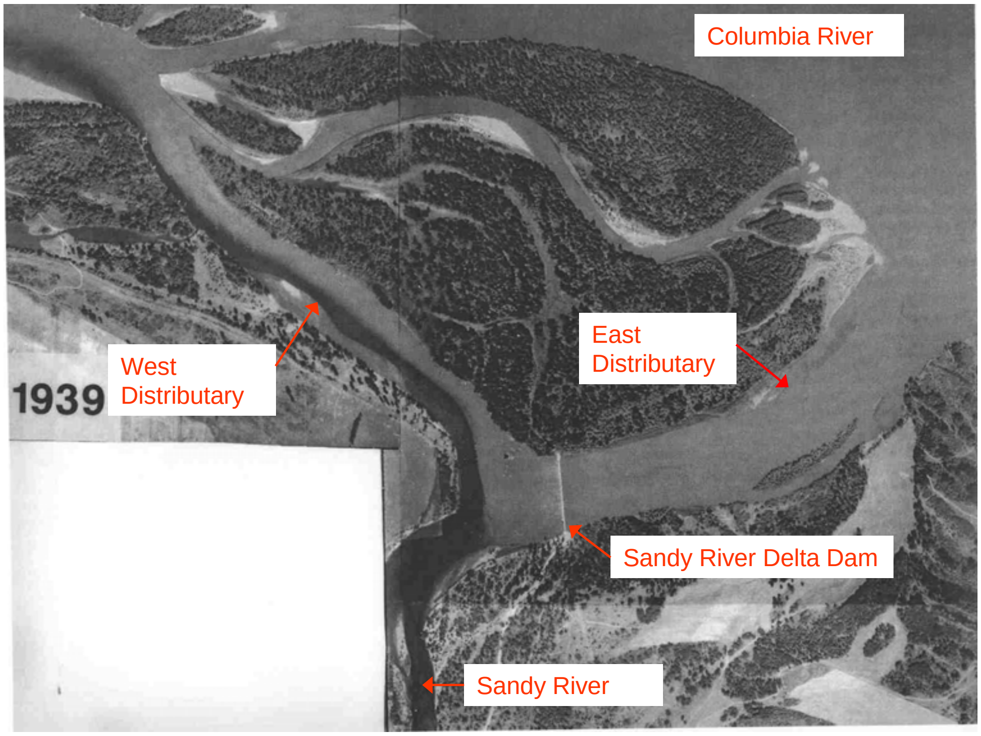


Figure 1.2. Sandy River Delta following closure of the SRD Dam in 1939.

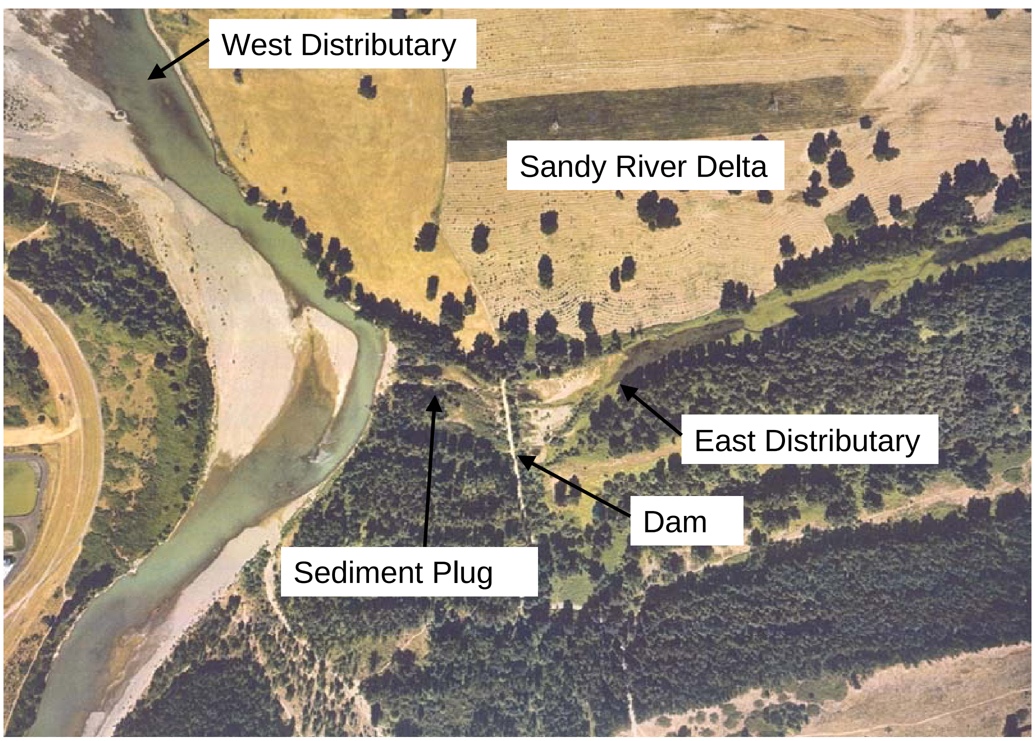


Figure 1.3. Present conditions of the SRD Dam and the sediment plug that has accumulated west of the dam.

Increased understanding of the ecological functions of the natural channel configuration and requirements of anadromous fish has initiated a reassessment of the role of the SRD Dam in improving fish passage. Recent efforts to improve aquatic habitat conditions have considered the removal of the SRD Dam. The goal of the dam removal would be to increase scouring flows through the east distributary channel to improve aquatic habitat conditions in the delta ecosystem and at least partially reestablish historic flow patterns to the Sandy River Delta.

2.0 Study Objectives

Several potential impacts of the dam removal still need to be examined. First, a sand and gravel mining company is currently operating on the Columbia River downstream of the confluence of the west distributary channel and the Columbia River (Figure 2.1). Currently, the effects of the dam removal on the volume and timing of sand- and gravel- sized sediment delivered to the mining operation are unknown. In addition, a railroad bridge and two highway bridges are located upstream of the division of distributary channels on the Sandy River (Figure 2.1). A hydraulic and sediment model of the system was proposed to more effectively evaluate possible effects related to removal of the SRD Dam, including reduced sediment delivery to the mining operation and local scour near the bridges.

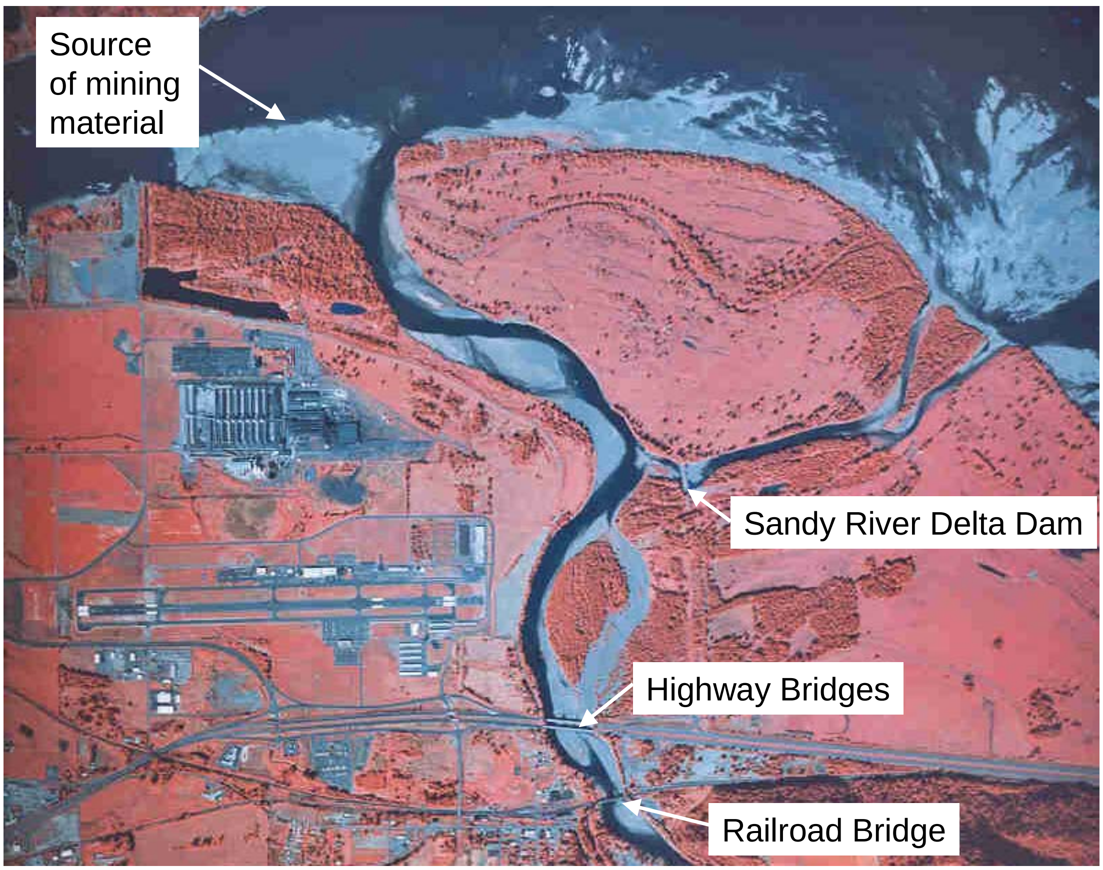


Figure 2.1. Locations of key issues within the project vicinity.

The primary objectives of the current study were to develop and apply a two-dimensional (2D) hydraulic and sediment transport model of the delta system to address (a) how sediment deliveries to a mining operation on the Columbia River change if the dam is removed, and (b) how the removal of the dam will impact channel scour near the railroad bridge and the two highway bridges.

Additional analyses were performed to (1) qualitatively evaluate how the planned removal of the Marmot Dam, located approximately 48 kilometers (km) upstream of the confluence with the Columbia River, might affect the accuracy of the numerical model, and (2) assess the impact of the removal of the SRD Dam on bank erosion along the right bank of the west distributary channel.

3.0 Data

A 2D hydraulic and sediment transport model was planned to evaluate existing conditions on the Sandy River and other alternatives following removal of the SRD Dam. Two-dimensional models generally require a large amount of topographic data to accurately represent river conditions and processes. An initial inspection indicated that a large amount of existing data for this area was available. The large amount of existing data not only made a multi-dimensional model possible, but it also reduced the amount of new data that would need to be collected. Rather than collecting all of the topographic and bathymetric data for the Sandy and Columbia Rivers in the study reach, additional data collection was limited the Sandy River, the margins of the Columbia River (shallow areas), and a portion of the Sandy River Delta.

3.1. Existing Data

Existing data were available for this project from several sources and were obtained prior to collection of new data. Existing data are described below.

3.1.1. U.S. Army Corps of Engineers (COE) Bathymetry

The COE regularly collects bathymetry data in the main channel of the Columbia River as part of the Columbia River Federal Navigation Channel Improvement Project. Data are collected in transects across the channel, spaced approximately 500 feet apart, and also parallel to the channel, consisting of 7 lines spaced 150 feet apart (Figure 3.1). COE data were collected in several horizontal coordinate systems and the Columbia River vertical datum. To maintain a consistent horizontal and vertical datum across all data, the COE data required conversion to the North American Datum of 1927 (NAD 27) state plane Oregon north with elevations referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). COE data were converted to the NGVD 29 vertical datum with a conversion provided by the COE (1978).

The project vicinity extended across three COE designated reaches of the Columbia River: the Lady Island Ranges (river mile 117+39+50 to 121+27+75), the Washougal Ranges (river mile 121+28+50 to 125+15+00), and Reed Island (river mile 125+15+75 to 128+49+25). Most of the survey data obtained from the COE were collected between 2003 and 2005; with the exception of the Reed Island transect data, which were collected in 1994. Due to the use of data from multiple surveys and the continual dredging of the river for navigation, the bathymetry data obtained from the COE collectively represent the average topography of the Columbia River over several years. Additional data collected were used to verify the existing COE bathymetric data (Section 3.2).

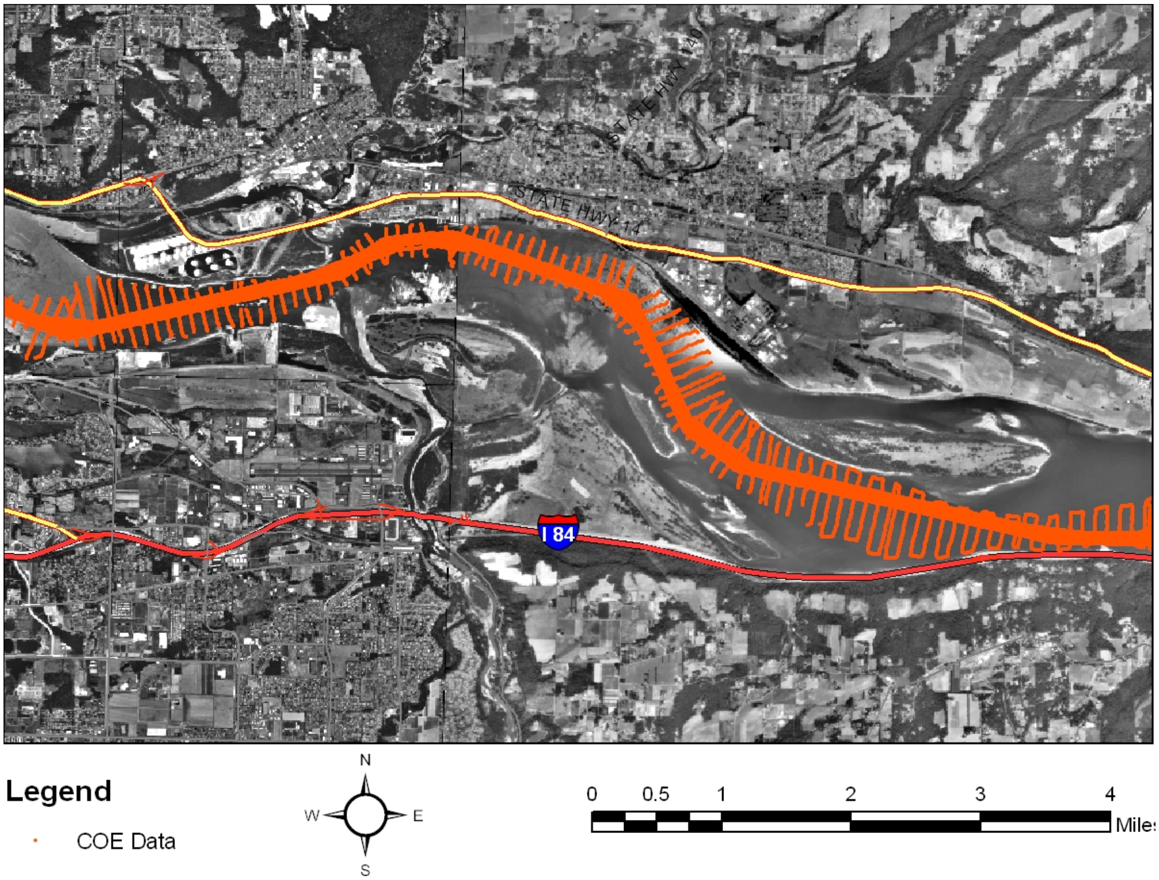


Figure 3.1. Location of U.S. Army Corps of Engineers Columbia River bathymetric data.

3.1.2. U.S. Forest Service (USFS) Contour Data

A 2-foot contour map of USFS property, located between Interstate 84 and the mouth of the Sandy River (Figure 3.2), was provided by the USFS, Columbia River Gorge National Scenic Area. The contour map was created from a photogrammetric survey of the site in 1993. The accuracy of the survey is not known, but elevations from the contour map generally agreed with ground shots collected with a Global Positioning System (GPS) in October, 2005. The contour data were collected in NAD 27 state plane Oregon north NGVD 29. Some of the data had to be adjusted due to migration of the Sandy River channel. In places where the river had migrated, contours were modified to more accurately represent the location and elevation of the river. Contours depicting bed elevations of the Sandy River were not used and were removed from the map.

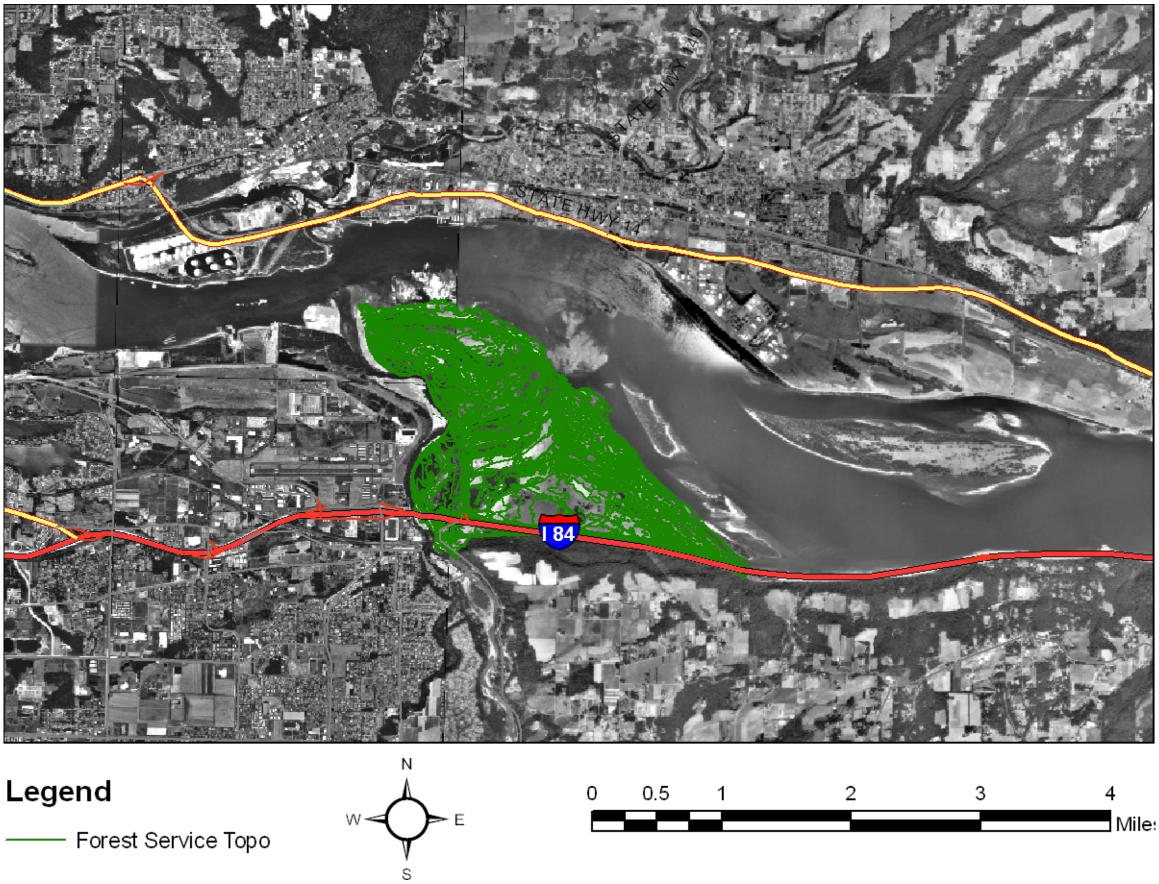


Figure 3.2. Location of USFS contour data.

3.1.3. USGS Contour Data

The study reach along the Columbia River is approximately 10 miles. Survey data for areas outside the main channel of the Columbia River and the USFS property was not available. Land surveying over 10 miles of banks and islands in this reach was outside the scope of the current study. In order to define elevations of the Columbia River banks and floodplain (Figure 3.3), contours were generated from a USGS 30-meter digital elevation model (DEM). The DEM was converted from the North American Datum of 1983 (NAD 83) UTM zone 10 to NAD 27 state plane Oregon north. In comparing the USGS contours to ground survey data, some discrepancies were noted. The contour data in the floodplain of the Columbia River were adjusted to more accurately reflect the ground survey data. These data were added to contain river flows and may not represent the true ground surface.

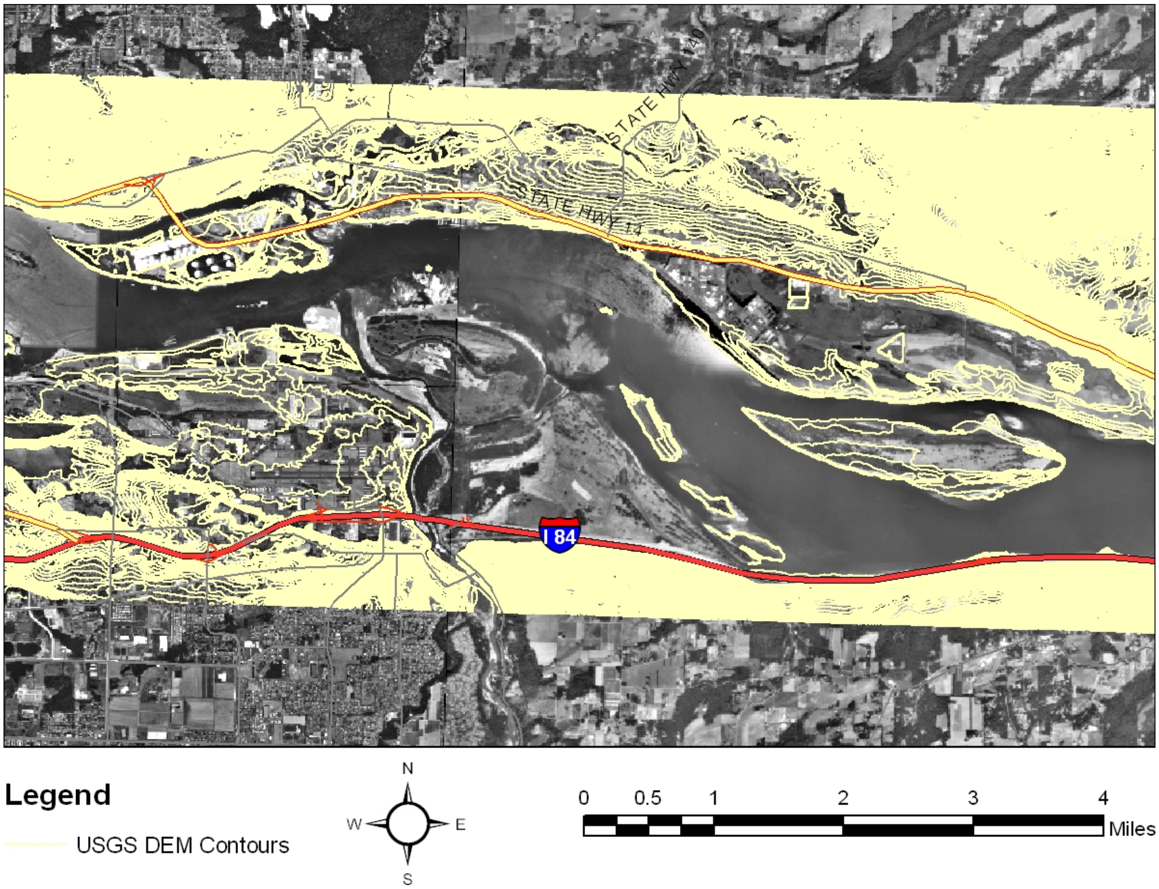


Figure 3.3. Contour lines generated from USGS 30-meter DEM.

3.2. New Data Collection

In order to fill in some of the missing data gaps and verify existing data, personnel from the Bureau of Reclamation (Reclamation) traveled to the project site in October 2005, to collect bathymetric data for the Sandy and Columbia Rivers, topographic data along the Sandy River and Sandy River Delta, and sediment samples from the Sandy and Columbia Rivers.

3.2.1. River Bathymetry

Bathymetry data for the Sandy River was collected using a RDI Rio Grande Workhorse Acoustic Doppler Current Profiler (ADCP). The ADCP was linked with a Trimble 5800 GPS and mounted on a 14-foot flat bottomed boat. Two runs were made down the Sandy River over 2 days. On the first day, data were primarily collected along the thalweg of the Sandy River. On the second day, additional data were collected by making multiple passes through pools. From the mouth of the Sandy River, the boat traveled upstream along the left bank of the Columbia River to obtain additional shallow-water data in the Columbia River.

A second ADCP and GPS were used to collect data along the Columbia River. This ADCP was mounted to a jet boat with a covered cabin so data could be collected during inclement weather. Data were primarily collected in areas not covered by the COE bathymetric surveys. However, data collected in areas already covered by the COE bathymetry were used to verify existing bed topography.

ADCP surveys collected depth information, which was used to determine bed elevations, and velocity data. Several discharge measurements were also collected on both the Sandy and Columbia Rivers (Figure 3.4). The GPS and ADCP data were collected in NAD 83 state plane Oregon north and NAVD 88. The data were subsequently converted to NAD 27 state plane Oregon north and NGVD 29.

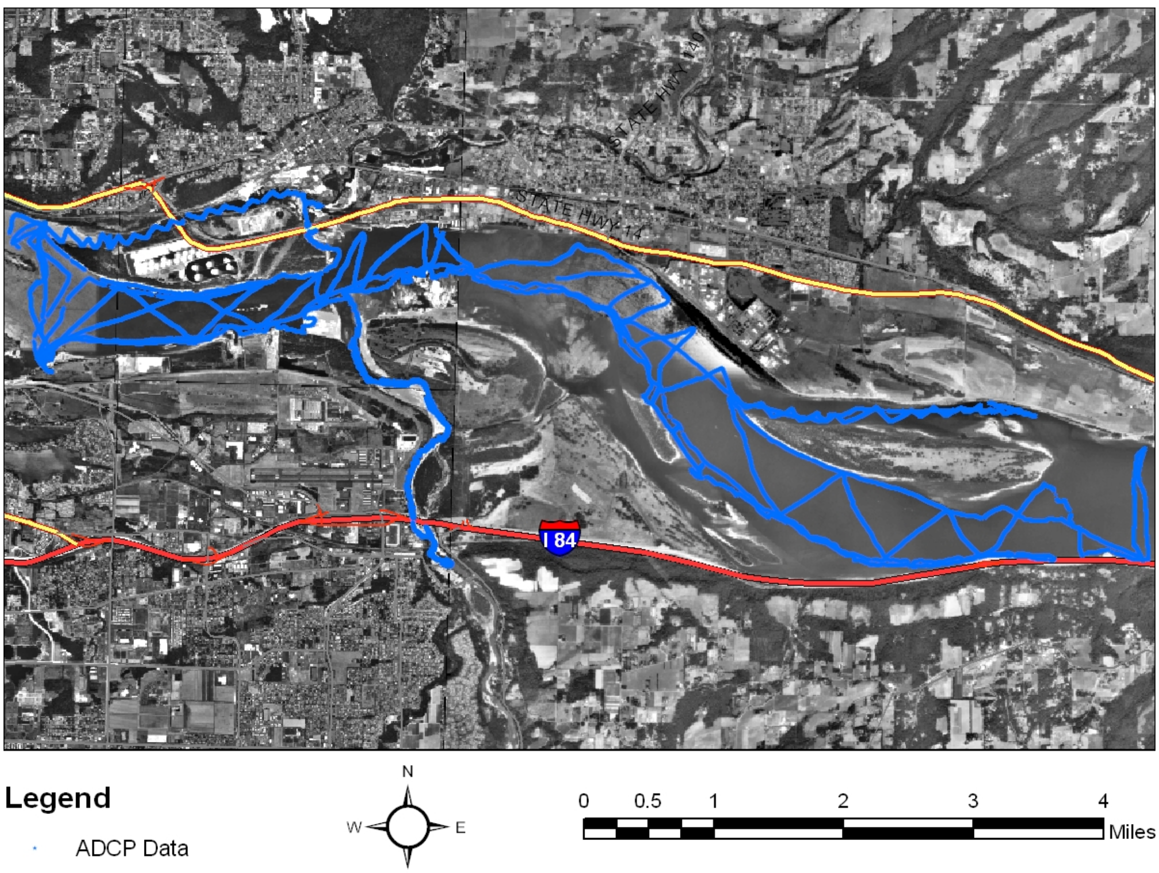


Figure 3.4. Location of bathymetric data collected with the ADCP.

3.2.2. Topographic Surveys

Flows on the Sandy and Columbia Rivers were very low during the survey. As a result, a substantial portion of the Sandy River channel and delta could not be surveyed by boat. Areas of the Sandy River that were dry during the collection of bathymetry data were surveyed with a Real Time Kinematic (RTK) GPS survey using Trimble GPS equipment. The ground surveys covered portions of the levee around Troutdale, the dry portion of the Sandy River, sand deposits at the mouth of the Sandy River, the distributary channels of the Sandy River, and portions of the Sandy River Delta between the mouths of the east and west distributary channels (Figure 3.5). These data were collected in NAD 83 state plane Oregon north NAVD 88 and later converted to NAD 27 state plane Oregon north NGVD 29.

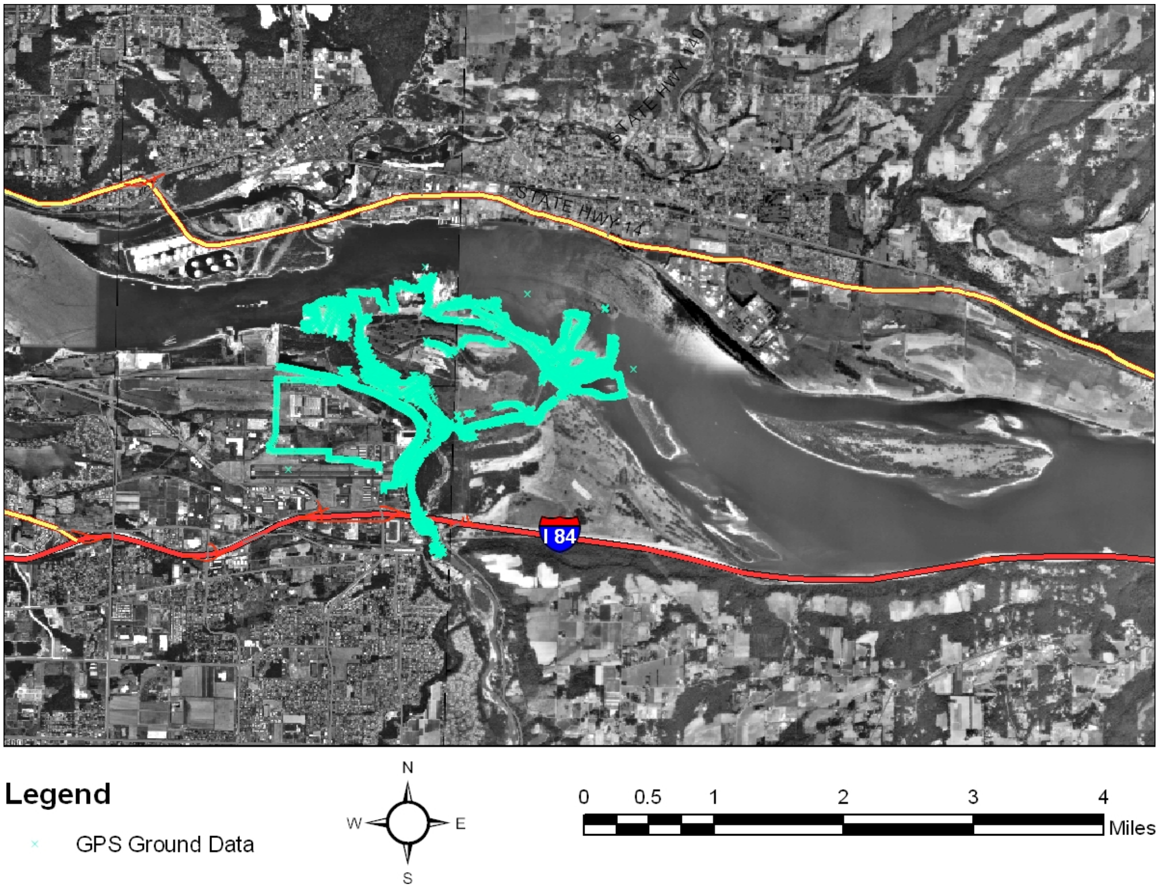


Figure 3.5. Location of topographic ground survey data with GPS.

3.2.3. Sediment Samples

Time, budget, and logistical constraints meant that only a limited number of sediment samples could be collected from the study reach. Sediment samples from the upper portion of the Sandy River were collected from the subsurface region to represent sediment conditions if the bed were fully mobilized. Samples were placed in 5 gallon bags and generally weighed between 50 and 60 pounds. Bunte and Abt (2001) recommend sample sizes from 90 to 660 pounds assuming a maximum sediment size between 64 and 128 mm. Logistically it is not possible to retrieve a 600 pound sample from the river without heavy equipment, field sieving, or many trips. Retrieval of sediment samples was complicated by the fact the too many samples would overload the boat used during the survey. A study designed to sample and analyze the distribution of sand and gravel in the lower Sandy River could provide more details on patch variability and grain size distribution. Samples were collected based on visual observations of geomorphic change and site accessibility.

Eight sediment samples were collected from the Sandy River and along the Columbia River (Figure 3.6). Samples from the Sandy River were collected from low bars that would be inundated at slightly higher discharges. Samples of sand deposits on gravel bars and of material contained within gravel bars were collected. The gravel samples were obtained from beneath the armor layer and are representative of a fully mobilized bed. Two samples were collected from sand deposits at the mouth of the Sandy River just upstream of the mining operation. These samples were later combined into Sandy River #4 for grain-size analysis. One sample was taken from sand deposits adjacent to the main channel of the Columbia River upstream from the Sandy River Delta. Additional samples were obtained from gravel deposits along the Sandy River Delta and the Columbia River. Figure 3.7 shows the particle size distributions for these samples.

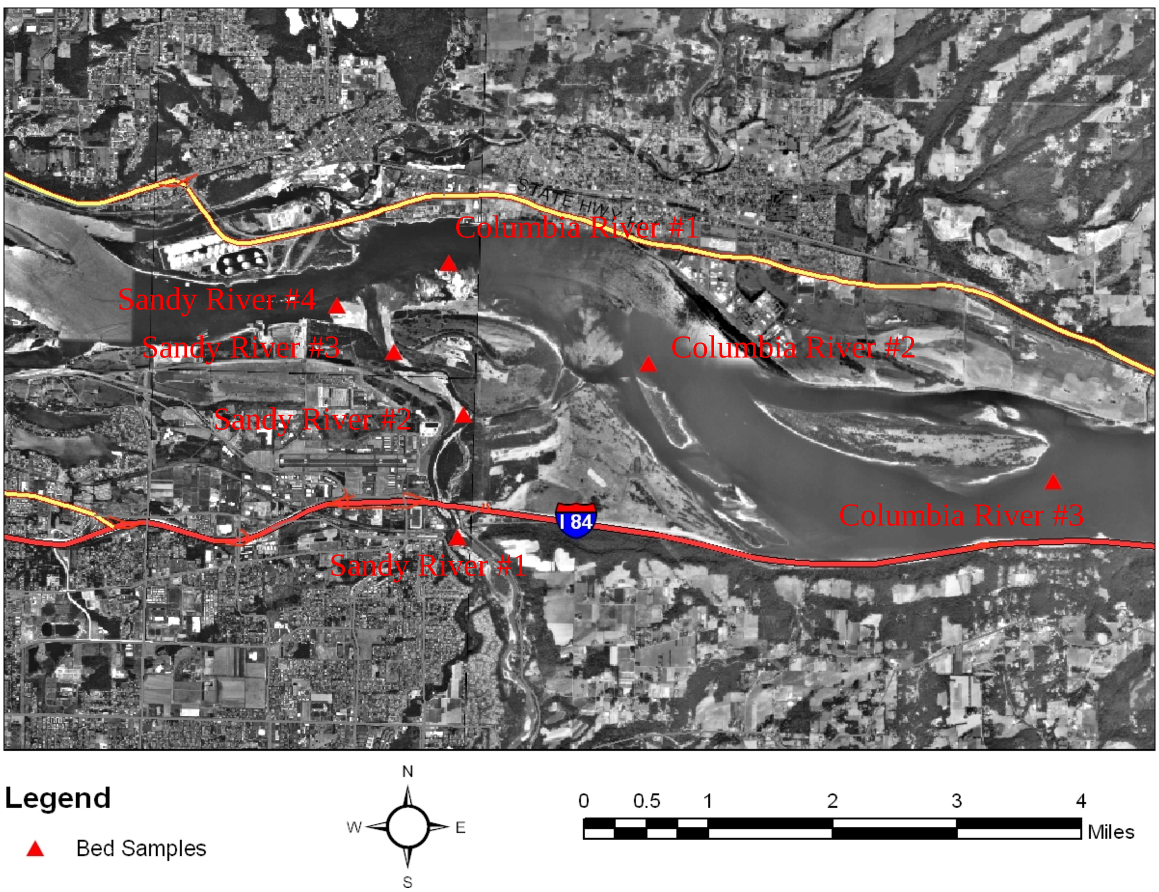
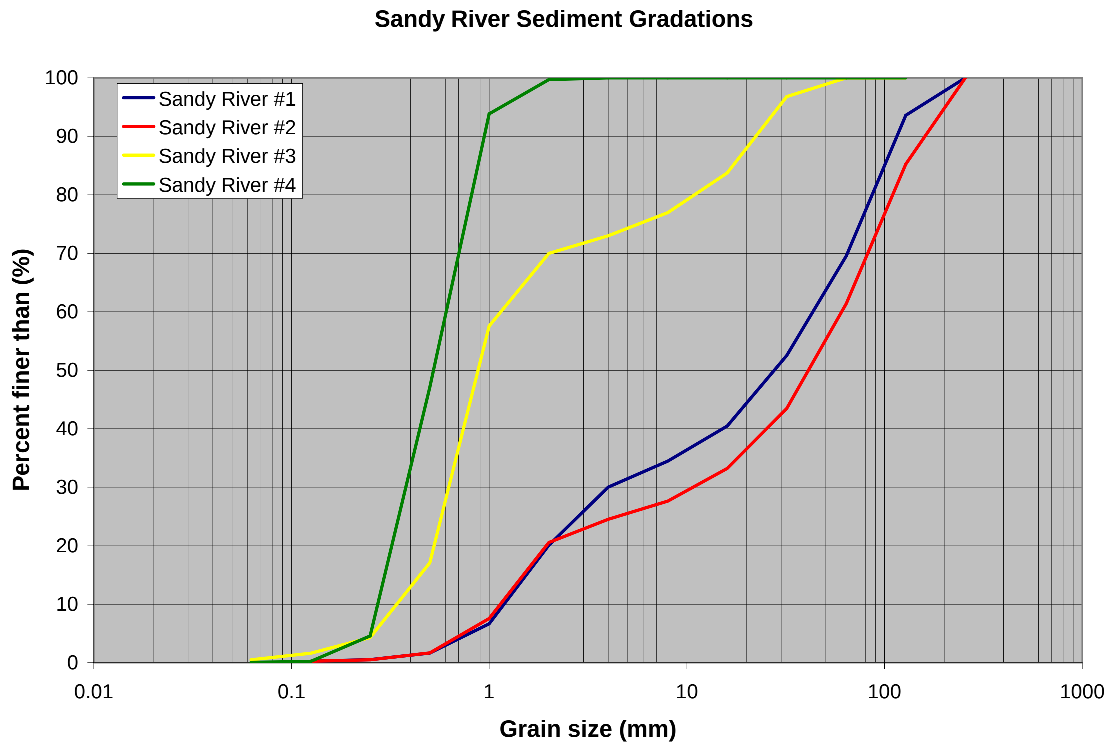


Figure 3.6. Location of Sandy and Columbia River sediment samples.



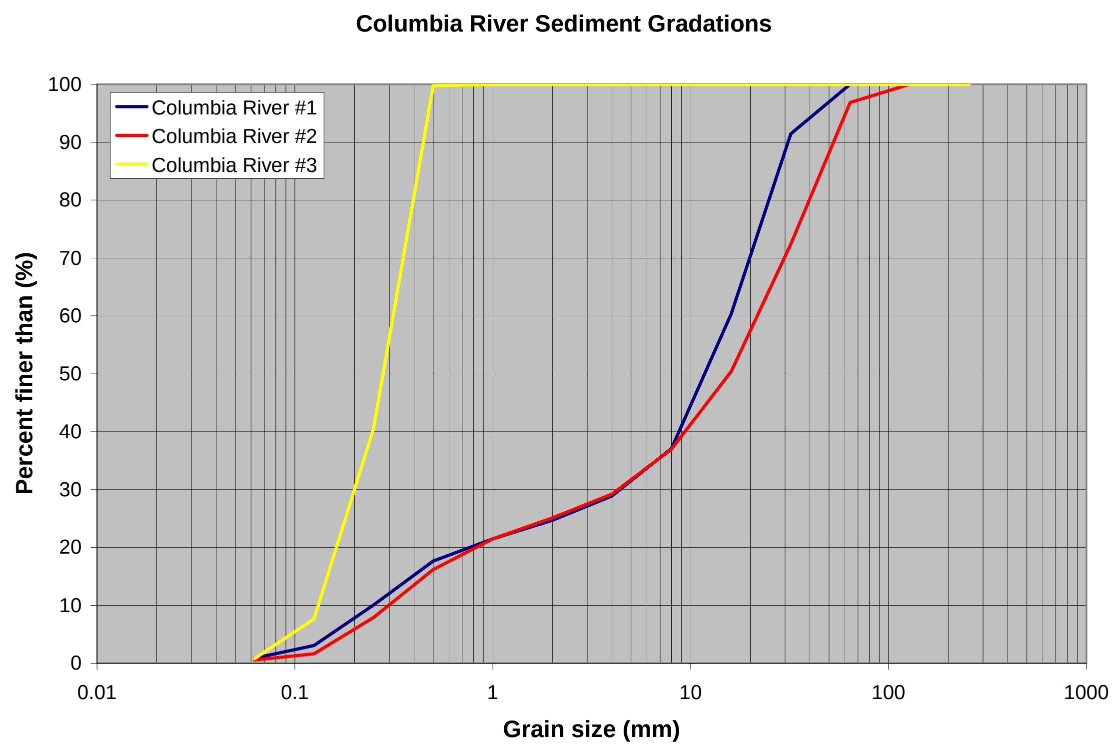


Figure 3.7. Particle size distributions for sediment samples collected on the Sandy and Columbia Rivers.

Additional information related to surface grain sizes of the Columbia River was available from the COE (2004). The COE provided general descriptions of the material taken from the channel during dredging operations. This information did not consist of particle size distributions but did include the percentage of silt, sand, and gravel in the samples. Descriptions of the COE samples were consistent with the samples collected during the field visit by Reclamation.

4.0 Methods of Analysis

4.1. Generalized Sediment Transport for Alluvial Rivers and Watersheds (GSTAR-W) Model

GSTAR-W is a 2D hydraulic and sediment transport model for river systems and watersheds. It has been developed primarily for use by Reclamation engineers to solve various hydraulic and sedimentation problems. GSTAR-W was selected as the numerical tool to assess the hydraulic and sediment impacts due to removal of the SRD Dam. This model was chosen for several reasons. First, there are not many mature 2D sediment models readily available to accomplish the objectives of the current project. GSTAR-W is a mature tool that has been applied successfully to other Reclamation projects. Reclamation's experience using the model should be valuable to conduct the current project. In addition, one of the project team members, Dr. Yong G. Lai, is the lead developer of GSTAR-W. Expert knowledge regarding a numerical model is critical for successful modeling and interpretation of the numerical results.

Just like any modeling project, a number of assumptions were made and certain aspects of the GSTAR-W capabilities were selected for the project. Specific assumptions and the associated uncertainties and model confidence are discussed in detail in Section 5.6. Reclamation is confident in the conclusions obtained from the model results presented in this report.

GSTAR-W is a 2D model that may be used to predict water flow and sediment transport for river reaches or water runoff and sediment delivery for a watershed. GSTAR-W adopts an approach for coupled modeling of channels, floodplains, and overland. Major features include the following:

<u>Hybrid Zonal Modeling:</u> GSTAR-W divides a watershed or river reaches into modeling zones. A zone may represent a one dimensional (1D) river reach or a 2D feature that may be solved with suitable models and algorithms. This layered hybrid approach facilitates the use of most appropriate models and solvers for each zone; it also extends the model to larger spatial and time scales.

<u>Geometry Representation:</u> The Arbitrarily Shaped Element Method (ASEM) of Lai (2000) is adopted for geometry representation. This unstructured meshing strategy is flexible and facilitates the implementation of the hybrid zonal modeling concept. It essentially allows the use of most existing meshing methods available. For example, it allows a natural representation of a channel network in 1D or 2D, as well as the surroundings (floodplains or watersheds). With ASEM,

a tight integration between the watershed and channel system is achieved, and a truly mesh-convergent solution may be obtained.

Major capabilities of GSTAR-W are listed below:

- GSTAR-W solves the 2D form of the diffusive wave or dynamic wave equations. The dynamic wave equations are the standard St. Venant depth-averaged equations;
- Both diffusive wave and dynamic wave solvers use the implicit scheme so that solution robustness and efficiency may be achieved for the majority of applications;
- Both steady or unsteady flows may be simulated;
- Unstructured or structured 2D meshes, with arbitrary element shapes, may be used with GSTAR-W. In most applications, a combination of quadrilateral and triangular meshes works the best. Cartesian or raster mesh is just a special mesh that may also be used by GSTAR-W;
- All flow regimes, i.e., subcritical, transcritical, and supercritical flows, are simulated simultaneously;
- Solution domain may include a combination of main channels, flood-plains, and overland;
- Both steady and unsteady sediment transport may be simulated with the nonequilibrium approach for nonuniform sediment transport;
- Sediment transport module includes more than 10 non-cohesive sediment transport capacity formulae that are applicable to a wide range of hydraulic and sediment conditions.
- Fractional sediment transport with bed sorting and armoring;

GSTAR-W is a 2D model, and it is particularly useful for problems where a 2D effect is important. Examples include flows with in-stream structures, through bends, with perched rivers, and for multiple channel systems. A 2D model may also be needed if one is interested in local flow velocities and eddy patterns.

4.2. Modeling Alternatives

Four modeling scenarios were identified for hydraulic and sediment analysis to achieve the project objectives. These scenarios included:

- **Existing Condition Scenario:** This scenario represents current conditions and uses topographical data from the field trip of October 2005, and other sources discussed in Section 3.0. The hydraulic model of the Existing Condition scenario was calibrated against the field-measured data on October 12, 2005. The calibrated model was then used to simulate flow and sedimentation cases under the 2-, 5-, and 10-year floods of the Sandy River. Results of the Existing Condition scenario were used as benchmarks to compare with those of other scenarios;

- **Removed Dam Scenario:** This scenario simulates the condition following removal of the SRD Dam and the sediment plug located between the Sandy River and the SRD Dam. Note that the removal (or excavation) was limited to the Dam and sediment plug area only, and the rest of the east distributary channel elevation was unchanged. The elevation of the Dam and plug removal was derived by projecting the current bed elevation in the east distributary channel out to the confluence of the east distributary and Columbia River.
- **Eroded East Channel Scenario:** This scenario was developed to represent likely bed topography along the east and west distributary channels a few years (e.g., five years) after the SRD Dam removal. Erosion is anticipated along the east distributary channel while deposition is expected to occur in the west distributary channel downstream from the fork of the east and west distributary channels. Details of the estimated bed elevation change are presented in Section 5.3.
- **Complete Blockage Scenario:** This scenario was added to represent the worst-case scenario, as the west distributary channel of Sandy River would be blocked completely. Under this scenario, the SRD Dam and sediment plug would be removed, and the entire Sandy River flow would be directed towards the east channel. This scenario represents the worst-case impact on the sediment supply to the mining area. It also served as an added benefit to address how the Columbia River alone would influence sediment deposition at the mining area.

More details of the above scenarios may be found in Section 5.0.

4.3. Flow Hydrology and Rating Curves

The Sandy River Delta is a very dynamic system where processes and patterns change under varying conditions. When Columbia River and Sandy River flows are low, all water flows down the west distributary channel of the Sandy River. With high flows on the Sandy River, the majority of Sandy River water flows down the west channel with a small portion flowing over SRD Dam and down the east channel. On the other hand, when Columbia River flows are high, both Sandy River channels become part of the Columbia River slough system. That is, Columbia River flows enter the east distributary channel, combine with the Sandy River, and continue down the west distributary channel.

Because of the armored nature of the Sandy River, high flow events transport a greater volume of sediment through the system than is transported during low flow conditions. In order to address short-term issues of sediment delivery to the mining operation and scour at the bridges, higher frequency, and lower magnitude flood flows were used in the model. Due to complex interactions between the Sandy and Columbia Rivers, a multitude of flow combinations may be considered. Within this project scope, only a limited number of cases were simulated. In this study, the flow combination in which the Sandy River is at flood stage and the Columbia River is at a moderate stage was simulated, as it was considered the most likely flow combination to occur. In addition, the use of this combination of flows was based on the anticipation that the primary sediment source of the mining operation is the west distributary channel of the Sandy River. Post-simulation analysis of the sediment transport results supports the anticipated results (Section 5.4) and further justifies the use of this combination of flows. The 2-, 5-, and 10-year peak discharges were selected to evaluate the hydraulics and sediment transport through the Sandy River system with Columbia River under moderate flow conditions. Flows of other magnitude were not covered under the scope of this study.

Sandy River annual peak flows were determined using USGS streamflow gage number 14142500, Sandy River below Bull Run River. This gage is located at river mile 18.4 near Bull Run, Oregon, approximately 17.2 miles upstream of the fork of the east and west distributary channels. Sixty-one annual peak streamflow values were recorded between 1911 and 2004, with missing data between 1914 and 1929 and then again between 1966 and 1984. A Log-Pearson Type III hydrologic frequency analysis was used to establish the discharges for the Sandy River that correlate with recurrence intervals of 2, 5, and 10 years (Table 4.1). Figure 4.1 indicates that Log-Pearson Type III model provides a close fit to the actual observed peak flows.

Table 4.1. Results of Log-Pearson Type III frequency analysis for Sandy River peak flows.

Exceedance Probability (%)	Recurrence Interval (yrs)	Discharge (cfs)
99	1.01	10,900
50	2	25,400
20	5	36,900
10	10	45,500

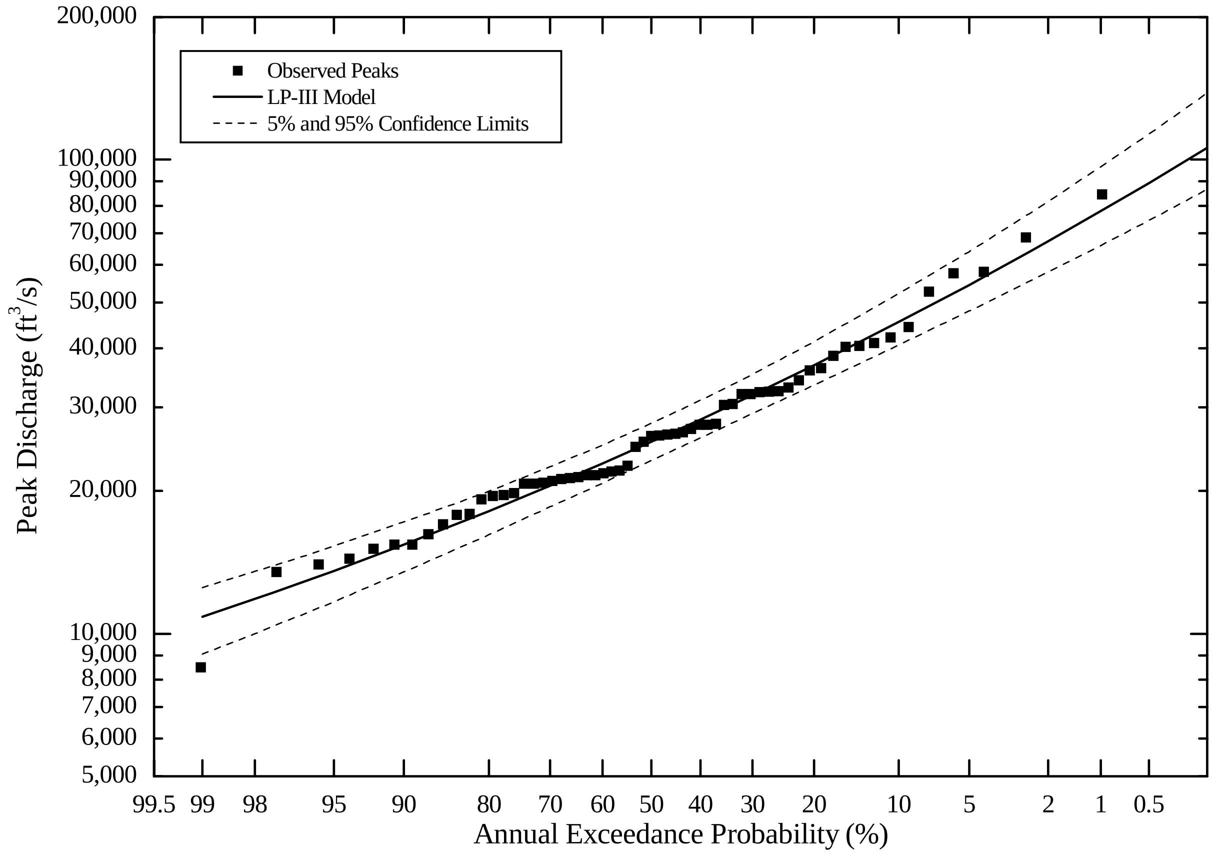


Figure 4.1. Graph of Log-Pearson Type III model fit to 61 years of annual instantaneous peak flows on the Sandy River.

In general, smaller recurrence interval flood flows on the Columbia River do not simultaneously occur with flood flows on the Sandy River. A Columbia River flow that corresponds to flood conditions on Sandy River was required as model input. Peak flows on the Sandy River generally occur each year between October and June, with 77 percent of the recorded historic peaks occurring between November and February. The nearest streamflow gage on the Columbia River is located at the Bonneville Dam, approximately 40 km upstream from the confluence of the Sandy and Columbia Rivers. Average daily outflow discharges from the Bonneville Dam were available for the time period between 1960 and present day from the COE, Northwest Division dataquery website (http://www.nwd-wc.usace.army.mil/perl/ dataquery.pl). Using this information, monthly average flows were calculated between November and February for each water year beginning in 1960, and an average monthly flow across all water years was established (Table 4.2). The mean value of flows occurring during the four months on the Columbia River, 160,300 cubic feet per second (cfs), was used for simulation when the Sandy River flow varied between the 2-, 5-, and 10-year flow events.

Table 4.2. Average monthly outflow discharge (cfs) from the Bonneville Dam between 1960 and 2004.

November	December	January	February	Average
132,300	155,800	171,000	182,200	160,300

The water surface elevation at the exit boundary, approximately located at river mile 118.5 on the Columbia River and about 2.6 miles downstream of the confluence of the west distributary channel and the Columbia River, was needed as the downstream boundary condition. Accordingly, a stage-discharge rating curve was developed. Discharges at the exit boundary were computed by combining the 2-, 5-, and 10-year flows on the Sandy River with the average of November to February flows on the Columbia River. An unsteady flow HEC-RAS model developed by the COE, Portland District, was used to evaluate the stage-discharge rating curve (Figure 4.2). The model was developed to simulate the first 145 river miles of the Columbia River between May 1, 2003 and July 15, 2003, with a 5 minute computation interval. This complex model incorporated 9 boundary conditions and 17 storage areas that affect Columbia River water surface elevations under varying discharges. A power function regression line was fit to the rating curve output data from the HEC-RAS model, as follows:

$$Z = 0.0003181 Q^{0.8533717} \tag{4.1}$$

where Q (cfs) is the flow discharge of the combined Columbia and Sandy River flows and Z is the water surface elevation (feet) at the exit of the simulated Columbia River reach. Figure 4.2 shows the data and the rating curve.

Scatter in the stage-discharge rating curve developed from the COE unsteady flow model may be attributed to continuously changing downstream hydraulic conditions and tidal fluctuations. The Columbia River flow at the Sandy River Delta is tidally influenced and fluctuates in elevation on the order of 1 to 1.5 feet under normal flow conditions (Kukulka and Jay, 2003).

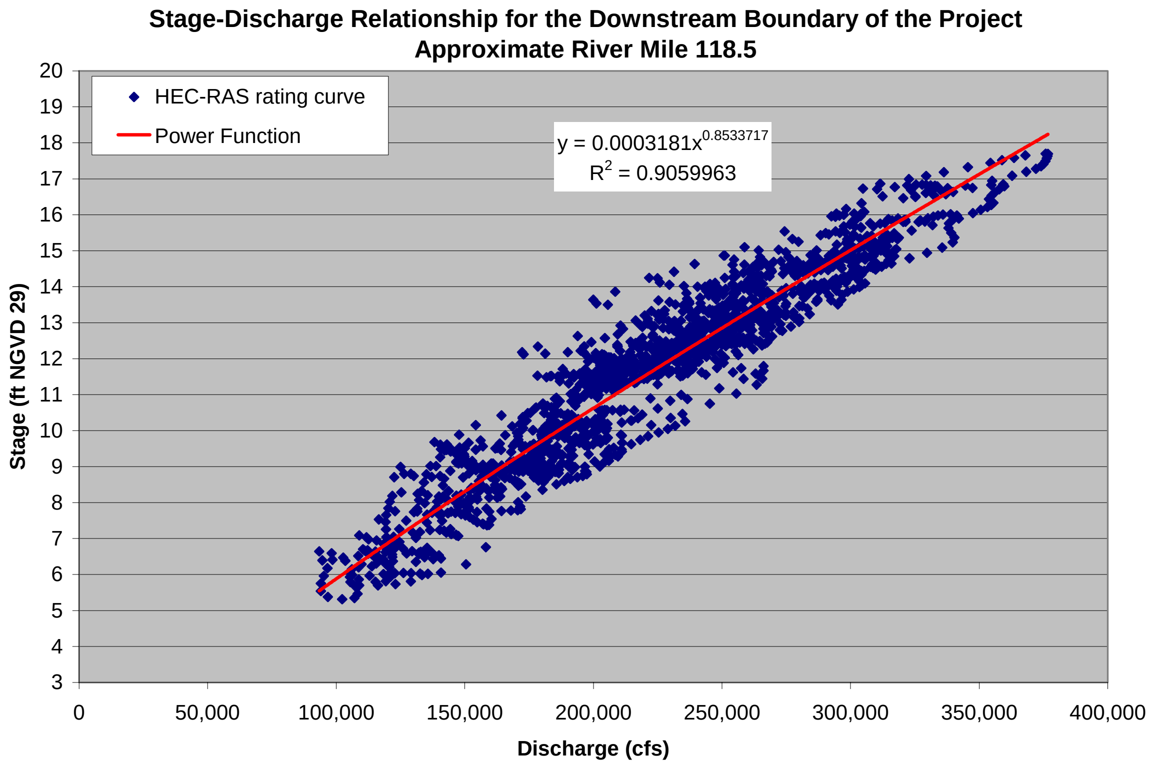


Figure 4.2. Stage-discharge rating curve at the exit boundary of the simulated Columbia River reach.

4.4. Hydraulic Analysis

Hydraulic analysis of river flows is the first step towards a sediment analysis. 2D GSTAR-W was used for this project due to complex flows created by the east and west distributary channels of the Sandy River and the Columbia River. Further, the dynamic wave solver of GSTAR-W that solves the 2D depth-averaged St. Venant equations was selected. Technical details of GSTAR-W may be found in the GSTAR-W Manual (Lai, 2006).

Hydraulic analysis includes the following steps:

(1) Selection of the solution domain for the project;
(2) Mesh generation for the solution domain;
(3) Topography and flow roughness representation on the mesh;
(4) Development of the calibrated hydraulic model; and
(5) Application of the calibrated hydraulic model to different flood flow scenarios.

The first three steps are discussed below, and descriptions of the calibrated model and hydraulic and sediment analysis results are presented in Section 5.0.

4.4.1. Solution Domain and Mesh Generation

2D hydraulic analysis starts with a solution domain and a mesh that covers the domain. The solution domain for the present analysis was selected based on the stated objectives of this project and was guided later by the topographic and bathymetric data available (Section 3.0). The final solution domain selected is displayed in Figure 4.3. The following considerations were taken into account in defining the solution domain:

- The upstream (inlet) boundary of the Sandy River was placed upstream of the railroad bridge and was at a location where the flow was relatively straight. It is approximately 2.6 miles from the confluence of the west distributary channel of the Sandy River and the Columbia River;
- The upstream (inlet) boundary of the Columbia River was located upstream of an island and was placed far enough from the Sandy River Delta that inaccuracy in inlet conditions would have negligible impacts to analysis results. The upstream boundary is located about 6.9 miles upstream of the confluence of the west channel of the Sandy River and the Columbia River (about 4.7 miles upstream of the easy distributary channel confluence);
- The downstream boundary of the Columbia River reach was located about 2.6 miles downstream of the confluence of the west distributary channel of the Sandy River and the Columbia River; the exit conditions would have negligible effect on model results of interest;
- The lateral extent of the solution domain for both the Sandy River and the Columbia River was determined such that floods less than the 10-year recurrence interval would not overtop the solution boundaries;
- The solution domain encompassed about 9.5 miles of the Columbia River and 2.6 miles of the Sandy River with an area of about 12.8 square miles.

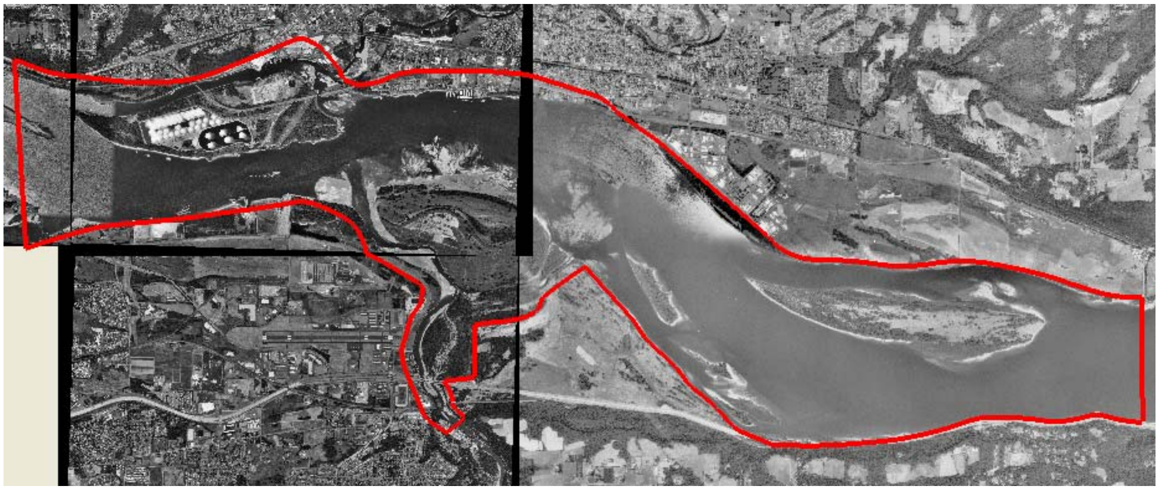


Figure 4.3. Solution domain used for the Sandy River Delta simulation. West (left) side of the Columbia River is the exit boundary, east (right) side is the inlet boundary of the Columbia River, and south (bottom) side is the inlet boundary of the Sandy River.

The next step was to generate a mesh that covered the solution domain. GSTAR-W uses the Surface Water Modeling System software (SMS) for this purpose. The following website link provides more information for the software: www.scientificsoftwaregroup.com. GSTAR-W Manual (Lai, 2006) may be consulted for an in-depth discussion on how to use SMS to prepare a 2D mesh for use by GSTAR-W.

The final mesh evolved after several iterations, taking the preliminary mesh and flow results into consideration. The mesh is displayed in a series of figures from Figure 4.4 to Figure 4.6. A combination of quadrilateral cells and triangular cells was used that provided the best compromise between the accuracy and computing time. The main river channels were mostly covered with quadrilateral cells that allow mesh stretching while the remaining areas were mostly covered with combined triangular-quadrilateral cells. The final mesh contained a total of 37,637 cells.

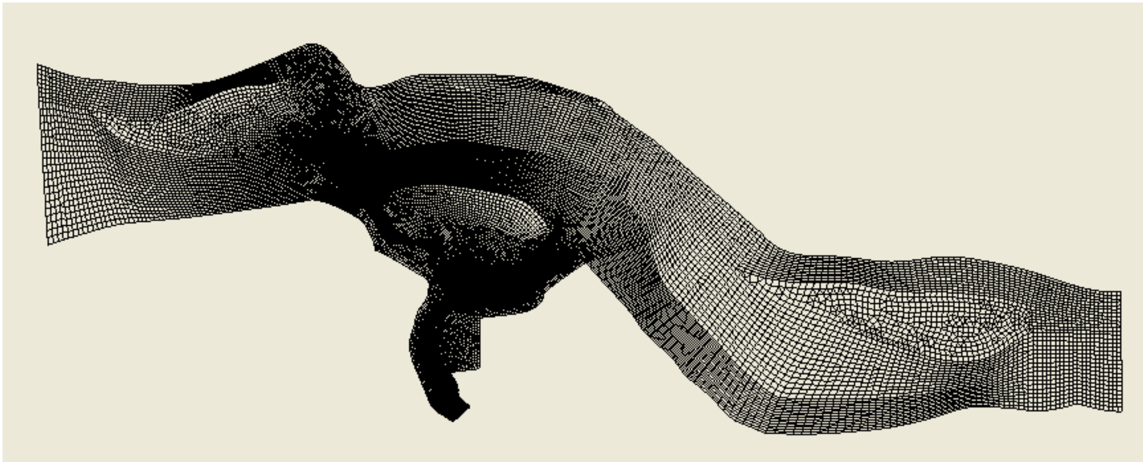


Figure 4.4. Mesh for the GSTAR-W simulation: Entire solution domain.

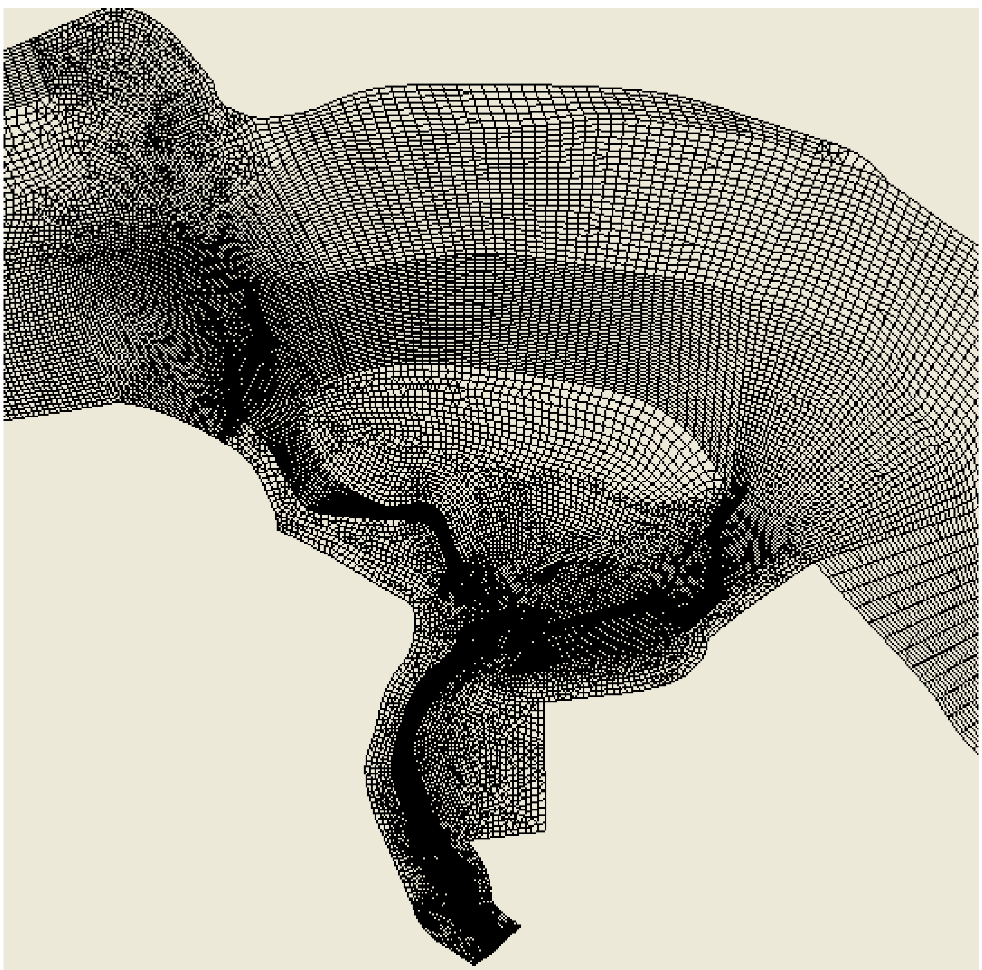


Figure 4.5. Mesh for the GSTAR-W simulation: Sandy River Delta area.

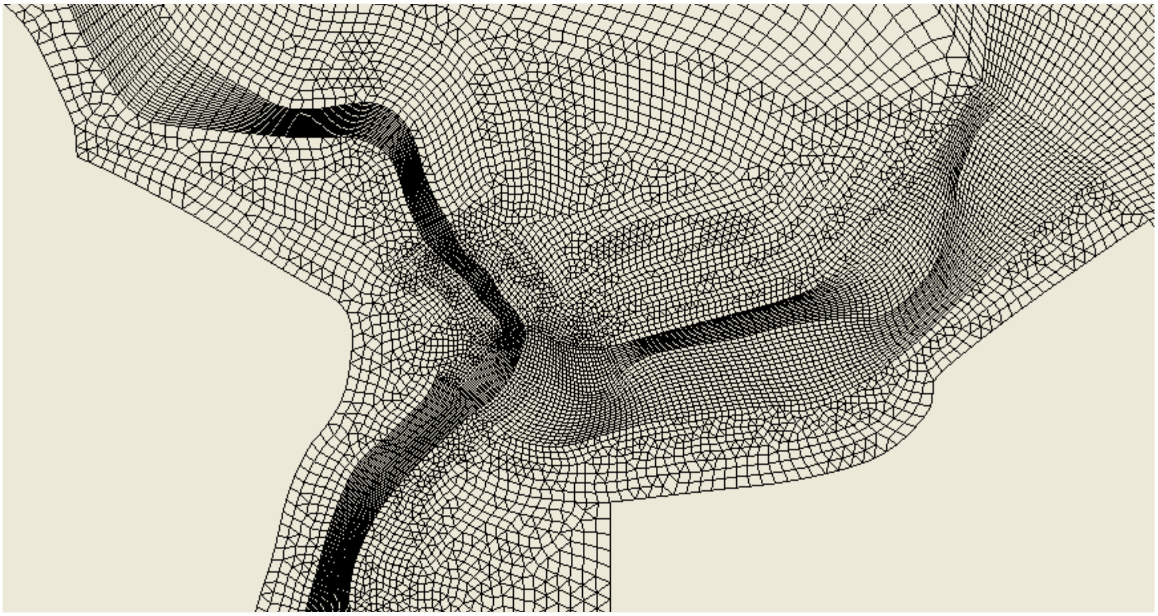


Figure 4.6. Mesh for the GSTAR-W simulation: SRD Dam area.

4.4.2. Model Topography

The next step was to obtain topography information and interpolate the topography onto the final mesh. Topography data were obtained from several sources, as discussed in Section 3.0, and represent existing conditions. All topographic and bathymetric data were in point form (Easting, Northing, and elevation). Topography data were imported into the SMS software and interpolated onto the mesh points. Bed elevation contour plots based on the original data and interpolated mesh elevations are shown in Figure 4.7 through Figure 4.10. The topography was accurately represented by the mesh used.

A clearer view of the topography may be achieved with three-dimensional (3D) perspective plots that are shown in Figure 4.11 and Figure 4.12.

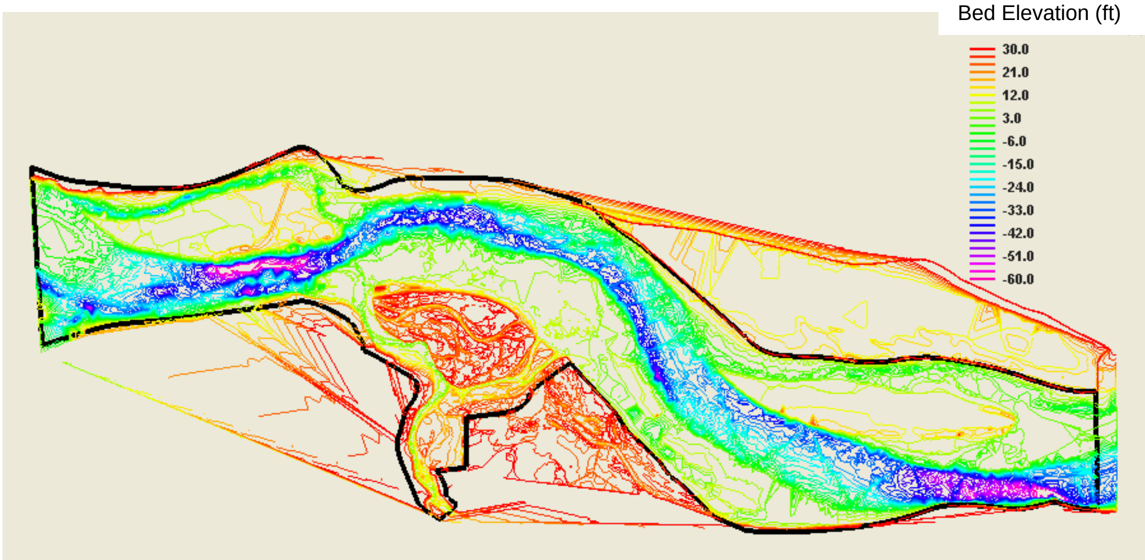


Figure 4.7. Topography contours based on field-surveyed data: Entire solution domain.

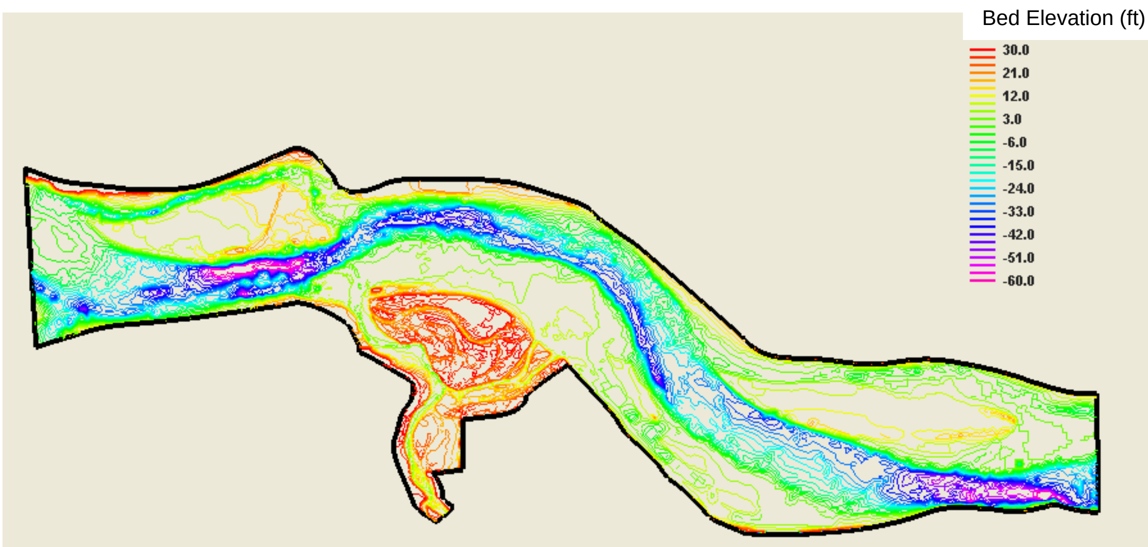


Figure 4.8. Topography contours based on the mesh interpolated from survey data: Entire solution domain.

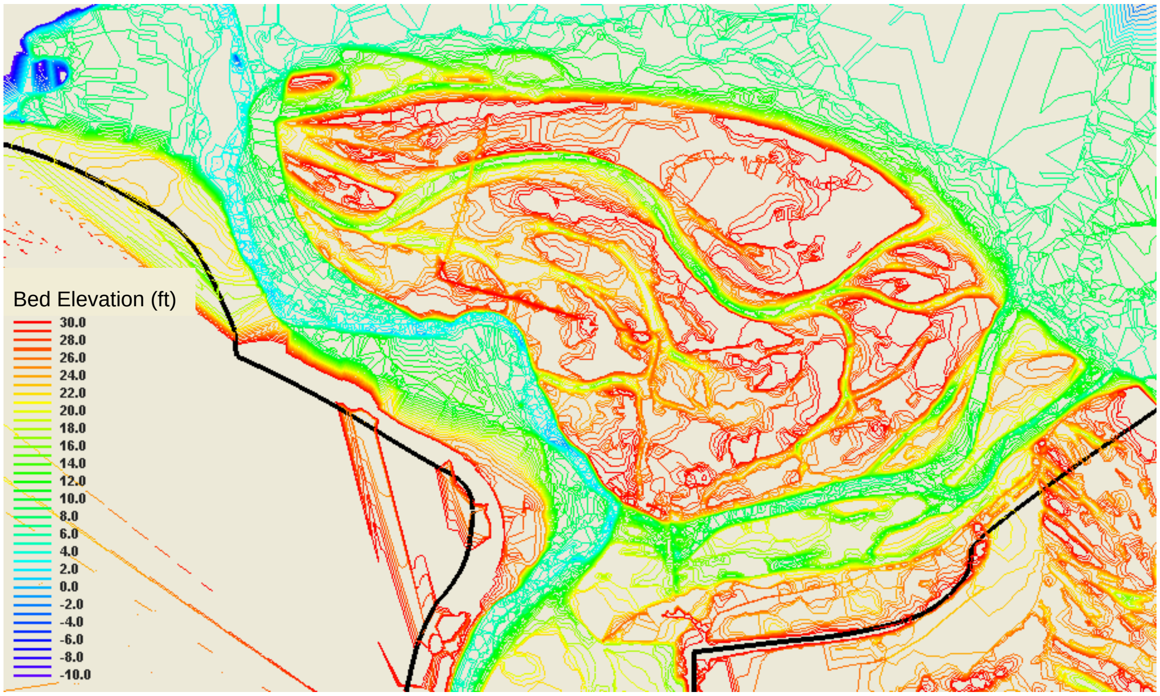


Figure 4.9. Topography contours based on field-surveyed data: Sandy River Delta area.

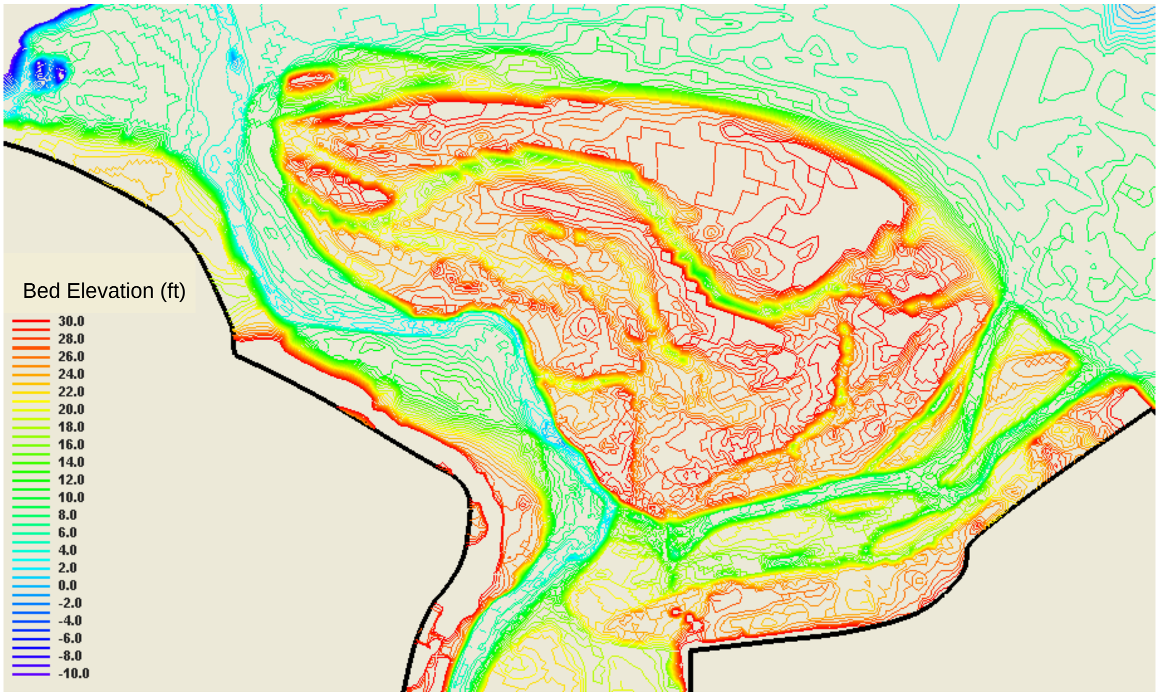


Figure 4.10. Topography contours based on the mesh interpolated from survey data: Sandy River Delta area.

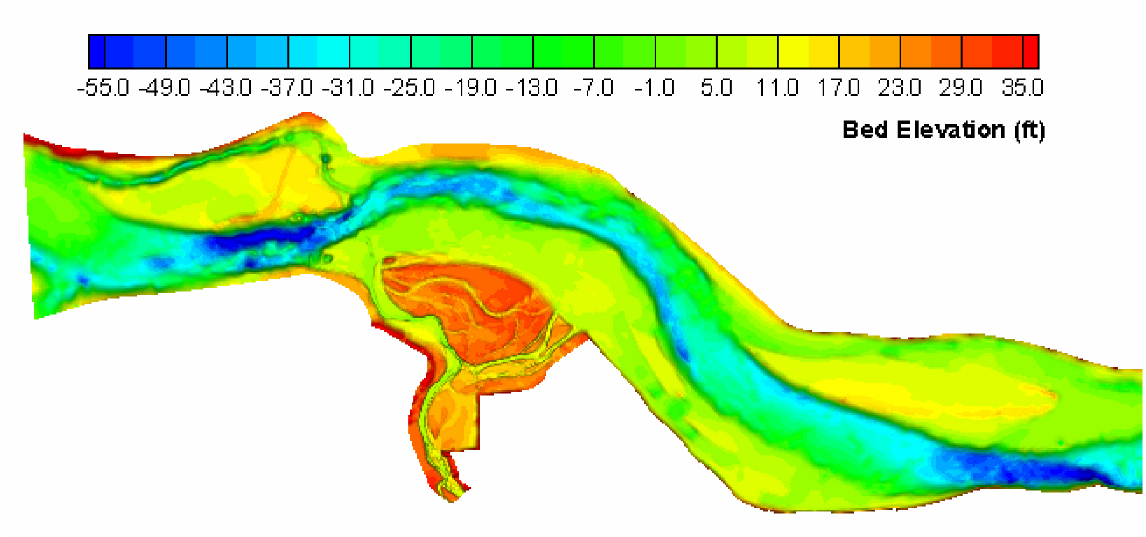


Figure 4.11. 3D perspective of the topography for the solution domain.

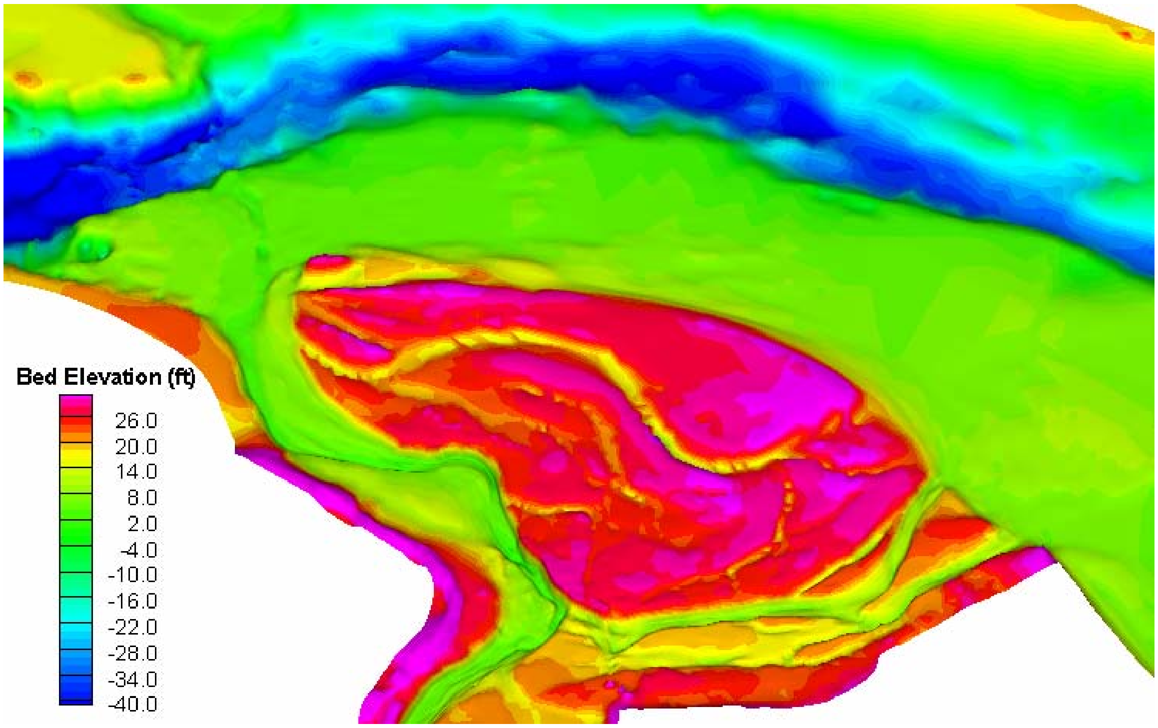


Figure 4.12. 3D perspective of the topography at the Sandy River Delta area.

4.4.3. Flow Roughness Representation

Flow resistance was calculated with the Manning's roughness equation in which the Manning's coefficient (*n*) was needed as the model input. In this project, the solution domain was divided into a number of roughness zones according to the underlying bed properties, and each zone was assigned a Manning's *n* value. Figure 4.13 shows the roughness zones used for the simulation. The Manning's *n* for each zone was determined through a calibration study presented in Section 5.0, by comparing roughness values with the field-measured data of October 2005.

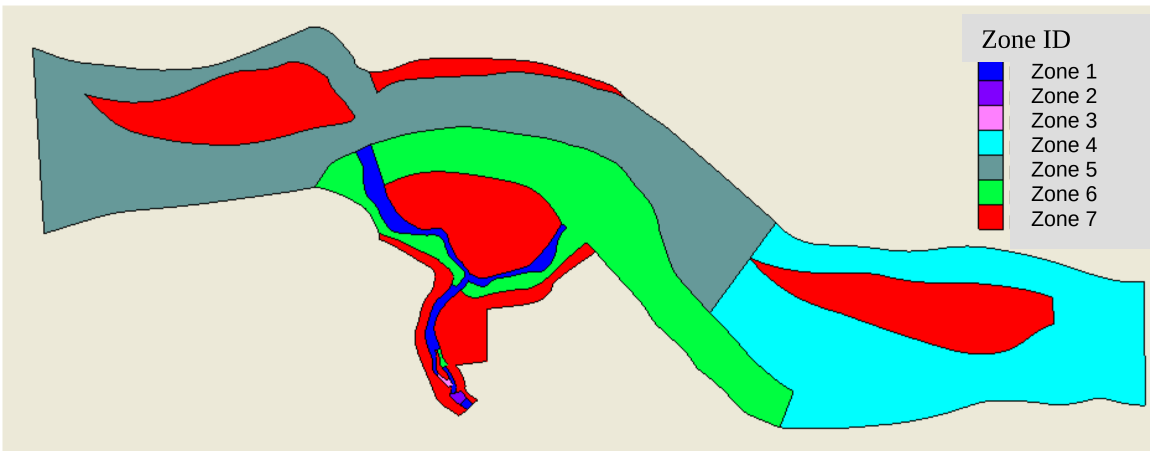


Figure 4.13. Roughness zones used over the solution domain.

Note that zones 1, 2 and 3 represent the main channel of the Sandy River, and zones 4 and 5 represent the main channel of the Columbia River. Zone 6 consists mostly of sand bars and less vegetated areas, while zone 7 represents islands and floodplains with more vegetation.

4.5. Sedimentation Analysis

GSTAR-W sediment module was used to execute the sedimentation analysis for the project. The current sediment analysis assumed the steady state flow with the fixed bed elevation simulation using the non-uniform sediment and non-equilibrium sediment transport transport. See Section 5.6 for a discussion of the uncertainty related to the modeling assumptions. Numerical modeling allows assessment and comparison of the sediment impact to the mining area and highway and railroad bridge areas under different scenarios. A brief description of the sediment analysis methodology and information is provided in the following sections.

4.5.1. Sediment Transport Equations

Sediment transport in a river reach depends on many variables, including flow hydraulics, bed gradation, and upstream sediment supply. The bed gradation changes from its initial state as sediment particles are eroded from or deposited on the bed, which also changes flow hydraulics and fractional sediment transport rates.

In general, the water column and riverbed may be divided into four separate vertical layers as follows:

- Suspended Load Layer: a layer in the water column where sediment particles are in suspension and are transported as suspended load (including wash load);
- Bed Load Layer: a layer near the bed where sediment particles roll, slide, or saltate; particles are transported as bed load;
- Active Layer: a layer on the bed top surface where sediment exchange (due to erosion and deposition) occurs between the bed and water; and
- Subsurface Layer: one or several bed layers underneath the active layer.

In this project, the bed material load transport is considered. That is, the combined suspended load and bed load, but without the wash load, is simulated. The wash load refers to those fine sediments that are transferred from the upstream boundary, but are not part of the bed sediments. Wash load is ignored as it does not contribute to the bed morphological changes. The sediment is assumed to be non-cohesive and non-uniform and is divided into a number of sediment size classes. Each size class (*k*) obeys the following mass conservation equation providing the non-equilibrium transport:

$$\frac{\partial hC_k}{\partial t} + \frac{\partial hUC_k}{\partial x} + \frac{\partial hVC_k}{\partial y} = \beta\omega_{sk}(C_k^* - C_k) \qquad (4.2)$$

where h is water depth; t is time; C_k is depth-averaged sediment concentration by volume for k^{th} sediment size class; U and V are depth-averaged velocity components in x and y direction, respectively; ω_{sk} is the settling velocity of k^{th} sediment size class; β is the non-equilibrium adaptation coefficient (by default, 1.0 if net erosion and 0.25 if net deposition); and C_k^* is the fractional sediment transport capacity for the k^{th} size class.

The Parker (1990) sediment transport equation was used to compute the fractional sediment transport capacity (C_k^*). This equation was originally developed for gravel transport but was later found to be applicable to sand and gravel mixture (Andrews, 2000).

The equation may be expressed as:

$$\frac{q_{Sk}\, g(s-1)}{(\tau_b / \rho)^{1.5}} = p_k G(\phi_k) \qquad \text{and} \qquad \phi_k = \frac{\theta_k}{\theta_c}\left(\frac{d_k}{d_{50}}\right)^{\alpha} \tag{4.3}$$

In the above, q_{Sk} is the volumetric sediment transport rate per unit width ($C_k^* = q_{Sk} / q$ with *q* the flow discharge per unit width); p_k is the volumetric fraction of the k^{th} sediment size class in the bed; $s = \rho_S / \rho - 1$, ρ and ρ_S are the water and sediment density, respectively; *g* is the gravitational acceleration; τ_b is bed shear stress, $\theta_k = \tau_b / [\rho g(s-1) d_k]$ is Shield's parameter of sediment size class *k*; θ_c is critical Shield's parameter; d_k is diameter of sediment size class k; and d_{50} is the median diameter of sediment mixture in bed. The function in the transport equation was fit to field data and is expressed as:

$$G = \begin{cases} 11.933(1 - 0.853/\phi)^{4.5}, & \phi > 1.59 \\ .00218 \exp\left[14.2(\phi - 1) - 9.28(\phi - 1)^2\right], & 1.0 \le \phi \le 1.59 \\ .00218\, \phi^{14.2}, & \phi < 1.0 \end{cases} \tag{4.4}$$

Note that two parameters must be defined by a user to apply the Parker equation: θ_c and α. θ_c Represents the critical value above which sediment is mobilized, and α is the exposure factor to account for reduction in critical shear stress for larger particles and increase in critical shear stress for smaller particles. Ideally, these two parameters should be fit to data for the river reach to be simulated. Due to lack of sediment transport rate data for this project, the parameters were determined based on past experiences. Several references may provide guidance, such as Komar (1989), Buffington and Montgomery (1997), Andrews (2000), and Wilcox and Crowe (2003). In general, θ_c may vary from 0.03 to 0.08, and α varies from 0.11 to 0.67. In this project, θ_c=0.04 and α =0.65 were used based on the recommendation by Komar (1989). The same values were found to give good predictions for other problems tested by Reclamation. Note that a more accurate determination of the two parameters is not critical for the current project as relative comparisons were the main interest.

Bed sediment dynamics and interaction with the bed material load transport were also simulated. In reality, the bed elevation is changing due to net erosion or deposition of the bed. The bed elevation (z_b) change due to sediment size class *k* may be calculated, as follows:

$$(1 - p_b)\left(\frac{\partial z_b}{\partial t}\right)_k = -\beta \omega_{sk} (C_k^* - C_k) \tag{4.5}$$

where p_b is the bed material porosity. In this project, the fixed bed elevation analysis was performed. This means the bed elevation equation (4.5) was used to calculate the sediment dynamics such as net erosion or deposition rate, bed gradation change, and sediment transport rate. The new bed elevation calculated was not used as a feedback to update the flow hydraulics. The fixed bed elevation analysis has its limitations as discussed in Section 5.6. However, it is an appropriate method to provide an estimate of erosion and deposition zones following the initial bed and obtain the relative change of sediment rate due to the change of project scenarios. Therefore, the method is adequate for the objectives of this project.

The bed is divided into two layers to account for the bed sediment dynamics: the active layer and the sub-surface layer. The active layer is the top bed layer participating in the sediment exchange between the bed and bed load; the sub-surface layer provides sediment supply to the active layer once eroded. The gradations of both layers may change over time and are calculated. The active layer gradation equation is given as:

$$\frac{\partial \delta_a p_{ak}}{\partial t} = \left(\frac{\partial z_b}{\partial t}\right)_k + p_{ak}^* \left(\frac{\partial \delta_a}{\partial t} - \frac{\partial z_b}{\partial t}\right) \tag{4.6}$$

where δ_a is the thickness of the active layer; p_{ak} is the active layer volumetric fraction of sediment size class k ($\sum_k p_{ak} = 1$); $p_{ak}^* = p_{ak}$ if $\left(\frac{\partial \delta_a}{\partial t} - \frac{\partial z_b}{\partial t}\right) < 0$; p_{ak}^* is the sub-surface fraction of sediment size class k if $\left(\frac{\partial \delta_a}{\partial t} - \frac{\partial z_b}{\partial t}\right) > 0$; and $\frac{\partial z_b}{\partial t} = \sum_k \left(\frac{\partial z_b}{\partial t}\right)_k$. Note that the sediment transport rate changes due to changes in the gradation of the active layer.

4.5.2. Input Data for Sediment Simulation

In the present sediment analysis, the sediment mixture was divided into five size classes as listed in the left-most column of Table 4.4. Class 1 represents the fine sand, and class 2 represents the coarse sand. The remaining three classes represent gravels and coarse cobble.

The initial bed sediment gradation is needed as input for sediment analysis and is usually spatially distributed. Limited bed gradation measurements were made during the field trip of October 2005 (see Section 3.0). Based on the limited bed gradation data, the bed gradation distribution was divided into five zones, with each zone assigned a unique bed gradation. Figure 4.14 depicts the distribution of the five bed gradations used for analysis. These zones are not to be confused with the Manning's coefficient roughness zones depicted in Figure 4.13.

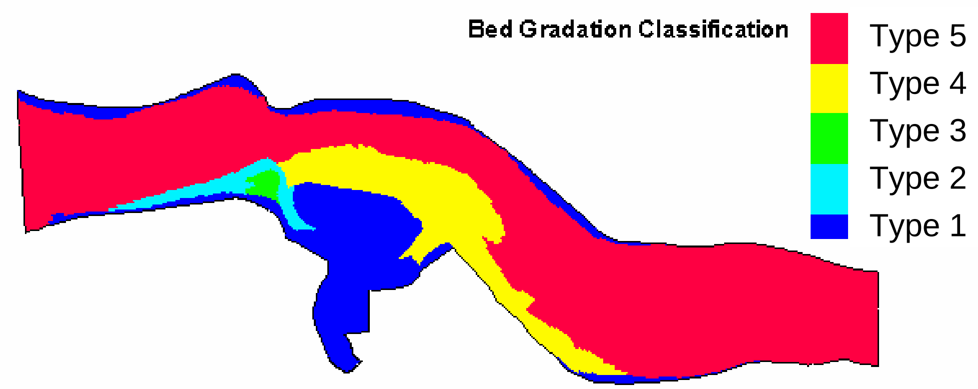


Figure 4.14. Bed sediment gradation distribution map.

Table 4.3 lists the bed gradation for each zone based on the field data of October 2005. The initial bed gradation used for the simulation was derived from data in Table 4.3 and is listed in Table 4.4.

Table 4.3. Bed gradation based on estimations from measured sediment data.

	Percentage Passing by Weight				
Size (mm)	Type 1	Type 2	Type 3	Type 4	Type 5
128	100.0	100.0	100.0	100.0	100.0
64	89.4	100.0	100.0	98.4	100.0
32	65.5	96.8	100.0	81.9	100.0
16	48.0	83.7	100.0	55.3	100.0
8	36.8	77.0	100.0	37.0	100.0
4	31.1	73.0	100.0	29.1	100.0
2	27.3	70.0	99.7	24.1	100.0
1	20.3	57.6	93.8	21.5	100.0
0.5	7.1	17.1	47.1	16.9	99.7
0.25	1.7	4.3	4.6	9.0	40.5
0.125	0.5	1.6	0.2	2.3	7.7
0.0625	0.3	0.5	0.1	0.7	0.8

Table 4.4. Percentage of sediment size fraction on the bed for each gradation zone (used for sediment modeling).

Percentage of Sediment Size Fraction					
Size Fraction (mm)	Type 1	Type 2	Type 3	Type 4	Type 5
0.0625 – 0.5	7.1	17.1	47.1	16.9	99.7
0.5 - 2	20.2	52.9	52.6	8.0	0.3
2 - 8	9.5	7.0	0.3	12.1	0.0
8 - 32	28.7	19.8	0.0	44.9	0.0
32 - 128	34.5	3.2	0.0	18.1	0.0

The Columbia River consists of mostly fine sands (Type 5), while the sand bar downstream of the confluence of the Columbia River and the west distributary channel of the Sandy River contains more than half coarse sands (Type 2).

Finally, the sediment transport rates at the Sandy River inlet boundary and the Columbia River inlet boundary are needed as boundary conditions. Due to the lack of available data, equilibrium condition was assumed at both inlets. That is, the local sediment transport capacity was imposed as the inlet sediment transport rate. Again, this assumption is not a concern as only the relative impact of sediment delivery to the mining site after dam removal is of interest.

5.0 Presentation of Model Results

5.1. Calibration of the Hydraulic Model

Data collected during the field trip in October 2005, were used to calibrate the GSTAR-W hydraulic model by adjusting the assigned Manning's values. Flow measured during the trip of October 2005 indicated that flow conditions were quite unsteady for both the Columbia River and the Sandy River, due mainly to the tidal influence and flow release from the Bonneville Dam. Flow unsteadiness often lead to difficulty in model calibration. Following a careful examination of the field data, conditions corresponding to the trip of October 12, 2005, were used for calibration, and calibration results turned out to be quite satisfactory.

Note that calibration and verification of the sediment model was not possible due to limited sediment data. A brief qualitative comparison of model simulation and field observation, however, is made in Section 5.5.1. Lack of a sediment transport verification study usually leads to possible uncertainty in the absolute values of the sediment transport. However, relative changes in the sediment transport rate under varying provide sufficient accuracy.

5.1.1. Input Data for the Hydraulic Model

The following input variables were used for the model calibration:

- Flow discharge for the Sandy River was set at 377 cfs, as recorded at the USGS Gage #14142500 (Sandy River below Bull Run River, near Bull Run, OR) on October 12, 2005. At one cross section of the Sandy River, field data from October 2005 estimated that the discharge was about 342 cfs based on the ADCP bottom tracking data.
- Flow discharge through the Columbia River was fixed at 123,000 cfs, which represented the average flow release from the Bonneville Dam on October 12, 2005. Releases from Bonneville Dam that day were very unsteady with a reported range of 118,000 to 132,000 cfs. Discharges calculated at several Columbia River cross sections from measured ADCP bottom tracking velocity data ranged from 98,310 to 125,700 cfs.
- The water surface elevation at the exit of the Columbia River reach was needed as the downstream boundary condition. Instead of applying the rating curve developed in Section 4.3, field data from October 2005 were used for determination of the water surface elevation at the exit boundary. The field-measured water surface elevation was also found to be quite unsteady and tidally influenced. However, two distinct elevations at the exit boundary were identified for the conditions during the field visit:

4.75 feet and 5.50 feet. Both elevations were used for the model calibration, which led to the development of two calibration runs: one low elevation case (4.75 feet) named Run #1, and another high elevation case (5.50 feet) named Run #2. Post-simulation analysis indicated that the difference in elevation at the exit boundary only influenced results near the confluence area of the Sandy and Columbia Rivers.

5.1.2. Determination of Manning's Roughness Coefficient

The Manning's roughness coefficients in different zones (Figure 4.13) were calibrated using the water surface elevation of the field data of October 2005. After a number of simulation runs, the final calibrated Manning's coefficients were determined (Table 5.1).

Table 5.1. Calibrated Manning's coefficients at different zones shown in Figure 4.13.

Zone Number	1	2	3	4	5	6	7
Manning's *n*	0.035	0.06	0.15	0.035	0.035	0.035	0.06

Both main channels of the Sandy River and Columbia River used a Manning's *n* of 0.035 (zone 1, 4 and 5). The same value was also used for the sand bar and less vegetated areas (zone 6). Heavily vegetated areas (zone 7) were assigned a Manning's *n* of 0.06. Zone 2 and 3 are two small areas on the Sandy River near the highway and railroad bridges. Different Manning's *n* values had to be used to match the measured water surface elevation in the area. Figure 5.1 provides an aerial photograph of zones 2 and 3. A Manning's *n* value of 0.06 was used for zone 2, attributable to several factors. First, the zone contains a large gravel bar that directs all flow into the left channel under low flow conditions. A large amount of seepage occurs through bar deposits; so more flow loss may occur. Second, based on sediment samples and visual observation in October 2005, the bed material in this area is particularly coarse consisting of large cobbles and even some boulders. Finally, this is a short reach with a steep slope that may contribute to flow loss through substrate.

Zone 3 was the troubling area during the calibration study since a very high Manning's *n* (0.15) was used to match the measured water surface elevation. Several factors affect the high roughness value in this area, but the presence of a large boulder field downstream from the railroad bridge (Figure 5.2) is the most likely cause. During the survey in October 2005, large differences in bed elevation were found between the boulders. It was not possible to obtain survey data for individual boulders that block substantial portions of the channel during low flows. The boulders also create backwater especially at low flows when they are more exposed. Therefore, the large Manning's *n* (0.15) calibrated for the area may be justified. However, the roughness effect would not be as significant when the Sandy River is at flood flows and the boulders are submerged, such as the discharges considered in this study. As such, the Manning's *n* for zone 3 was reduced to 0.08 when flood flows at the Sandy River were simulated.

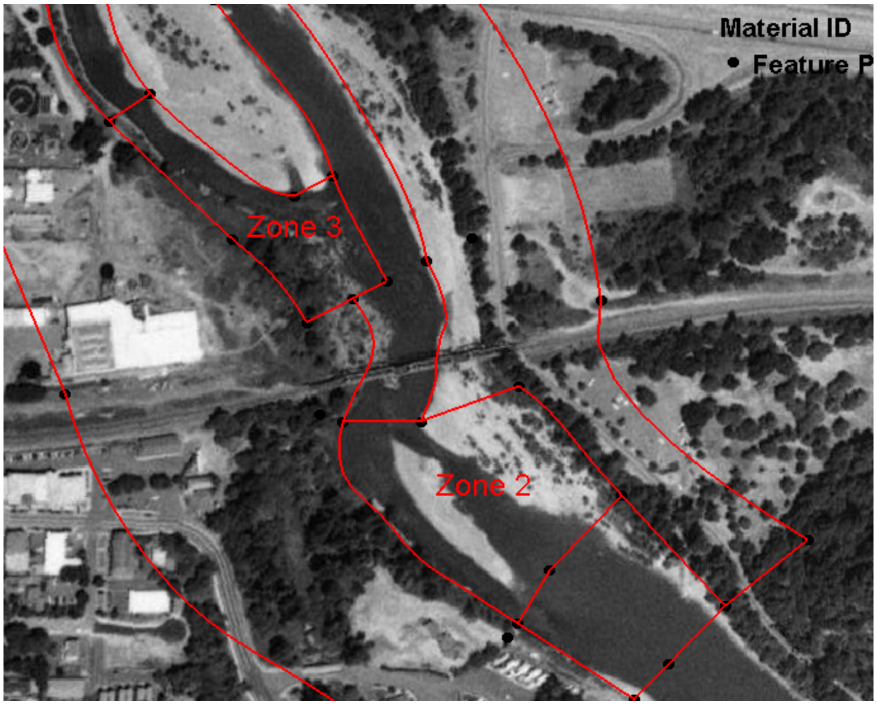


Figure 5.1. Aerial photograph of roughness zones 2 and 3.

Figure 5.2. Photograph taken at roughness zone 3 during the field trip of October 2005.

The model was calibrated using the low flow data and was then applied to flood flows by assuming the roughness remained unchanged for all zones. Current research offers no consensus on the criteria of changing the roughness for different flows. The same approach adopted in this project was used for several other projects, and experience by Reclamation showed that the approach was adequate. A qualitative verification of the model under flood flows is discussed in Section 5.5.

5.1.3. Comparison of Water Surface Elevation

Three sets of results were obtained with the calibrated hydraulic model, and they are named Run #1, #2 and #3. Run #1 and Run #2 reflect effects due to different water surface elevations specified at the exit boundary of the Columbia River reach. The two runs also indicate the sensitivity of model results to the exit boundary condition. Run #1 used the low elevation condition (4.75 feet), and Run #2 was based on the high elevation condition (5.50 feet). Both Run #1 and Run #2 used a Manning's coefficient of 0.15 for zone 3 in Figure 5.1. A third run (Run #3) was added to examine the impact of using a different Manning's coefficient in zone 3. Run #3 used the same downstream boundary condition as Run #1, but used a Manning's coefficient of 0.08 in zone 3 (versus 0.15 with Run #1 and #2). The reason of using 0.08 in Run #3 is explained below.

The simulated water surface elevations on the Sandy River project reach are compared with the field data of October 2005, Figure 5.3. The following observations may be made:

- The hydraulic model predicted the water surface elevation along the Sandy River quite well despite uncertainty in measured data and the unsteady nature of river flows. The thalweg profile was also plotted in Figure 5.3 to demonstrate how well the model predicted water surface elevation despite large fluctuations in the bed topography. The difference between the field-measured and model-predicted elevation was typically within 0.3 feet, except near the confluence of the west distributary of the Sandy River and the Columbia River. This difference at the west confluence is likely associated with tidal fluctuations during the survey of October 2005.
- Major elevation changes at riffle and pool areas of the Sandy River reach were also predicted by the model. This indicates that the bed topography represented the riffle and pool areas correctly and that the model also represented the flow loss correctly.
- Uncertainty in the value of the Manning's *n* at Zone 3 is discussed in Section 5.1.2. Reducing *n* from 0.15 to 0.08 alone led to a drop in water surface elevation upstream of the zone by about 0.65 feet for the calibrated case. It should be noted that model-predicted elevations in other parts of the reach are not affected by this change. This assures that uncertainty in the roughness of zone 3 is limited to zone 3 only. A Manning's roughness

coefficient of 0.08 was used when the model was applied to flood flow scenarios, in which case boulders would be completely submerged.

Comparison of water surface elevations on the Columbia River reach are shown in Figure 5.4. Again on the Columbia River, the river flow was quite unsteady and two distinct water surface elevations were identified. When different water surface elevations were used as the exit boundary conditions, represented by Run #1 and Run #2, the GSTAR-W model predicted water surface elevations within the range of the measured values. Comparison of the field-measured and model-predicted water surface elevations demonstrates a satisfactory agreement along the Columbia River reach.

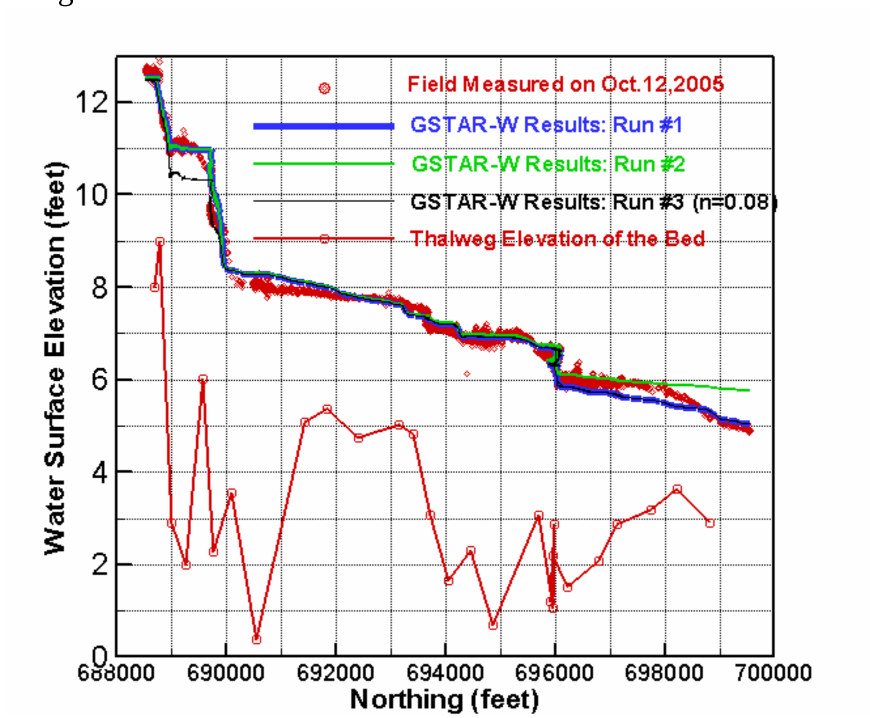


Figure 5.3. Comparison of simulated and field-measured water surface elevations along the Sandy River reach for October 12, 2005 flow conditions.

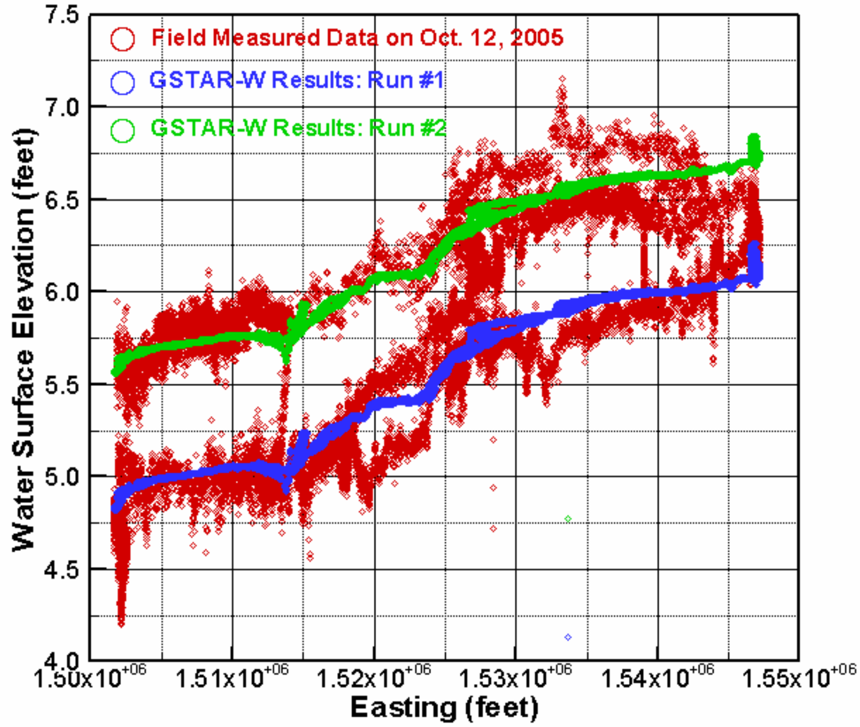


Figure 5.4. Comparison of simulated and field-measured water surface elevations along the Columbia River reach for October 12, 2005 flow conditions.

5.1.4. Comparison of Flow Velocity

Verification of the model was further carried out by comparing predicted and field-measured velocity results. ADCP measured velocity data were collected along both the Sandy and Columbia Rivers. An ensemble of ADCP data is a combination of water velocity (profile) and bottom tracking (boat velocity) data, and can be comprised of an average of several water velocity pings and several bottom pings. A ping is a single pulse of acoustic energy. Sandy River depth-averaged velocity data were processed from the ADCP velocity profiles (Water Mode 12) with 12 sub-pings. The Columbia River depth-averaged velocity data were from a single ADCP ensemble (velocity profile).

In both rivers, a measured data point represents an instantaneous, depth-averaged velocity for a single location. As a result, the data can be noisy, and averaging several adjacent velocity profiles is recommended in some situations. Research indicates that spatial averaging, sampling time, and sampling frequency affects the accuracy of mean velocity estimates (González-Castro *et al.*, 2000). However, no averaging of the field data was performed in this study for comparison with the model results, as we were only interested in evaluating if the simulated data fell within the range of measured data. An effort was made to remove all extreme outlier velocity data from the field-measured dataset. Nevertheless, the dataset may still contain some erroneous data points (as can be seen from several velocity vectors presented in Figure 5.8 to Figure 5.14). This does not affect the model calibration, but may contribute to a portion of the observed noise in the field-measured data.

Field-measured and model-predicted velocity magnitude comparisons at all measurement points were made for both the Sandy River (Figure 5.5) and the Columbia River (Figure 5.6). Although field data were noisy, results of the comparison are quite satisfactory. The large fluctuations in measured velocity values may be attributed to flow unsteadiness created by local geometry features, such as boulders and large turbulent eddies, and partly due to a few erroneous field data points.

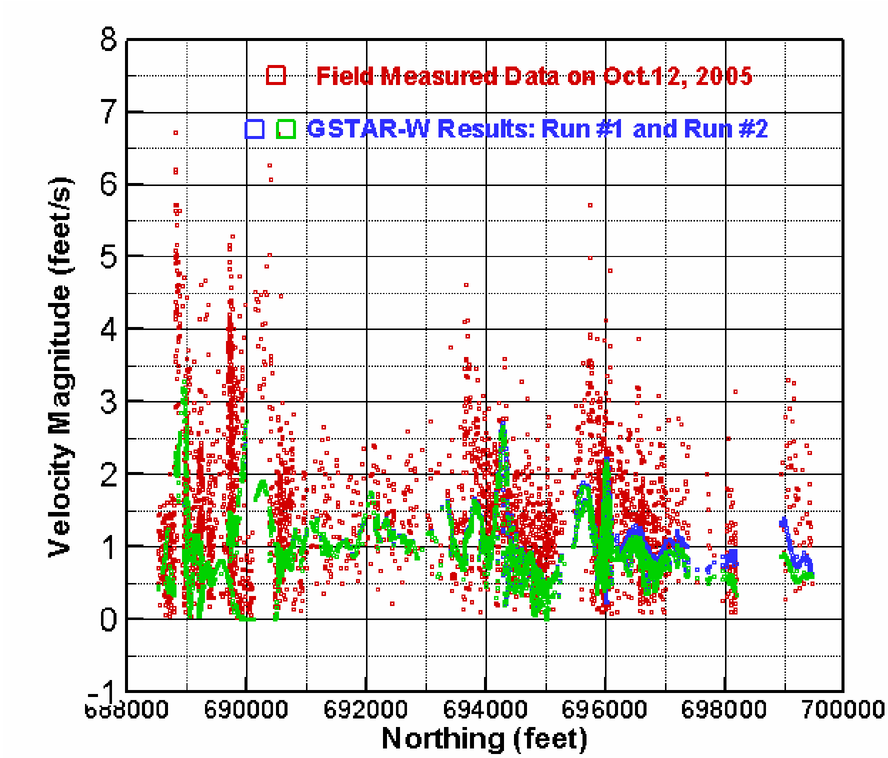


Figure 5.5. Comparison of simulated and field-measured velocity magnitudes along the Sandy River reach for October 12, 2005 flow conditions.

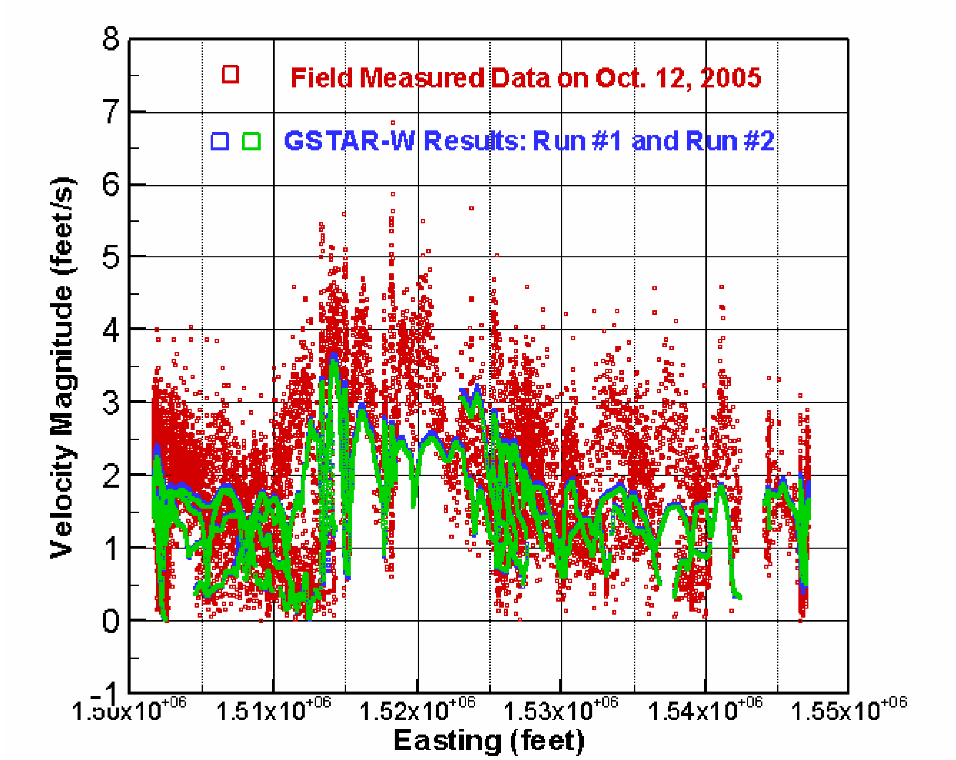


Figure 5.6. Comparison of simulated and field-measured velocity magnitudes along the Columbia River reach for October 12, 2005 flow conditions.

Comparison of velocity data was also achieved through assessment of velocity vectors in different regions of the river reaches. Seven regions were used for comparison (Figure 5.7). Vector comparison plots in the seven regions were also generated (Figure 5.8 to Figure 5.14). In view of uncertainty associated with some of the field data, the comparison between the field-measured and model-predicted data is deemed satisfactory.

In summary, the hydraulic model has been calibrated and comparison of the calibrated model and the field measured data was quite satisfactory, which lends us confidence in the calibrated model.

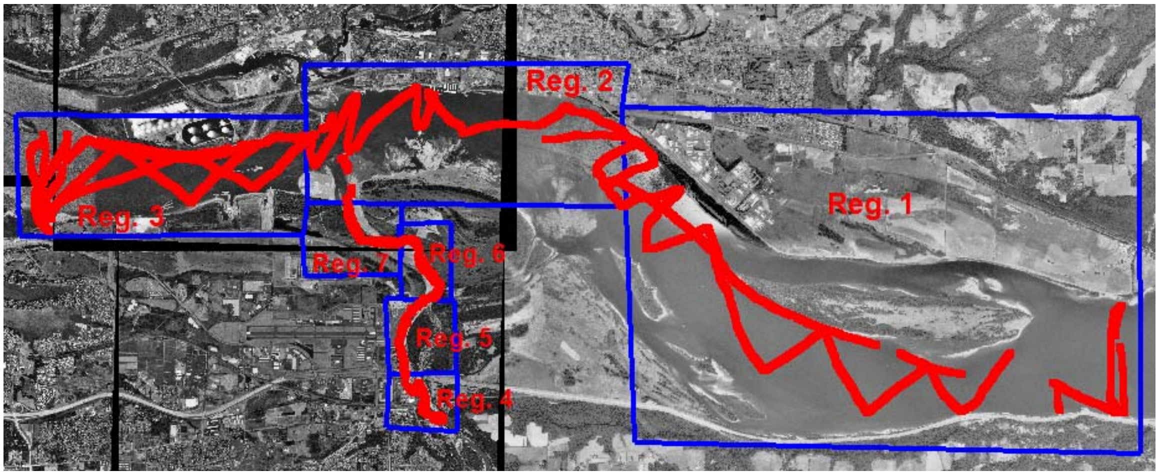


Figure 5.7. Seven regions (blue boxes) used for velocity vector comparison; Red points are the locations where velocity measurements were made.

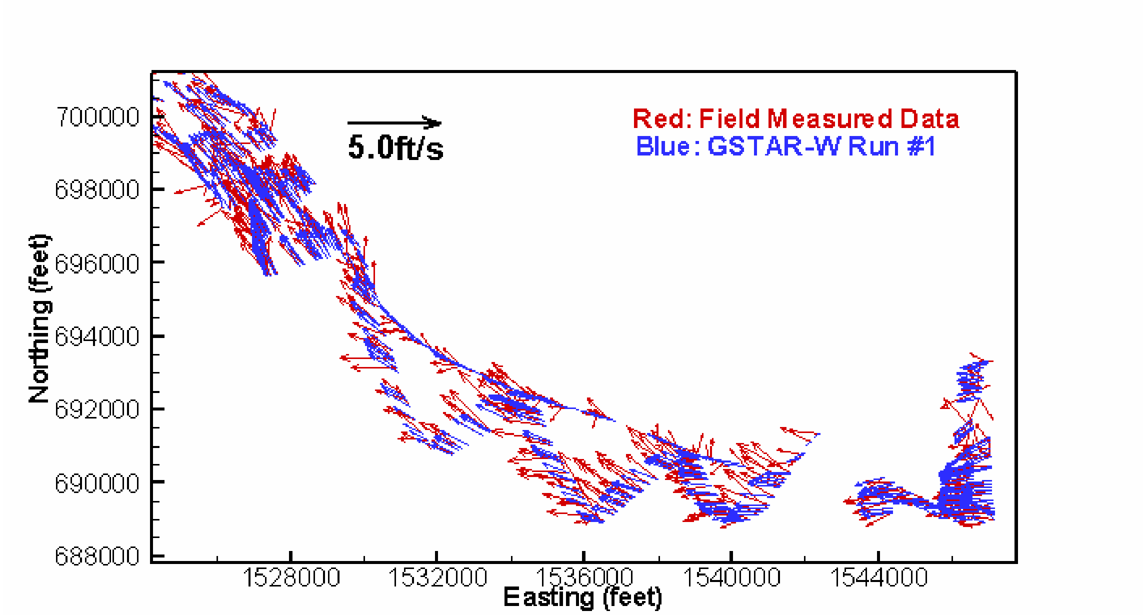


Figure 5.8. Comparison of velocity vectors in Region 1.

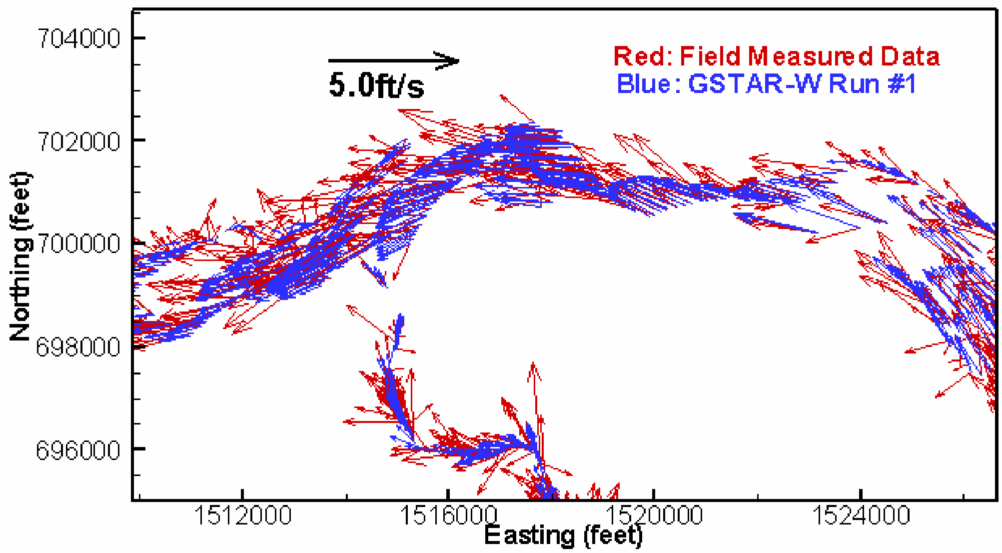


Figure 5.9. Comparison of velocity vectors in Region 2.

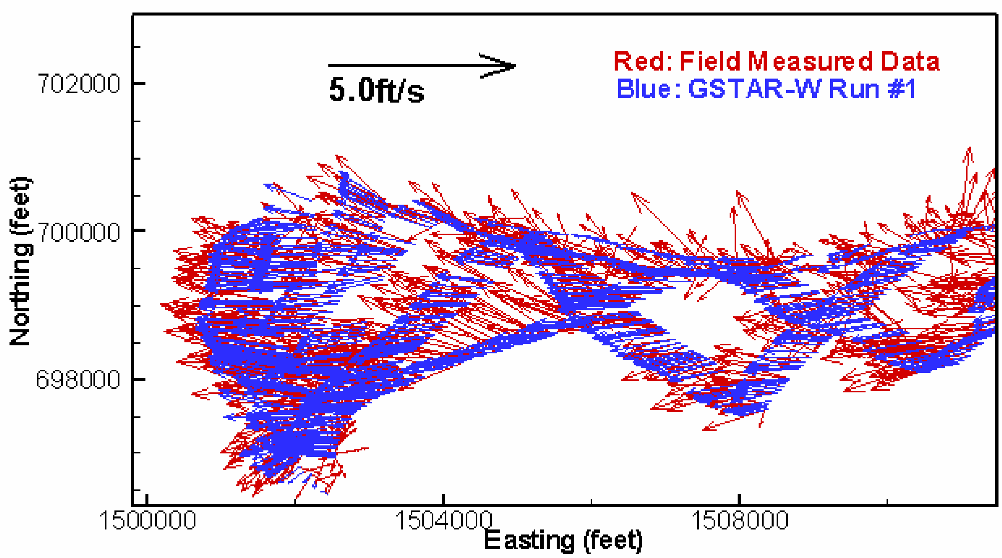


Figure 5.10. Comparison of velocity vectors in Region 3.

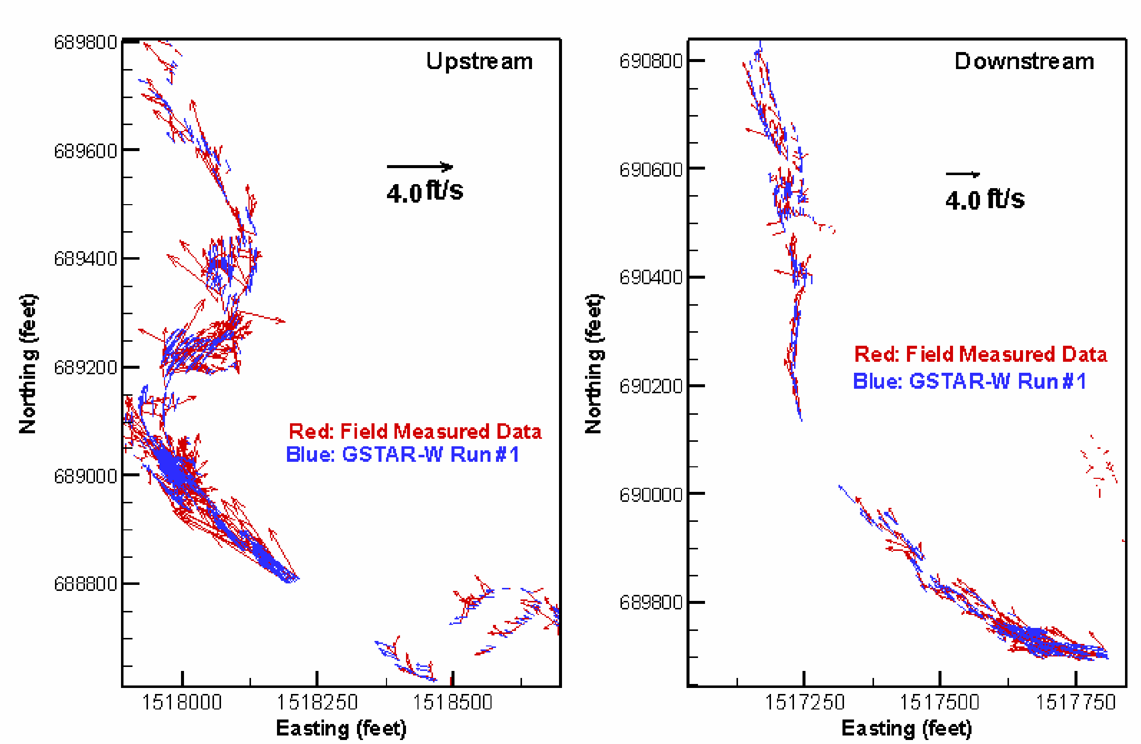


Figure 5.11. Comparison of velocity vectors in Region 4: Left is upstream and right is downstream portion of the region.

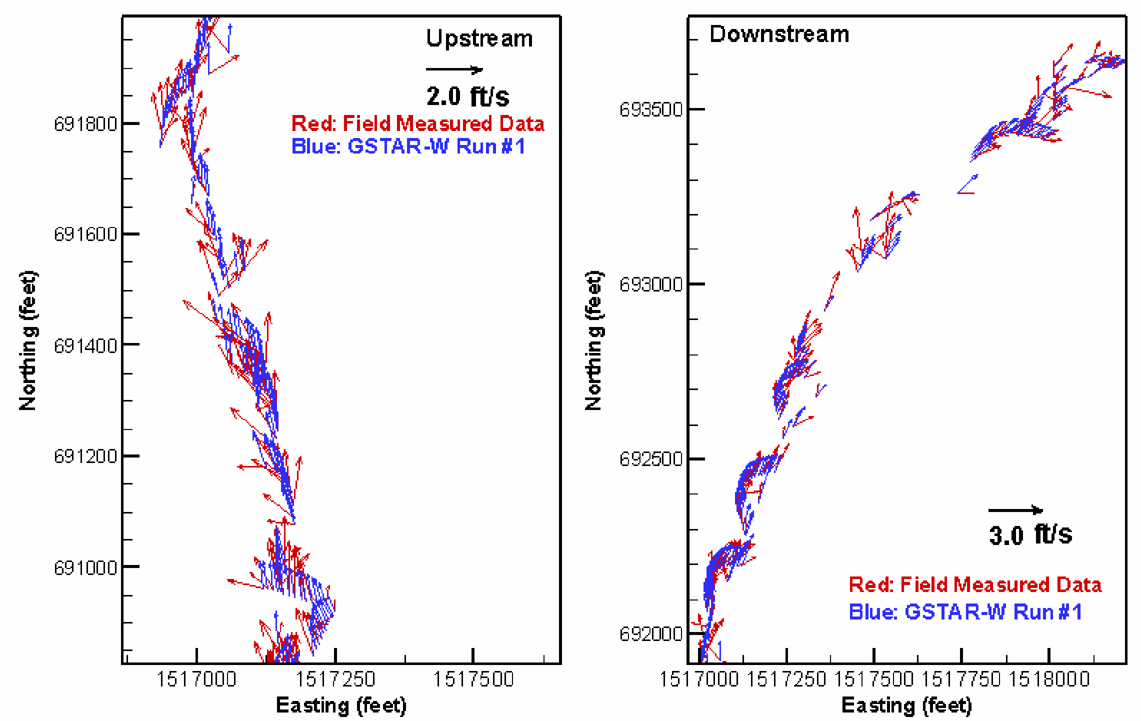


Figure 5.12. Comparison of velocity vectors in Region 5: Left is upstream and right is downstream portion of the region.

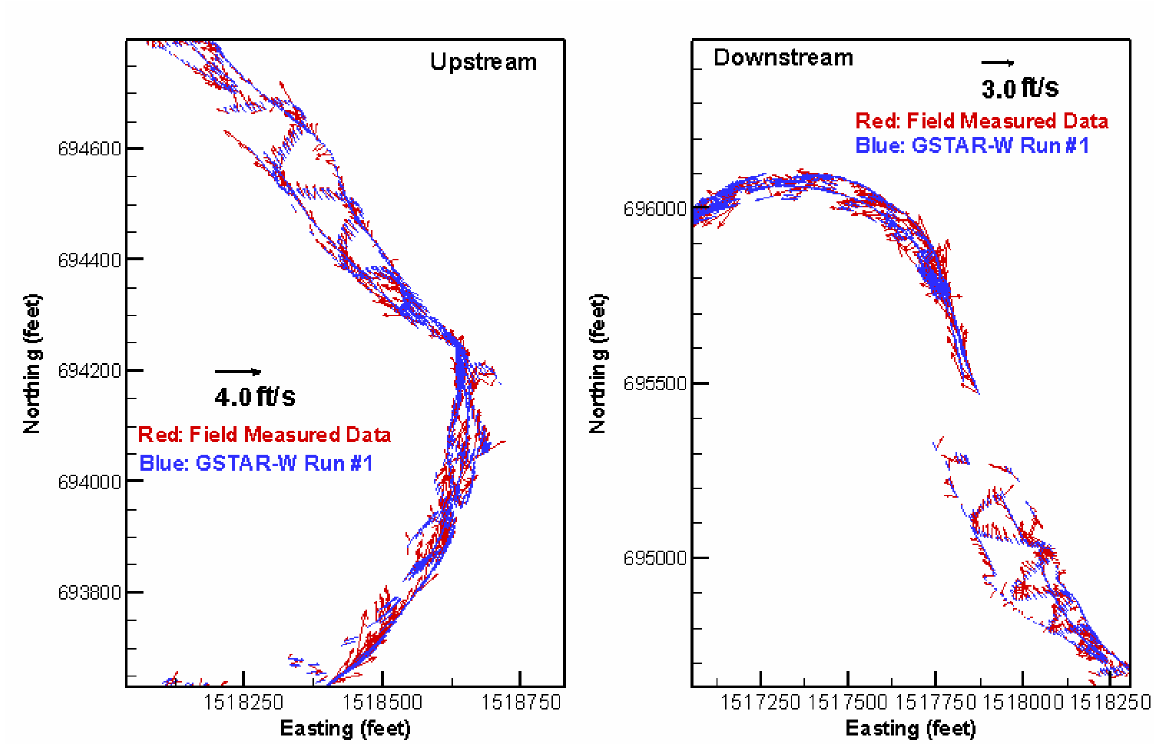


Figure 5.13. Comparison of velocity vectors in Region 6: Left is upstream and right is downstream portion of the region.

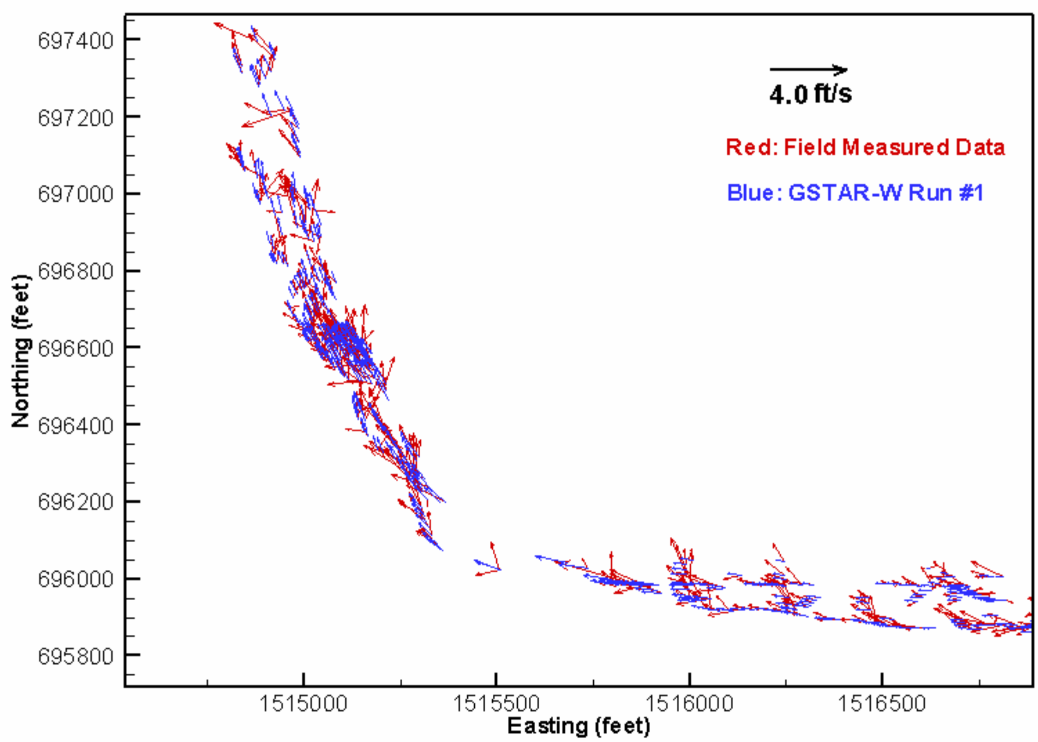


Figure 5.14. Comparison of velocity vectors in Region 7.

5.2. Impact of Removing the Sandy River Delta Dam

This section presents hydraulic and sediment analysis results to evaluate the impact of removing the SRD Dam and the sediment plug on the west side of the dam. Simulations were executed for both the Existing Condition and Removed Dam scenarios with different Sandy River flood flows.

5.2.1. Topography Features

Existing condition topography was discussed in Section 4.4.2. The topography of the Removed Dam scenario was developed as follows:

- Start with the same mesh and topography as the Existing Condition scenario presented in Section 4.4.2;
- The SRD Dam on the east distributary channel and the sediment plug on the west side of the dam were removed down to an elevation of 8.0 feet, while keeping the remaining topography consistent with the existing conditions. The decision to remove the dam and the sediment plug down to 8.0 feet was based on the average surveyed bed elevation along the east distributary channel of the Sandy River as shown in Figure 5.15.

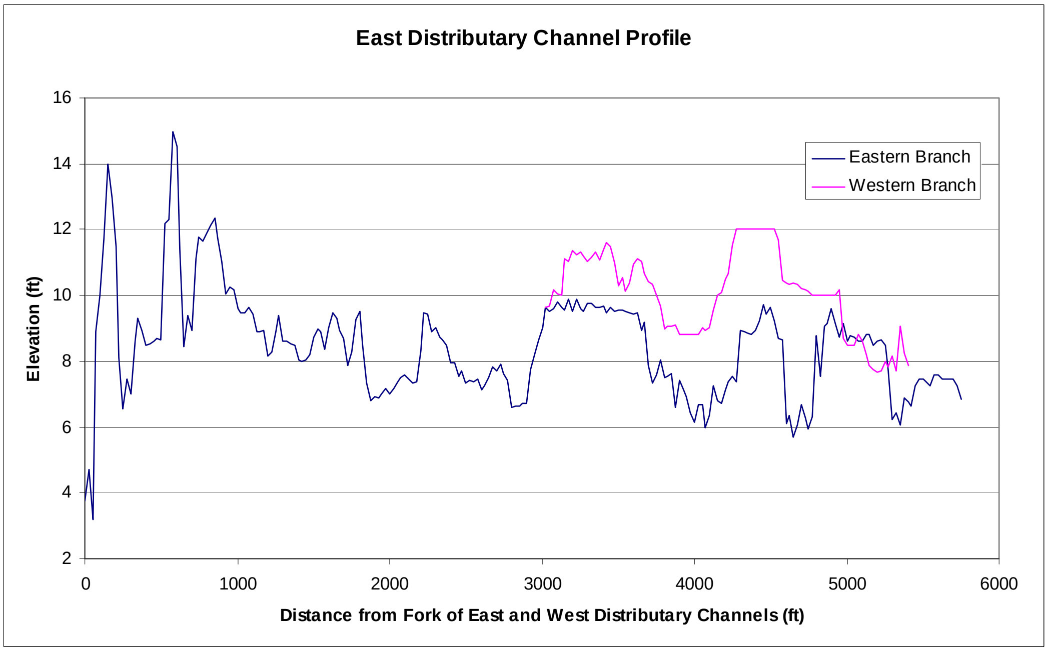
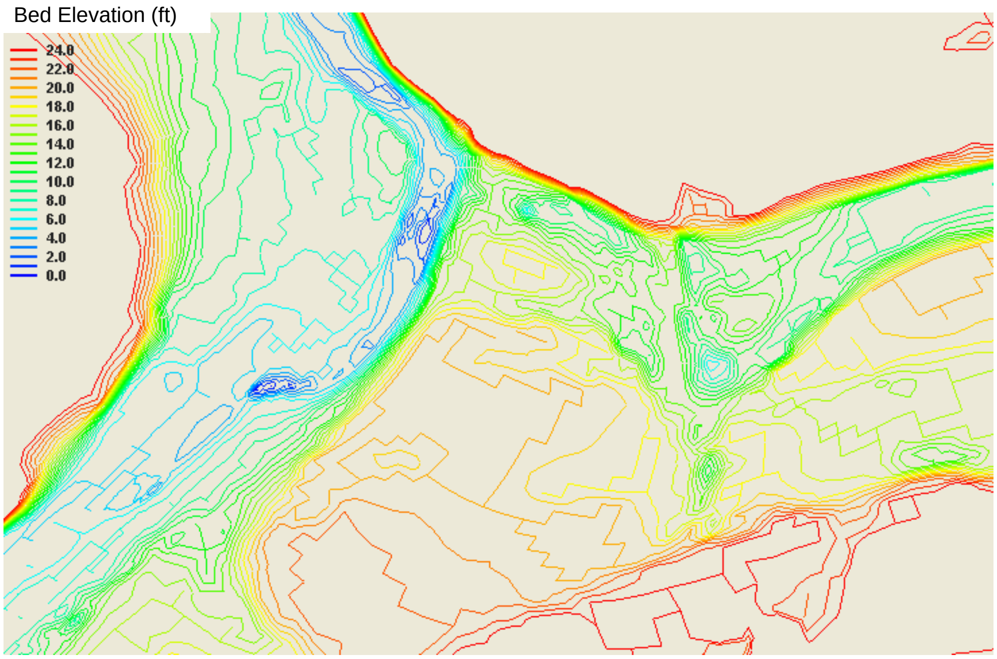
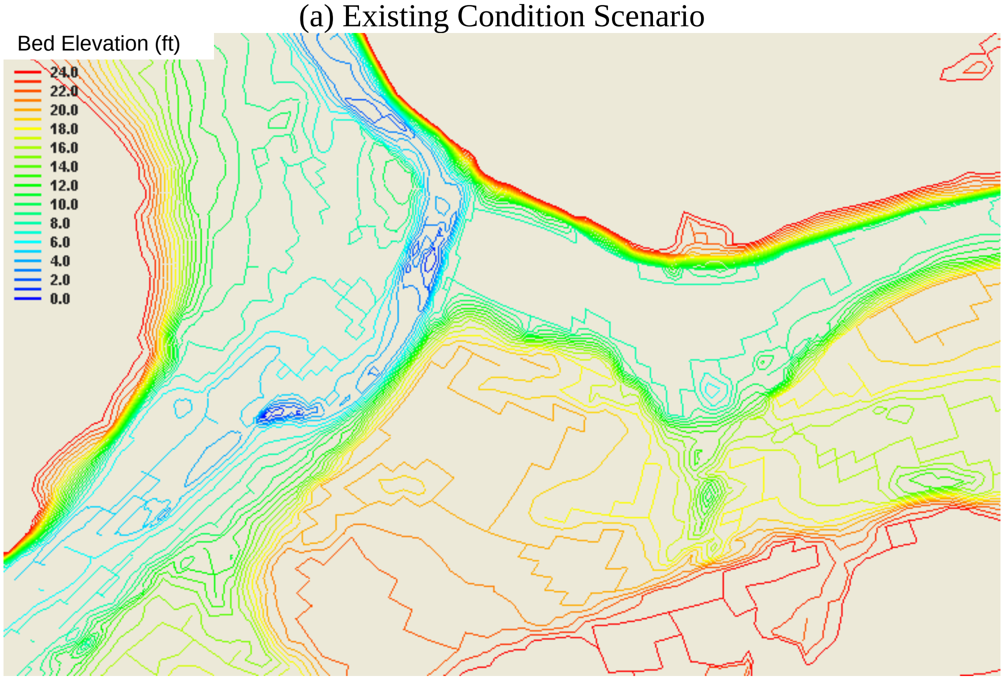


Figure 5.15. Channel profile along the east distributary channel. The east and west branches represent separate flow paths after the east distributary splits near its mouth.

Comparison of bed elevations in the surrounding area of the SRD Dam between the Existing Condition and Removed Dam scenarios is shown in Figure 5.16



(a) Existing Condition Scenario



(b) Removed Dam Scenario

Figure 5.16. Comparison of topography between Existing Condition and Removed Dam scenarios.

5.2.2. Hydraulic Results

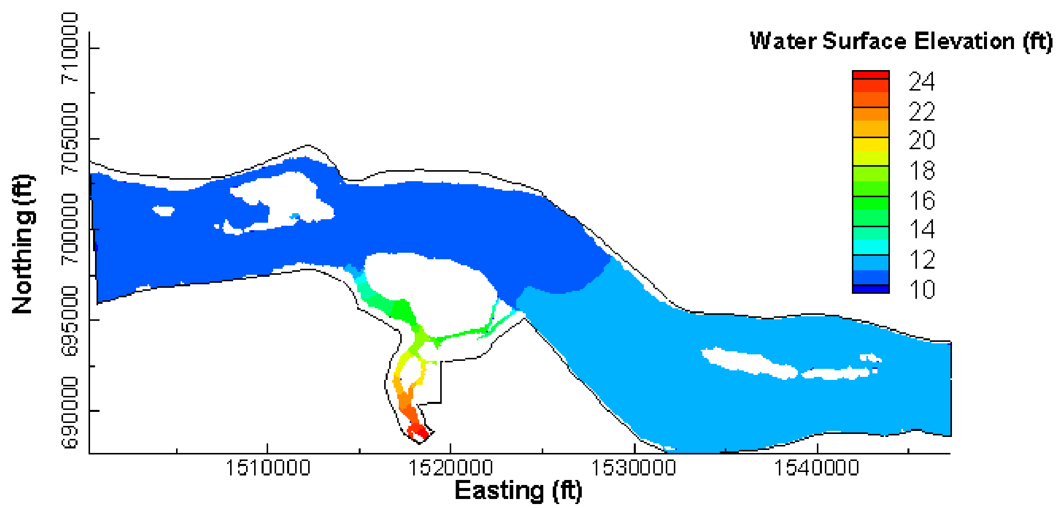
Simulated flow hydraulics was compared between the Existing Condition scenario and the Removed Dam scenario with different floods.

The predicted water surface elevation, which also indicates the flood inundation, is compared in Figure 5.17 to Figure 5.19; the simulated velocity magnitude is displayed in Figure 5.20 to Figure 5.22 over the entire solution domain. In addition, the velocity and flow patterns near the mining area and the dam area are compared in Figure 5.23 to Figure 5.28, and flow velocities near the highway and railroad bridges are shown in Figure 5.29 for the 2-year flood case. The following observations may be made with regard to the hydraulic results:

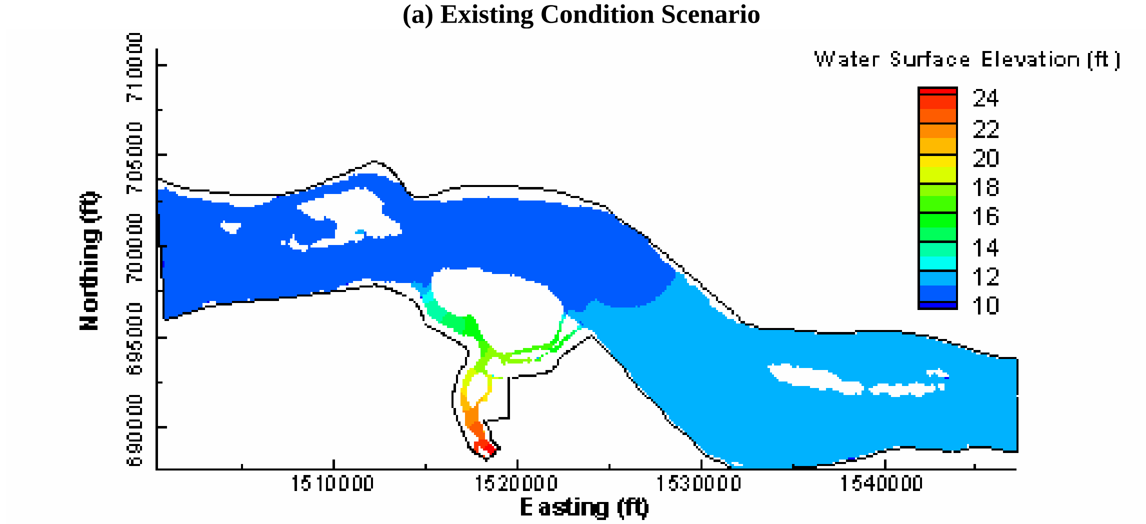
- Under all Sandy River flood conditions examined, model simulation showed that the Sandy River flow overtopped the SRD Dam, and a portion of the flow passed through the east distributary channel, even under the Existing Condition scenario.
- Table 5.2 provides the Sandy River flow split between the east and west distributary channels for the Existing Condition scenario and the Removed Dam Scenario.
- More flow passed through the east distributary channel when the dam and the sediment plug were removed.
- Only small changes in inundation and velocity were noticeable between the Existing Condition and Removed Dam scenarios. This may be attributed to the fact that under the Removed Dam scenario, the majority of the Sandy River still flowed through the west distributary channel, as indicated in Table 5.2.
- The flow pattern near the mining area was characterized by a decrease in flow velocity from the west distributary channel of the Sandy River, a lateral flow component to the upstream portion of the mining area, and the formation of an eddy at the mining area downstream of the sand bar. This pattern existed over the range of simulated Sandy River discharges (i.e., from 2-year to 10-year Sandy River floods). This flow pattern implies that the primary source of sediment deposition to the mining area is from the Sandy River, not the Columbia River, at least under Sandy River flood conditions. Sediment analysis evaluates this issue in more detail in Section 5.2.3. The existence of the eddy should promote increased deposition of sediments at the mining area.
- Flow at the highway and railroad bridges did not change significantly due to the dam removal, indicating little impact to flow hydraulics and local scour (Figure 5.29).

Table 5.2. Flow split to the east and west distributary channels at the Sandy River Delta under the Existing Condition and Removed Dam scenarios.

Discharge at Sandy River (cfs)	Existing Condition Scenario		Removed Dam Scenario	
	West Channel Flow Rate (cfs)	East Channel Flow Rate (cfs)	West Channel Flow Rate (cfs)	East Channel Flow Rate (cfs)
25,406 (2-Year)	22,580	2,820	21,050	4,353
36,757 (5-Year)	31,121	5,636	29,458	7,299
45,239 (10-Year)	37,316	7,921	35,480	9,759

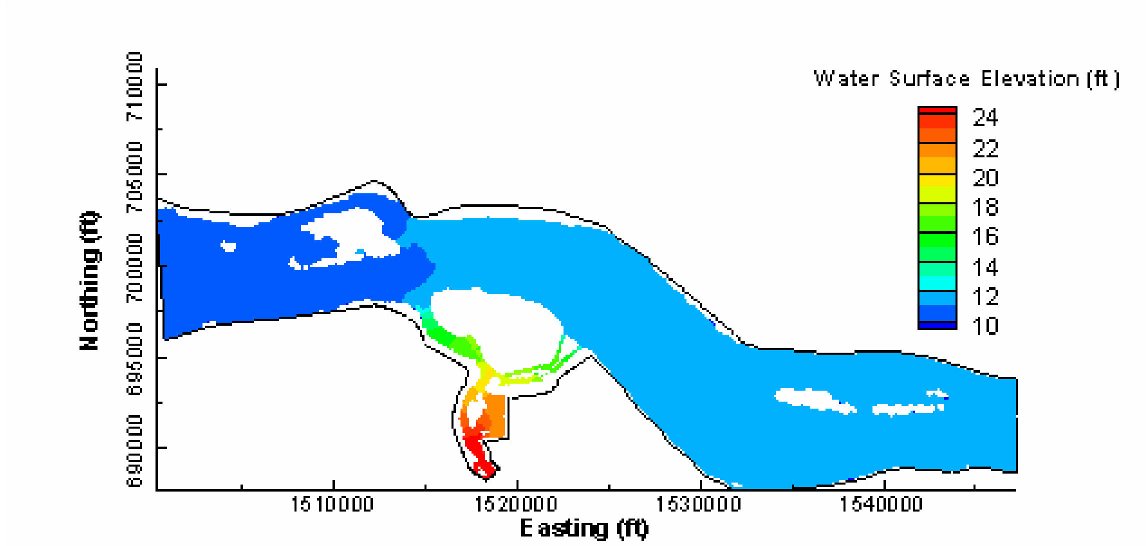


(a) Existing Condition Scenario

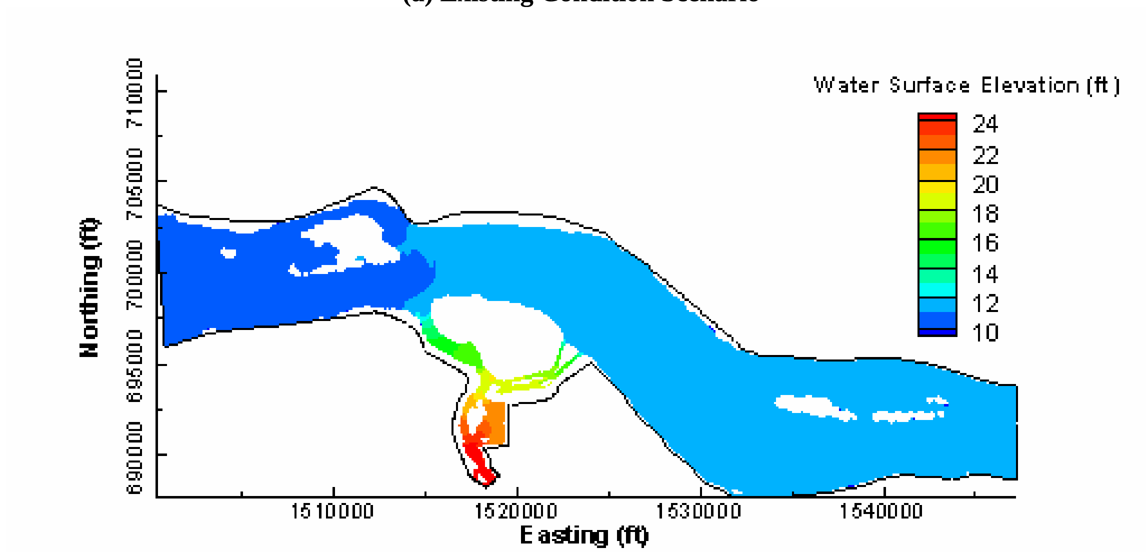


(b) Removed Dam Scenario

Figure 5.17. Comparison of water surface elevations between the Existing Condition and Removed Dam scenarios for the 2-year flood on the Sandy River.

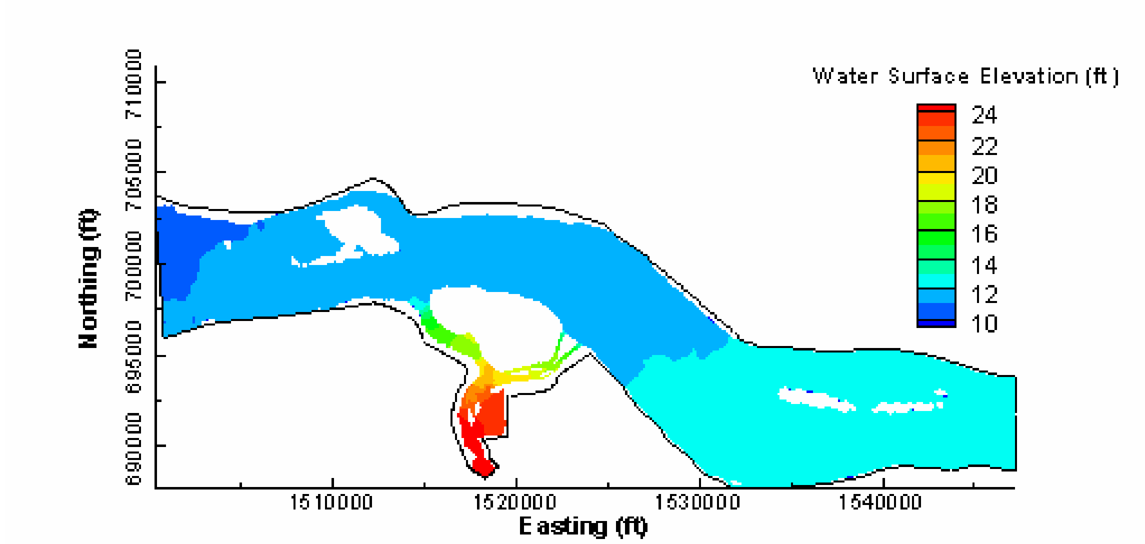


(a) Existing Condition Scenario

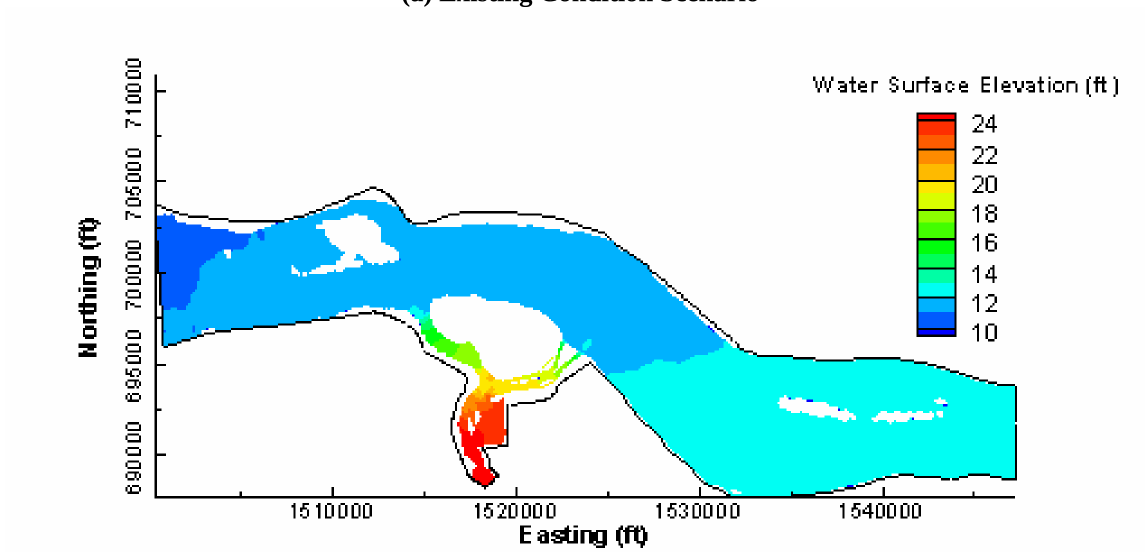


(b) Removed Dam Scenario

Figure 5.18. Comparison of water surface elevations between the Existing Condition and Removed Dam scenarios for the 5-year flood on the Sandy River.

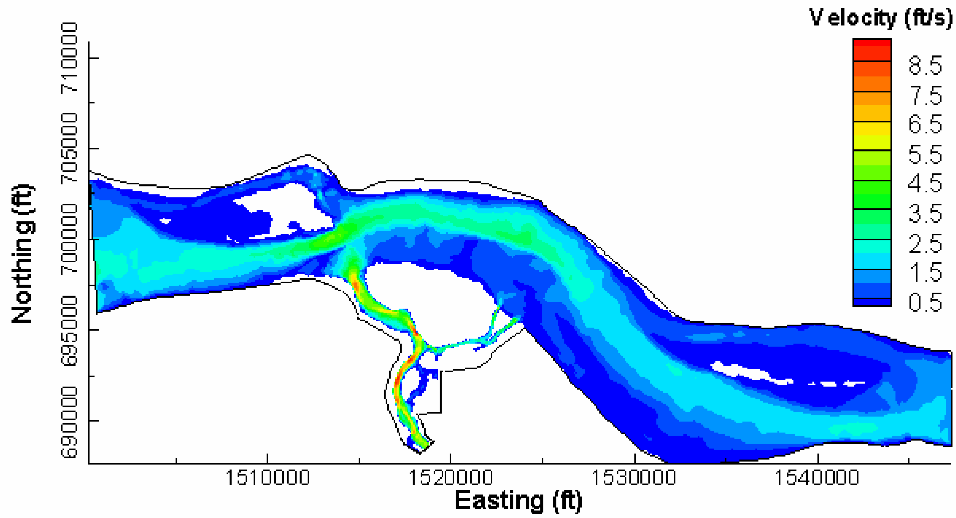


(a) Existing Condition Scenario

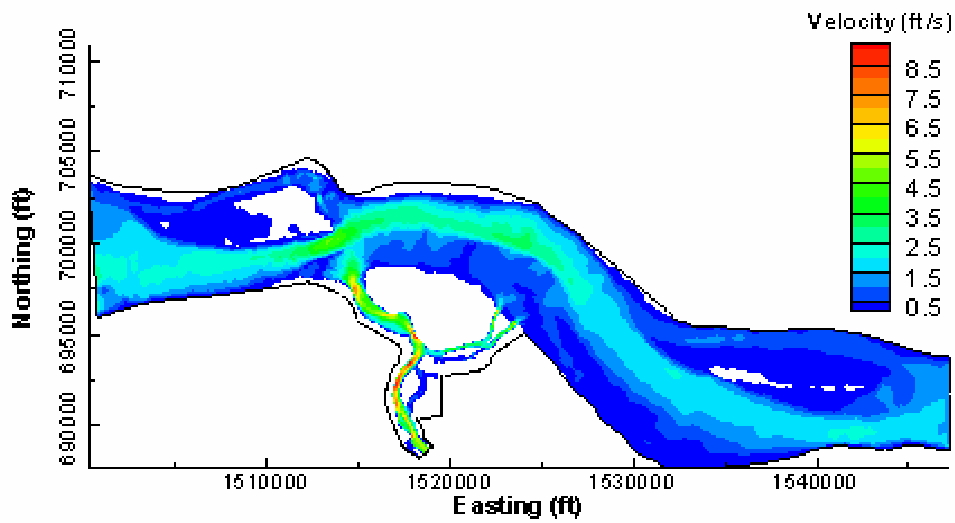


(b) Removed Dam Scenario

Figure 5.19. Comparison of water surface elevations between the Existing Condition and Removed Dam scenarios for the 10-year flood on the Sandy River.

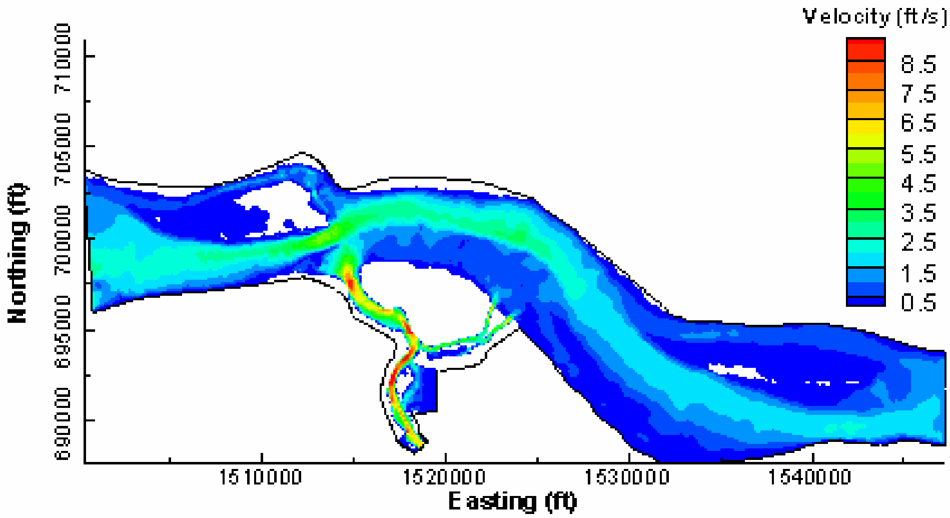


(a) Existing Condition Scenario

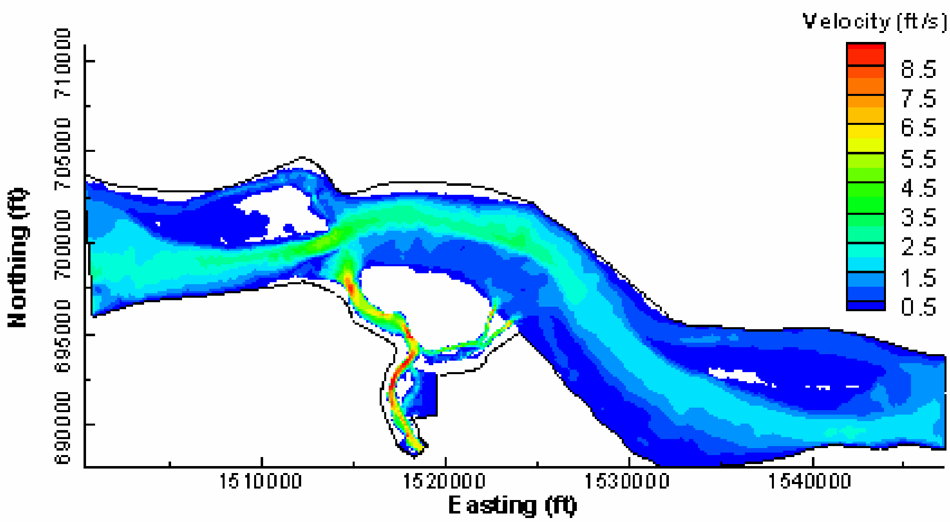


(b) Removed Dam Scenario

Figure 5.20. Comparison of velocity magnitudes between the Existing Condition and Removed Dam scenarios for the 2-year flood on the Sandy River.

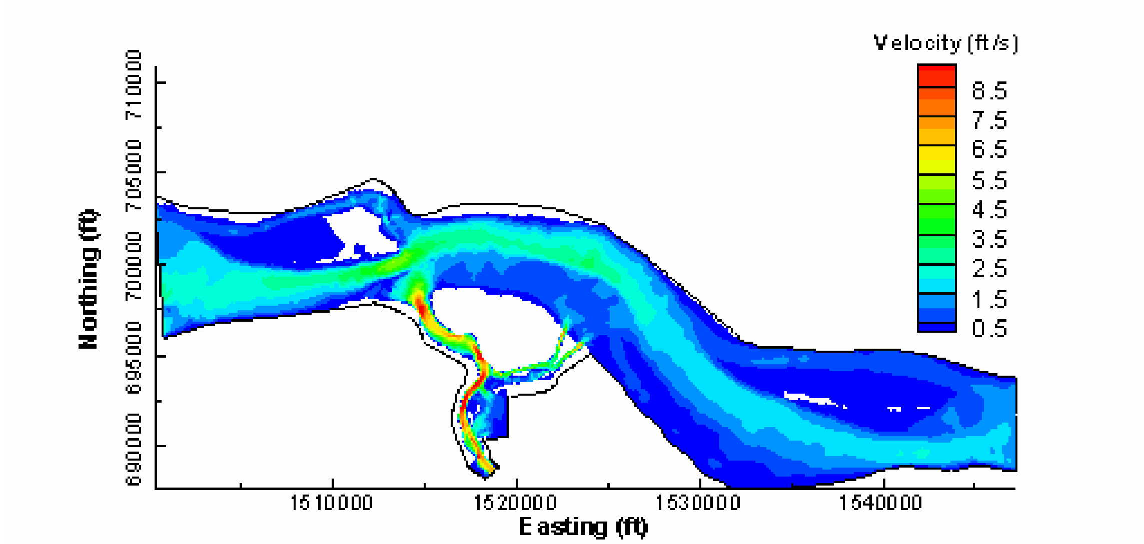


(a) Existing Condition Scenario

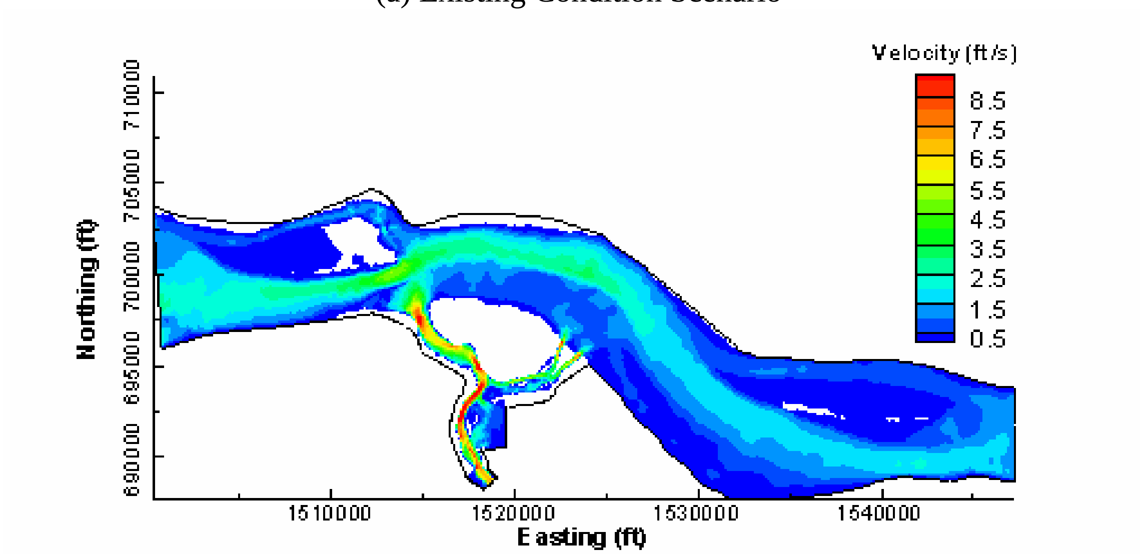


(b) Removed Dam Scenario

Figure 5.21. Comparison of velocity magnitudes between the Existing Condition and Removed Dam scenarios for the 5-year flood on the Sandy River.

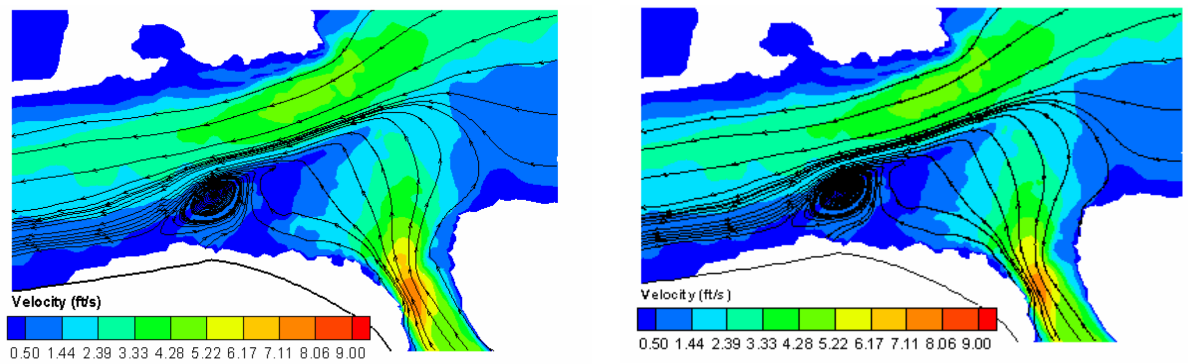


(a) Existing Condition Scenario



(b) Removed Dam Scenario

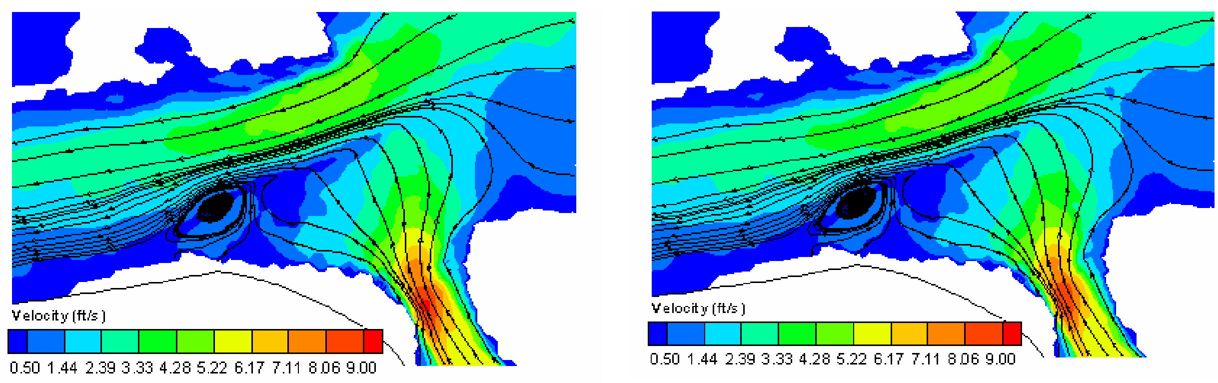
Figure 5.22. Comparison of velocity magnitudes between the Existing Condition and Removed Dam scenarios for the 10-year flood on the Sandy River.



(a) Existing Condition Scenario

(b) Removed Dam Scenario

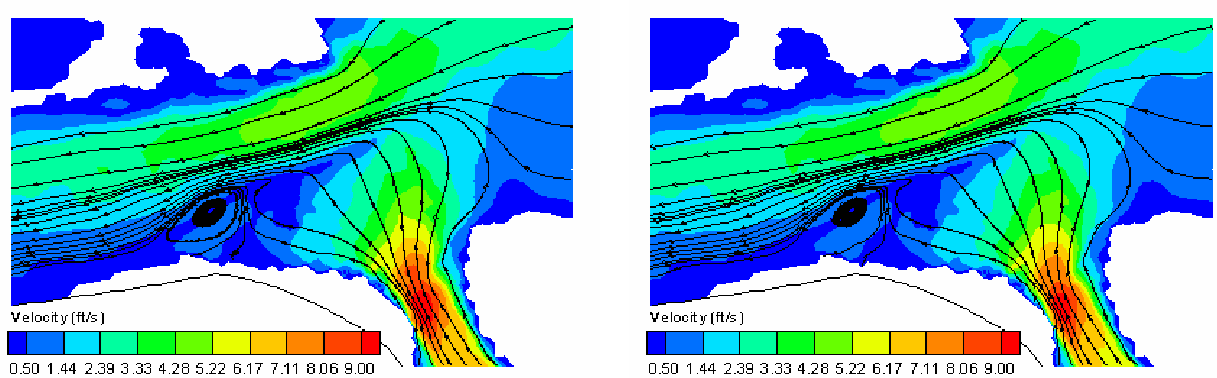
Figure 5.23. Comparison of velocities near the mining area for the 2-year Sandy River flood.



(a) Existing Condition Scenario

(b) Removed Dam Scenario

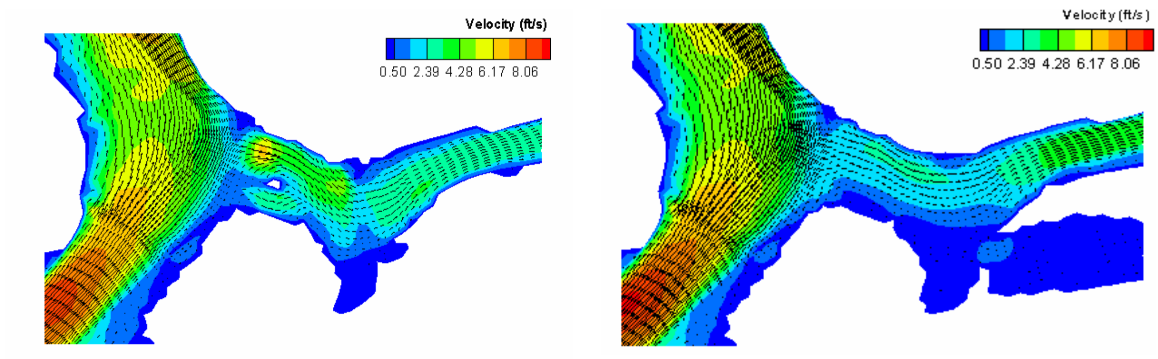
Figure 5.24. Comparison of velocities near the mining area for the 5-year Sandy River flood.



(a) Existing Condition Scenario

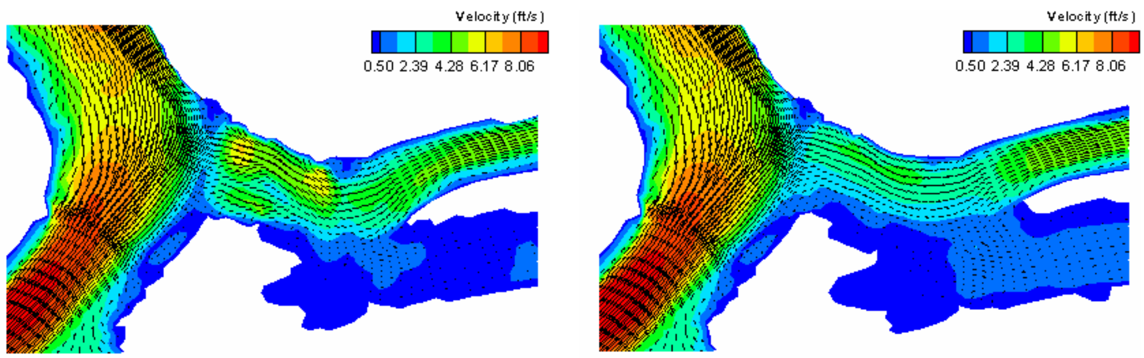
(b) Removed Dam Scenario

Figure 5.25. Comparison of velocities near the mining area for the 10-year Sandy River flood.



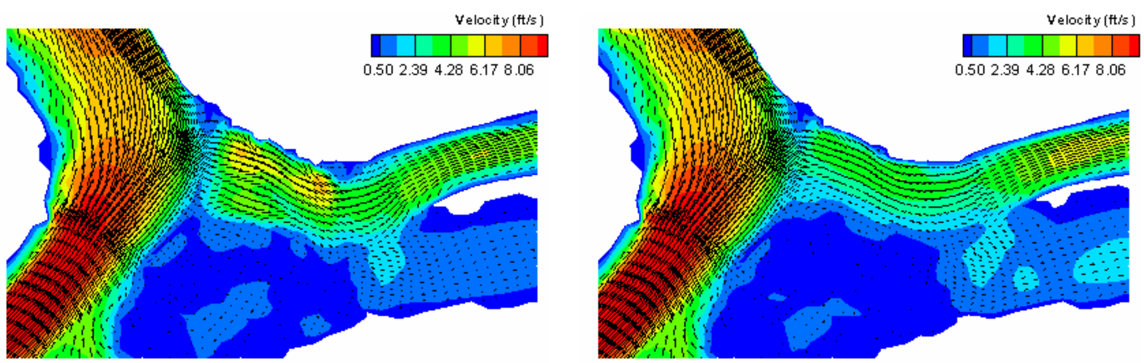
(a) Existing Condition Scenario (b) Removed Dam Scenario

Figure 5.26. Comparison of velocities near the SRD Dam for the 2-year Sandy River flood.



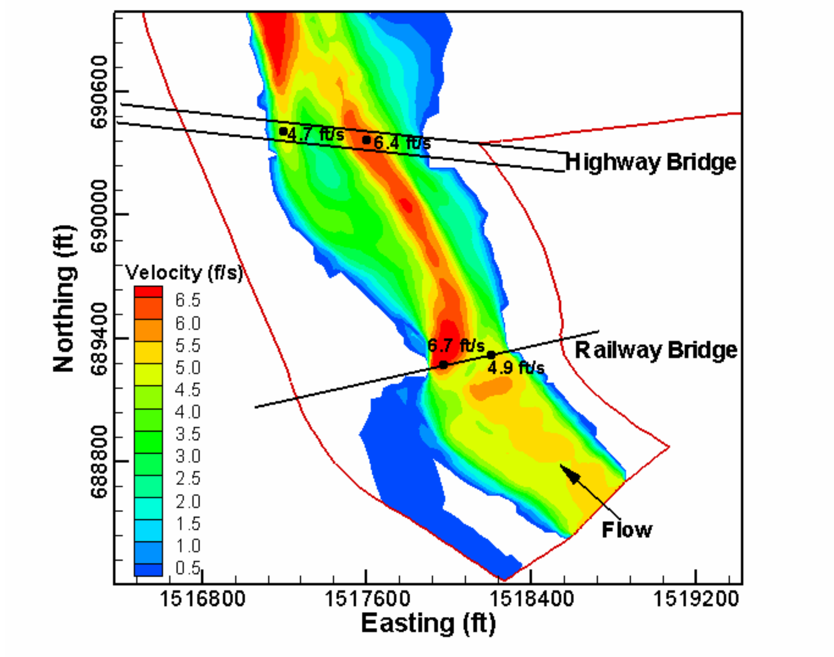
(a) Existing Condition Scenario (b) Removed Dam Scenario

Figure 5.27. Comparison of velocities near the SRD Dam for the 5-year Sandy River flood.

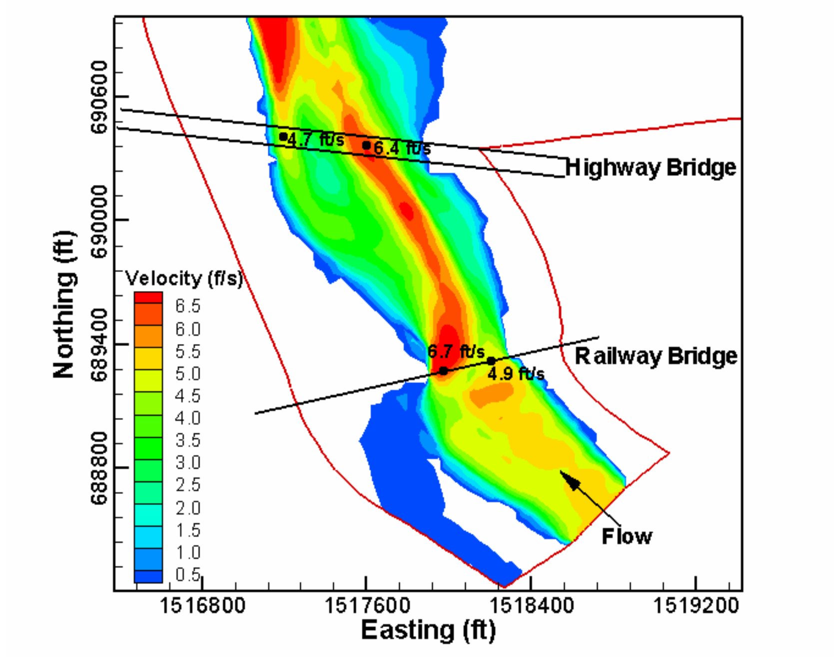


(a) Existing Condition Scenario (b) Removed Dam Scenario

Figure 5.28. Comparison of velocities near the SRD Dam for the 10-year Sandy River flood.



(a) Existing Condition Scenario



(b) Removed Dam Scenario

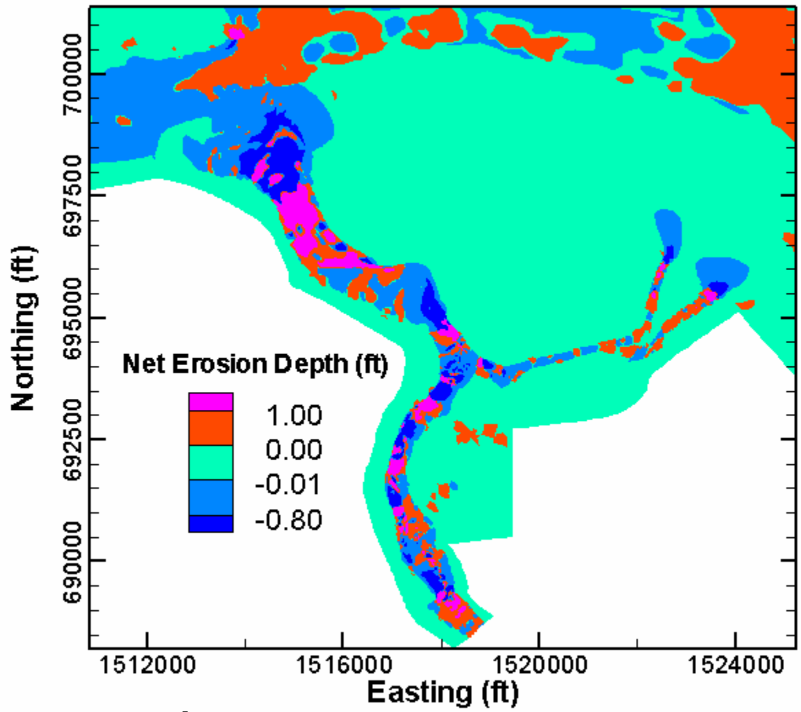
Figure 5.29. Comparison of simulated velocities at the highway and railroad bridge area for the 2-year flood on the Sandy River.

5.2.3. Sediment Results

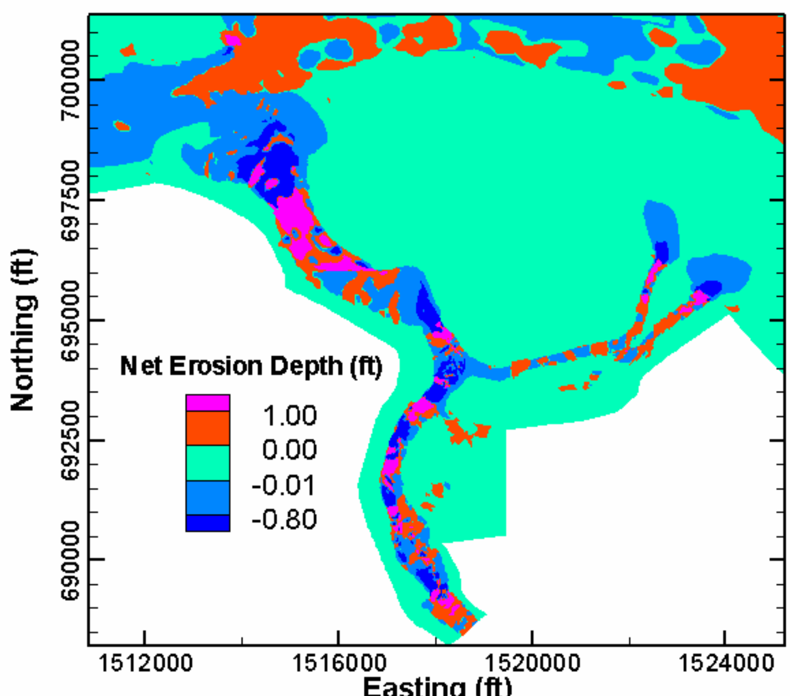
This section presents the sediment analysis results. Given the flow hydraulics and initial bed gradation, sediment analysis was performed for a period of 24 hours. Post-simulation analysis indicated that the sediment transport reached steady state condition within a few hours, and thus, the simulation period of 24 hours was sufficient.

The fixed bed elevation analysis will not predict absolute values of net erosion and deposition depth accurately, as discussed in Section 5.6. However, the erosion and deposition pattern may be simulated with accuracy and are presented in Figure 5.30 and Figure 5.31 for the 2-year flood Existing Condition scenario. Figure 5.30 illustrates a plan view over the Sandy River Delta area, and Figure 5.31 offers a 3D perspective at the mining area. Plots for other scenarios and floods were not included due to their similarities with these results.

The predicted erosion/deposition pattern alternated along the Sandy River. Deposition dominates the sandbar area at the confluence of the west distributary of the Sandy River and the Columbia River, as well as at the mining area. Figure 5.32 illustrates the erosion and deposition pattern at the highway and railroad bridge areas for the Existing Condition and Removed Dam scenarios. The difference in sediment erosion/deposition between the Existing Condition and Removed Dam scenarios was predicted to be negligible at the bridges.



(a) Existing Condition Scenario



(b) Removed Dam Scenario

Figure 5.30. Predicted erosion and deposition pattern 24 hours after a 2-year Sandy River flood. Note that the pattern is relative to the initial topography measured on October 12, 2005. Positive depth (red and purple) indicates erosion and negative depth (green and blue) indicates deposition.

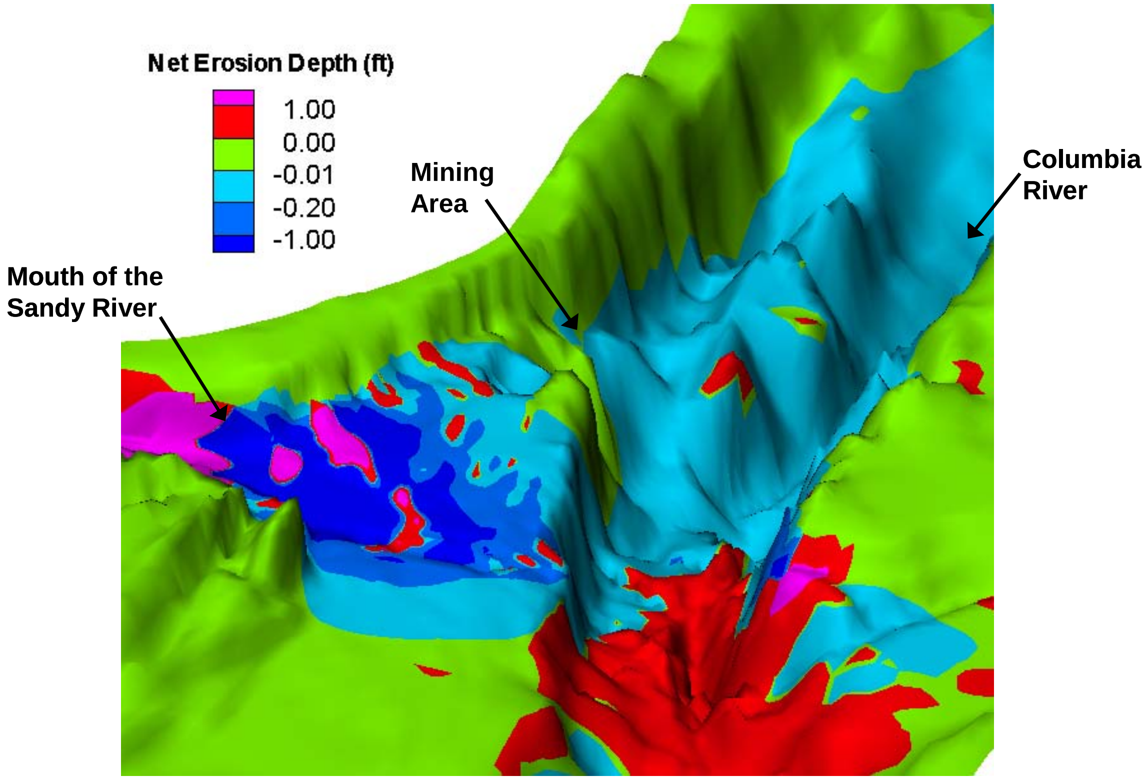
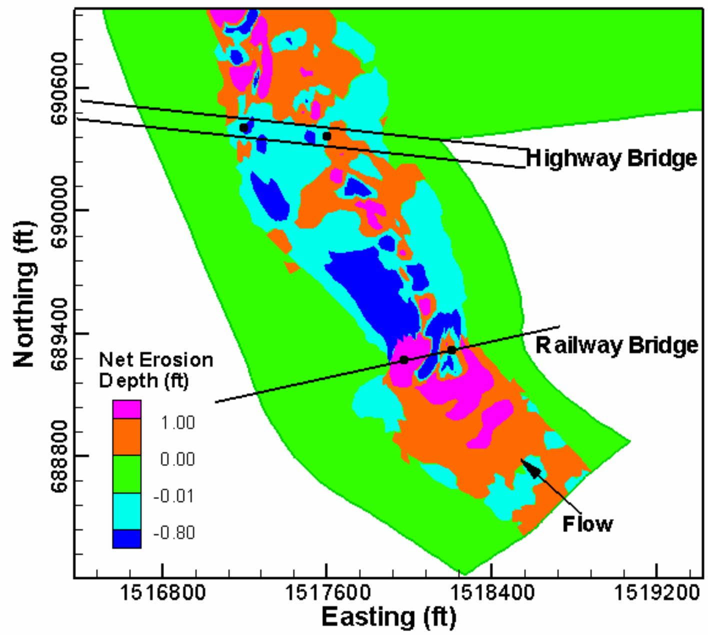
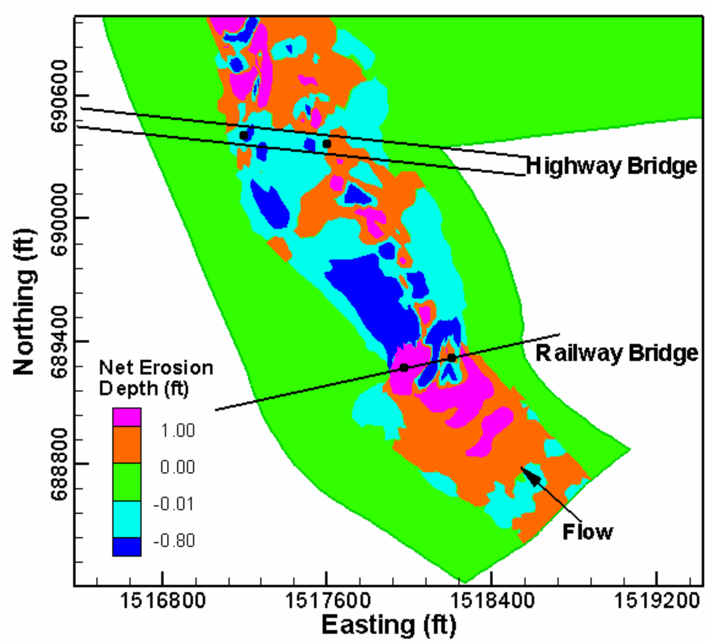


Figure 5.31. Predicted erosion and deposition pattern at the mining area 24-hours after a 2-year Sandy River flood for the Existing Condition scenario. Note that the pattern is relative to the initial topography measured on October 12, 2005. Positive depth (red and purple) indicates erosion and negative depth (green and blue) indicates deposition.



(a) Existing Condition Scenario



(b) Removed Dam Scenario

Figure 5.32. Comparison of simulated erosion/deposition patterns in the area of the highway and railroad bridges.

Impacts on sand delivery to the mining area resulting from removal of the SRD Dam were of particular interest to this project. To more thoroughly evaluate this impact, a cross section of the west channel of the Sandy River near the confluence, was used to monitor the sediment transport rate through the cross section (labeled as West Channel CS in Figure 5.33). The sediment transport rate at this cross section provided information about the amount of sediment available from the west channel of the Sandy River. This rate should be proportional to the amount of sediment delivery to the mining area. Further, the perimeter of a sediment source area, labeled Upstream Area in Figure 5.33, was also used to monitor the sediment rate through and total volume deposited in the source area of mined sediment. Post-simulation analysis indicated that the sediment transport rates through the cross section and the perimeter were correlated. Despite differences in the scales and timings of Figure 5.33 and Figure 5.34, the permitted mining area boundary appears to be located within the region labeled Upstream Area.

The permitted mining area boundary depicted in Figure 5.34 became available following completion of model simulation. However, the selection of the Upstream Area as an indicator of sediment delivery to the mining area was justified. Results suggested that sediment deposition was much greater on the east portion of the Upstream Area than on the west portion (Figure 5.31). Existing condition topography illustrated that the bed elevation in the mining area was very low compared to the elevation in the east part of Upstream Area (Figure 4.9 and Figure 5.31). The model results indicate that deposition in the Upstream Area is the main sediment source for the mining area, as upstream deposits would be moved into the mining area by gravity. The current sediment model does not include sediment movement due to gravity. In addition to gravitational action, the remaining sediment storage at the Upstream Area will be mobilized and transported into the mining area during high flows on the Columbia River.

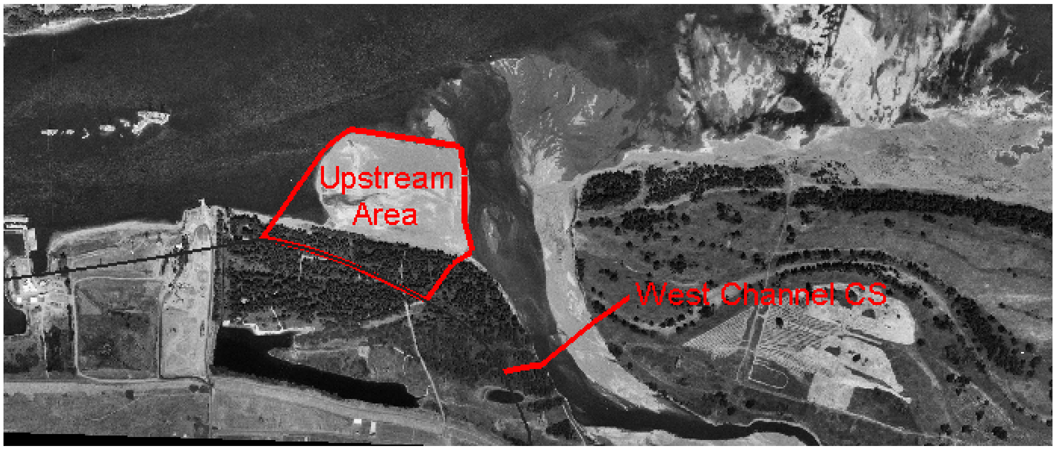


Figure 5.33. Cross sections through which sediment transport rates were calculated.

Figure 5.34. Photograph showing the permitted mining boundary (outlined in red). Note scale difference from Figure 5.33.

Figure 5.35 to Figure 5.37 display the sediment transport rate by size classes through the West Channel Cross Section (CS) versus time for the 2-, 5-, and 10-year floods. The same plots are also repeated for the sediment rates through the Upstream Area boundary in Figure 5.38 to 5.40. Comparisons between the Existing condition and Removed Dam scenarios are also provided in these plots. Sediment flux, as shown on the y-axis of Figure 5.35 to Figure 5.40, represents the mass of sediment through the cross section or into the area per unit time. The following observations were made during comparison of the results:

- Sediment transport rates through the West Channel CS and Upstream Area boundary reached steady state values within a few hours for all simulation runs.

- Coarse sand (size class 2) has the highest transport rate, followed by fine sand (size class 1), medium gravel (size class 4), fine gravel (size class 3), and coarse gravel and fine cobble (size class 5).
- Despite noticeable transport of fine and medium gravels through the Sandy River West Channel CS, the transport of gravel into the Upstream Area is relatively very small.

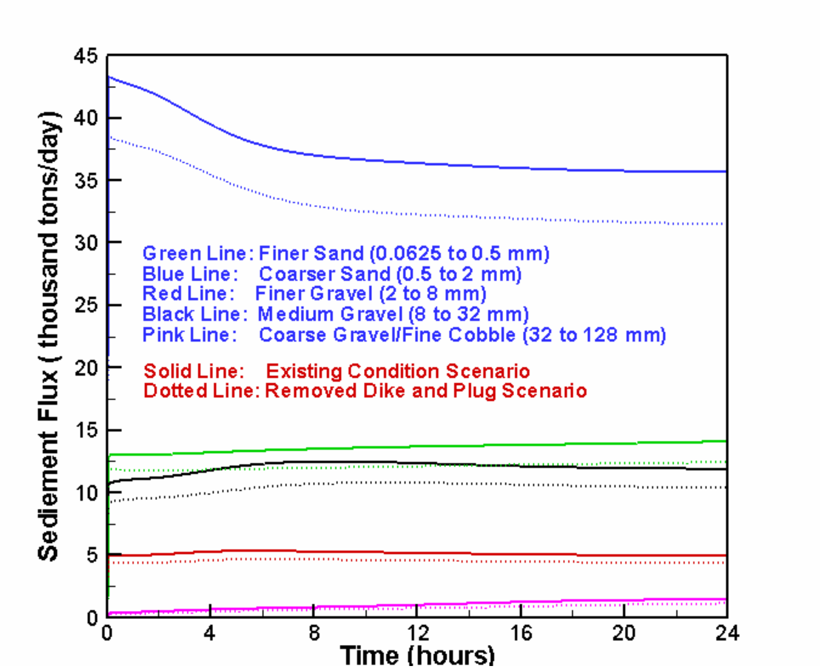


Figure 5.35. Comparison of sediment flux (sediment mass through the cross section per unit time) by size class through the West Channel CS between the Existing Condition and Removed Dam scenarios under 2-year Sandy River flood.

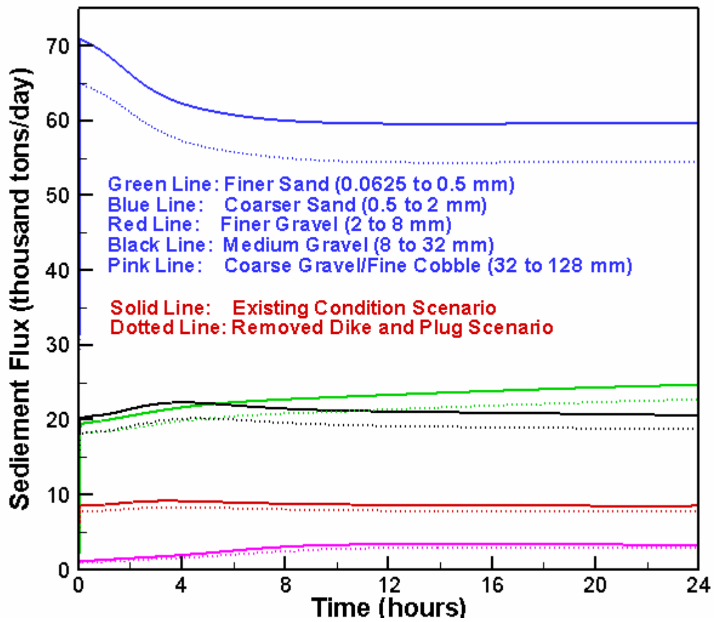


Figure 5.36. Comparison of sediment flux (sediment mass through the cross section per unit time) by size class through the West Channel CS between the Existing Condition and Removed Dam scenarios under 5-year Sandy River flood.

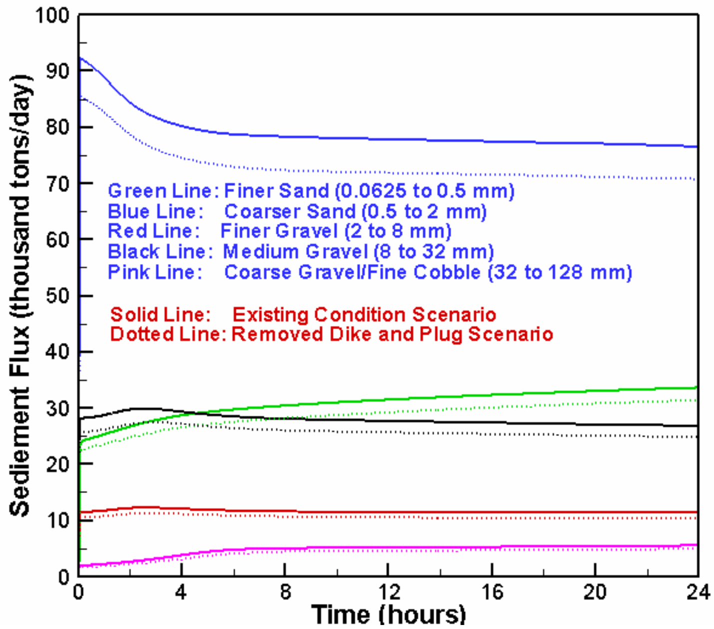


Figure 5.37. Comparison of sediment flux (sediment mass through the cross section per unit time) by size class through the West Channel CS between the Existing Condition and Removed Dam scenarios under 10-year Sandy River flood.

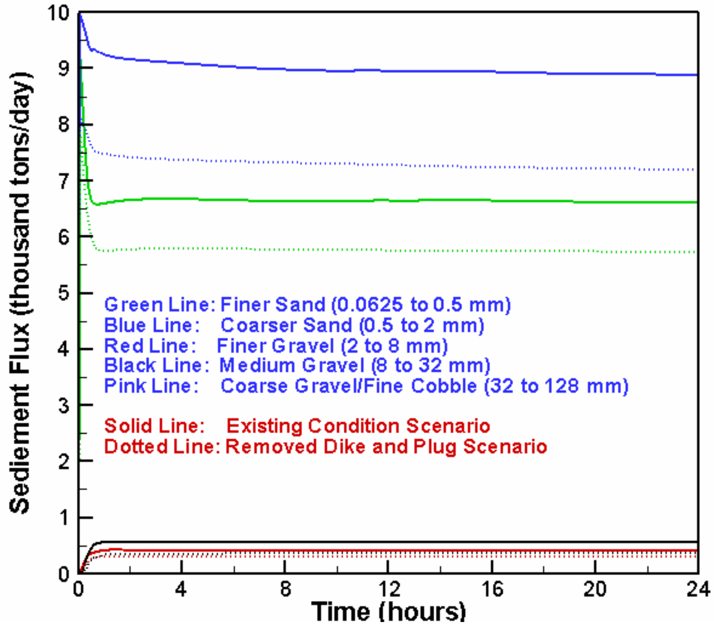


Figure 5.38. Comparison of sediment flux (sediment mass into the area per unit time) by size class into the Upstream Area between the Existing Condition and Removed Dam scenarios under 2-year Sandy River flood.

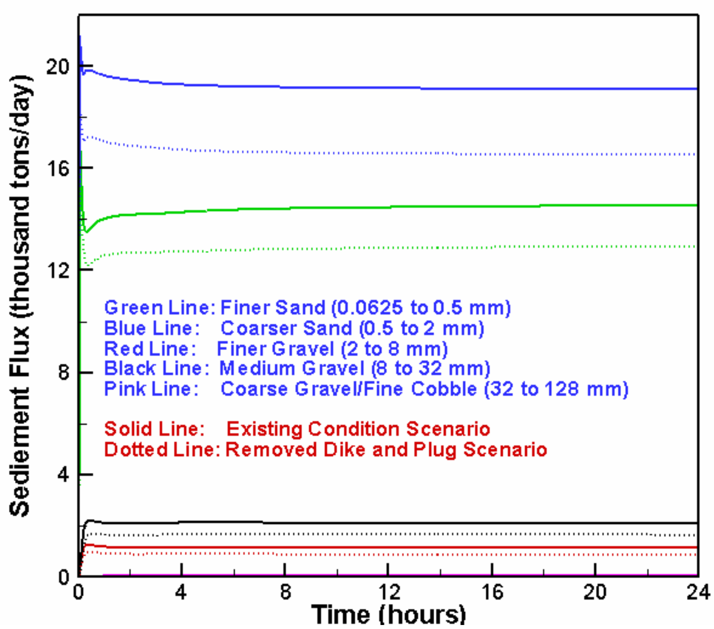


Figure 5.39. Comparison of sediment flux (sediment mass into the area per unit time) by size class into the Upstream Area between the Existing Condition and Removed Dam scenarios under 5-year Sandy River flood.

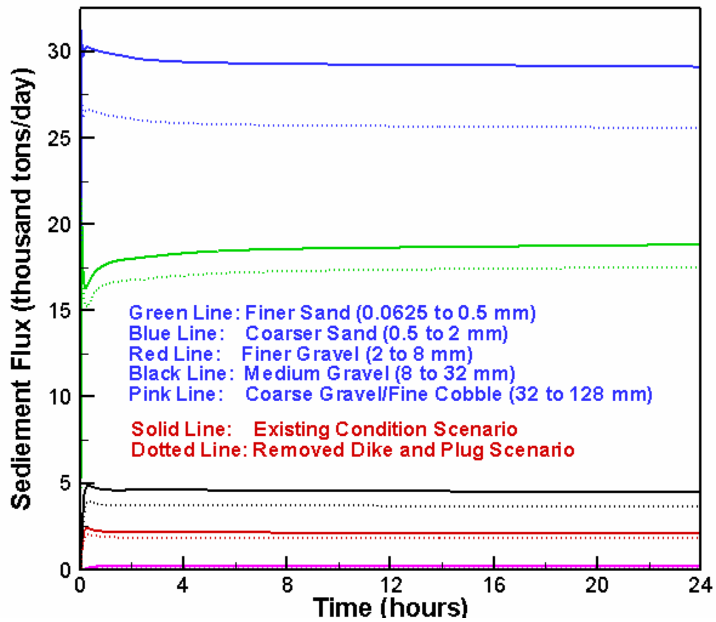


Figure 5.40. Comparison of sediment flux (sediment mass into the area per unit time) by size class into the Upstream Area between the Existing Condition and Removed Dam scenarios under 10-year Sandy River flood.

The steady state sand transport rates (i.e., the sum of sediment class 1 and class 2) after 24 hours of simulation are tabulated in Table 5.3 and Table 5.4 in which a quantitative comparison is made. Table 5.5 also lists the total sand volume deposited within the Upstream Area over a 24-hour period under the 2-, 5-, and 10-year Sandy River floods. The model predicted a reduction in sand transport rate through the West Channel CS of approximately 7 percent to 12 percent following removal of the SRD Dam for floods between 2- and 10-year recurrence intervals (Table 5.5). Sediment delivery to the Upstream Area was predicted to have a reduction of 10 percent to 14 percent for floods between 2- and 10-year recurrence intervals. In general, as the flood magnitude is increased, the percentage of reduction in sand delivery to the mining area is decreased. The percentage reduction was 16 percent for the 10-year flood if the total sand volume was used (Table 5.5). However, it is recommended that the sediment flux be used instead of the total sand volume. Sediment flux represents the equilibrium sediment flow into the Upstream Area that is independent of the initial conditions used for the simulation; while the total sand volume is the accumulated value from the start to end of the simulation and is dependent on the initial conditions. Initial conditions contain some uncertainties. Despite differences between the sediment flux and total volume, percentage changes from existing conditions do not substantially differ from each based on results in Table 5.4 and Table 5.5.

Table 5.3. Comparison of sand transport rates through West Channel CS at 24 hours between the Existing Condition and Removed Dam scenarios.

Sandy River Flow	Sand Flux through West Channel CS (tons/day)		
	Existing Condition	Removed Dam	Percent Reduction
2-Year	49,700	43,900	11.8
5-Year	84,300	77,200	8.5
10-Year	110,000	102,000	7.1

Table 5.4. Comparison of sand transport rates into Upstream Area at 24 Hours between the Existing Condition and Removed Dam scenarios.

Sandy River Flow	Sand Flux into the Upstream Area (tons/day)		
	Existing Condition	Removed Dam	Percent Reduction
2-Year	15,500	13,300	14.3
5-Year	33,700	29,400	12.5
10-Year	47,900	43,100	10.0

Table 5.5. Comparison of total sand volume (porosity is included) delivered to Upstream Area within 24 Hours between Existing Condition and Removed Dam scenarios.

Sandy River Flow	Total Sand Volume Delivered to the Upstream Area (cubic yards)		
	Existing Condition	Removed Dam	Percent Reduction
2-Year	11,700	9,800	15.7
5-Year	25,100	22,000	12.6
10-Year	35,700	32,000	10.3

5.3. Impact of Eroded East Channel Scenario

This section presents hydraulic and sediment analysis results for the Eroded East Channel scenario, which represents the expected channel morphology a number of years (e.g., five years) after the SRD Dam removal.

5.3.1. Topography Features

Topography of the Eroded Channel scenario was estimated based on engineering judgment and is described as follows:

- The vertical thalweg elevation along the east distributary channel, from the fork of the east and west distributary channels to the mouth of the Columbia River, would be eroded down to a bed elevation of 7 feet. This estimated erosion creates a flat channel bed through the east distributary with an elevation similar to the current elevation at the mouth of the east distributary channel and the Columbia River. The existing thalweg profile along the east distributary channel is displayed in Figure 5.15 as the blue line.

- The bed elevation at the mouth of the east distributary channel and the Columbia River is assumed to maintain its current elevation of 7 feet after dam removal. Because the bed elevation at the mouth is most likely controlled by the Columbia River, this assumption is valid. The proposed vertical erosion through the east distributary channel represents the maximum erosion possible.
- The flat bed assumption is justified by the fact that the slope of the existing east distributary channel is very small and will decrease after erosion. The flatness of the east distributary channel may further be justified by the fact that flow occurs in both directions of the east distributary, depending on the relative flow levels of the Sandy River and the Columbia River.
- The horizontal extent of erosion in the east distributary channel was more difficult to estimate. Currently, much of the pre-dam east distributary channel area has been vegetated and now supports mature cottonwood stands. Mature vegetation is not likely to be removed within 5 years after the dam removal, nor is the pre-dam east distributary channel likely to ever be restored. The horizontal extent of the erosion was estimated based on comparison of an August 2004 aerial photograph and an aerial photograph of the February 1996 flood. Rough sketches of the extents of horizontal erosion are illustrated in Figure 5.41 and 5.42
- In developing the topography for the Eroded East Channel scenario, two islands were identified along the east distributary channel: the west island close to the Dam and the east island close to the Columbia River. Elevations of the two islands were not modified. Elevations along the north channels of the two islands and the south channel of the east island were eroded down to an elevation of 7 feet. However, the south channel of the west island was only lowered by 2 feet in elevation from the existing topography due to the presence of thick vegetation in the area.
- Finally, following the SRD Dam removal, net deposition is anticipated along the west distributary channel downstream from the fork of the east and west distributaries. This is mainly due to the occurrence of reduced flow discharge along the west distributary channel once the dam is removed. The horizontal extent of sediment deposition was estimated to be contained within the channel banks and is depicted in Figure 5.42. The average depth of deposition on the west distributary channel was more difficult to estimate. In a study by Stillwater Sciences (2000a), it was determined that up to 0.4 meters (1.3 feet) of sand aggradation might occur along the west distributary channel following the removal of Marmot Dam. Despite differences between the present study and the study completed by Stillwater Sciences (2000a), it was assumed that the impact of reduced water supply to the west distributary channel years after removal of the SRD Dam would be similar to the increased sediment supply following removal of Marmot Dam. Therefore, the average depth of sediment deposition within the west distributary channel several years after the SRD Dam removal was assumed to be between 1 and 1.5 feet.

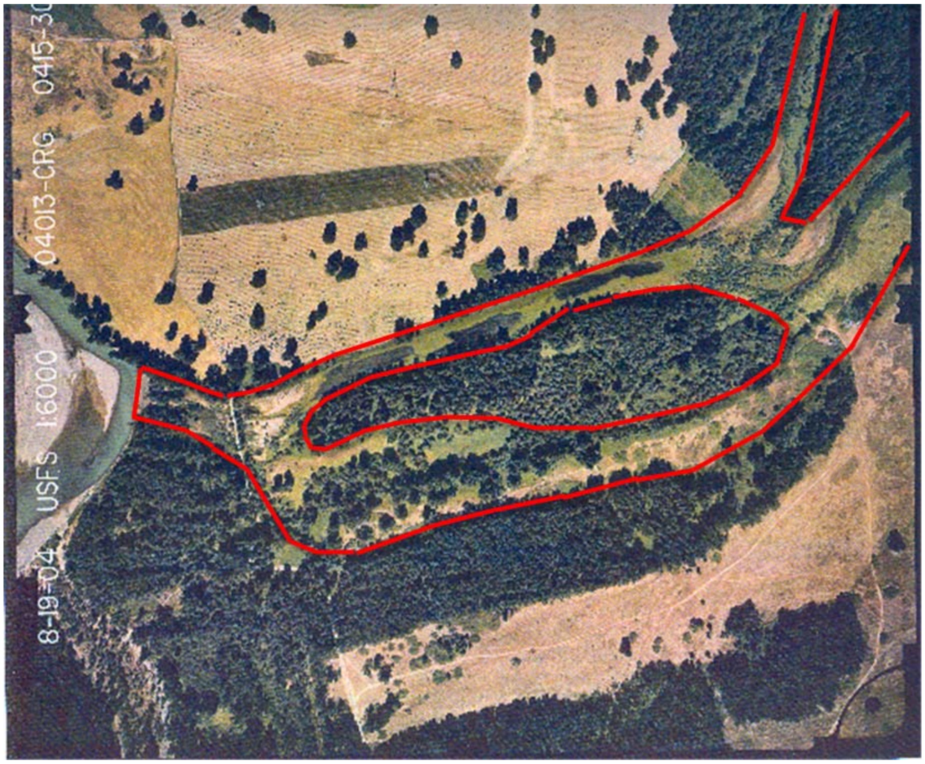


Figure 5.41. Horizontal extent of erosion along the east distributary channel based on the August 2004 aerial photograph.

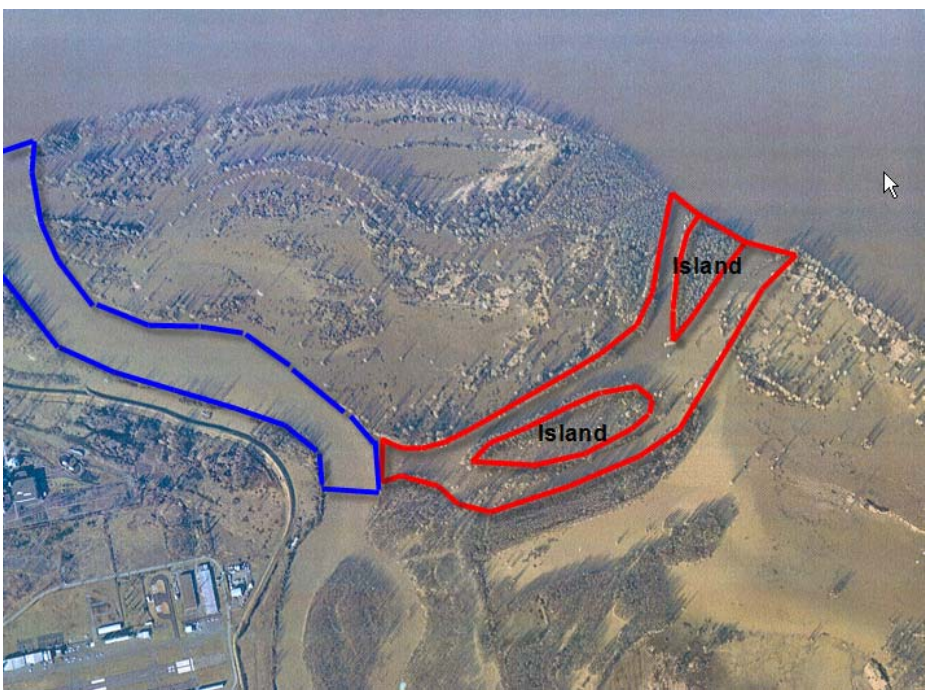


Figure 5.42. Horizontal extent of erosion along the east distributary channel and deposition extent along the west distributary channel, based on the aerial photograph a few days after the February 2006 flood.

Bed elevations for the east and west distributary channels and the surrounding area topography under the Eroded East Channel scenario are shown in Figure 5.43. This figure may be compared with Figure 4.10 for the Existing Condition scenario. Figure 5.44 provides a closer view of the Eroded East Channel topography and may be compared to Figure 5.16, which illustrates the topography of the area near the SRD Dam for the Existing Condition and Removed Dam scenarios.

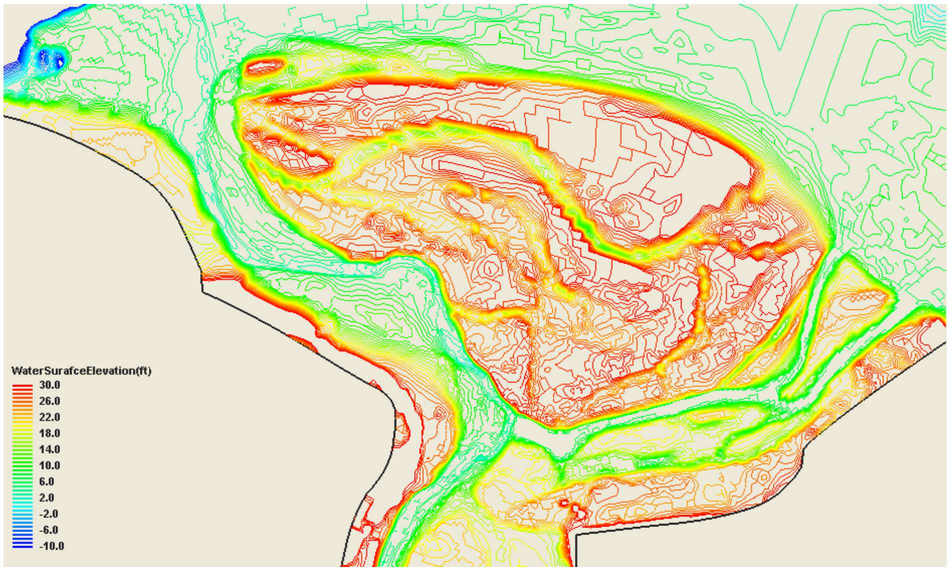


Figure 5.43. Bed elevation contour plot of the east and the west distributary channels for the Eroded East Channel scenario.

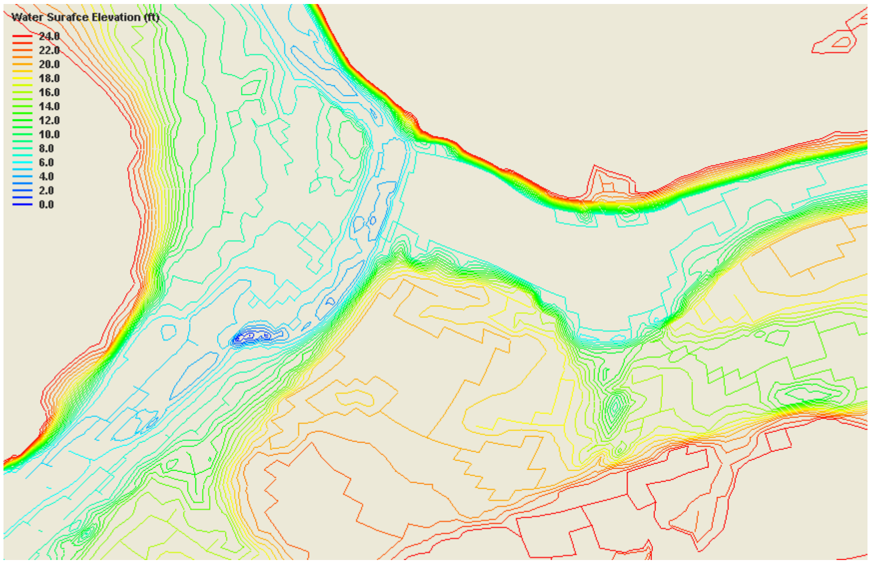


Figure 5.44. Bed elevation contour plot of the SRD Dam area for the Eroded East Channel scenario.

5.3.2. Hydraulic Results

Table 5.6 lists the Sandy River flow split between the east and west distributary channels for the Eroded East Channel scenario. Table 5.6 may be compared with Table 5.2 for other scenarios. Under the Eroded East Channel scenario, 27 percent to 29 percent of Sandy River flow is directed through the east distributary channel, depending on the flow event. Under the Removed Dam scenario, only 17 percent to 22 percent of flow is directed through the east distributary.

Table 5.6. Flow split to the east and west distributary channels at the Sandy River Delta under the Existing Condition and Eroded East Channel scenarios.

Discharge at Sandy River (cfs)	Existing Condition Scenario		Eroded East Channel Scenario	
	West Channel Flow Rate (cfs)	East Channel Flow Rate (cfs)	West Channel Flow Rate (cfs)	East Channel Flow Rate (cfs)
25,406 (2-Year)	22,580	2,820	18,640	6,762
36,757 (5-Year)	31,121	5,636	26,584	10,172
45,239 (10-Year)	37,316	7,921	32,283	12,955

Predicted water surface elevations, along with flood inundation extents, are shown in Figure 5.45 to Figure 5.47; simulated velocity magnitudes are displayed in Figure 5.48 to Figure 5.50 over the entire solution domain. In addition, velocity and flow patterns near the mining area and the dam area are presented in Figure 5.51 to Figure 5.54, and flows at the highway and railroad bridge areas are plotted in Figure 5.55.

Overall, figures depicting flow pattern, inundation and velocity for the Eroded East Channel scenario were not drastically different from those of the Removed Dam scenario. However, slight differences between these two scenarios are present in the magnitudes of velocity and water surface elevations. Flow pattern and eddy formation near the mining area (Figure 5.51) also remained similar to the Removed Dam scenario. Furthermore, flow pattern and velocity magnitude (Figure 5.55) at the highway and railroad bridges were almost unchanged in comparison with the Existing Condition scenario (Figure 5.29). It can be concluded that flow hydraulics and local scour at the bridges are not expected to be impacted by the SRD Dam removal.

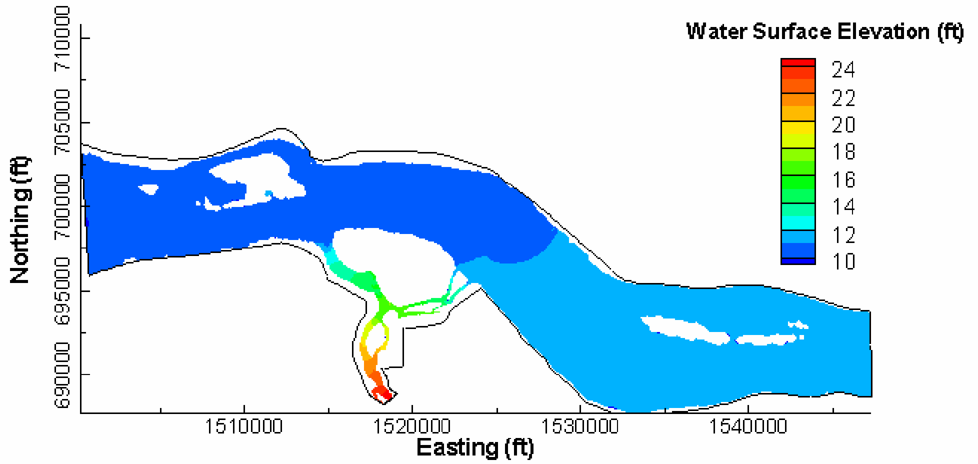


Figure 5.45. Computed water surface elevations for the Eroded East Channel scenario with the 2-Year flood on the Sandy River.

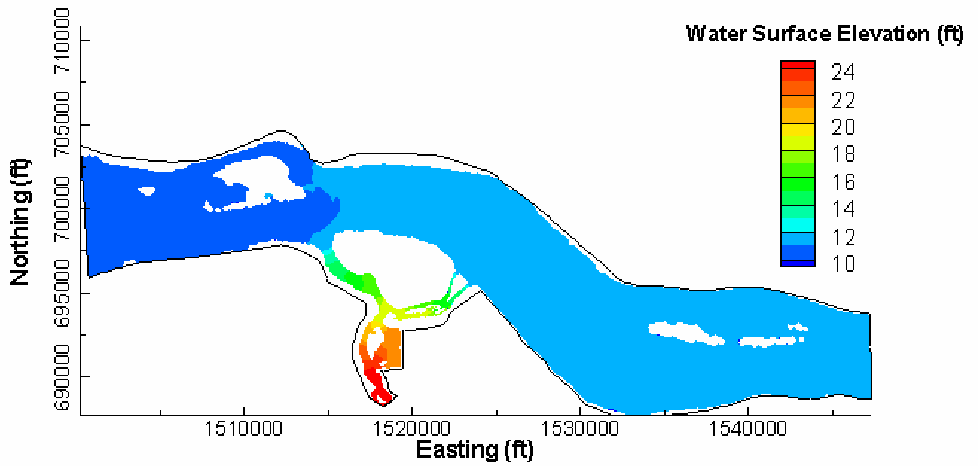


Figure 5.46. Computed water surface elevations for the Eroded East Channel scenario with the 5-year flood on the Sandy River.

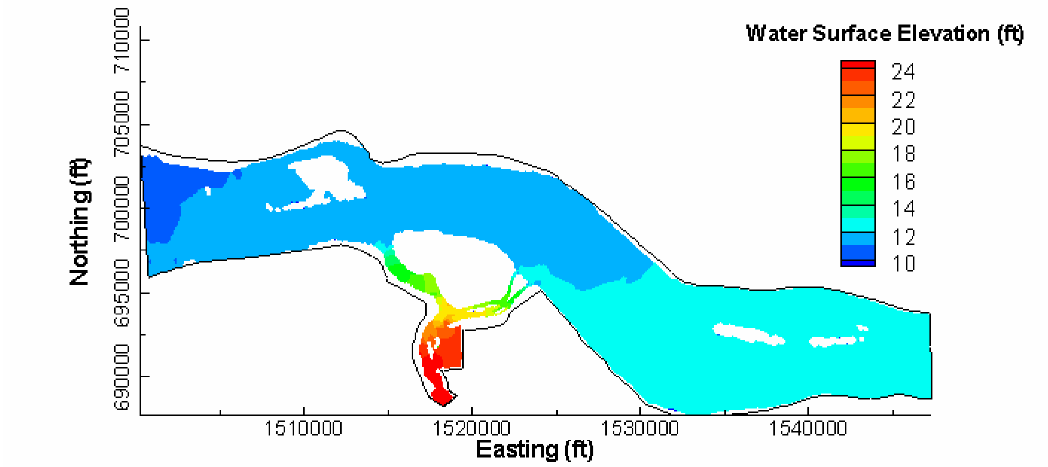


Figure 5.47. Computed water surface elevations for the Eroded East Channel scenario with the 10-year flood on the Sandy River.

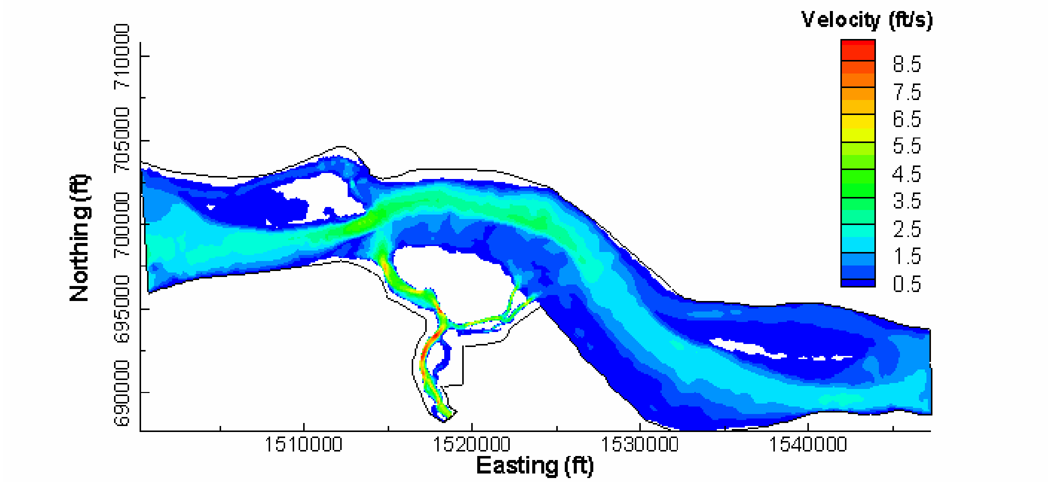


Figure 5.48. Computed velocity magnitudes for the Eroded East Channel scenario with the 2-year flood on the Sandy River.

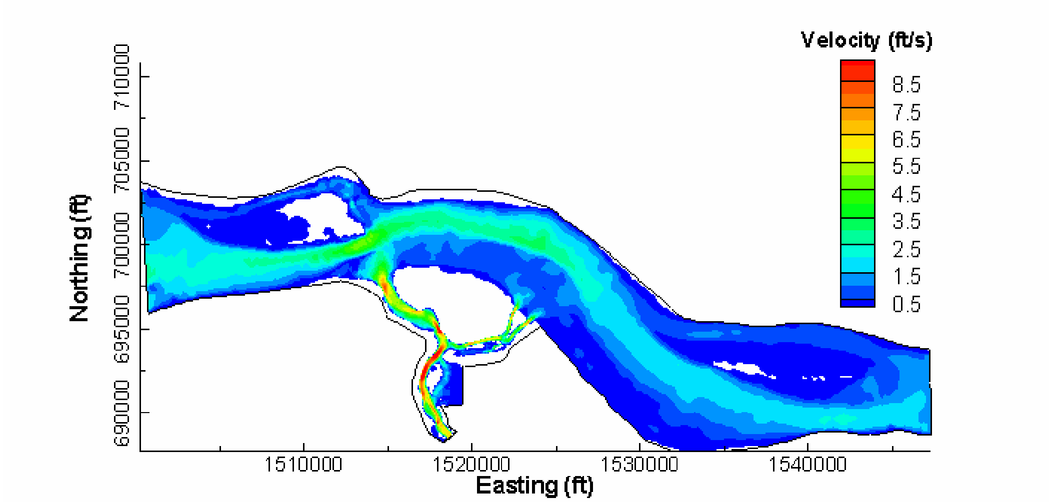


Figure 5.49. Computed velocity magnitudes for the Eroded East Channel scenario with the 5-year flood on the Sandy River.

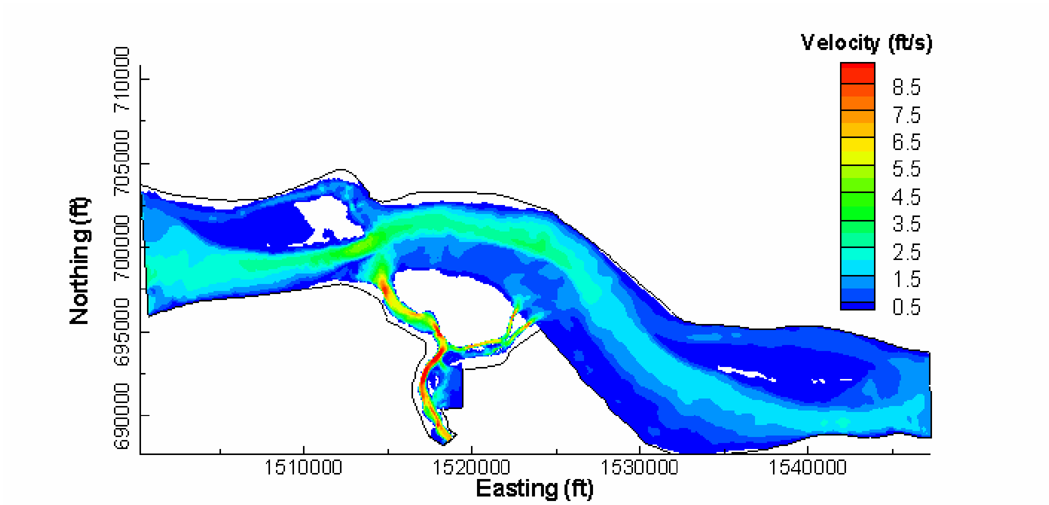


Figure 5.50. Computed velocity magnitudes for the Eroded East Channel scenario with the 10-year flood on the Sandy River.

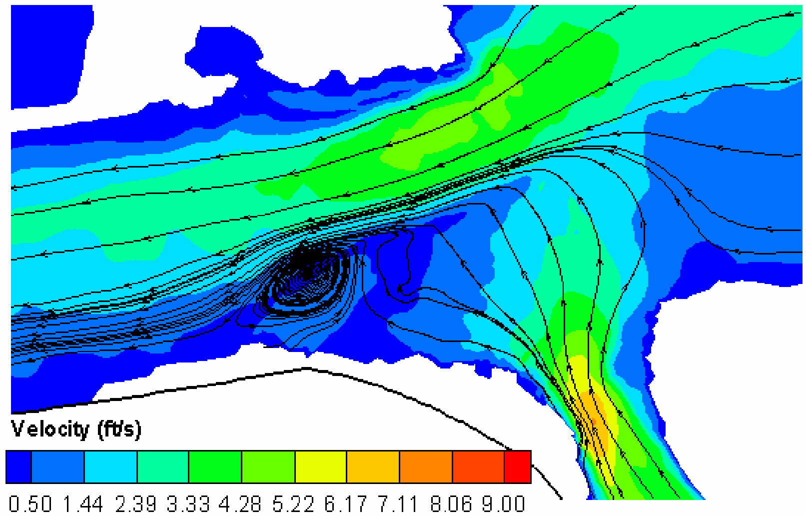


Figure 5.51. Computed velocity and flow patterns near the mining area for the Eroded East Channel scenario with the 2-year flood on the Sandy River.

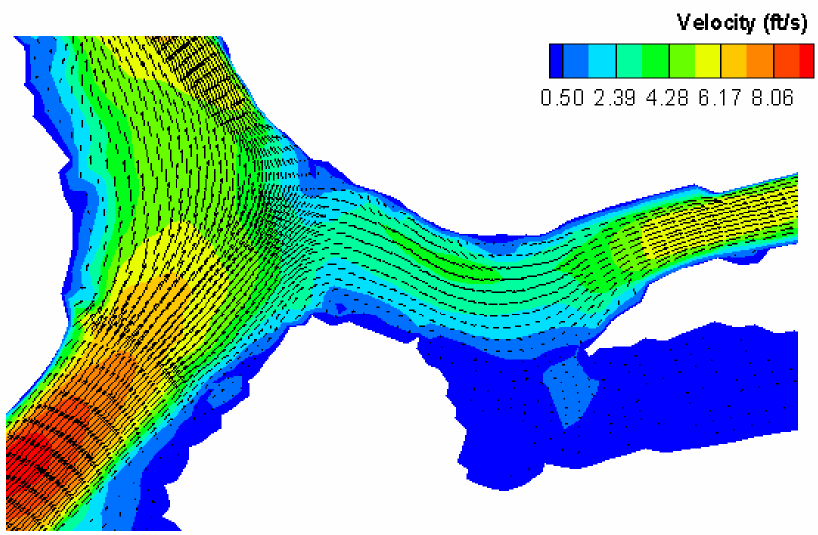


Figure 5.52. Computed velocities near the SRD Dam for the Eroded East Channel scenario with the 2-year flood on the Sandy River.

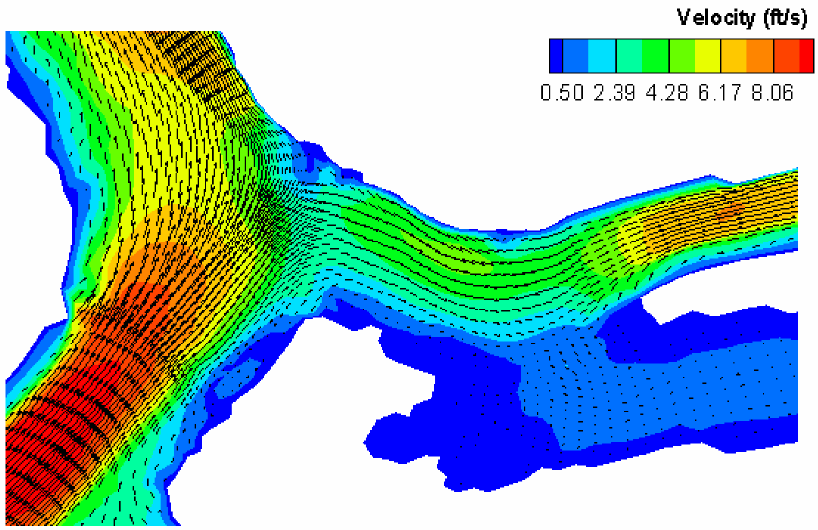


Figure 5.53. Computed velocities near the SRD Dam for the Eroded East Channel scenario with the 5-year flood on the Sandy River.

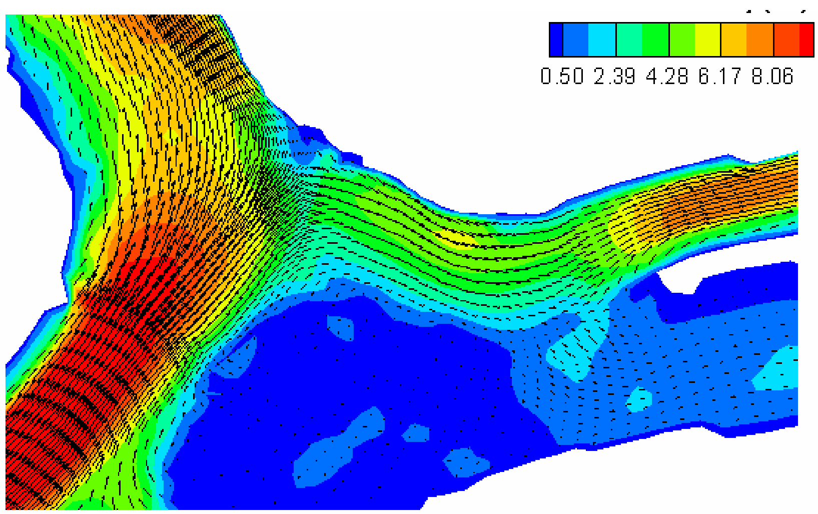


Figure 5.54. Computed velocities near the SRD Dam for the Eroded East Channel scenario with the 10-year flood on the Sandy River.

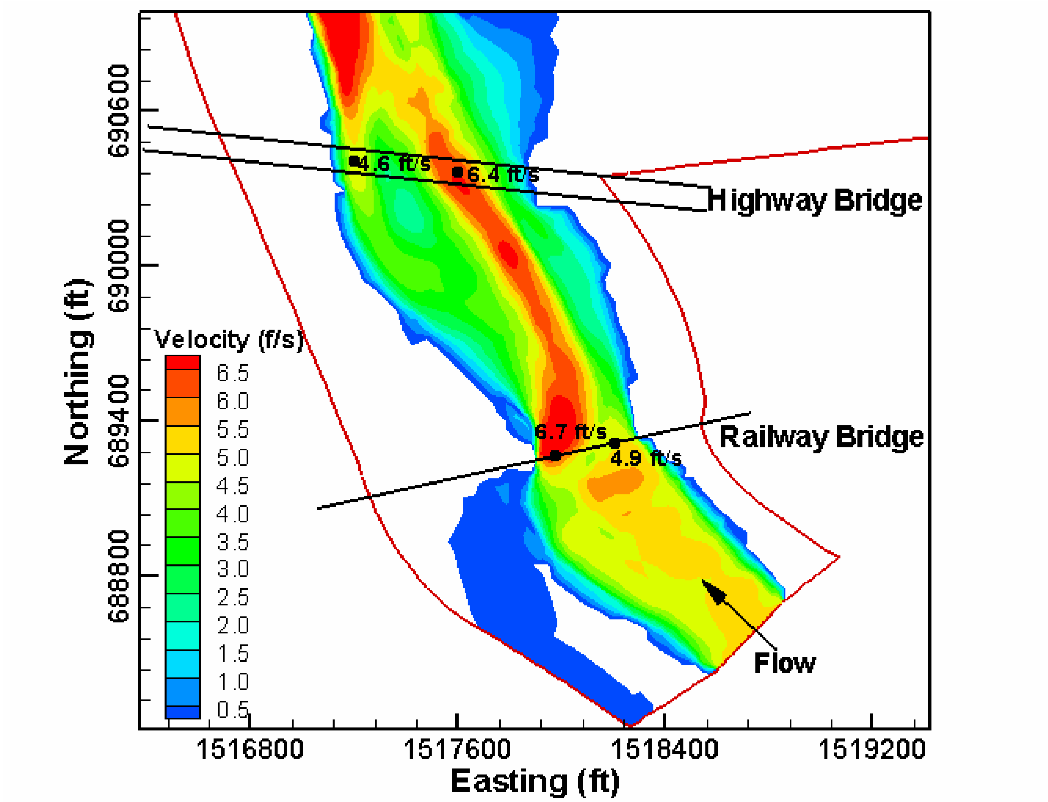


Figure 5.55. Simulated velocities at the highway and railroad bridge area for the Eroded East Channel Scenario with the 2-year food on the Sandy River.

5.3.3. Sediment Results

Given the flow hydraulics and initial bed gradation, sediment analysis was performed for a period of 24 hours for the Eroded East Channel scenario.

The erosion and deposition patterns are shown in Figure 5.56 with the 2-year flood and may be compared with Figure 5.30 with the Existing Condition scenario. Plots for the 5- and 10-year floods are not shown, as they are very similar to those for the 2-year flood. As with the Removed Dam scenario, the predicted erosion/deposition pattern alternated along the Sandy River. Overall, the pattern is similar to that of the Removed Dam scenario.

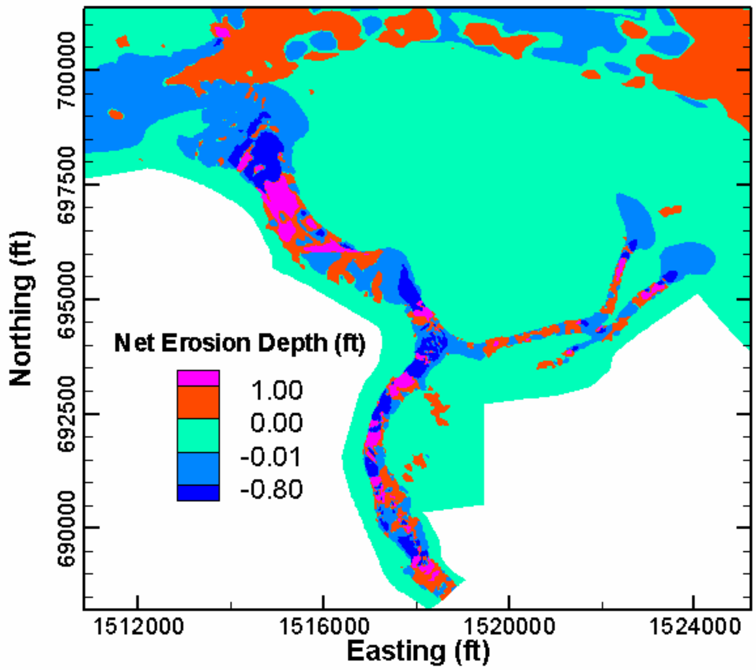


Figure 5.56. Predicted erosion and deposition pattern 24 hours after a 2-Year Sandy River flood for the Eroded East Channel Scenario. Note that the pattern is relative to the initial topography used. Positive depth (red and purple) indicates erosion and negative depth (green and blue) indicates deposition.

The sediment transport rates by size classes through the West Channel CS and the Upstream Area (see Figure 5.33 for their definition) versus time for the 2-, 5-, and 10-year floods are displayed in Figure 5.57 to Figure 5.62. These plots may be compared with plots in Figure 5.35 to Figure 5.40 for the Removed Dam scenario. Overall, less sediment are going through the west distributary channel and delivered to the mining area for the Eroded East Channel scenario than the Removed Dam scenario. The sand transport rates through the West Channel CS and the Upstream Area after 24 hours are tabulated in Table 5.7 and Table 5.8 to gain a quantitative evaluation of sediment delivery impact to the mining area. Table 5.9 also lists the total sand volume deposited within the Upstream Area over a 24-hour period under the 2-, 5-, and 10-year Sandy River floods. These may be compared with results in Table 5.3 to Table 5.5 for the Removed Dam scenario. Results suggest that up to 40 percent less sediment may be delivered to the mining area for the Eroded East Channel scenario in comparison with the Existing Condition scenario.

Table 5.7. Comparison of sand transport rates through the West Channel CS at 24 hours between the Existing Condition and Eroded East Channel scenarios.

Sandy River Flow	Sand Flux through West Channel CS (tons/day)		
	Existing Condition	Eroded East Channel	Percent Reduction
2-Year	49,700	34,500	30.6
5-Year	84,300	64,300	23.7
10-Year	110,000	87,900	20.1

Table 5.8. Comparison of sand transport rates into the Upstream Area at 24 hours between the Existing Condition and Eroded East Channel scenarios.

Sandy River Flow	Sand Flux into the Upstream Area (tons/day)		
	Existing Condition	Eroded East Channel	Percent Reduction
2-Year	15,500	9,430	39.2
5-Year	33,700	22,900	31.8
10-Year	47,900	34,900	27.0

Table 5.9. Comparison of total sand volume (porosity is included) delivered to the Upstream Area within a 24 hour period between the Existing Condition and Eroded East Channel scenarios.

Sandy River Flow	Total Sand Volume Delivered to the Upstream Area (cubic yards)		
	Existing Condition	Eroded East Channel	Percent Reduction
2-Year	11,700	7,170	38.6
5-Year	25,200	17,200	31.8
10-Year	35,700	26,000	27.1

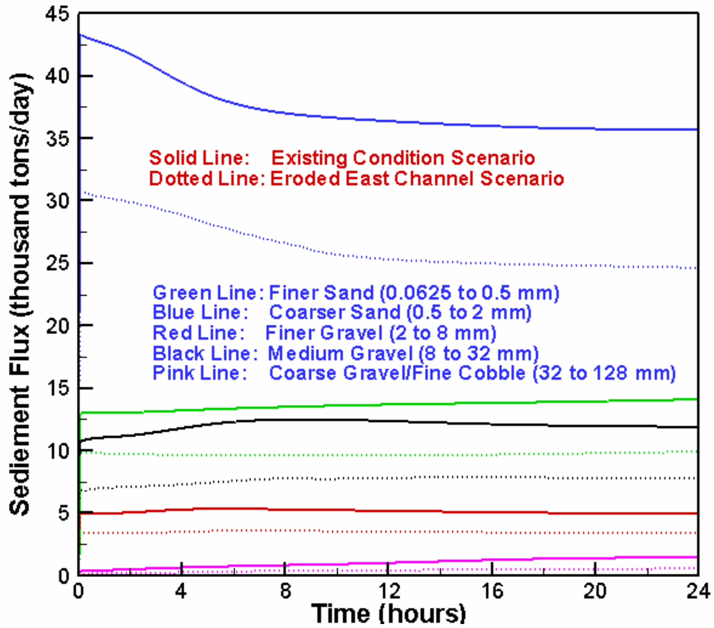


Figure 5.57. Comparison of sediment flux (sediment mass through the cross section per unit time) by size class through the West Channel CS between the Existing Condition and Eroded East Channel scenarios under the 2-year Sandy River flood.

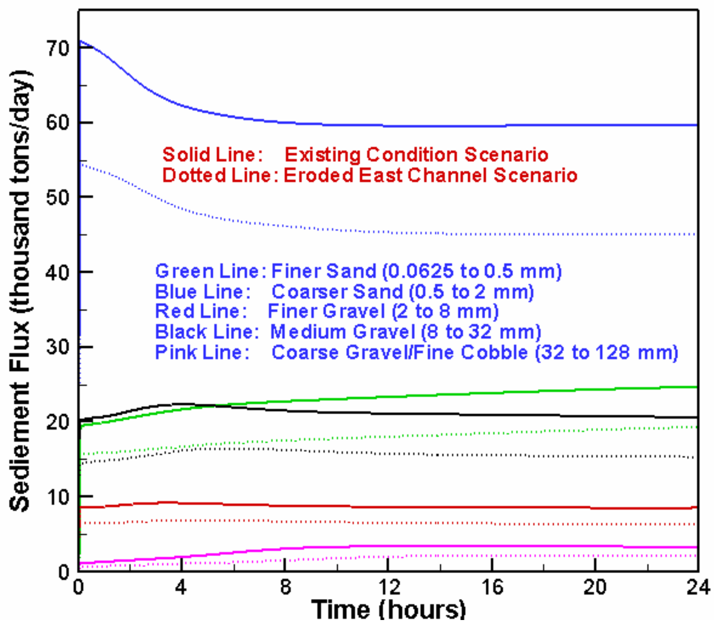


Figure 5.58. Comparison of sediment flux (sediment mass through the cross section per unit time) by size class through the West Channel CS between the Existing Condition and Eroded East Channel scenarios under the 5-year Sandy River flood.

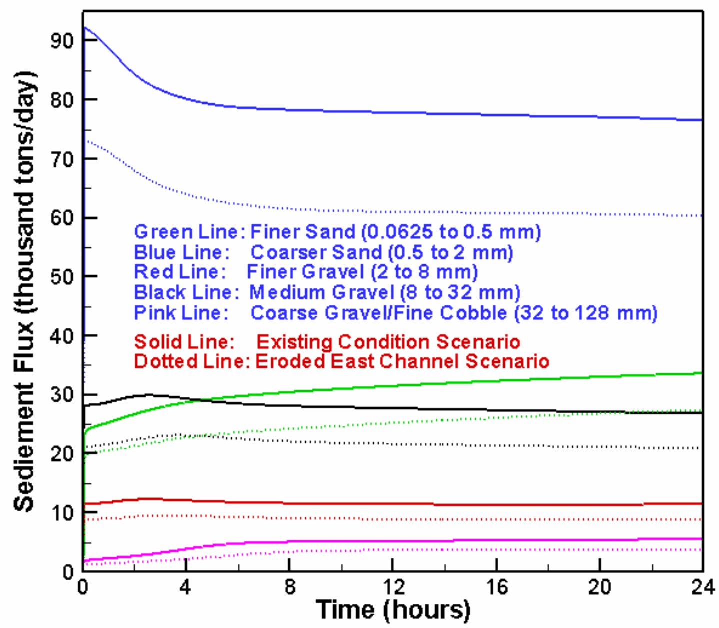


Figure 5.59. Comparison of sediment flux (sediment mass through the cross section per unit time) by size class through the West Channel CS between the Existing Condition and Eroded East Channel scenarios under the 10-year Sandy River flood.

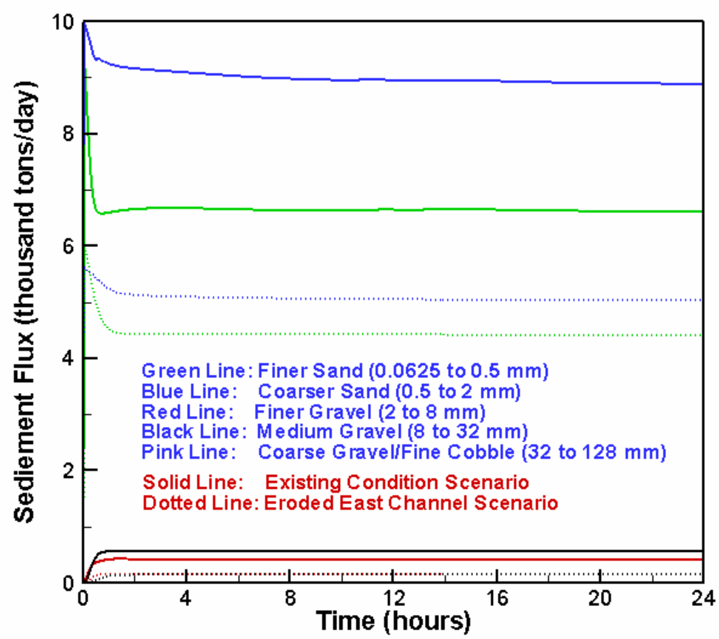


Figure 5.60. Comparison of sediment flux (sediment mass into the area per unit time) by size class into the Upstream Area between the Existing Condition and Eroded East Channel scenarios under the 2-year Sandy River flood.

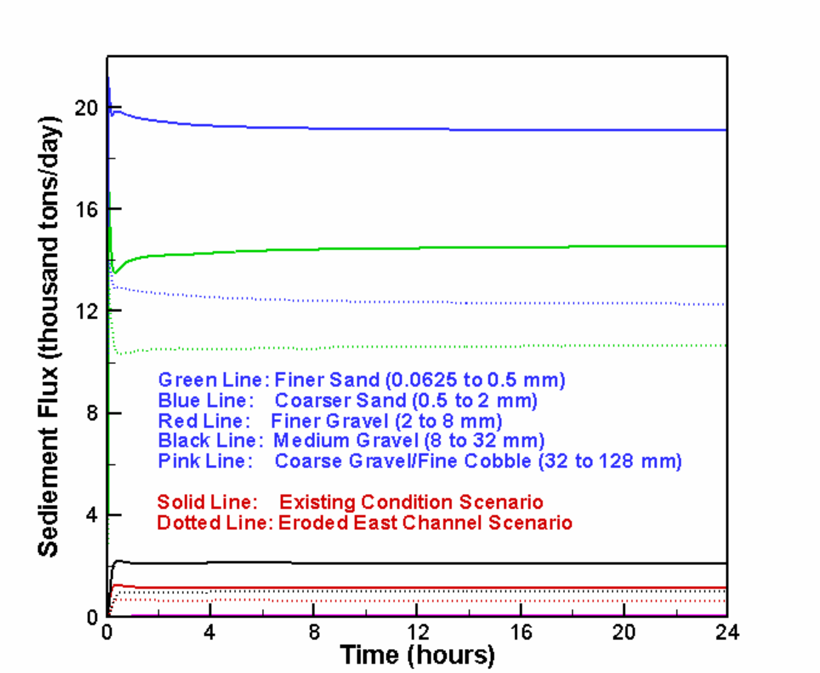


Figure 5.61. Comparison of sediment flux (sediment mass into the area per unit time) by size class into the Upstream Area between the Existing Condition and Eroded East Channel scenarios under the 5-year Sandy River flood.

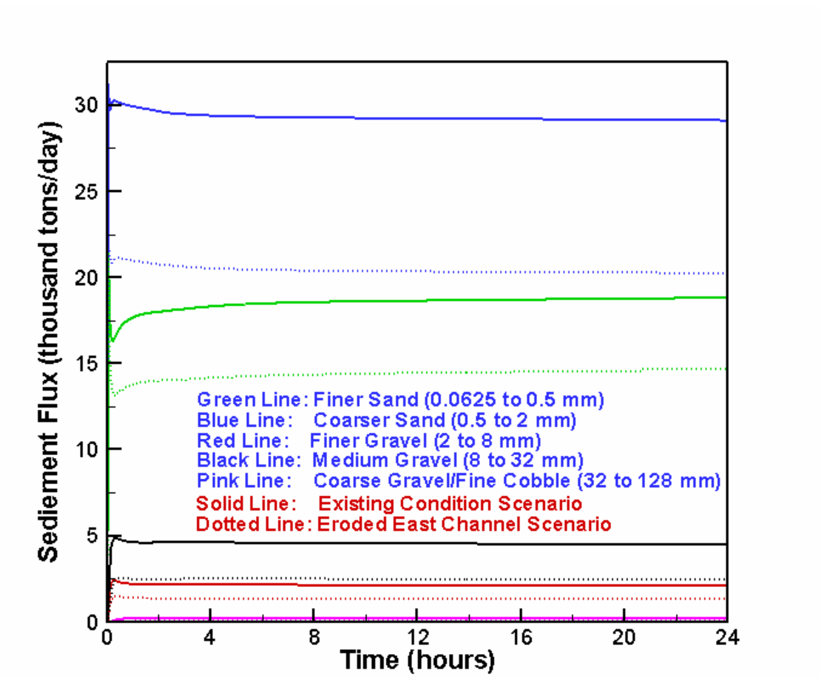


Figure 5.62. Comparison of sediment flux (sediment mass into the area per unit time) by size class into the Upstream Area between the Existing Condition and Eroded East Channel scenarios under the 10-year Sandy River flood.

Finally, the predicted erosion/deposition patterns at the highway and railroad bridge areas are compared in Figure 5.63. In comparison with results from the Existing Condition scenario, no noticeable change is predicted (Figure 5.32).

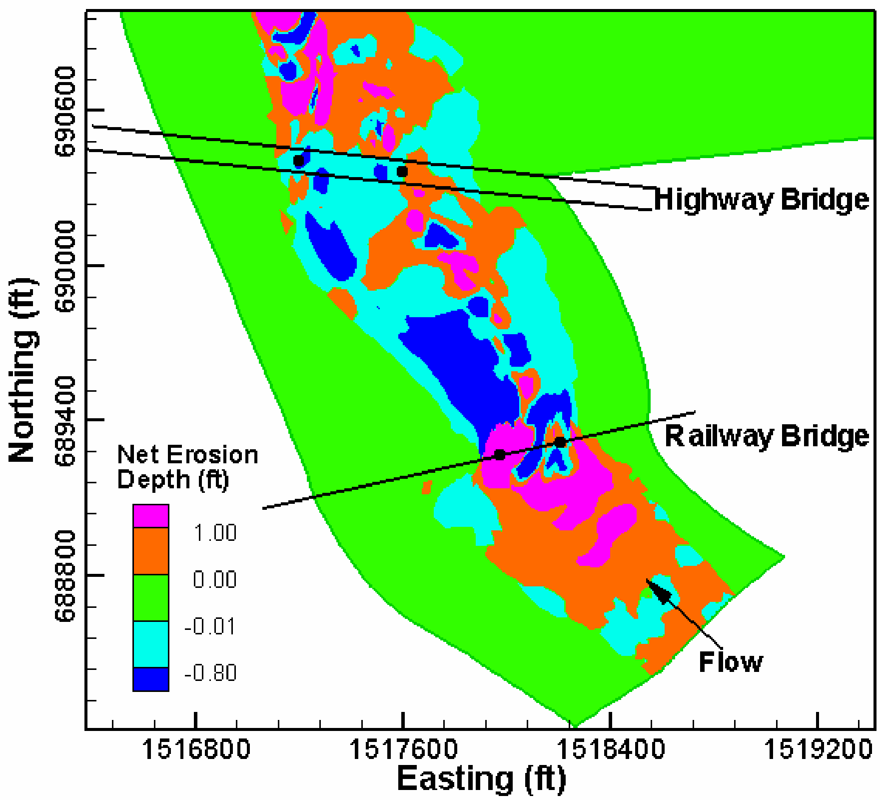


Figure 5.63. Simulated erosion/deposition pattern in the area of the highway and railroad bridges for the Eroded East Channel scenario.

5.4. Impact of Complete Blockage of the West Channel

This section presents hydraulic and sediment analysis results for the scenario when the west distributary channel is completed blocked. The scenario is less likely to occur naturally, but it represents the worst-case (or extreme case) scenario for the impact analysis to the mining area, as well as the highway and railroad bridge areas.

5.4.1. Topography Features

The topography of the Complete Blockage scenario was developed as follows:

- Start with the same mesh and topography as the Removed Dam scenario;
- A high elevation (100-foot) levee was installed across the west distributary channel near fork of the east and west distributary channel so that all flood flows were directed towards the east distributary channel. Bed topography along the east distributary channel remained the same as the Removed Dam scenario.

The bed elevation near the dam area for the Complete Blockage scenario is shown in Figure 5.64.

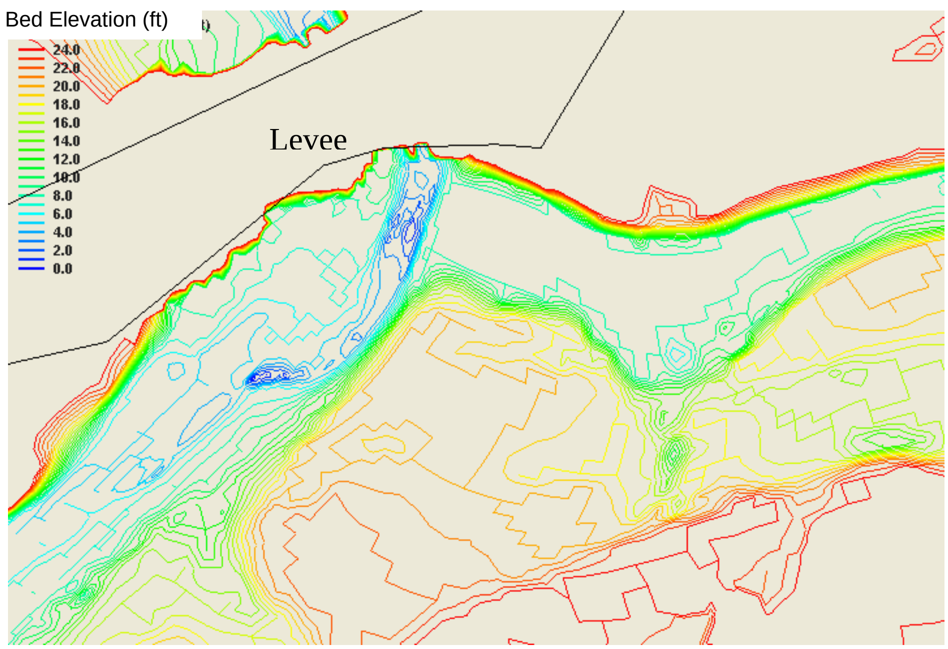


Figure 5.64. Topography near the SRD Dam for the Complete Blockage scenario.

5.4.2. Hydraulic Results

Predicted water surface elevations, along with flood inundation extents, are shown in Figure 5.65 to Figure 5.67; simulated velocity magnitudes are displayed in Figure 5.68 to Figure 5.70 over the entire solution domain. In addition, velocity and flow patterns near the mining area and the dam area are presented in Figure 5.71 to Figure 5.74, and flows at the highway and railroad bridge areas are compared in Figure 5.75.

The velocity and flow pattern near the mining area (Figure 5.71) is plotted only for the 2-year Sandy River flood case, as those for the 5- and 10-year floods were almost identical to that of the 2-year. This flow pattern may be compared with those in Figure 5.23 to Figure 5.25 and Figure 5.51, when the west distributary channel was not blocked. Under the worst-case scenario, the eddy at the mining area still existed, indicating that the eddy is mainly formed due to the combined effects of local topography and the Columbia River flow. This eddy should promote sediment deposition at the mining area and the Upstream Area (depicted in Figure 5.33). This eddy will not be present when the Columbia River is at high flows (Section 5.5).

The flow pattern in Figure 5.71 implies that under the Complete Blockage scenario, the sediment source to the mining area would primarily be the sediment bar on the Columbia River upstream of the confluence of the west distributary channel and the Columbia River (i.e., the bar along the north side of the Sandy River Delta). This area corresponds to bed gradation Zone 4 (Figure 4.14) and consists of mostly gravels (75 percent based on Table 4.3). Therefore, it may be inferred that sediment supply to the mining area would be greatly reduced. Results also suggest that sediment deposition at the mining area under this scenario is probably influenced mainly by the Columbia River, an issue discussed further in Section 5.4.3 and Section 5.5. Sediment deposited at the mouth of the east distributary channel is discussed in Section 5.4.3.

Comparison of velocity results between the Existing Condition and Complete Blockage scenarios in Figure 5.75 indicates that a large impact in flow hydraulics is expected if the entire Sandy River flows through the east distributary channel. Velocities at the bridge areas were predicted to be substantially reduced (between 15 percent and 30 percent). Therefore, greatly reduced erosion at the bridge area is anticipated under this scenario.

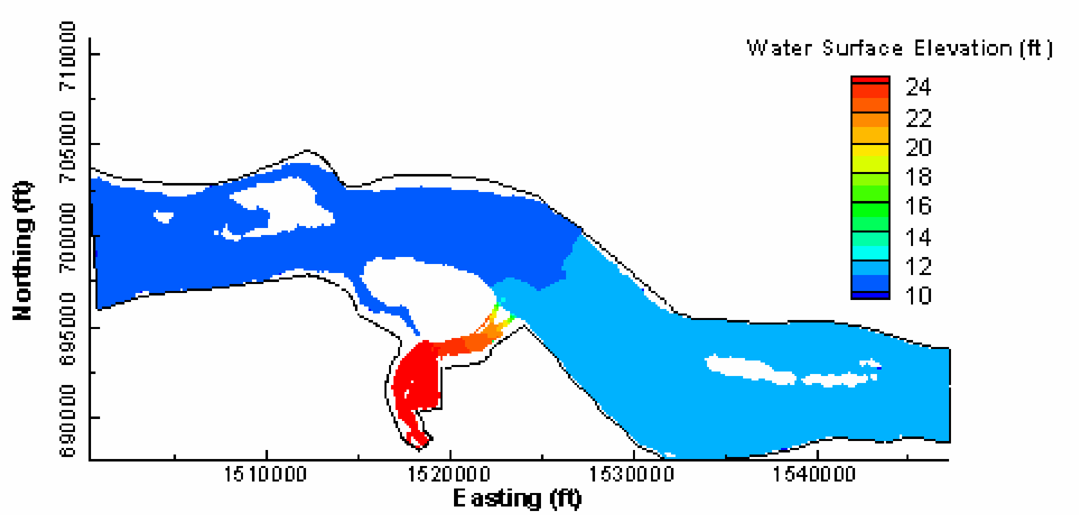


Figure 5.65. Computed water surface elevations for the Complete Blockage scenario with the 2-year flood on the Sandy River.

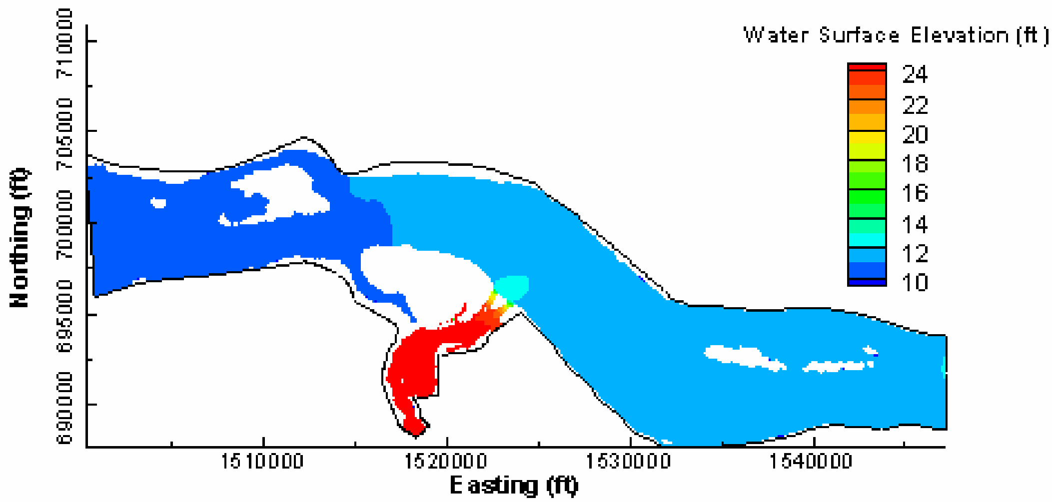


Figure 5.66. Computed water surface elevations for the Complete Blockage scenario with the 5-year flood on the Sandy River.

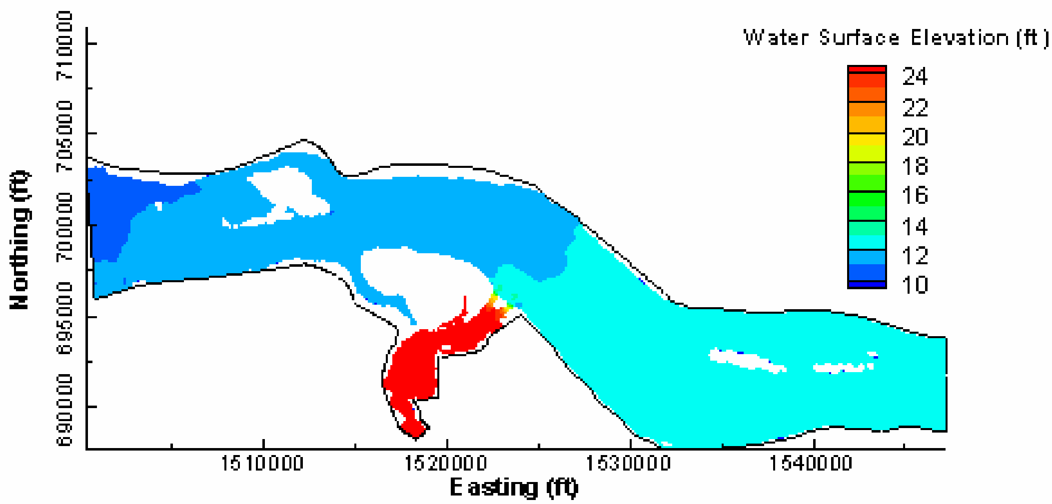


Figure 5.67. Computed water surface elevations for the Complete Blockage scenario with the 10-year flood on the Sandy River.

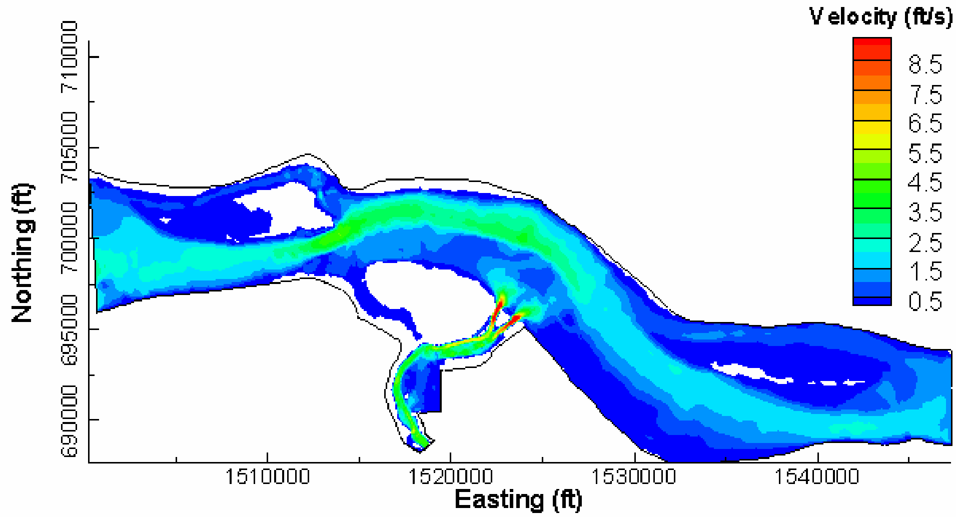


Figure 5.68. Computed velocity magnitudes for the Complete Blockage scenario with the 2-year flood on the Sandy River.

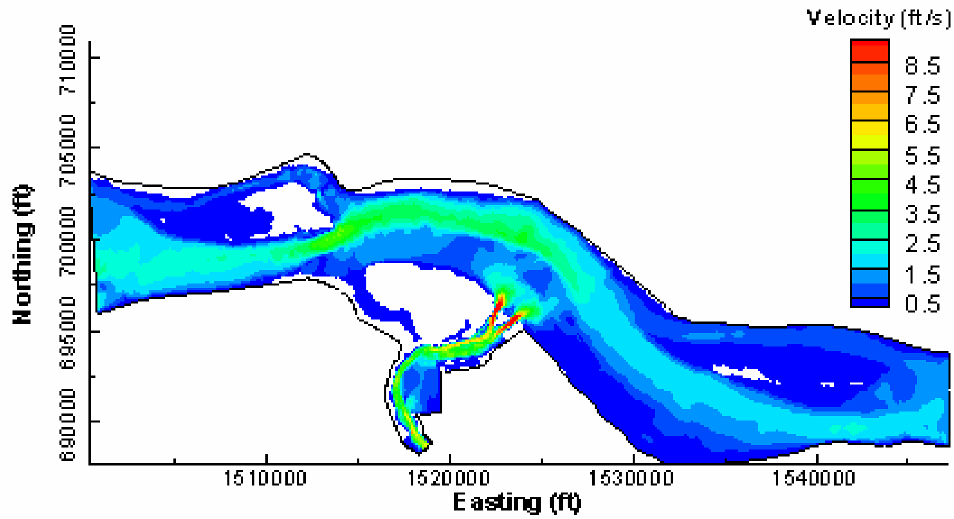


Figure 5.69. Computed velocity magnitudes for the Complete Blockage scenario with the 5-year flood on the Sandy River.

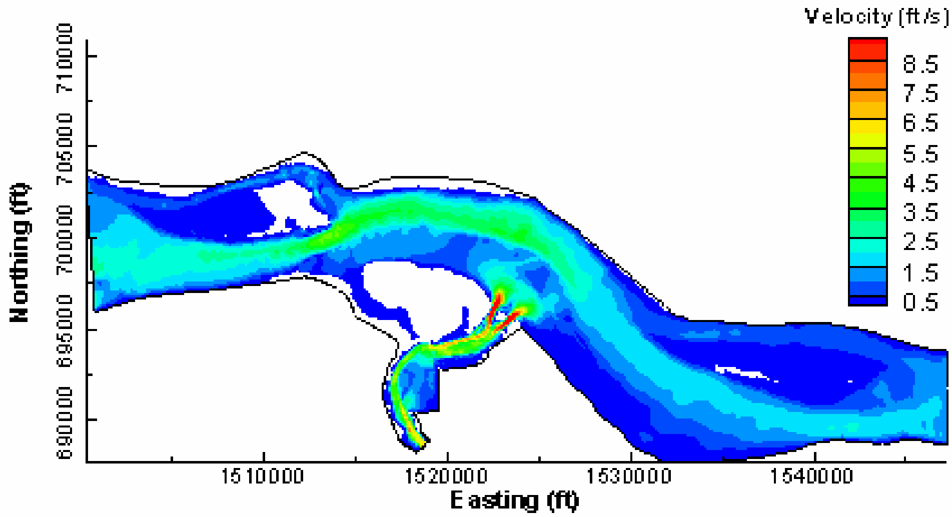


Figure 5.70. Computed velocity magnitudes for the Complete Blockage scenario with the 10-year flood on the Sandy River.

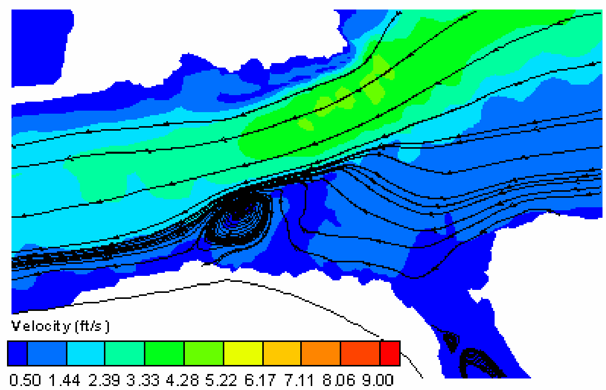


Figure 5.71. Computed velocity and flow patterns near the mining area for the Complete Blockage scenario with the 2-year flood on the Sandy River.

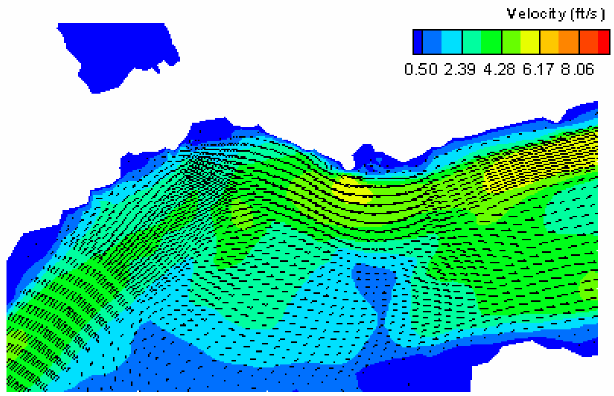


Figure 5.72. Computed velocities near the SRD Dam for the Complete Blockage scenario with the 2-year flood on the Sandy River.

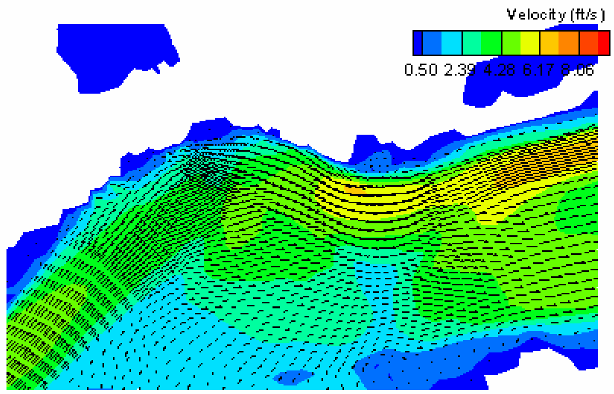


Figure 5.73. Computed velocities near the SRD Dam for the Complete Blockage scenario with the 5-year flood on the Sandy River.

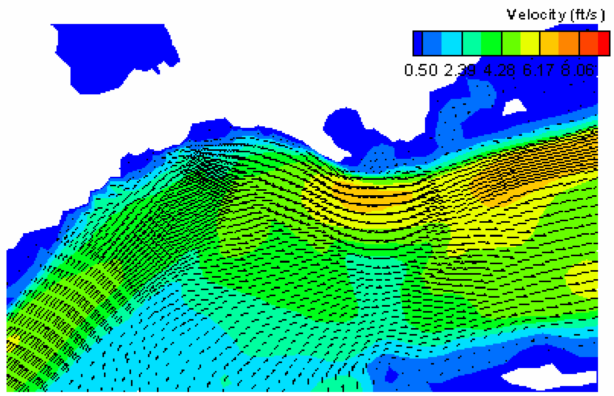
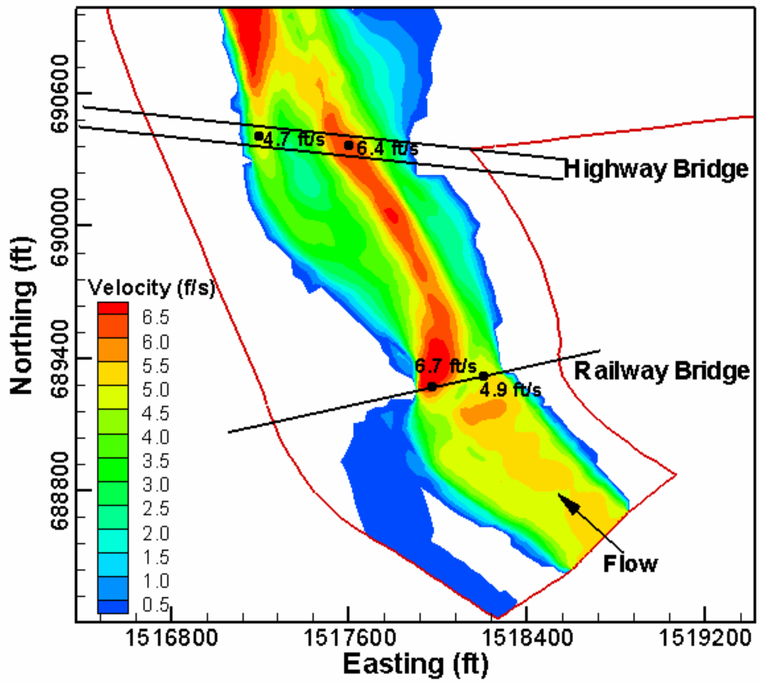
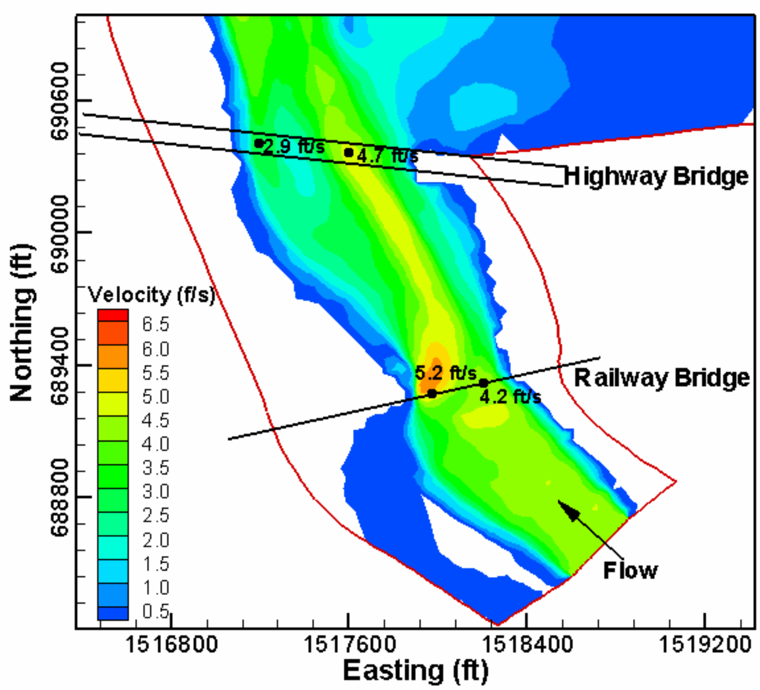


Figure 5.74. Computed velocities near the SRD Dam for the Complete Blockage scenario with the 10-year flood on the Sandy River.



(a) Existing Condition Scenario



(b) Complete Blockage Scenario

Figure 5.75. Comparison of simulated velocities at the highway and railroad bridge area.

5.4.3. Sediment Results

Given the flow hydraulics and initial bed gradation, sediment analysis was performed for a period of 24 hours for the Complete Blockage scenario.

The erosion and deposition patterns are shown in Figure 5.76 and Figure 5.77 with the 2-year flood and may be compared with Figure 5.30 and Figure 5.31 of the Existing Condition scenario. Plots for the 5- and 10-year floods are not shown, as they are very similar to those for the 2-year flood. As with the Removed Dam scenario, the predicted erosion/deposition pattern alternated along the Sandy River. However, net erosion was predicted on the east distributary channel if averaged over the reach. A visual inspection of the results between the Complete Blockage and the Existing Condition scenarios (Figure 5.77 and Figure 5.31) suggests that much less deposition is predicted at the mining area for the Complete Blockage scenario.

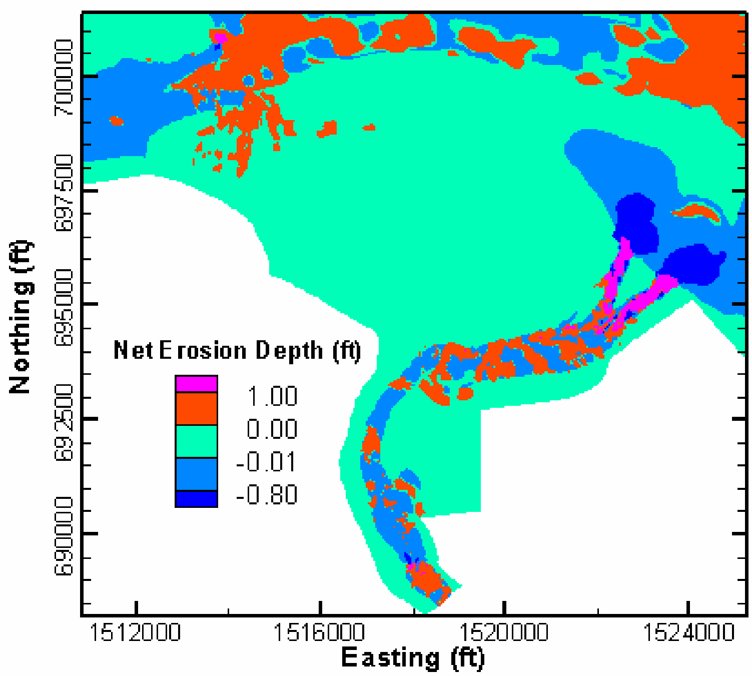


Figure 5.76. Predicted erosion and deposition pattern 24 hours after a 2-year Sandy River flood for the Complete Blockage scenario. Note that the pattern is relative to the initial topography used. Positive depth (red and purple) indicates erosion and negative depth (green and blue) indicates deposition.

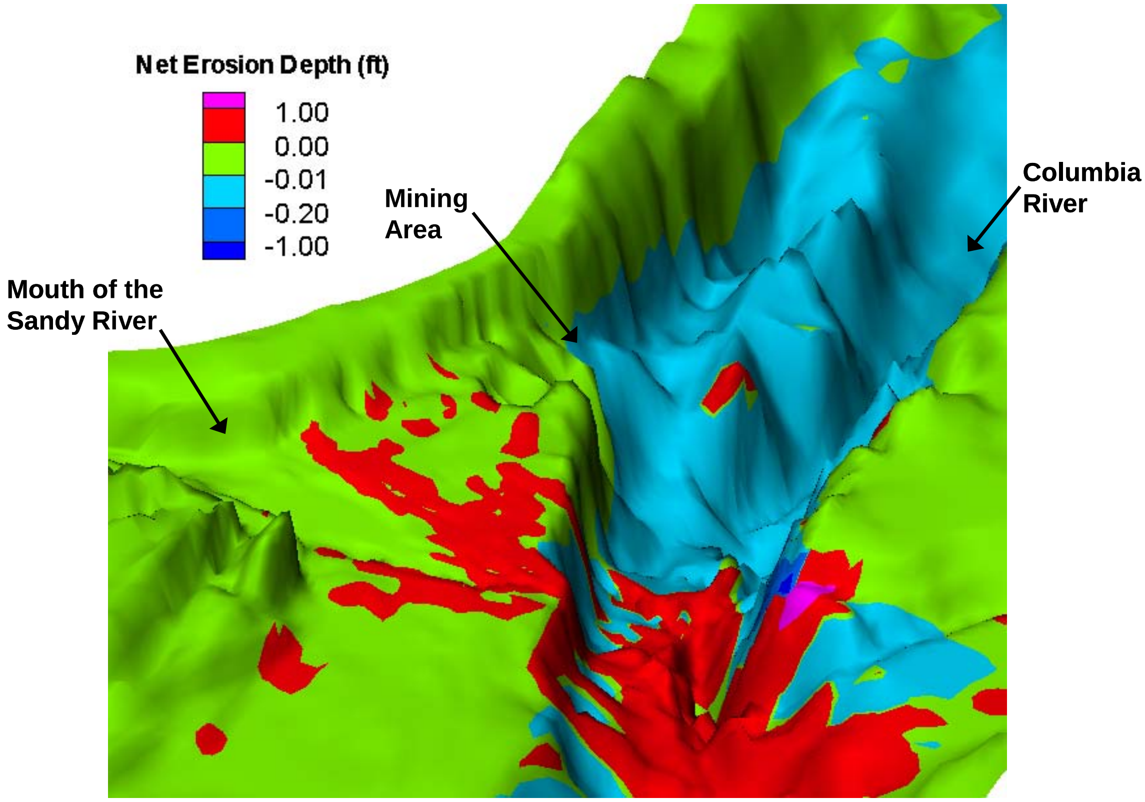


Figure 5.77. Predicted erosion and deposition pattern at the mining area 24 hours after a 2-year Sandy River flood for the Complete Blockage scenario. Note that the pattern is relative to the initial topography used. Positive depth (red and purple) indicates erosion and negative depth (green and blue) indicates deposition.

The sand transport rates (i.e., the sum of sediment size class 1 and class 2) to the Upstream Area (depicted in Figure 5.33) after 24 hours of simulation are tabulated in Table 5.10 to gain a quantitative evaluation. Table 5.11 also lists the total sand volume deposited within the Upstream Area over a 24-hour period under the 2-, 5-, and 10-year Sandy River floods. These results indicate that very little sand would be deposited at the mining area if the west distributary channel of the Sandy River is completed blocked.

Table 5.10. Comparison of sand transport rates into the Upstream Area at 24 hours between the Existing Condition and Complete Blockage scenarios.

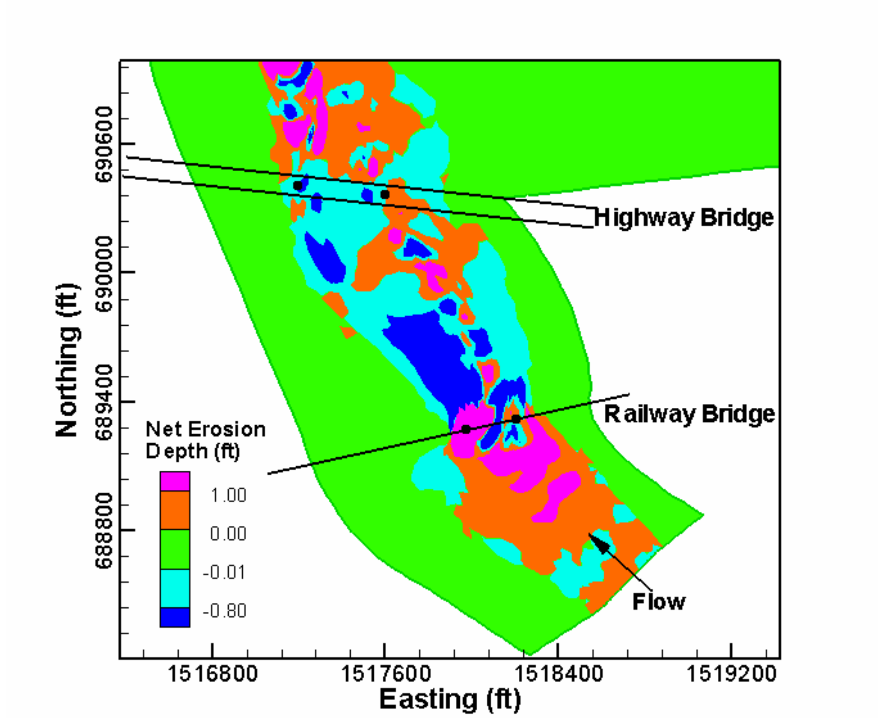
Sandy River Flow	Sand Transport Rate into the Upstream Area (tons/day)	
	Existing Condition	Complete Blockage
2-Year	15,500	15.0
5-Year	33,700	13.6
10-Year	47,900	9.3

Table 5.11. Comparison of total sand volume (porosity is included) delivered to the Upstream Area within a 24-hour period between the Existing Condition and Complete Blockage scenarios.

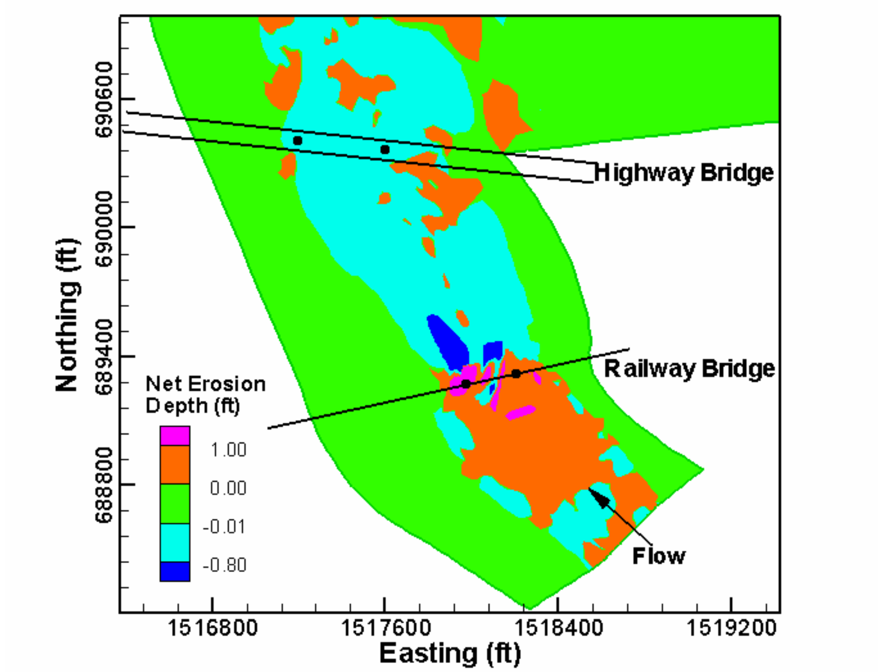
Sandy River Flow	Total Sand Volume Delivered to the Upstream Area (cubic yards)	
	Existing Condition	Complete Blockage
2-Year	11,700	10.7
5-Year	25,200	9.7
10-Year	35,700	6.3

Caution has to be mentioned concerning the above conclusion as it is only applicable to the assumed flow conditions. The sediment simulation showed that high quantities of sediment were deposited at the confluence of the east distributary channel and the Columbia River if the west channel were blocked. For the simulated Columbia River flow fixed at 160,311 cfs, the Sandy River deposited at the confluence of the east distributary channel, and the Columbia River did not seem to contribute to the mining area. A question remains as to whether the majority of the sediment deposits from the Sandy River would eventually be transported to the mining area when the Columbia River has higher flows. An extra hydraulic simulation presented in Section 5.4 considered the case when the Columbia River was at 2-year flood. Results based on this extra case indicate that even high flows of the Columbia River would not contribute additional sediment to the mining area if the west distributary was completely blocked. Sediments deposited at the mouth of the east distributary would likely be transported by the Columbia River under high flows, but would not be delivered to the mining area. This suggests that the primary sediment source to the mining area is the west channel of the Sandy River, and that the Columbia River is not the sediment source for the mining area.

Finally, the predicted erosion/deposition patterns at the highway and railroad bridge areas are compared in Figure 5.78. Erosion at the bridges would be greatly reduced for the Complete Blockage scenario.



(a) Existing Condition Scenario



(b) Complete Blockage Scenario

Figure 5.78. Simulated erosion/deposition pattern in the area of the highway and railroad bridges for the Complete Blockage scenario.

5.5. Additional Modeling of the Sandy River Delta Flow Hydraulics

The scenarios presented above all represent conditions under which the dam would be overtopped and the Sandy River would flow through both the west and east distributary channels towards the Columbia River. We believe this to be the dominant flow pattern whenever the Sandy River flow is high. Inspection of the topography along the current east distributary channel seems to support the results.

In this section, a number of additional hydraulic simulations were performed and reported. Additional simulations were performed either for a qualitative verification of the numerical model or for answering questions related to the Sandy River – Columbia River interaction.

5.5.1 Simulation of Flow Conditions on January 23, 2006

Historically, the west and east distributary channels acted as a slough system of the Columbia River, meaning that the Columbia River may enter the east channel, overtop the dam, and force flows through the west distributary channel. We were interested in assessing the abilities of GSTAR-W to simulate this scenario.

On January 23, 2006, a field visit of the SRD Dam was made by Mark Kreiter, USFS, Columbia River Gorge National Scenic Area, Hood River Ranger District, Hood River, OR. At the time of his visit, the Sandy River was flowing at approximately 3,700 cfs (USGS streamflow gage number 14142500) and the Columbia River was flowing close to 182,000 cfs (COE gage at the outfall of Bonneville Dam). The following observations were made (taken from his note):

- Backwater from the Columbia River was just spilling over a 5-foot wide portion of the dam. This overflow was approximately 275 feet south of the northern side of the dam.
- The Sandy River was backwatering into the east distributary channel and current water level was 1 to 2 feet below the top of the dam.

Figure 5.79 and Figure 5.80 show two photographs taken during the field visit.

Figure 5.79. Photograph taken on January 23, 2006, standing on the SRD Dam looking Northeast at the Columbia River backwater.

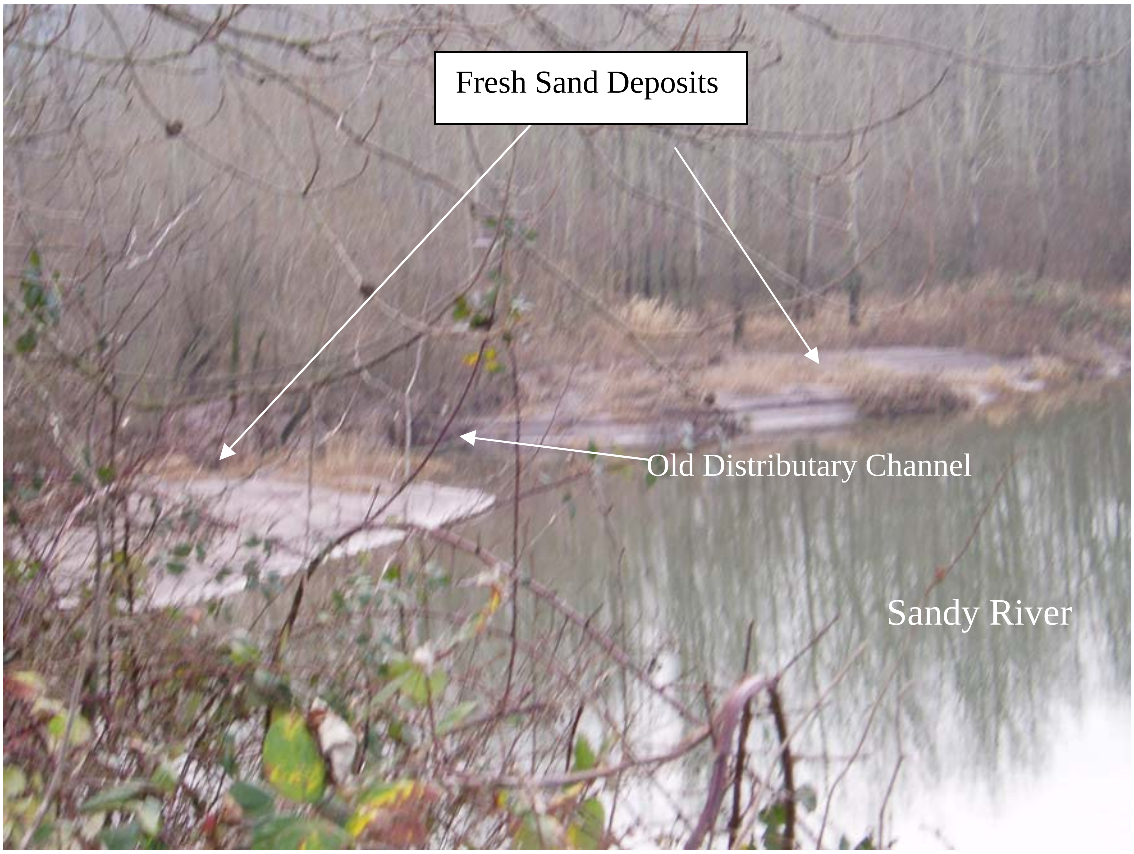


Figure 5.80. Fork of the east and west distributaries taken on January 23, 2006. Fresh sand deposits can be seen in the picture from recent high flows.

GSTAR-W hydraulic simulation was performed using conditions of the January 23, 2006. The purpose was to gain a qualitative comparison between field observations and the model simulation so that the calibrated model may be further verified under higher flow conditions than those of the October 2005 field visit. In addition, this simulation provided insight as to how the model could reproduce the scenario under which the east channel acts as a slough system of the Columbia River.

As mentioned above, discharge of the Sandy River was about 3,700 cfs, and discharge of the Columbia River was about 182,000 cfs on the morning of January 23, 2006. The water surface elevation at the exit of the modeled Columbia River reach was not known and was strongly influenced by the tidal fluctuations. An elevation of 13.5 feet was used, with the understanding that the simulation was only for a qualitative comparison. Simulated velocity and flow patterns are shown in Figure 5.81 and Figure 5.82, and the results qualitatively match field observations.

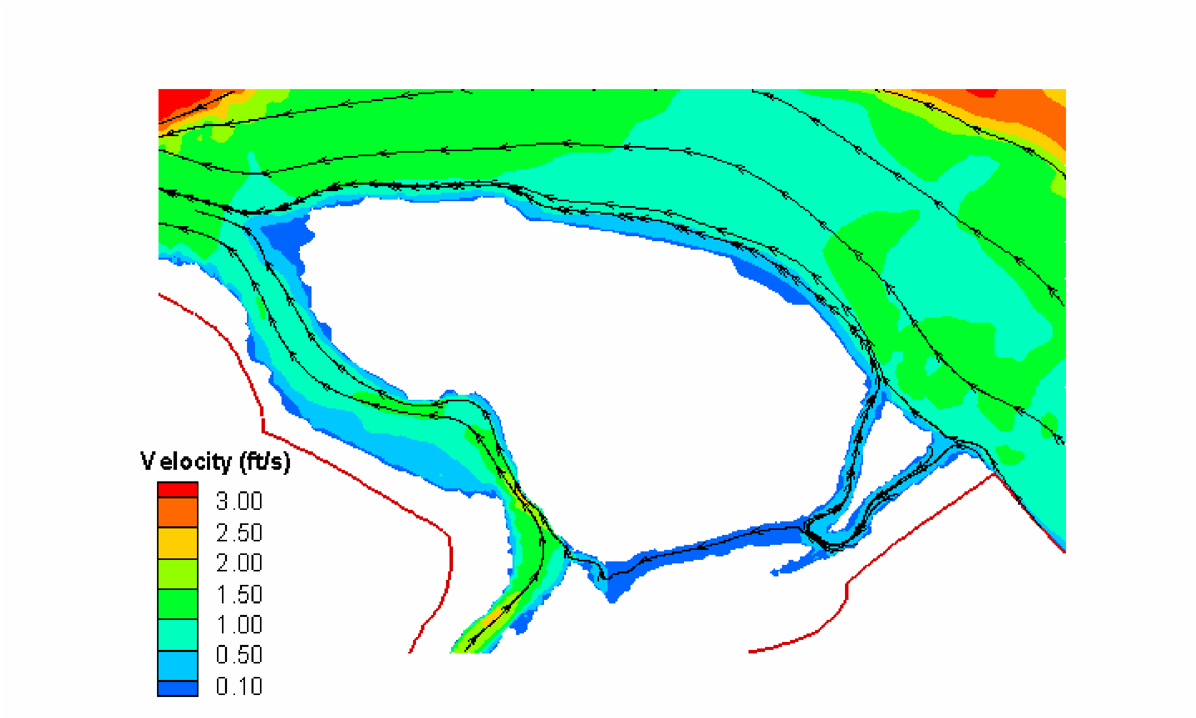


Figure 5.81. Predicted velocity and flow lines at the Sandy River Delta on January 23, 2006.

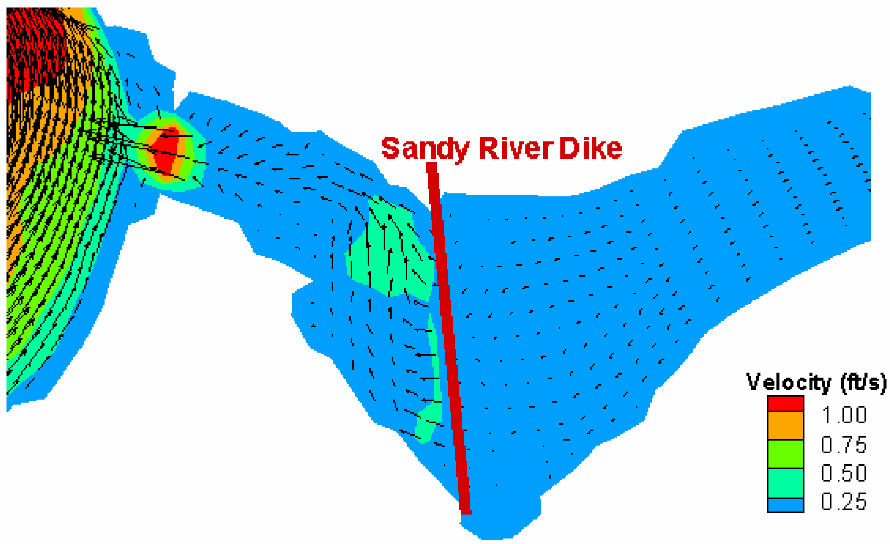


Figure 5.82. Predicted velocity at the SRD Dam for January 23, 2006.

A further qualitative comparison between the model and the field observation may be made concerning the sediment deposition pattern. It is noted that several flood events (close to the magnitude of a 2-year flood) occurred following the field trip of October 11-13, 2005. Therefore, the fresh sediment deposition pattern observed during the January 23, 2006 field trip might be compared with the model simulated sediment deposition pattern for the 2-year flood (Figure 5.30). The photograph in Figure 5.80 shows fresh sand deposits at the entrance to the east channel of the Sandy River. This seems to support the predicted deposition pattern in the same area presented in Figure 5.30.

5.5.2 Simulation with Flood Flows in the Columbia River

The Existing Condition, Removed Dam, Eroded East Channel, and Complete Blockage scenarios assumed that the Columbia River was at 160,000 cfs while the Sandy River was at flood flows. An extra case was simulated by assuming that the Columbia River was at 2-year flood (386,800 cfs) and that the Sandy River was also at the 2-year flood (25,400 cfs). Further, the Complete Blockage scenario topography was used. The purpose of the case was to examine the potential impact of the Columbia River flood flow on the flow pattern at the mining area.

The simulated flow pattern is displayed in Figure 5.83. The results show that water would flow over the mining area when the Columbia River was at flood flows; note that no eddy existed in comparison with scenarios in Figure 5.23 to Figure 5.25, Figure 5.51, and Figure 5.71. This flow pattern implies that sediment deposition would be very small and much reduced at the mining area when the

Columbia River is at flood flows. This supports the previous conclusion that the primary sediment source of the mining area is the Sandy River, not the Columbia River.

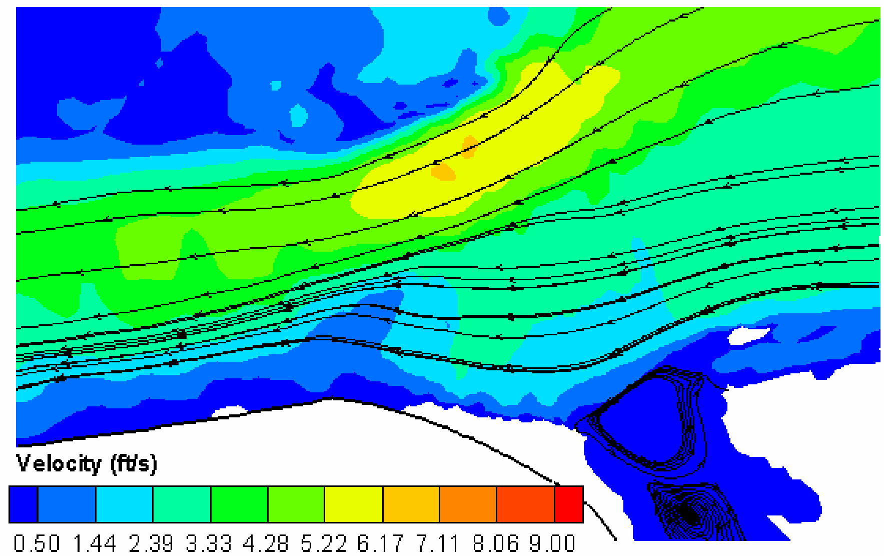


Figure 5.83. Predicted flow pattern at the confluence of the west distributary and the Columbia River when both the Sandy and Columbia Rivers are at 2-year floods.

5.6. Uncertainties and Confidence of the Numerical Modeling

The sediment transport modeling performed in this project represents a current state-of-the-art modeling approach. However, even the most advanced modeling typically cannot accurately predict the complex three-dimensional geomorphic response over time. Uncertainty is inherent in any numerical modeling due to many assumptions used. Assumptions are mostly related to the theoretical development (e.g., the sediment transport equation and bed dynamics) and the method and input data used. Key areas of modeling uncertainty and limitations for this project are listed below:

- 2D modeling was necessary for the present analysis due to the complex nature of the flow, such as the flow split of the Sandy River and the interaction between the Sandy and Columbia Rivers. 2D sediment modeling performed in this project had to be limited to a short-term scale analysis (1 day). Therefore, any long-term effect has to be interpreted in a qualitative manner.

- Sediment modeling is based on steady state flow discharges (flood flows) and the associated hydraulic solutions. Because floods are mostly responsible for sediment mobilization, steady state analysis is adequate for the application. However, sediment timing is difficult to estimate with the approach unless an unsteady hydrograph was used.
- Fixed bed elevation analysis method was adopted. With this analysis, the flow hydraulics were calculated first and then used for the sediment analysis. During the sediment analysis, complex dynamics involving sediment transport and interaction of sediment exchange between water and the bed was simulated. The predicted bed erosion and deposition, however, were not used to feedback to flow hydraulic changes. This analysis method mainly answers short-term sediment trends and impacts due to the action of changes. Extension of the results to long-term impacts should be done with caution. The fixed bed elevation analysis, however, is capable of providing an estimate of erosion and deposition patterns following the initial bed; it is also adequate in obtaining the relative change of sediment rate due alternative scenarios. It is note that the absolute value of the sediment transport rate should only be used in a qualitative way and with caution.
- The sediment model was not calibrated or verified with field-measured sediment transport rate as such data were unavailable. A qualitative comparison of sediment depositional patterns between the model predictions and field observation was discussed in Section 5.5.1.
- Uncertainties due to the sediment transport mechanics, such as the capacity equation and bed dynamics equations, are well known. The best available information, however, has been used in this project. The Parker's (1990) transport equation was used based on our past experience for the mixed sand/gravel river. An attempt has been made to use the Engelund-Hansen equation (1972) under the Existing Condition scenario with the 2-year flood at the Sandy River. The purpose was to examine the sensitivity of results to different transport equations. The total sand transport rates through the West Channel CS and Upstream Area were predicted to be 37,400 tons/day and 17,600 tons/day, respectively, with the Engelund-Hansen model. For comparison, the predicted rates with the Parker (1990) model were 49,700 tons/day and 15,500 tons/day (

Table 5.3 and Table 5.4), respectively. The difference between the two models is within the expected uncertainty associated with the transport equations.

- Sediment supply at the inlet boundary of the Sandy River (the south inlet boundary in Figure 4.3) is maintained at the capacity value. Higher or lower values will result in corresponding changes in the absolute values of the sediment transport rate and net erosion and deposition. This would not be a concern for the present project as only the relative change of sediment transport is of interest.
- One of the uncertainties concerns the estimated erosion in the east distributary channel and deposition in the west distributary channel, as used in the Eroded East Channel scenario. This scenario represents the best estimate of channel morphology a number of years (e.g., five years) after SRD Dam removal.
- Other uncertainties include the impact of hydraulic flows, the initial bed gradation, etc., and would influence the absolute value of the sediment transport rate. However, the influence on the relative change in the sediment transport due to varying scenarios is expected to be small.

Despite various uncertainties, this analysis is based on a current state-of-the-art modeling approach. The analysis method chosen should be adequate and well suited to allow relative comparison of different project scenarios. When each project scenario is modeled using identical input data and flow and sediment models, except the change of local topographic features, the results assist evaluation of the relative impact associated with each scenario. Relative comparison eliminates many uncertainties discussed above and provides greater confidence in the percentage of impact in sediment delivery to the mining area obtained in this study. The main caution is that the absolute sediment transport rate and deposition amount reported contain a high degree of uncertainty and should be used with care.

6.0 Additional Considerations

6.1. Removal of the Marmot Dam

Approximately 48 km upstream from the mouth of the Sandy River, Marmot Dam (Figure 6.1) has filled with 750,000 m^3 of sediment and is scheduled for removal in 2007 as part of the decommissioning of the Bull Run Hydroelectric Project (Stillwater Sciences, 2002b). Removal of the dam is expected to mobilize the trapped sediment, which is comprised of about 490,000 m^3 of pebble and gravel sized sediment and 260,000 m^3 of sand (Squire Associates, 2000).

Figure 6.1. The Marmot Dam on the Sandy River is scheduled for removal in 2007. Photograph courtesy of Portland General Electric.

Numerical modeling of sediment transport following the removal of Marmot Dam was performed by Stillwater Sciences (2000a). Results of the modeling effort suggest that gravel and other coarse sediment will be deposited upstream of river mile 13 with minor deposition in the most downstream 6 miles of the Sandy River. However, sand deposition is primarily expected to occur between river miles 0 to 6, with depths up to 0.4 meters in the first 2 miles of the river within the first year following removal. Backwater effects from the Columbia River are not considered in the model and could further increase sediment deposition in the lower reach of the Sandy River (Stillwater Sciences, 2000a). Sensitivity analyses performed to characterize model uncertainties indicate that a maximum of 1.0 meters of sand may deposit between river miles 0 and 6.

The area of greatest anticipated sand deposition corresponds to the region of the current study. Consequently, Reclamation was asked to evaluate how the removal of Marmot Dam might affect our model results of the Sandy River Delta system, and if the removal of the Marmot Dam can be qualitatively considered as a mechanism that will add more sediment and modify the timing and volume of flows entering the study reach.

Based on the numerical model of Stillwater Sciences (2000a), the study reach will likely aggrade up to 0.4 meters with sand-sized sediment. Over time, this sediment will be transported through the system and likely supply additional material to the mining operation downstream of the confluence of the Columbia and Sandy Rivers. An increase in the bed elevation of 0.4 meters resulting from sand deposits following the removal of Marmot Dam may cause a temporary increase in water surface elevations of the study reach. To analyze the impact of the removal of Marmot Dam on the model results, two possible scenarios were considered: (1) sediment from Marmot Dam would only accumulate in Area A of Figure 6.2, and (2) sediment from Marmot Dam would accumulate in both Areas A and B of Figure 6.2.

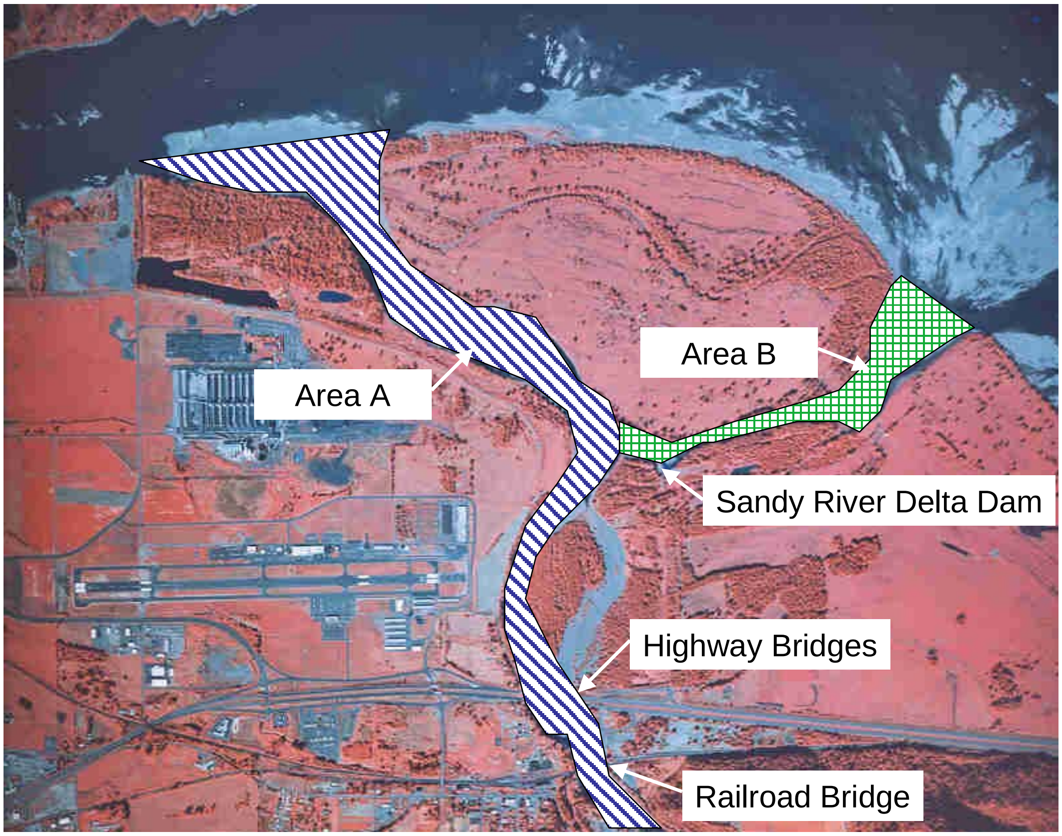


Figure 6.2. Areas within which sediment deposition may occur following removal of Marmot Dam.

Scenario 1 reflects maximum impacts to the model results. Under scenario 1, if the SRD Dam were removed following the removal of Marmot Dam and aggradation was limited to the west distributary only; more flow would be conveyed through the east distributary channel than predicted with the current model. This may result in an increase in the predicted percent reduction of sand delivered to the mining operation. However, aggradation of the west distributary could also provide a short-term increase in sand sized material delivered to the mining site. The net change is uncertain, at least from a short-term perspective. Over time, sediments deposited in the west distributary channel are expected to erode. Scenario 1 would accelerate the erosion process of the east distributary channel and consequently may reduce sand delivery to the mining area over the long term.

Under scenario 2, temporary aggradation would occur throughout both distributaries (Areas A and B), and the predicted distribution of flow through each channel would be minimally affected. Predicted reductions in sand transported to the mining operation may temporarily decrease, as more reservoir sediments become available to the mining area. Independent of the scenario, deposited sediments following the removal of Marmot Dam will be an additional source of material to the mining operation for a short period of time. Over the course of multiple high flow events, a substantial portion of this material will be transported to the permitted dredging site.

Scenario 1 is most likely to occur if the SRD Dam is removed following arrival of reservoir sediments from the Marmot Dam, while scenario 2 is expected to occur if the SRD Dam and sediment plug are removed prior to removal of the Marmot Dam. Currently, high flow conditions on the Sandy River result in overtopping of the SRD Dam and activation of the east distributary. However, the majority of the sediment transported through the east distributary from the Sandy River is carried in suspension, not as bedload. As such, this sediment does not significantly contribute to aggradation of the east distributary, except in the region of the sediment plug.

While scenario 1 could potentially impact the results of the model, the extent of the impacts cannot be predicted without further modeling. The 0.4 meters of predicted deposition in the project reach represents the maximum that may occur in some areas (Stillwater Sciences, 2000a), but this depth of deposition will not be uniformly distributed across the length of the project reach. Sediments will temporarily be deposited within pools and other low velocity areas. Without a numerical model of these scenarios, the only qualitative conclusion is that the addition of sediment to the system following removal of Marmot Dam is anticipated to provide a short-term increase in the volume of sediment delivered to the mining operation. Additional modeling could provide greater insight as to the degree to which sediments from removal of Marmot Dam, in conjunction with removal of the SRD Dam, impact sand delivery to the mining area and scour at the bridges sites.

The SRD Dam could be removed after the removal of Marmot Dam and after the subsequent transport of reservoir sediments. This would tend to avoid sediment deposition in the east distributary. However, the transport of Marmot Dam sediments past the Sandy River Delta could take years to occur. If the SRD Dam is removed prior to the removal of Marmot Dam, sediment deposition in the east distributary is more likely. However, the amount of deposition in the east distributary may be small and eventually eroded by the flow velocities from the Sandy and Columbia Rivers.

Prediction of stream behavior following the removal of these dams in conjunction is complex and highly uncertain. Geomorphic channel response to the dam removals at the Sandy River Delta will be strongly influenced by flow conditions of both the Columbia and Sandy Rivers. While an unlimited number of possible scenarios could be incorporated into a numerical model, a more resourceful approach under these complex conditions would be to initiate a monitoring program to test the hypotheses proposed in this study. Monitoring activities following the dam removals might include bed load sampling, repeat topographic surveys, and grain size sampling.

6.2. Assessment of Bank Erosion in the West Distributary Channel

Under the present conditions of the Sandy River, the right bank of the west distributary channel is actively eroding downstream of the fork of the east and west distributary channels. The eroding right bank is located on the outside bend of a river. Rip rap and wooden piles were placed along the right bank of the west distributary following the construction of the SRD Dam. However, this rip rap was only placed for approximately 800 feet downstream of the fork of the distributaries. Downstream from the rip rap, the present channel bank is eroding.

An evaluation was performed to address how the potential removal of the SRD Dam might affect future erosion of the right bank of the west distributary. During a field visit on February 23, 2006, Mark Kreiter, (USFS, Columbia River Gorge National Scenic Area, Hood River Ranger District, Hood River, Oregon) took photographs at five locations along the bank of concern (Figure 6.3). Figure 6.3 provides a key to the photographs taken during his visit. The following observations were noted by Mr. Kreiter:

- The entire area is overlain by 2 to 3 feet of silty loam soil (Figures 6.4 to Figure 6.6). Underneath the loam is thinly bedded silty sand that has little cohesion, extending down to the river level. The loam is visible as the gray material in Figure 6.7.
- The mechanism for erosion appears to be erosion of the sand layer by the river, followed by collapse of the loam layer into the river. The loam layer is undercut to some degree along the entire meander.
- Bank protection includes a set of wooden piles (Figures 6.9 and Figure 6.10). These piles have rip rap backfill behind them (Figure 6.10). Upstream of the rip-rapped piles, the bank is only protected by rip rap up to the fork of the east and west distributary channels (Figures 6.11 and Figure 6.12).
- Very little vegetation other than grasses, are found adjacent to the stream. Some trees are found in the downstream portion of the meander (Figure 6.4) but the majority of riparian vegetation is grass (Figure 6.8).

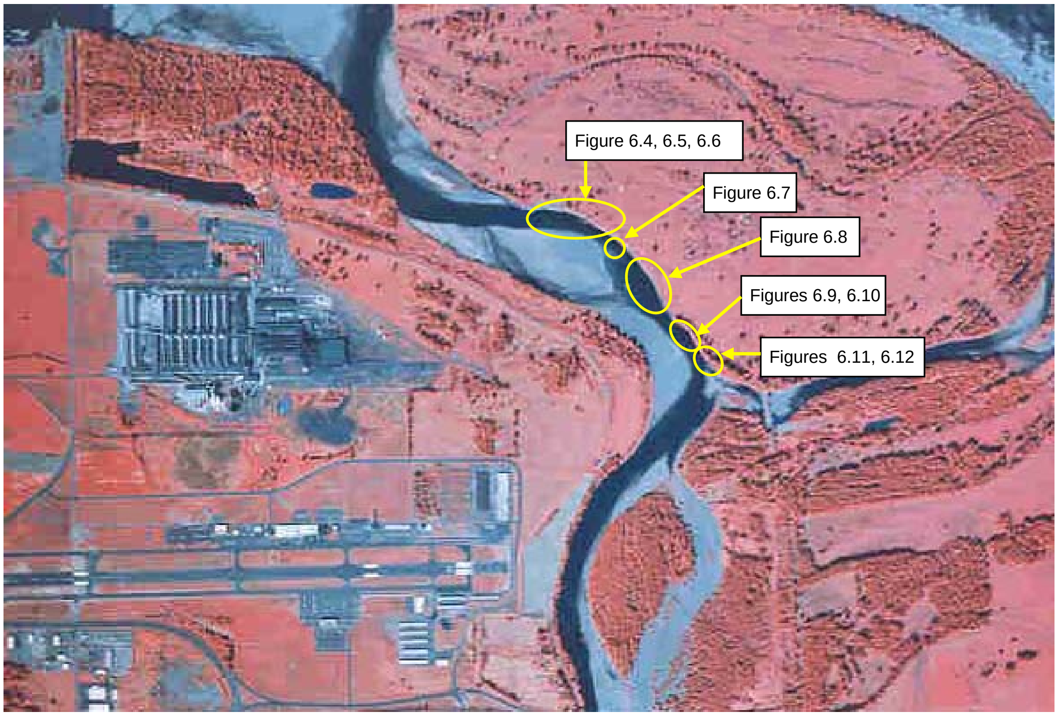


Figure 6.3. Locations of bank erosion concern and key to photographs taken during field visit by Mark Kreiter on February 23, 2006.

Figure 6.4. Bank erosion along right bank of west distributary channel.

Figure 6.5. Silty loam layer on bank of the Sandy River Delta.

Figure 6.6. Bank erosion along right bank.

Figure 6.7. Non-cohesive loam that comprises the bank.

Figure 6.8. With the exception of grass, very little vegetation is present along the bank downstream of the rip-rapped reach.

Figure 6.9. Edge of bank protection composed of wooden piles and rip rap.

Figure 6.10. Bank protection on right bank of west distributary.

Figure 6.11. Bank protection composed only of rip rap. Note the established vegetation.

Figure 6.12. Rip rap protecting right bank of west distributary just downstream of the fork of the distributaries.

Bank erosion by hydraulic processes is associated with near-bank velocities and the magnitude of hydraulic shear. High rates of outer bank erosion, commonly encountered on meander bends, are due to secondary flow, steep velocity gradients and high shear stresses acting against the bank (Thorne, 1982; Knighton, 1998). GSTAR-W does not yet model bank erosion, nor does it provide the velocity and shear stress on the bank directly. However, GSTAR-W does predict depth-averaged velocity and the bed shear stress in the wetted channel. Due to hydraulic processes acting near the bank, depth-averaged velocities and bed shear stress values at points near the bank should be correlated to the bank erosion and can be used to compare expected rates of bank erosion under alternative management actions. Therefore, depth-averaged velocities and bed shear stresses for 5 points near the right bank of the west distributary were quantitatively compared for the Existing Condition, Removed Dam and Eroded East Channel scenarios. Each point correlates to a location of interest along the right bank as indicated in Figure 6.13.

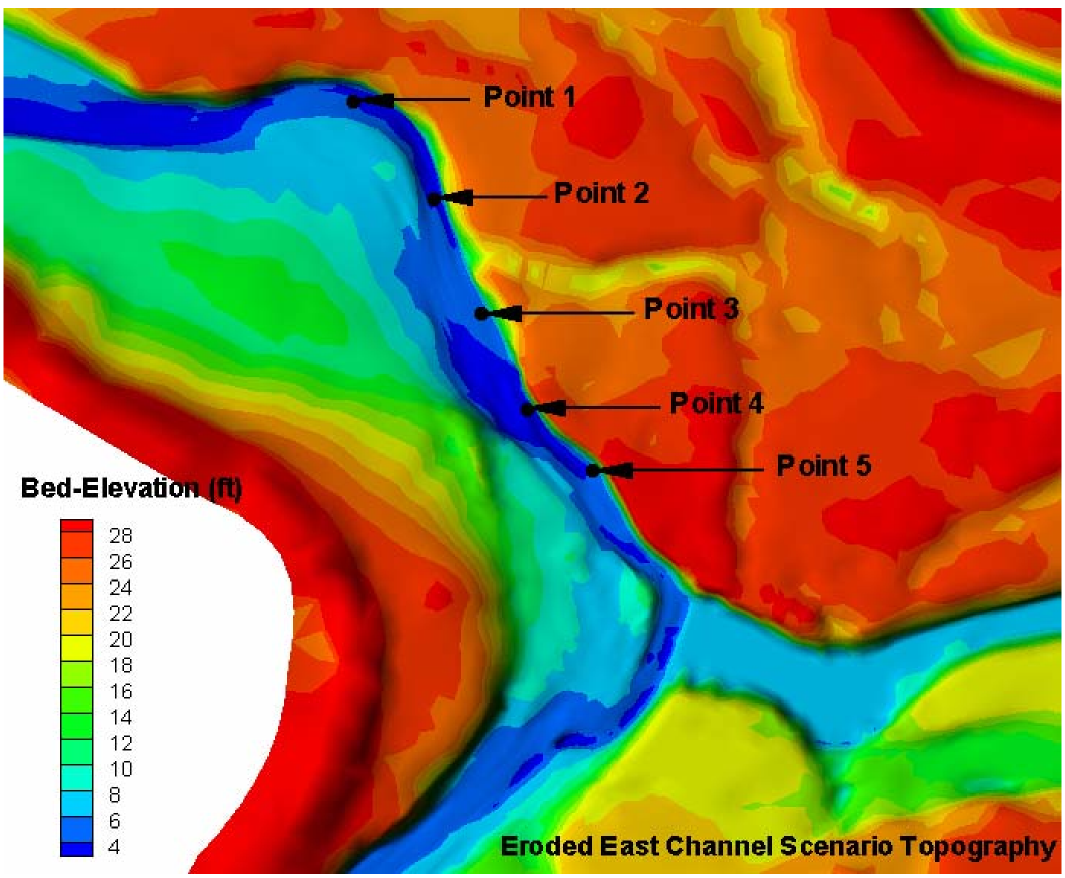


Figure 6.13. Locations of 5 points near the right bank of the west distributary where velocity and shear stress were compared to assess bank erosion.

Results of the comparison of the Existing Condition scenario with the Removed Dam and Eroded East Channel scenarios generally indicate small reductions (typically less than 10 percent) in the velocities and shear stress values near the right bank of the west distributary following removal of the SRD Dam (Tables 6.1 to Table 6.6). Accordingly, the erosion rate of the right bank will slightly decrease under the 2-, 5-, and 10-year flows after the dam removal. Under the extreme case of the Complete Blockage scenario, bank erosion due to hydraulic processes of the river at the locations of concern would cease completely.

Table 6.1. Velocity (ft/s) for 2-year Sandy River flow conditions. Values in parentheses indicate percent difference from the Existing Condition scenario.

Velocity (ft/s) for 2-yr flood			
Point	**Existing Condition**	**Removed Dam**	**Eroded East Channel**
1	2.50	2.52 (0%)	2.49 (-1%)
2	3.49	3.44 (-1%)	3.32 (-5%)
3	5.84	5.55 (-5%)	5.24 (-10%)
4	9.34	9.03 (-3%)	8.98 (-4%)
5	5.39	5.31 (-1%)	5.20 (-4%)

Table 6.2. Velocity (ft/s) for 5-year Sandy River flow conditions. Values in parentheses indicate percent difference from the Existing Condition scenario.

Velocity (ft/s) for 5-yr flood			
Point	**Existing Condition**	**Removed Dam**	**Eroded East Channel**
1	2.54	2.52 (-1%)	2.44 (-4%)
2	3.88	3.79 (-2%)	3.60 (-7%)
3	7.26	7.02 (-3%)	6.68 (-8%)
4	10.67	10.47 (-2%)	10.43 (-2%)
5	6.03	5.98 (-1%)	5.89 (-2%)

Table 6.3. Velocity (ft/s) for 10-year Sandy River flow conditions. Values in parentheses indicate percent difference from the Existing Condition scenario.

Velocity (ft/s) for 10-yr flood			
Point	**Existing Condition**	**Removed Dam**	**Eroded East Channel**
1	2.61	2.58 (-1%)	2.51 (-4%)
2	4.19	4.10 (-2%)	3.91 (-7%)
3	7.99	7.79 (-3%)	7.48 (-6%)
4	11.42	11.25 (-1%)	11.24 (-2%)
5	6.44	6.26 (-3%)	6.19 (-4%)

Table 6.4. Shear stress (N/m^2) for 2-year Sandy River flow conditions. Values in parentheses indicate percent difference from the Existing Condition scenario.

Shear Stress (N/m^2) for 2-yr flood			
Point	**Existing Condition**	**Removed Dam**	**Eroded East Channel**
1	4.60	4.66 (1%)	4.62 (0%)
2	8.80	8.62 (-2%)	8.15 (-7%)
3	25.64	23.35 (-9%)	21.07 (-18%)
4	59.93	56.39 (-6%)	58.47 (-2%)
5	20.74	20.35 (-2%)	19.96 (-4%)

Table 6.5. Shear stress (N/m^2) for 5-year Sandy River flow conditions. Values in parentheses indicate percent difference from the Existing Condition scenario.

Shear Stress (N/m^2) for 5-yr flood			
Point	**Existing Condition**	**Removed Dam**	**Eroded East Channel**
1	4.50	4.46 (-1%)	4.25 (-6%)
2	9.86	10.04 (2%)	9.19 (-7%)
3	38.05	35.87 (-6%)	32.85 (-14%)
4	75.73	73.33 (-3%)	75.94 (0%)
5	24.87	24.70 (-1%)	24.41 (-2%)

Table 6.6. Shear stress (N/m^2) for 10-year Sandy River flow conditions. Values in parentheses indicate percent difference from the Existing Condition scenario.

Shear Stress (N/m^2) for 10-yr flood			
Point	**Existing Condition**	**Removed Dam**	**Eroded East Channel**
1	3.13	3.09 (-1%)	3.00 (-4%)
2	8.04	7.73 (-4%)	7.14 (-11%)
3	30.34	29.10 (-4%)	27.10 (-11%)
4	57.33	55.91 (-2%)	58.1 (1%)
5	18.68	18.00 (-4%)	17.9 (-4%)

One note of interest relates to points 1 and 2, the locations that have recently experienced the greatest rates of erosion. The results provided indicate that these locations have fairly low velocities and shear stress values when compared to points 3, 4, and 5, which contradicts the observed high rates of bank erosion at points 1 and 2. This may be partially attributed to the curvature of flow in river bends and the development of strong secondary flow, a purely three-dimensional

(3D) effect. Strong secondary flow significantly contributes to the erosion processes at the outer bank of a bend (Thorne, 1982; Richardson, 1997). Secondary flow results in a steepening of the near-bank velocity gradient and produces a zone of high shear stress (Bathurst, 1979; Bathurst et al., 1979). This process is particularly important near the outer bank of a bend as it promotes hydraulic entrainment and scour near the toe of the bank (Thorne, 1982).

GSTAR-W-predicted velocities in Tables 6.1 through 6.3 represent depth-averaged velocities and are not representative of local secondary flow. Shear stress values in Table 6.4 through 6.6 are measures of hydraulic shear acting on the stream bed near the bank, not against the bank. Therefore, absolute values of the near-bank depth-averaged velocity and bed shear stress at the bend should not be used directly in estimating the quantitative erosion rate. Instead, a relative comparison in terms of percent reduction between scenarios (shown in parentheses in Tables 6.1 to 6.6) is more meaningful. The percent reductions from the Existing Condition scenario can be used with more confidence to indicate probable impacts to bank erosion rates, but the actual values of velocity and shear stress may differ from those experienced by the bank.

In summary, the removal of the SRD Dam is not anticipated to accelerate bank erosion along right bank of the west distributary channel; conversely, it may marginally allay erosion of the west distributary channel. Following removal of the SRD Dam, bank erosion without protection is likely to continue, but at a reduced rate.

7.0 References

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8.0 Appendices

8.1. Additional Hydraulic Results of Water Surface Elevation on Selected Cross Sections along the East Distributary Channel of the Sandy River

This Appendix presents some additional hydraulic results of the simulated scenarios, namely, the water surface elevations on selected cross sections on the east distributary channel of the Sandy River. Three cross sections were selected and are depicted in Figure 8.1 below.

Figures 8.2 and Figure 8.3 show the computed water surface elevations at the three cross sections under the 2-, 5-, and 10-year floods with the Existing Condition scenario and Eroded East Channel scenario.

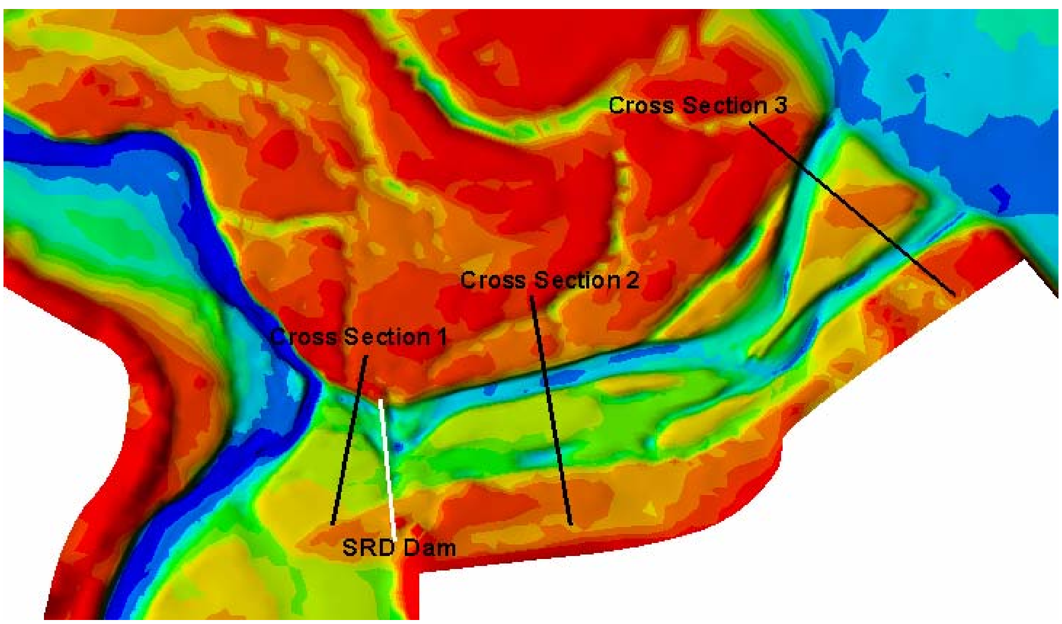
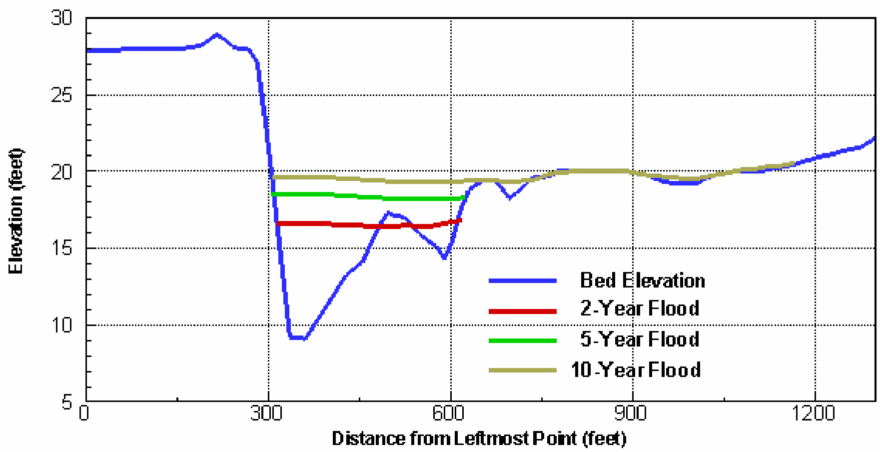
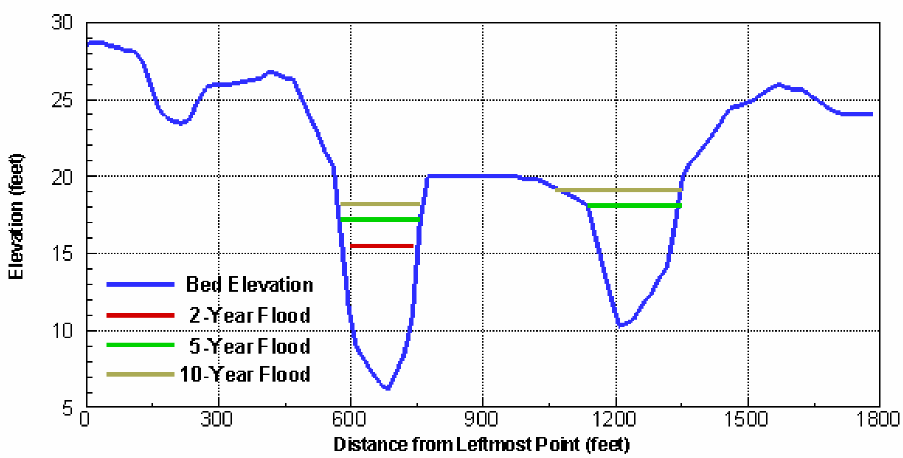


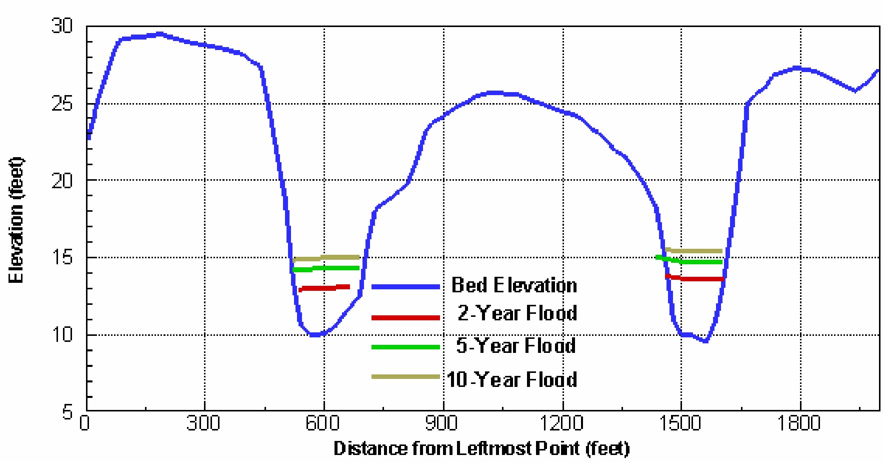
Figure 8.1. Graphic showing the locations and sizes of three selected cross sections on the east distributary channel of the Sandy River.



(a) Cross Section 1

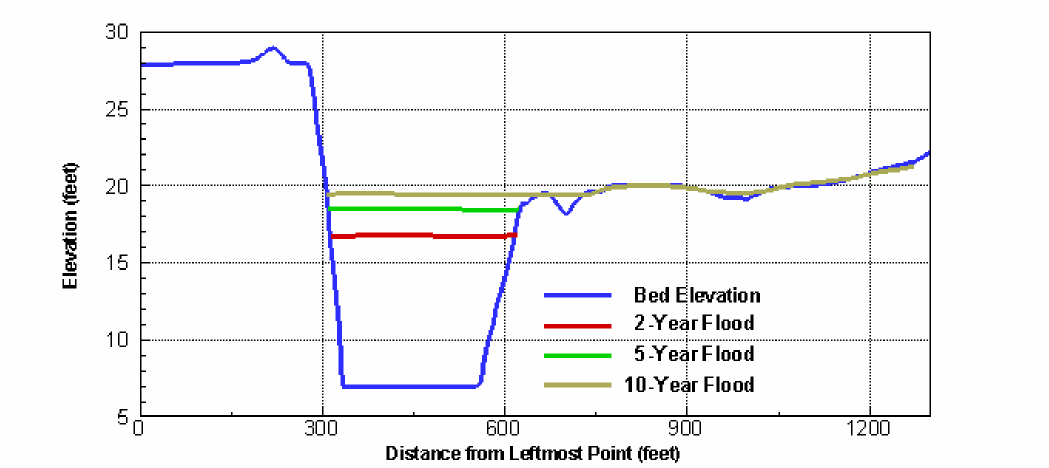


(b) Cross Section 2

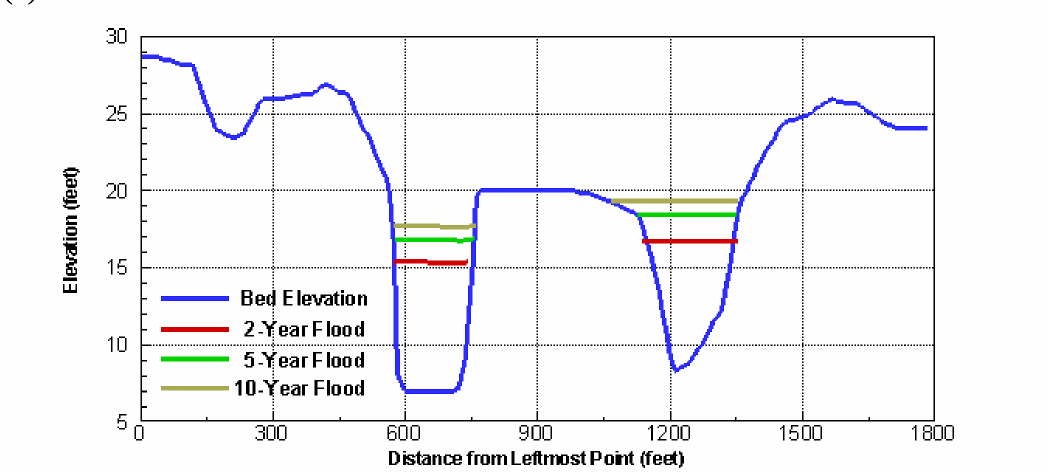


(c) Cross Section 3

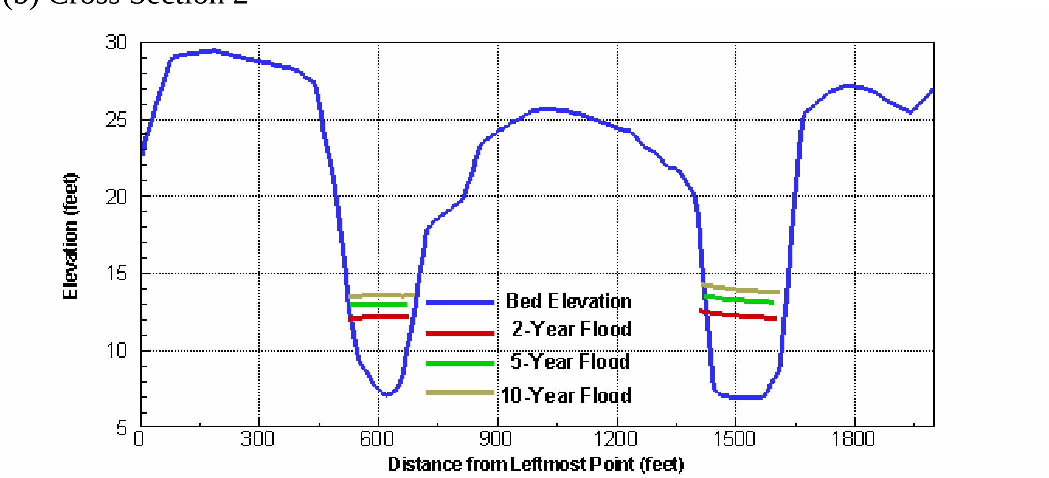
Figure 8.2. Computed water surface elevation on three cross sections of the Sandy River with 2-, 5- and 10-year floods for Existing Condition scenario.



(a) Cross Section 1



(b) Cross Section 2



(c) Cross Section 3

Figure 8.3. Computed water surface elevation on three cross sections of the Sandy River with 2-, 5- and 10-year floods for the Eroded East Channel scenario.

8.2. Photographs of field visit (electronic)

8.3. Topographic data (electronic)