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Managing Water in the West

WATER RESOURCES RESEARCH LABORATORY TECHNICAL PAPER - 954

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February 2006

Acknowledgements

The Klamath Basin Area Office and the Office of Science and Technology provided support for this study. Richard Piaskowski (KBAO) assisted in coordinating the study and provided the river bathymetry for the numerical model. Rudy Campbell (WRRL) provided assistance in developing the model geometry. Robert Einhelig provided peer review.

Link River Falls
Flow Velocity Simulation

Background

Link River is located within the city of Klamath Falls Oregon. The river runs for approximately one mile between Upper Klamath Lake and Lake Ewauna at the head of the Klamath River. Link River Dam controls Upper Klamath Lake elevation and releases to Link River. The river contains a number of natural falls where the river passes over basalt outcroppings. The falls are a series of cascading drops containing bedrock and large alluvial material (figure 1). The main cascade provides a drop of about 15 feet in elevation over a length of about 450 feet. Nearly 10 feet of the drop is concentrated in a single cascade that is about 100 feet long. The main cascade starts about 320 ft downstream of the dam (following the thalweg) with the steepest section starting about 500 feet downstream of the dam. The Klamath and Link Rivers are a natural migratory route for the endangered Lost River sucker and Shortnose sucker. Monitoring of radio tagged suckers suggests the falls is a barrier to many upstream migrating suckers. Although the falls are natural, river flows are now regulated by Link River Dam. An understanding of how flow conditions in the falls change with river flow is needed to determine if fish passage can be improved by managing flow releases. Currently, there is not sufficient data available to indicate how the opportunity for passage varies with river flow. The highly aerated and complex flow within the falls makes field measurements difficult to obtain. The objective of this study is to conduct a three-dimensional computational fluid dynamics (CFD) numerical simulation of the falls to gain insight on the hydraulic flow field of the falls.

Limitations of the Study - The falls were numerically modeled in an attempt to develop a better understanding of the complex flow field within the falls as a function of river discharge. By comparing model results for different river flows the authors hoped to identify flow field differences spatially and as a function of river discharge. River discharges of 1,000 ft^3/s, 2,000 ft^3/s, 3,000 ft^3/s and 4,000 ft^3/s were modeled.

For each flow, the hydraulic boundary conditions for the model had to be estimated. There is little field data available defining river stage within the extent of the reach modeled. Mefford et al. 2001gives an estimate for tailwater elevations below the dam for 100 ft^3/s and 3,000 ft^3/s of 4131.5 ft and 4136.5 ft, respectively. These elevations were based on a measurement at low flow and an observation of high water marks on the dam's outlet works training wall following a known flow event. It was not within the scope of this study to conduct a water-surface profile study of the river from Lake Ewauna to Link River Dam. Therefore, critical flow was assumed at the upstream brink of the falls.

The model geometry is based on a field survey of the falls that attempts to define 1.0 ft differences in elevation. The river channel through the falls is complex and could not be fully represented by the survey. Small scale or isolated channel roughness not defined by the field survey are not represented in the model. An example of the general roughness of the Link River channel in the area of the falls is evident in a 1918 photograph of the channel (figure 1). A contour plot and a profile along the channel thalweg of the river bathymetry used to develop the model are shown in figure 2. The contour plot is shown overlaid on an aerial photograph of the river for visual orientation.

The modeling effort focused on a 350 ft long by 70 ft wide reach of the river channel that contains the major falls (figure 4). This area was numerically modeled using a high density of points referred to herein as a fine mesh. A coarse mesh was used to model the flow conditions upstream and downstream of the falls area. These areas were modeled with a coarse mesh to provide approximate flow conditions at the fine mesh flow boundaries. Data presented from the coarsely meshed areas should be viewed as approximate. A further discussion of the meshing is presented in the section on Model Description.

Within the falls the flow is highly aerated. The model does not reflect the bulking of the flow due to aeration.

Model Description

CFD Program Description

There are many steps required to develop an appropriate Computational Fluid Dynamics (CFD) model. These include development, refinement, and testing of the grid, boundary conditions, model extents, and obstacles (structures) for the CFD program. The CFD program FLOW-3D, by Flow Science Inc., was used. FLOW-3D[i] is a finite difference/volume, free surface, transient flow modeling system that was developed to solve the Navier[ii]-Stokes[iii] equations in three spatial dimensions.

The finite difference equations are based on an Eulerian mesh of non-uniform hexahedral (brick shaped) control volumes (to form mesh-blocks) using the Fractional Area/Volume (FAVOR)[iv] method. Free surfaces and material interfaces are defined by a fractional volume-of-fluid (VOF) function[v]. FLOW-3D uses an orthogonal coordinate system as opposed to a body-fitted system.

Due to an upgrade during this project, Version 8.2 of Flow-3D was used on the 1,000 ft^3/s simulation. Version 9.0 of Flow-3D was used on the 2,000 ft^3/s, 3,000 ft^3/s and 4,000 ft^3/s simulations.

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i Flow Science Inc., FLOW-3D version 9.0 User's Manual. 2005.

ii C.L.M.H. Navier, M´emoire sur les lois du mouvement des ?uides, M´em. Acad. Sci. Inst. France 6 (1822), 380–440.

iii G.G. Stokes, On the theories of internal friction of ?uids in motion, Trans. Cambridge Philos. Soc. 8 (1845).

iv J.M. Sicilian, "A FAVOR Based Moving Obstacle Treatment for FLOW-3D," Flow Science, Inc. Technical Note #24, April 1990 (FSI-90-TN24).

v Michael R. Barkhudarov, "Semi-Lagrangian VOF Advection Method for FLOW-3D," Flow Science, Inc. Technical Note 63, July 2003 (FSI-03-TN63)

Model Parameters

The options within Flow-3D chosen for the simulations are shown in Table 1. Other parameters used default options.

Table 1. Parameters used for the Link River Falls simulations.

Turbulence model	Renormalization-Group (RNG) Model
Momentum advection	First order
Pressure solver	Line implicit in the x- and y-directions.
Viscosity of water	2.25E-5 ft^2/s
Density of water	1.937 $slugs/ft^3$
Gravity	32.14 ft/s^2

Model Geometry

Survey data was manipulated in AutoCAD using the Land Development software to generate elevation data for a grid with 1-foot spacing in the X and Y (horizontal) directions. An in-house program was used to translate the coordinates and to create a three dimensional stereolithography file used as input into Flow-3D (figure 3). It is often advantageous to translate a model to be close to the coordinate axis to increase the number of usable significant digits within the numerical program. Smaller values allows for more accuracy in Flow-3D which uses double precision real numbers. Accordingly, the x-coordinate value was reduced by 4,568,948.19 ft, the y-coordinate value was reduced by 208,430.58 ft, and the z-coordinate value was reduced by 4,109.41 ft. This caused the minimum x, y, and z value of the stereolithography to be zero. The maximum value of x was 405.95 ft, y was 1,252.58 ft, and z was 50.86 ft. Elevations outside of the surveyed space were assigned the maximum z value of 50.86 ft to mimic a steep bank.

Boundaries

All boundaries except the downstream boundary were modeled as “walls” (no flow passes through the boundary). The downstream boundary was modeled as a hydrostatic pressure boundary, thus fixing the flow depth at the boundary. River stage at the downstream boundary was estimated for each flow using a channel invert elevation of 4116.0 and flow depths for similar flows recorded at the USGS gage 11507500 located about one half mile downstream. Since critical flow occurs within the falls, velocities in the falls are insensitive to the downstream depth assuming tailwater does not inundate the main falls.

Flow into the river was controlled with a source-object. The object was place at the base of the dam, and provided a constant velocity flow field out of the object’s surface. This provides precise flowrate control. A high water-surface elevation was used at the upstream boundary as an initial condition. This excess water drained down during model execution until it reached a nearly-constant water-surface elevation.

Meshing

Flow-3D can have a single mesh-block, nested (one completely contained by another) mesh blocks, linked (adjacent) mesh blocks, or a combination of nested and linked mesh blocks. The Link River Falls simulations used two mesh-blocks where one was nested. The nested mesh-block contained the falls which allowed for a more refined definition of the flow fields that are of concern (figure 4). The cell sizes for the simulations are shown in Table 2.

Table 2. Cell sizes used in the simulations.

Simulations	1,000 ft^3/s & 2,000 ft^3/s		3,000 ft^3/s & 4,000 ft^3/s	
	Outer (ft)	Nested (ft)	Outer (ft)	Nested (ft)
X (feet)	3	1	4.5	1.5
Y (feet)	3	1	4.5	1.5
Z (feet)	2.1	1	3.3	1.5

Modeling Results

In the following models, near steady-state conditions were determined using output information from the program, such as total volume of fluid, average turbulent kinetic energy, estimated mean kinetic energy, and apparent flow conditions. The model results are presented as spatial plots of flow-velocity magnitude.

Typically, the higher the flow, the higher the velocities and the number of cells used in Flow-3D. This becomes apparent when comparing the different simulations times. The reader should use caution when interpreting the velocity data shown within the coarsely meshed model area. The surface plots display only full cells. Therefore, areas where the simulated flow depth is less than a full cell (see Table 2) are shown as grey, indicating no flow. This is a problem that was encountered with the display software and does not reflect the accuracy of the numerical simulation, which can handle partially-full cells. For each river flow, similar plots are presented for comparison. Four plots are presented for each flow simulation. The first plot in each series (figures 6, 7, 8 & 9) is a plan view showing water surface velocity for the full model. For ease of comparison between flows the color codes used to define velocity magnitude on the water-surface plots were fixed. The plan views are followed by cross sections cut at model stations 525, 546 and 575 (figures 10, 11 & 12). At each station, results for all flows are given on a single plot to illustrate flow velocity changes as a function of river discharge. Due to the wide range of flow conditions that occur in the falls, the color scheme shown on the cross sections generally vary as a function of velocity range. The location of the cross sections are shown in figures 1 and 5. The third set of plots gives horizontal slices at one foot depth increments through the main falls, (figures 13, 14, 15 & 16). These plots cover only the falls area modeled using a fine mesh for simulation. The Z value below each section represents height above the model datum (Z=0). Gray areas are bed rock, areas colored in blue to red represent flow velocity and white indicates area lying above the water surface. Colors representing flow velocity are a function of velocity range. The fourth set of plots (figures 17, 18, 19 & 20) presents the same data as the third set of plots with the velocity scale capped at 8 ft/s. Truncating the velocity scale on the plots highlights the flow areas that could be considered suitable (< 8 ft/s) and unsuitable (>8 ft/s) for fish passage. All velocities exceeding 8 ft/s are shown in red.

1,000 ft^3/s simulation

The 1,000 ft^3/s simulation required 21.7 days of computer time to simulate 620 seconds. For the simulation, the water-surface elevation at the downstream model boundary was set as 4118.4. Figure 6, shows a plot of surface velocity covering the full model. Velocity magnitude is indicated by color. The surface plot shows thalweg flow velocities within the reach modeled upstream and downstream of the main falls range from about 4 to about 12 ft/s. In the main falls the flow is dominated by chutes between large rocks bounded by small pools. The high-velocity flow in the chutes is shown on the surface plot in yellow. Velocities in the chutes range from about 15 ft/s to 20 ft/s. The main fall within the reach is controlled by a series of large bedrock outcroppings that run roughly diagonally across the river from the west bank downstream to the east bank, (see figure 1). The rock protrusions form a long cascading flow along the west bank and several shorter steep drops close to the east bank. Variability of flow velocity with depth at three locations in the main falls is presented in figures 10, 11 and 12. Figure 10 presents velocity profiles at model Station 525. This station is located at the downstream end of the main falls and represents conditions fish encounter approaching the main falls. Flow velocities are generally highest near the west bank and lower near the east bank. At this station flow on the east side of the river is slower due to large upstream rocks that concentrate flow toward the west bank and cause slackwater areas in their wake. Fish could easily move up the east bank to about Station 546 where they encounter a high velocity chute (16 ft/s to 18 ft/s) between two large rocks, figure 11. For sucker species, movement from Station 546 upstream to Station 575 (figure 12) likely requires multiple attempts and searching for low velocity zones near the boundary. Horizontal slices through the falls are depicted on figure 13. The model predicts velocities in the falls varying by location from < 4 ft/s in the wake of boulders and at the extreme edges to > 20 ft/s in many locations. The highest velocities occur in the main falls between model sta. 540 and sta. 590. Figure 17 shows the data of figure 13 with velocities greater than 8 ft/s presented in red. The red areas likely pose a significant barrier to sucker passage.

2,000 ft^3/s simulation

The 2,000 ft^3/s simulation ran for 30.9 days to simulate 385 seconds. For the simulation, the water surface elevation at the downstream model boundary was set as 4119.4. Figure 7 shows a plot of surface flow velocity. The dominant flow in the falls is along the west bank. Downstream of the main falls the strong current along the west bank moves off the bank and flows downstream to the west side of river centerline. Fish approaching the falls encounter flow velocities on the west side of the river averaging from 6 ft/s to 14 ft/s, (shown in light green). Flow velocities to the east of centerline are generally lower, averaging from 4 ft/s to 8 ft/s, (shown in light blue). Comparing the simulations for 1,000

ft^3/s and 2,000 ft^3/s reveals a general increase in flow velocities through the reach at the higher flow. Cross-sections of flow velocity given on figures 10, 11 and 12 indicate a significant thinning of lower velocity zones near the channel boundary with increased river flow. A general loss of near-bank low-velocity area is also evident from comparing 1,000 ft^3/s (figures 13 and 17) and 2,000 ft^3/s (figures 14 and 18) river flows.

3,000 ft^3/s simulation

The 3,000 ft^3/s simulation ran for 20 days to simulate 148 seconds. Due to the uncertainty of tailwater elevation at high river flows, the downstream water surface elevation was set at 4124.4. Elevation 4124.4 is about the average river bed elevation within the falls at model station 580. This tailwater elevation is expected to be higher than actual. Therefore, velocity predictions approaching the falls may be lower than actual. This is a conservative approach when identifying flow areas that do not support fish passage. Surface flow velocities for 3,000 ft^3/s are presented in figure 8. The rapid along the west bank and the large drop at about mid-falls adjacent to the east bank (shown as red) are clearly evident. Compared to model results for lower river flows, the model predicts increasing the river discharge to 3,000 ft^3/s will result in increased velocities within the falls. The high tailwater simulated in the model does not indicate a noticeable effect on flow through the falls. Surface velocities in the falls are predicted to exceed 15 ft/s in most locations. The model results show a few low velocity (< 8 ft/s) areas downstream of large rock protrusions and in some locations along the banks that may serve as fish refuges (figures 15 and 19). However, these refuge areas are surrounded by flow conditions that may limit sucker access or further upstream movement.

4,000 ft^3/s simulation

The 4,000 ft^3/s simulation ran for 25 days to simulate 167 seconds. The downstream water-surface elevation was set at 4124.4. A model simulation of surface velocity is given in figure 9. The simulation predicts flow velocities in the falls range from 10 ft/s to 20 ft/s with localized areas of lower velocity downstream of large rocks. In nearly all locations, the model predicts flow velocity increases with river discharge. The main refuge within the falls where velocities are less than 8 ft/s occurs along the east bank from model stations 470 to 645 (see figures 16 and 20) elevations Z=8.0 to Z=14.1. As with lower discharge simulations, these refuge areas appear to be surrounded by high velocity flow.

Conclusions

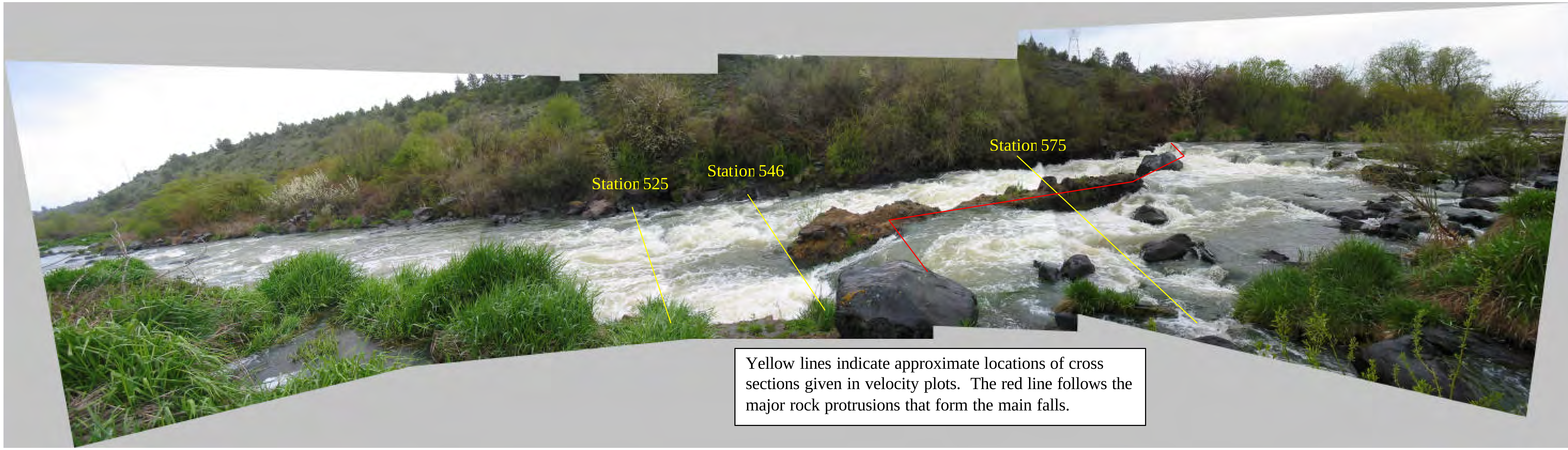
The model indicates conditions supporting fish passage through the falls becomes progressively worse as river flow increases from 1,000 ft^3/s to 4,000 ft^3/s. The results generally show highest flow velocities in the main falls occur in a long rapid along the west bank and in a single drop at approximately the middle of the falls on the east bank. These flow patterns are also evident when looking at the layout of the large rock protrusions that compose the falls (figure 1). The velocity pattern at the downstream entrance to the falls suggests fish are likely to concentrate along the east bank and move upstream to about model station 546. Fish may hold in this area for some time as passage above station 546 requires ascending through a chute between large boulders that, for the range of river flows modeled, conveys flow at velocities in excess of 8 ft/s. The model does not address the potential for passage through small runs (waterways) that skirt the falls on the east overbank area. Field observations suggest these overbank runs may become accessible for passage as river flow increases.

References

Flow Science Inc., 2005. Flow 3-D Version 9 Users Manual

Mefford et al., 2001. *Link River Dam Fishway Replacement Feasibility Study*, Water Resources Research Laboratory, Bureau of Reclamation, Technical Paper No. 955.

Ott Engineering, 1990. Link *River Dam Fishway Conceptual Design Study*, Pacific Power and Light Company.



Link River in 1918, after development of the Klamath Irrigation Project. Strong winds on Upper Klamath Lake, likely combined with heavy irrigation diversions, caused this unprecedented temporary de-watering. Photograph from "50 Years on the Klamath" by John C. Boyle.

Figure 1. Panoramic photograph of the main falls below Link River Dam. The lower photograph illustrates the roughness of the channel invert through the falls.

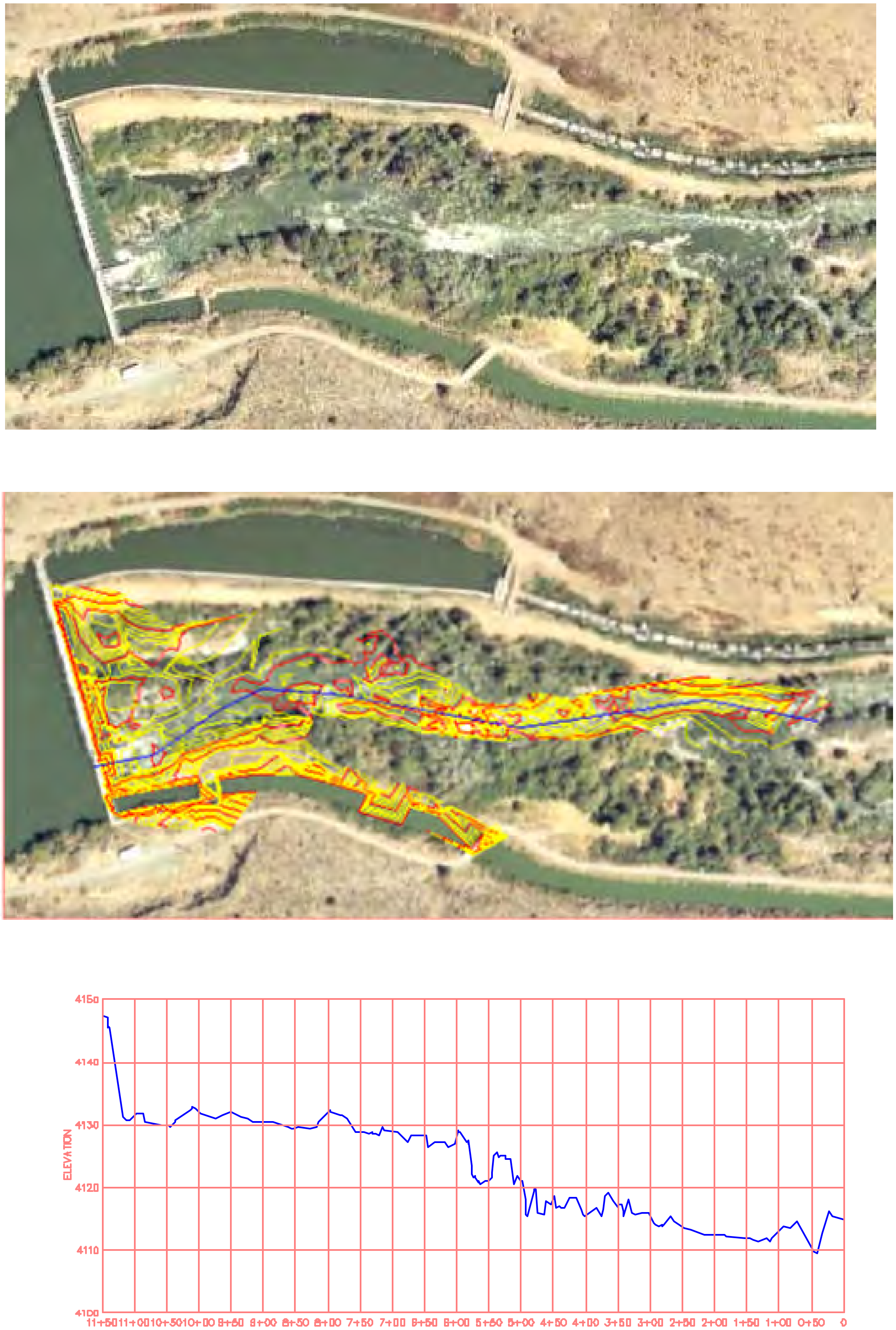


Figure 2 – Top, aerial photograph of Link River Dam and Falls. Middle, river bed topography developed from a field survey. Lower, longitudinal section along the river thalweg denoted in blue on the middle plot. Stationing increases upstream from the numerical model origin.

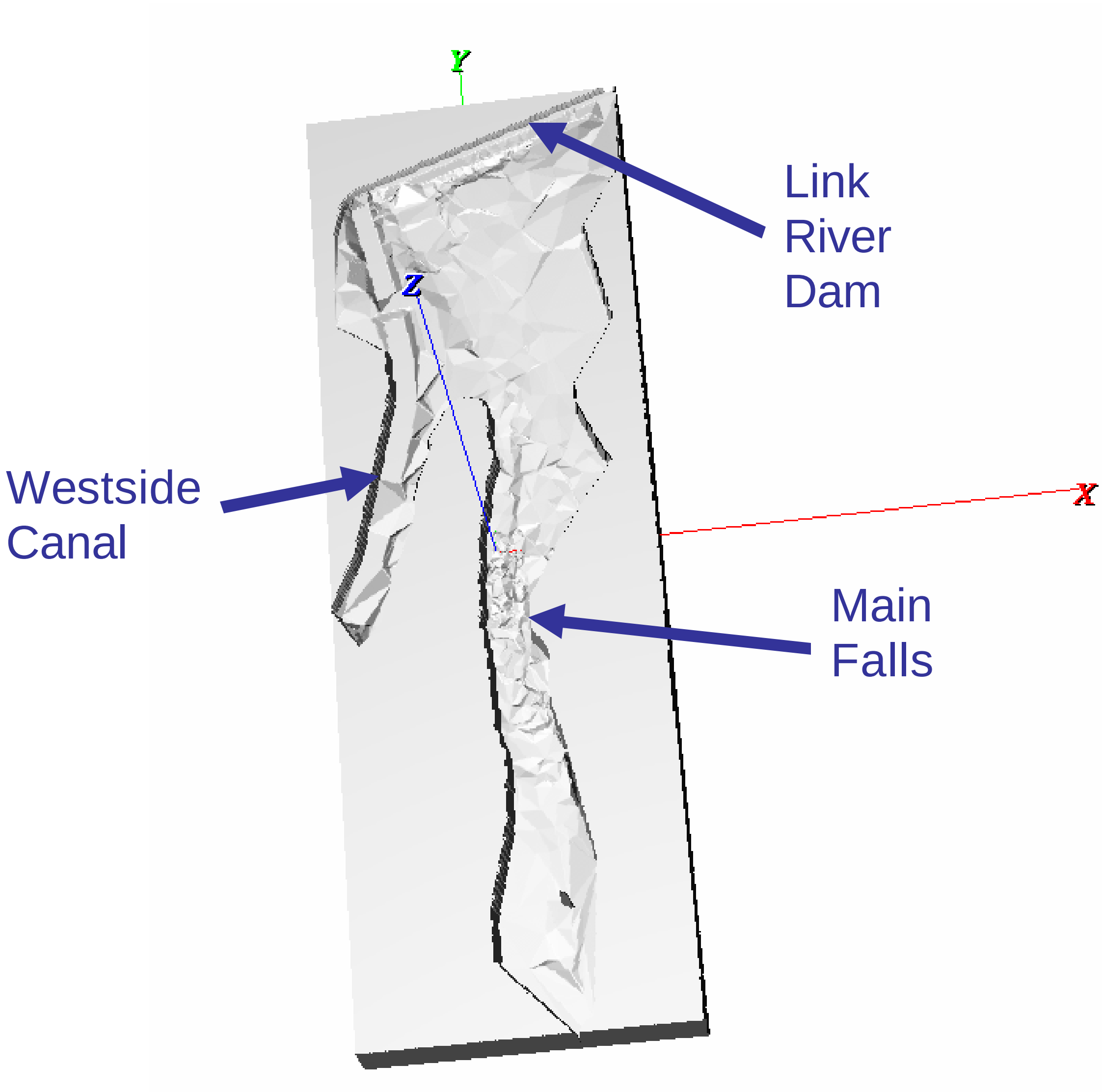


Figure 3 – Three-dimensional stereolithography model used for numerical modeling of the river channel.

Figure 4 – Numerical model physical boundaries. The area modeled using a single-mesh grid is shown in blue. The falls area modeled using a fine (nested) mesh is shown in yellow.

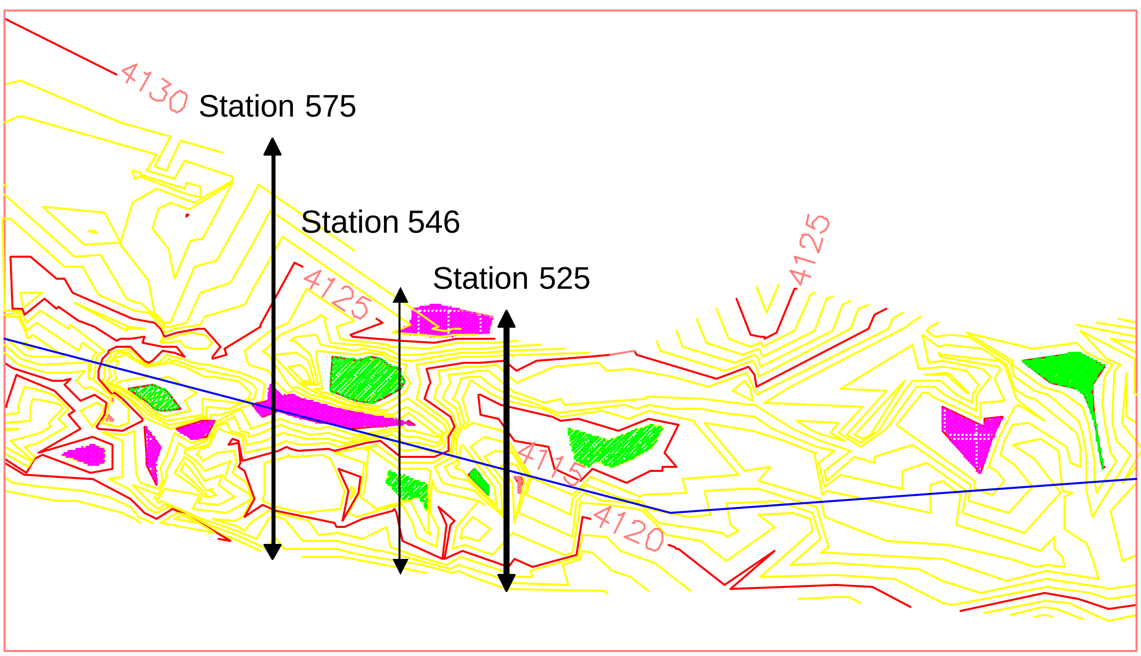


Figure 5 – Close up view of river topography in the main falls. The purple shaded areas indicate high points (large rocks or bed rock protrusions). The green shaded areas indicate low points that are scoured areas. The vertical lines indicate the location for which cross-sections are shown for model results.

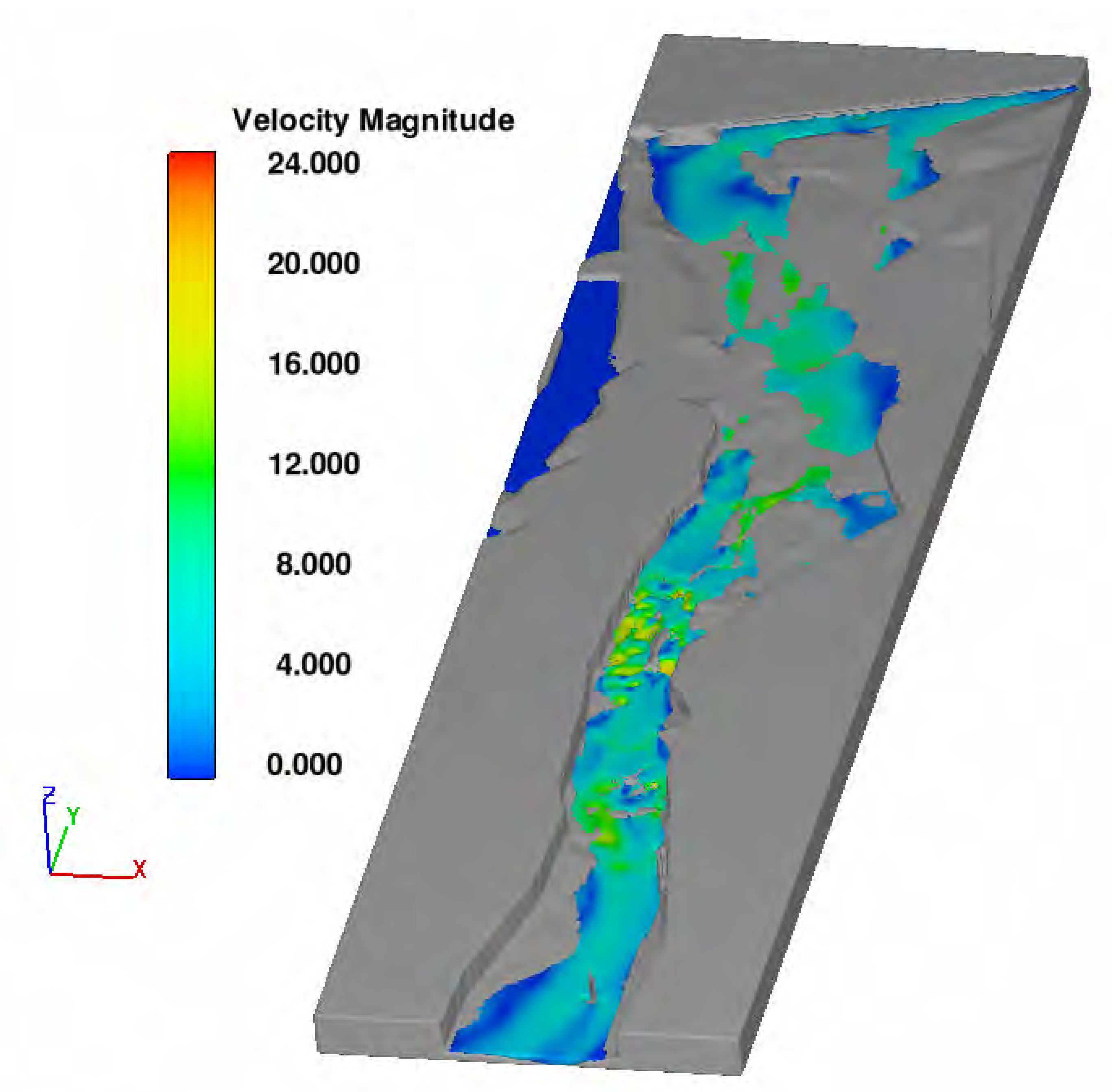


Figure 6 – Plan view of surface flow velocity for 1,000 ft^3/s river flow. Note, the plan view does not show flow where depths are small compared to the grid size. Therefore, some areas outside the main falls modeled using a coarse meshed grid do not represent model results. This problem was encountered with the display software only.

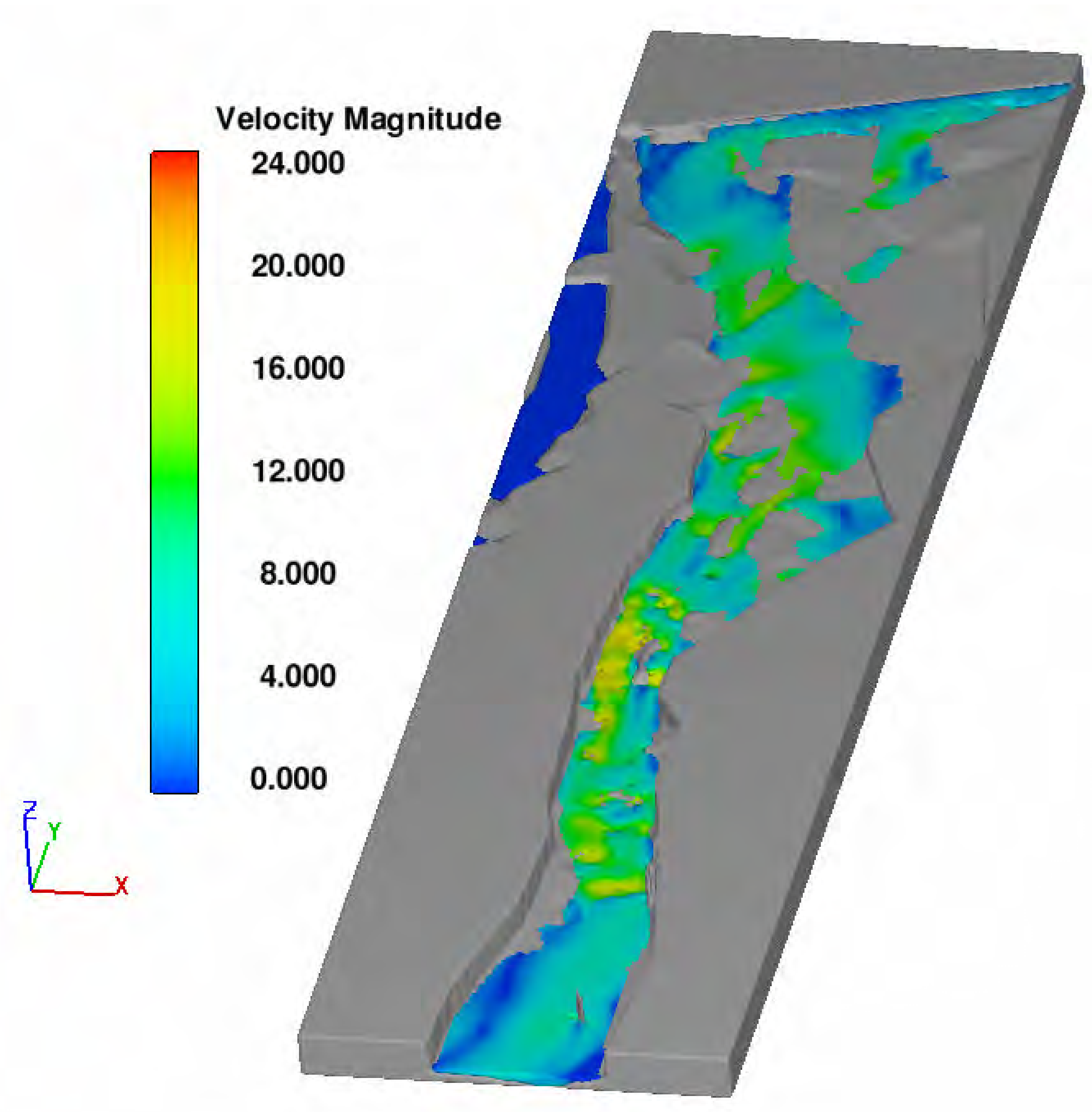


Figure 7 – Plan view of surface flow velocity for 2,000 ft^3/s river flow. Note, the plan view does not show flow where depths are small compared to the grid size. Therefore, some areas outside the main falls modeled using a coarse meshed grid do not represent model results. This problem was encountered with the display software only.

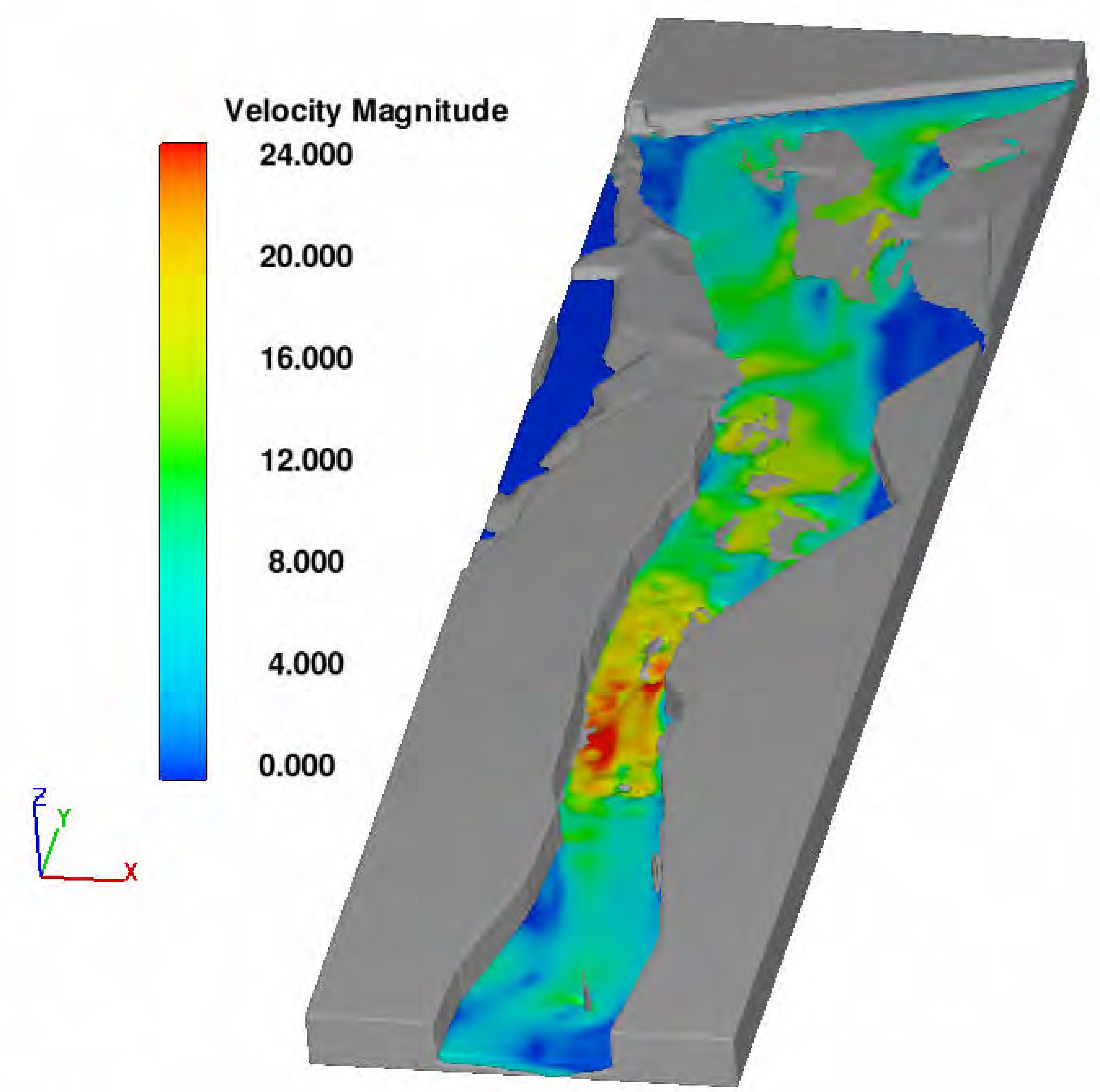


Figure 8 – Plan view of surface flow velocity for 3,000 ft^3/s river flow. Note, the plan view does not show flow where depths are small compared to the grid size. Therefore, some areas outside the main falls modeled using a coarse meshed grid do not represent model results. This problem was encountered with the display software only.

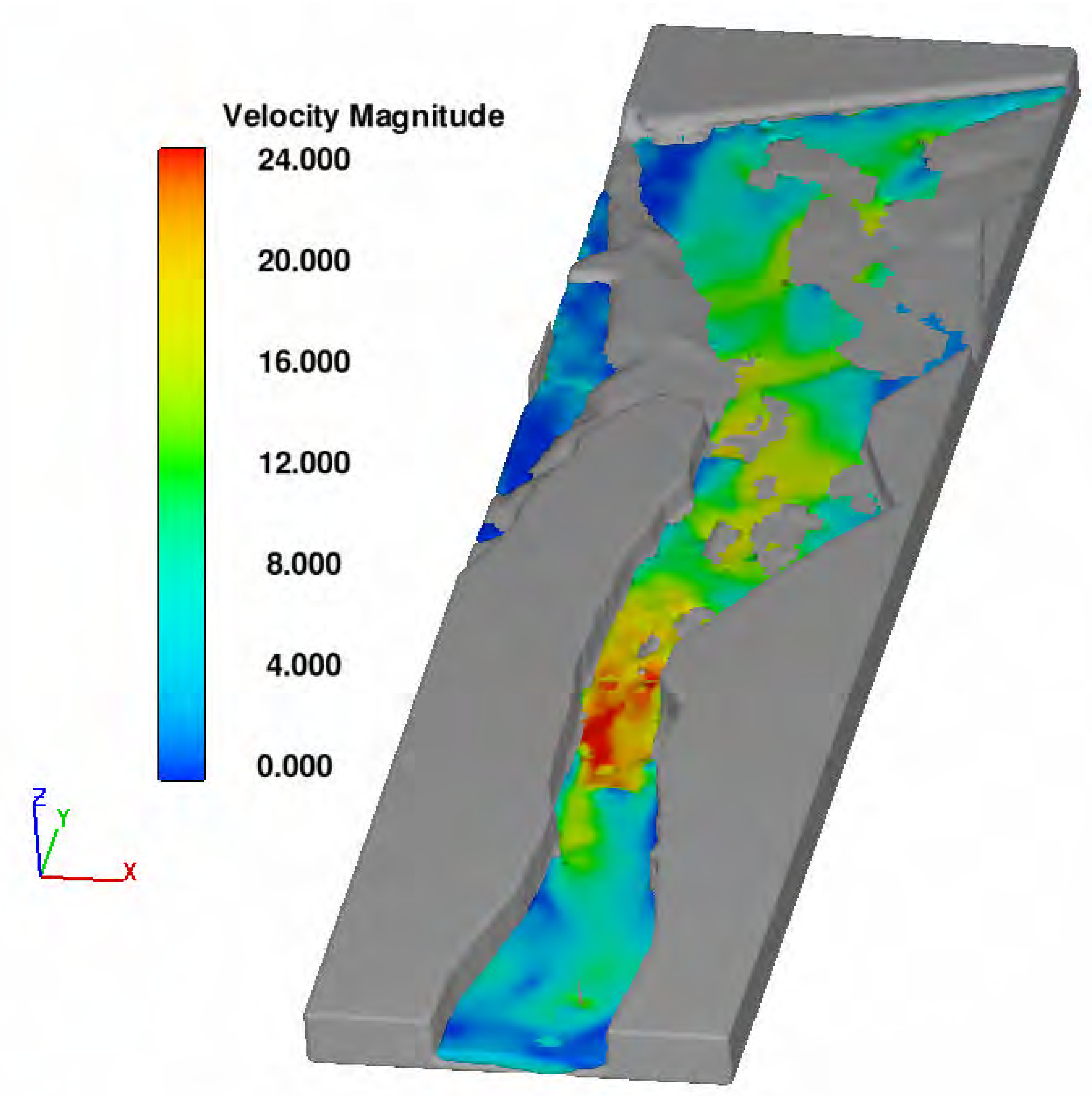


Figure 9 – Plan view of surface flow velocity for 4,000 ft^3/s river flow. Note, the plan view does not show flow where depths are small compared to the grid size. Therefore, some areas outside the main falls modeled using a coarse meshed grid do not represent model results. This problem was encountered with the display software only.

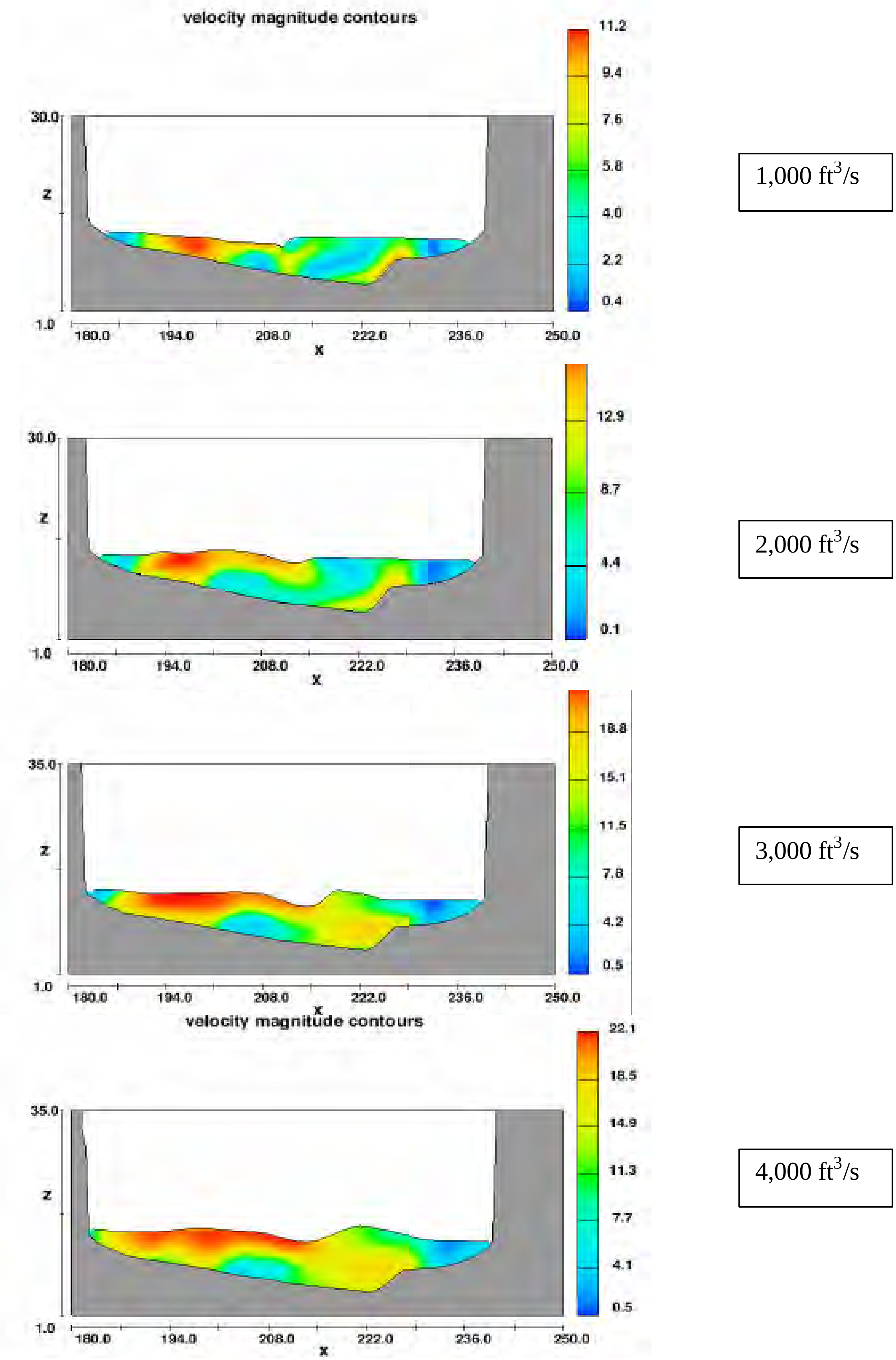


Figure 10 – View of flow velocity at Section 525 for river flows of 1,000 ft^3/s, 2,000 ft^3/s, 3,000 ft^3/s and 4,000 ft^3/s. These plots present flow velocities at the downstream end of the main falls. Note, color and velocity scales differ between plots.

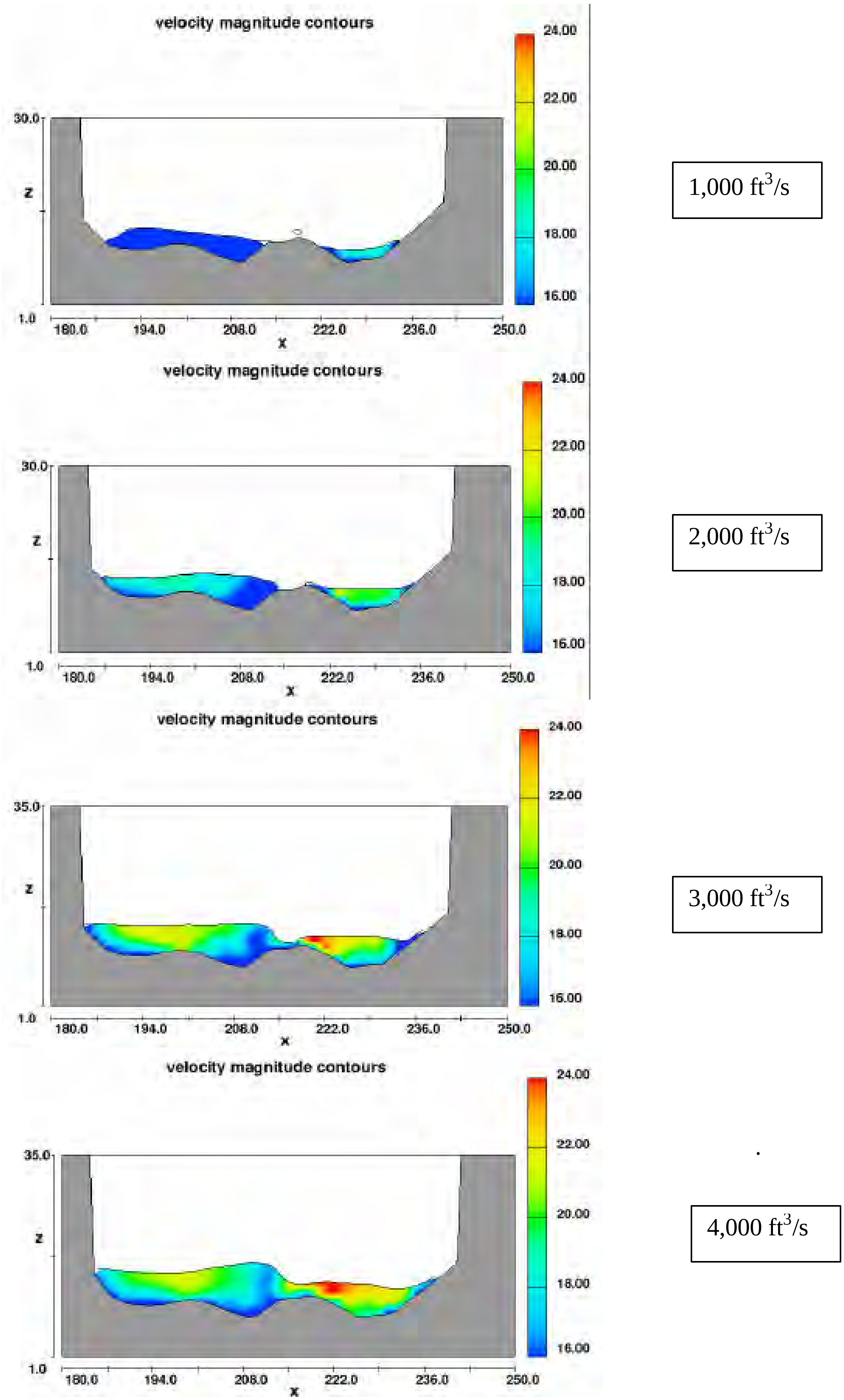


Figure 11 –View of flow velocity at Section 546 at flows of 1,000 ft^3/s, 2,000 ft^3/s, 3,000 ft^3/s and 4,000 ft^3/s. This section shows presents velocity at the toe of the largest single drop located adjacent to the east bank (right side of figures).

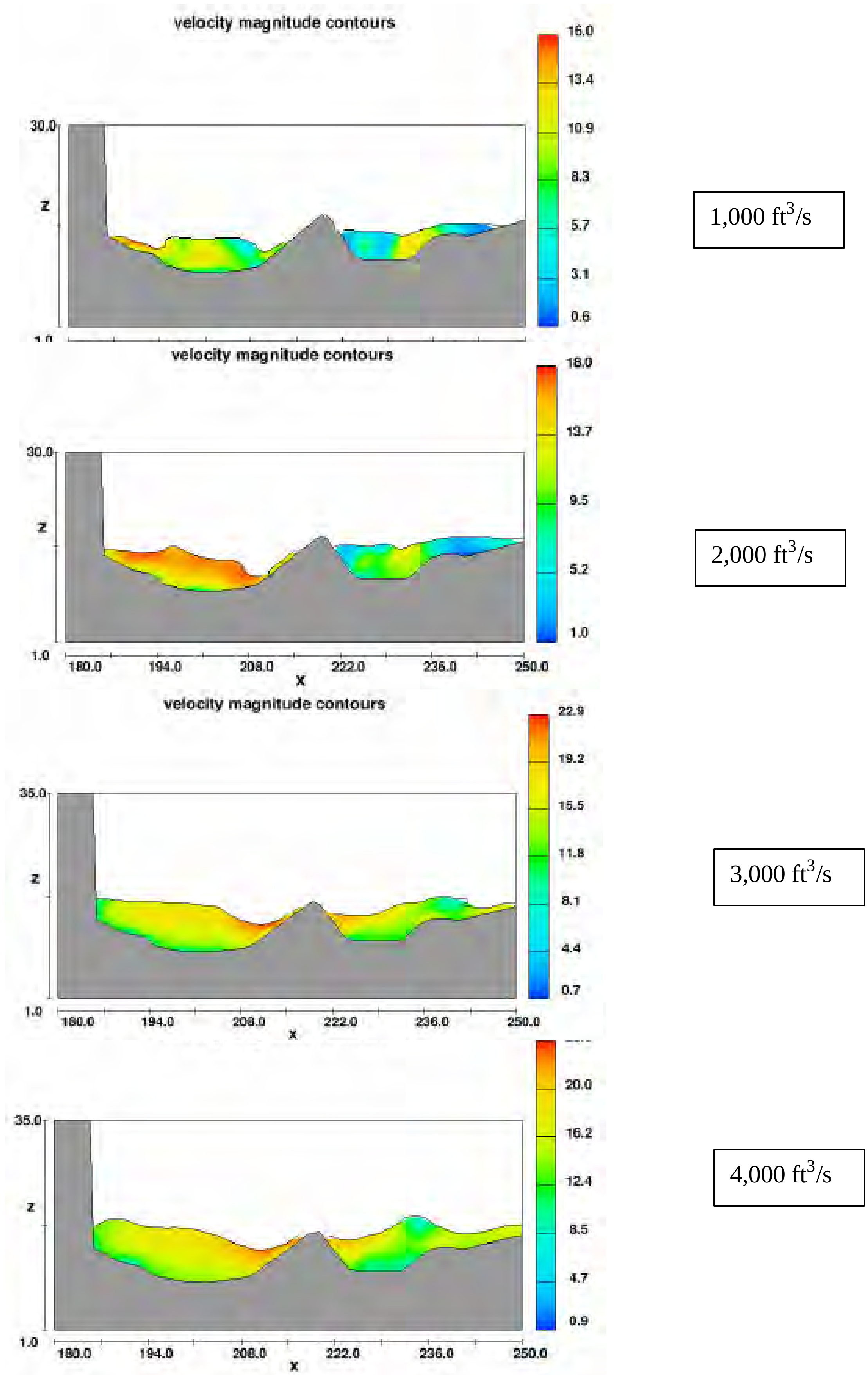


Figure 12 - View of flow velocity at Section 575 for river flows of 1,000 ft^3/s, 2,000 ft^3/s, 3,000 ft^3/s and 4,000 ft^3/s. These plots present flow velocities typical of conditions in the upstream end of the main falls. Note, color and velocity scales differ between plots.

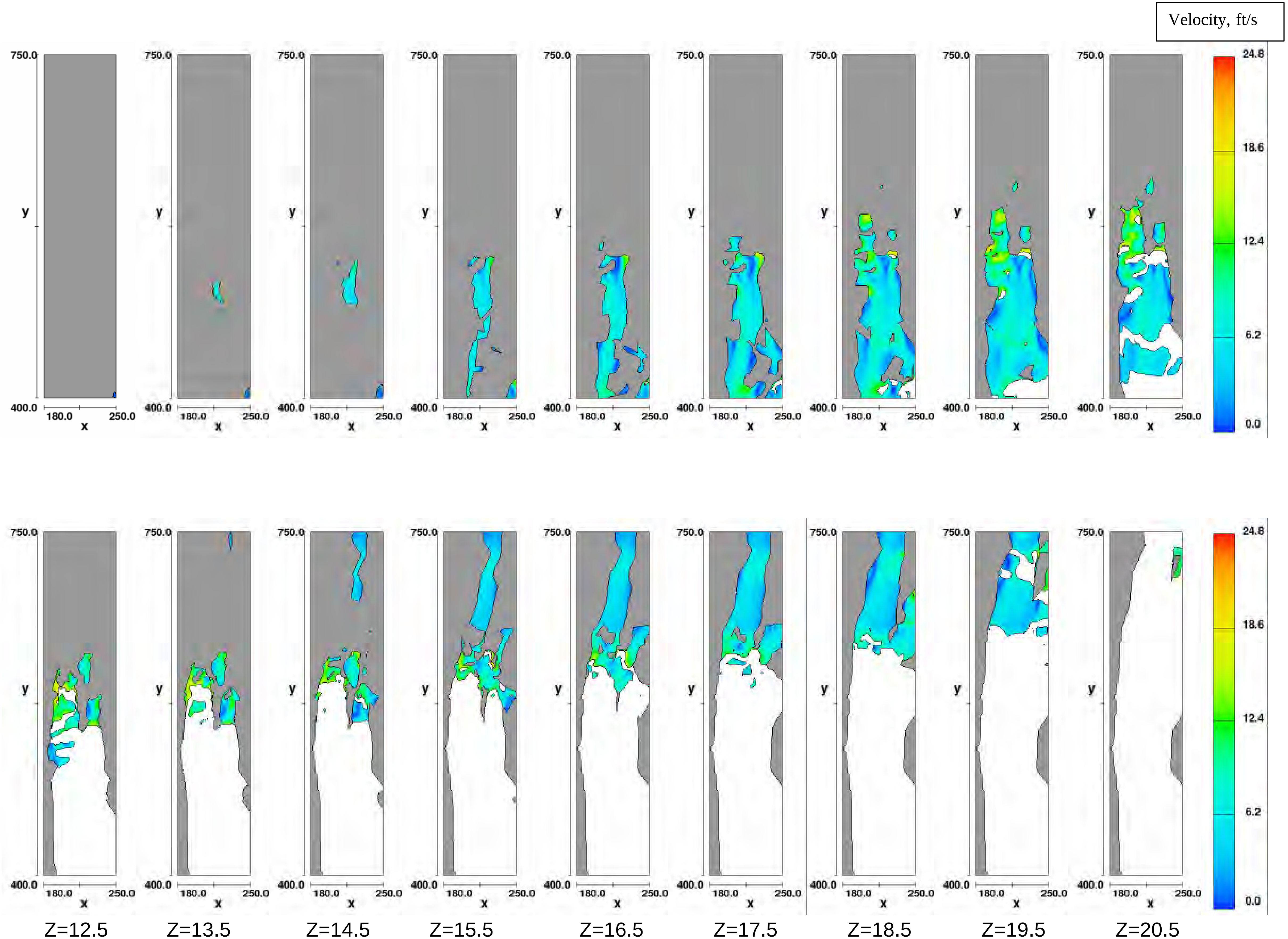


Figure 13 – Total flow velocities for 1,000 ft^3/s river flow simulation. The color contours are horizontal slices through the falls at elevation Z above the model datum.

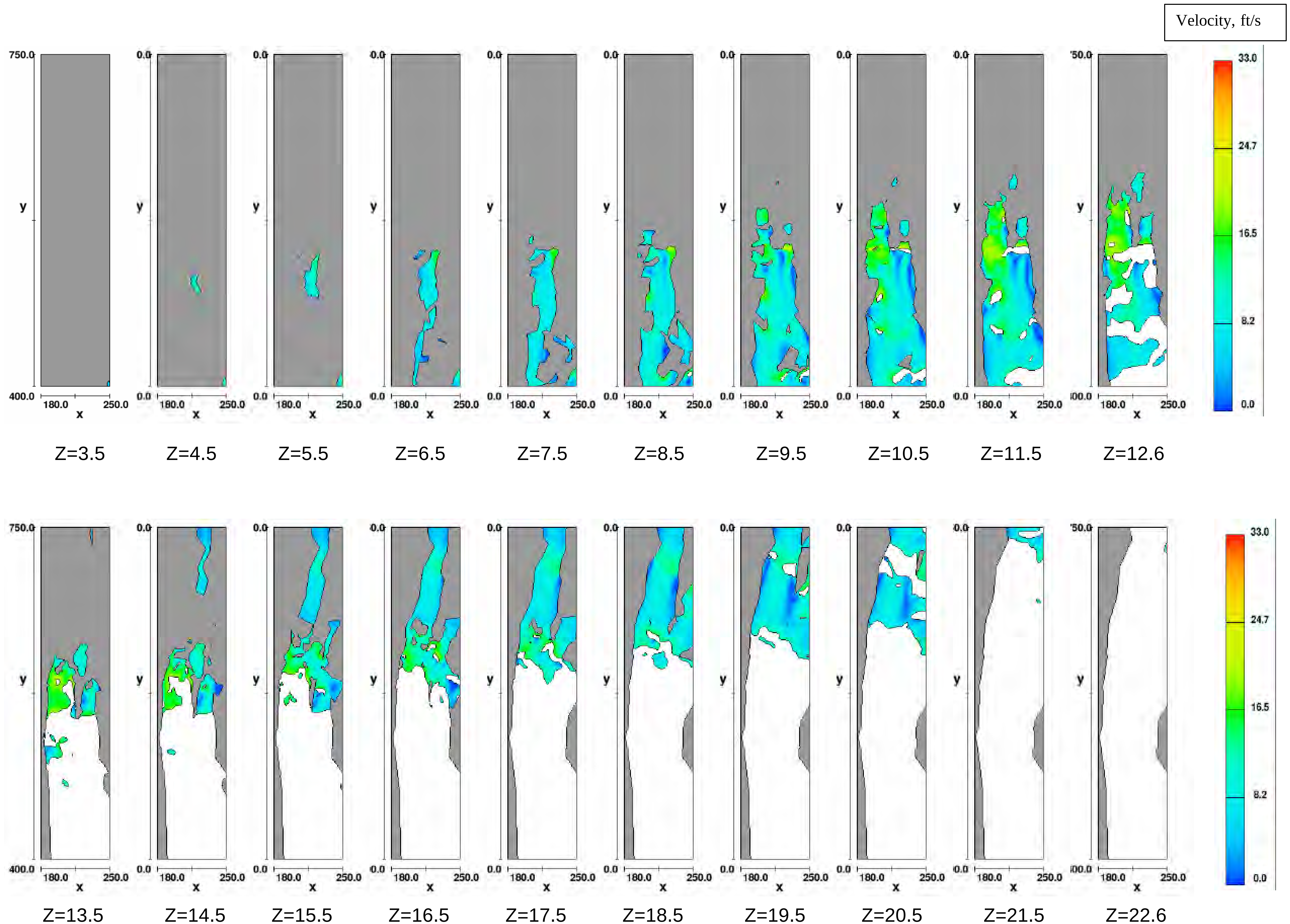


Figure 14 – Total flow velocities for 2,000 ft^3/s river flow simulation. The color contours are horizontal slices through the falls at elevation Z above the model datum.

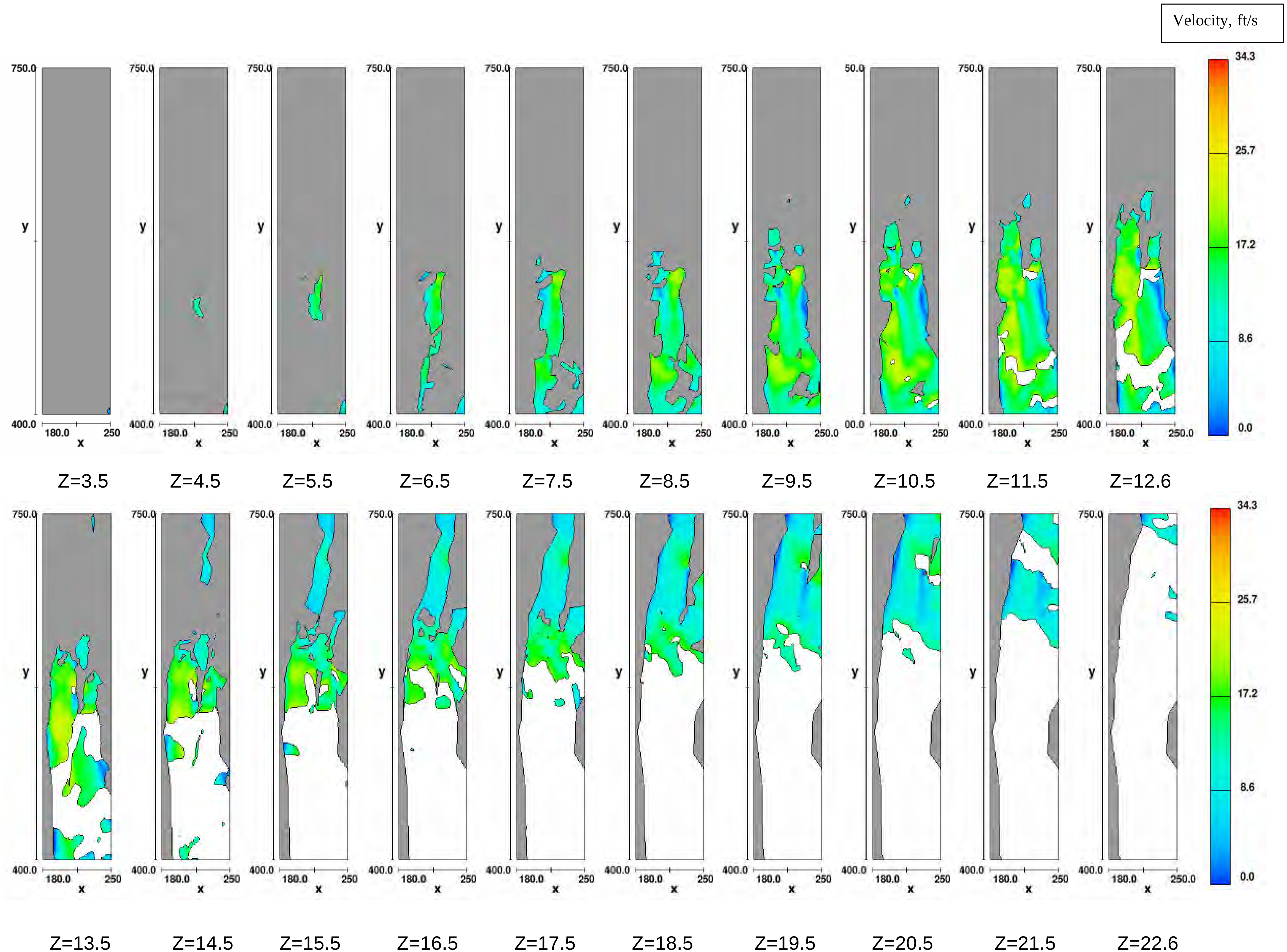


Figure 15 – Total flow velocities for 3,000 ft^3/s river flow simulation. The color contours are horizontal slices through the falls at elevation Z above the model datum.

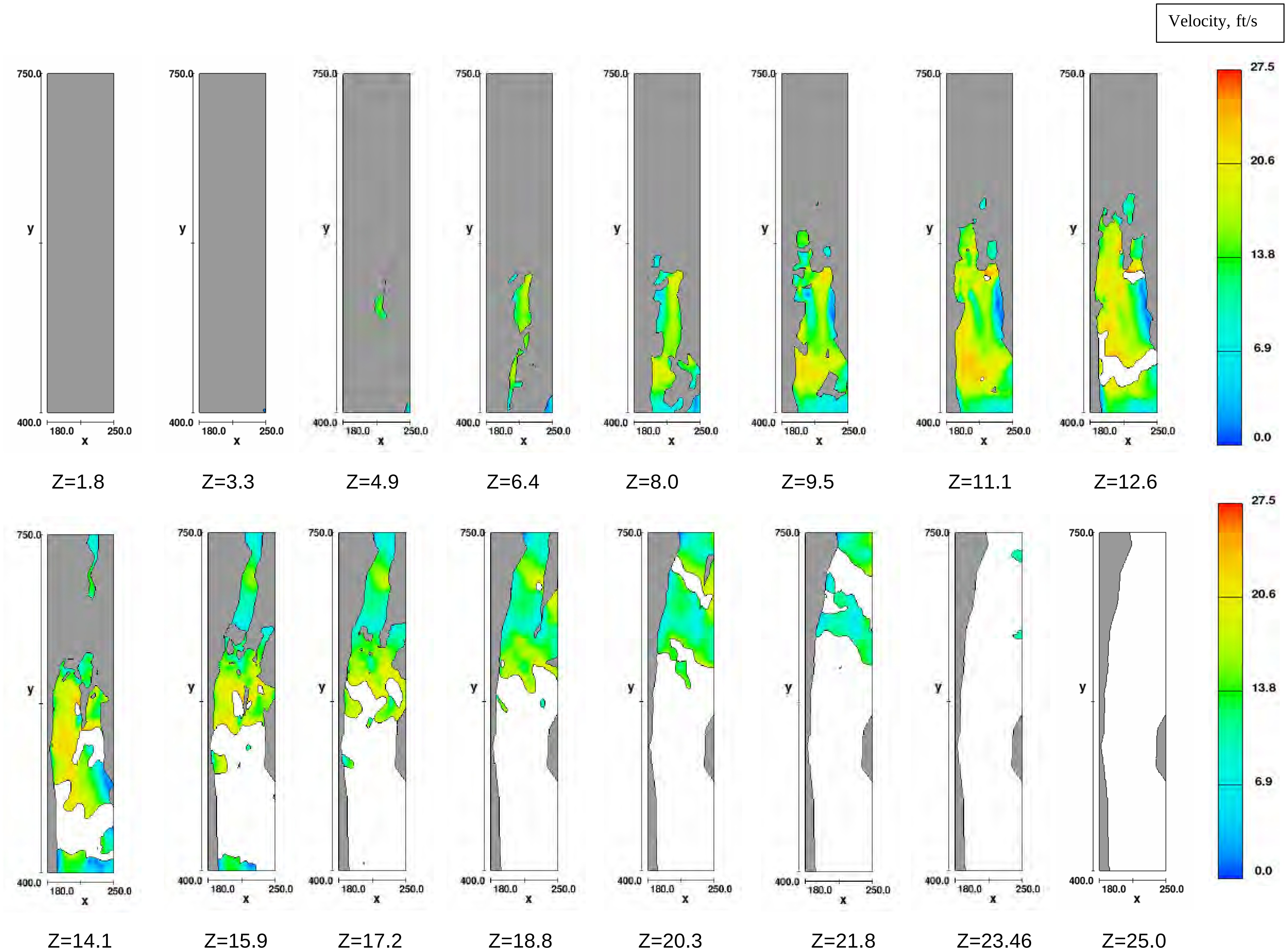


Figure 16 – Total flow velocities for 4,000 ft^3/s river flow simulation. The color contours are horizontal slices through the falls at elevation Z above the model datum.

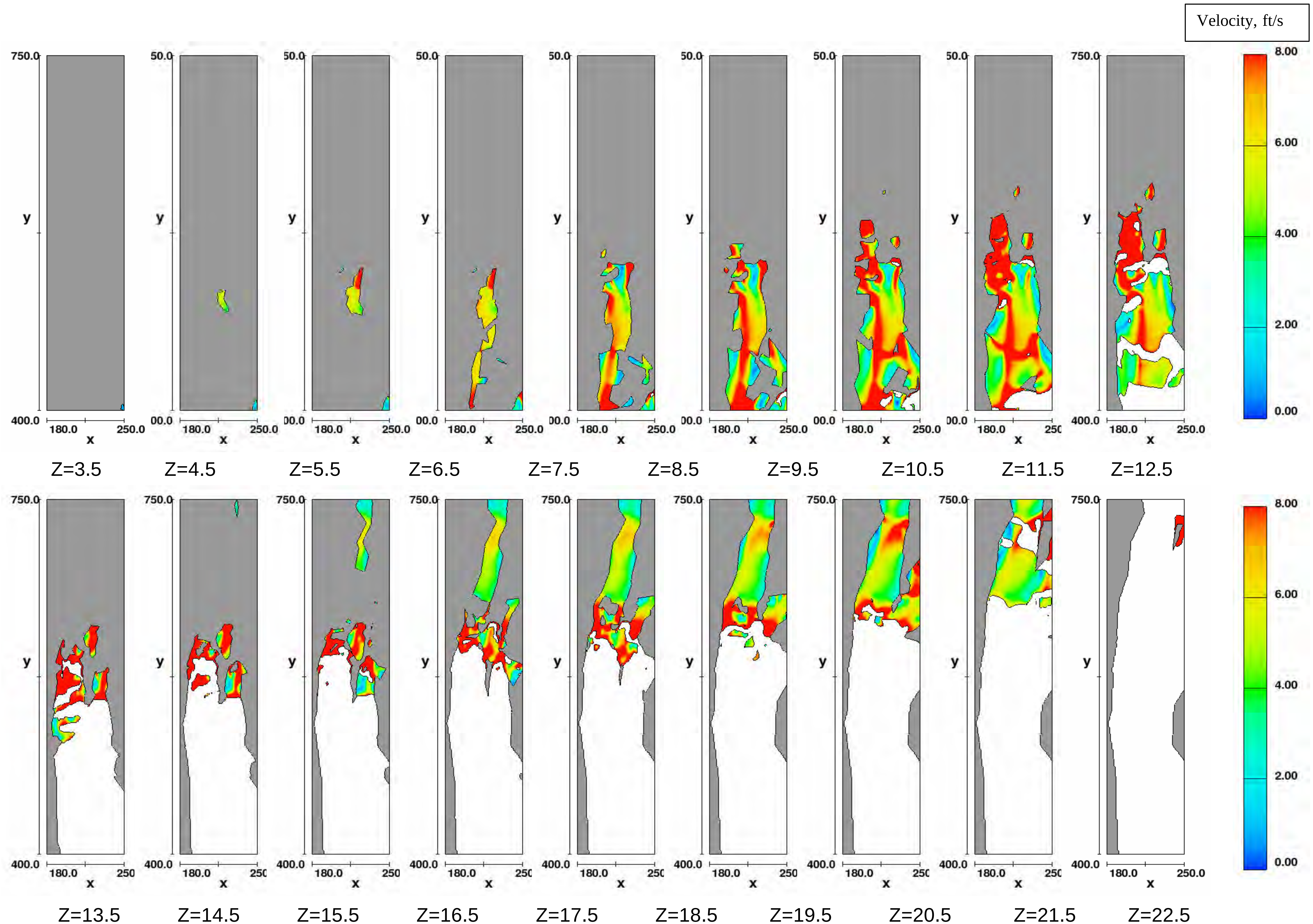


Figure 17 – Total flow velocities for 1,000 ft^3/s river flow simulation with all velocities > 8 ft/s shown in red. The color contours are horizontal slices through the falls at elevation Z above the model datum.

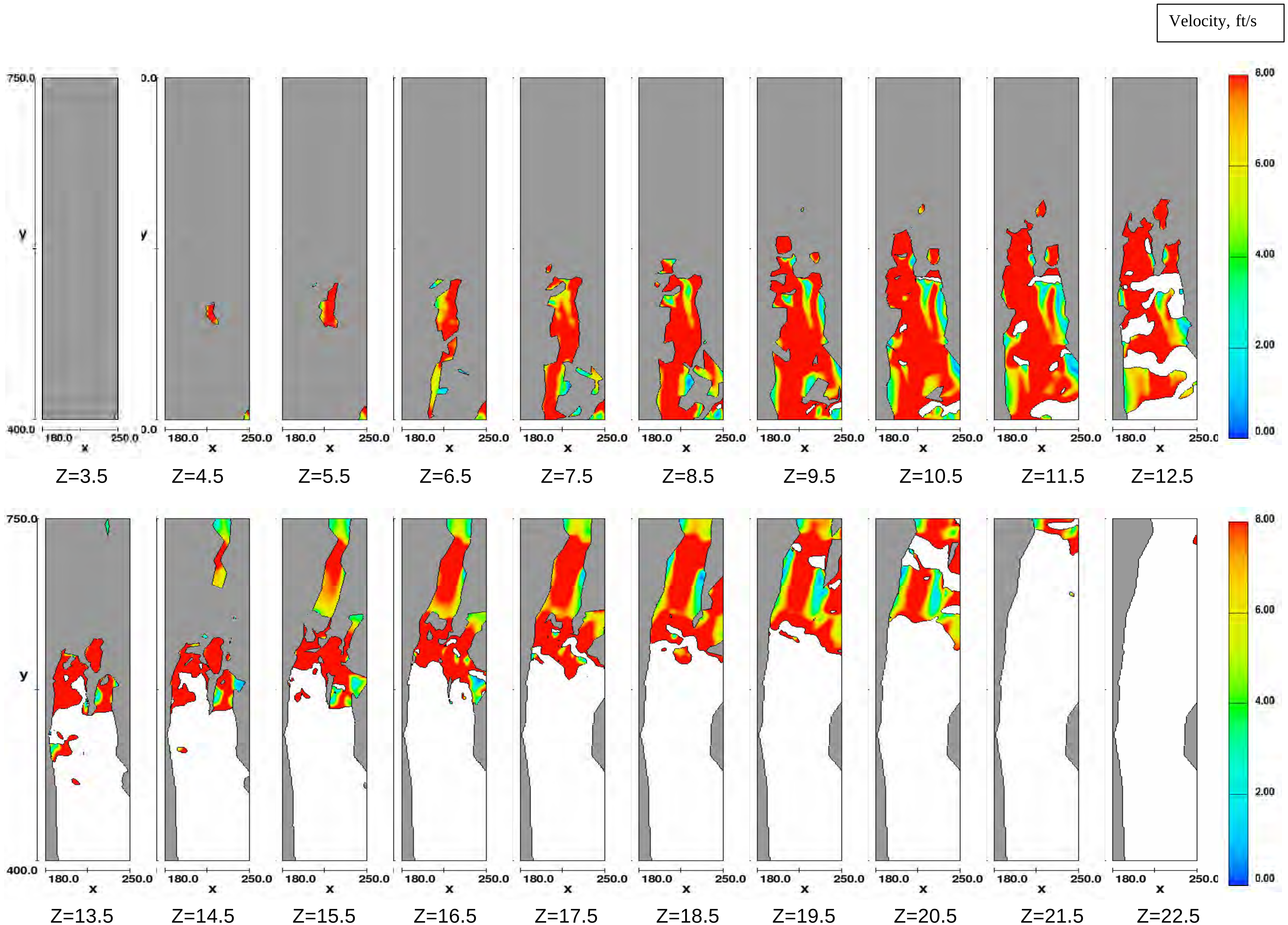


Figure 18 – Total flow velocities for 2,000 ft^3/s river flow simulation with all velocities > 8 ft/s shown in red. The color contours are horizontal slices through the falls at elevation Z above the model datum.

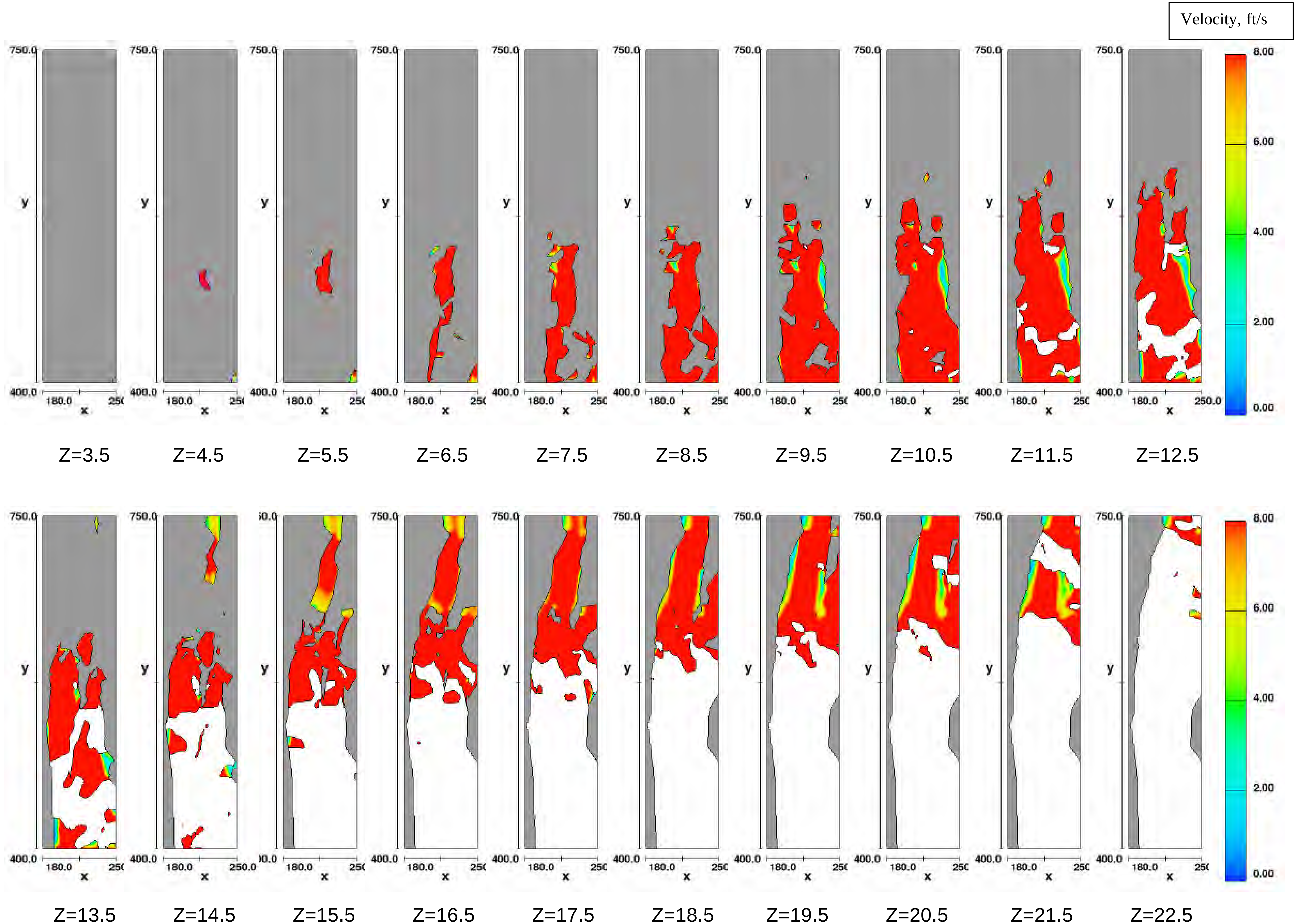


Figure 19 – Total flow velocities for 3,000 ft^3/s river flow simulation with all velocities > 8 ft/s shown in red. The color contours are horizontal slices through the falls at elevation Z above the model datum.

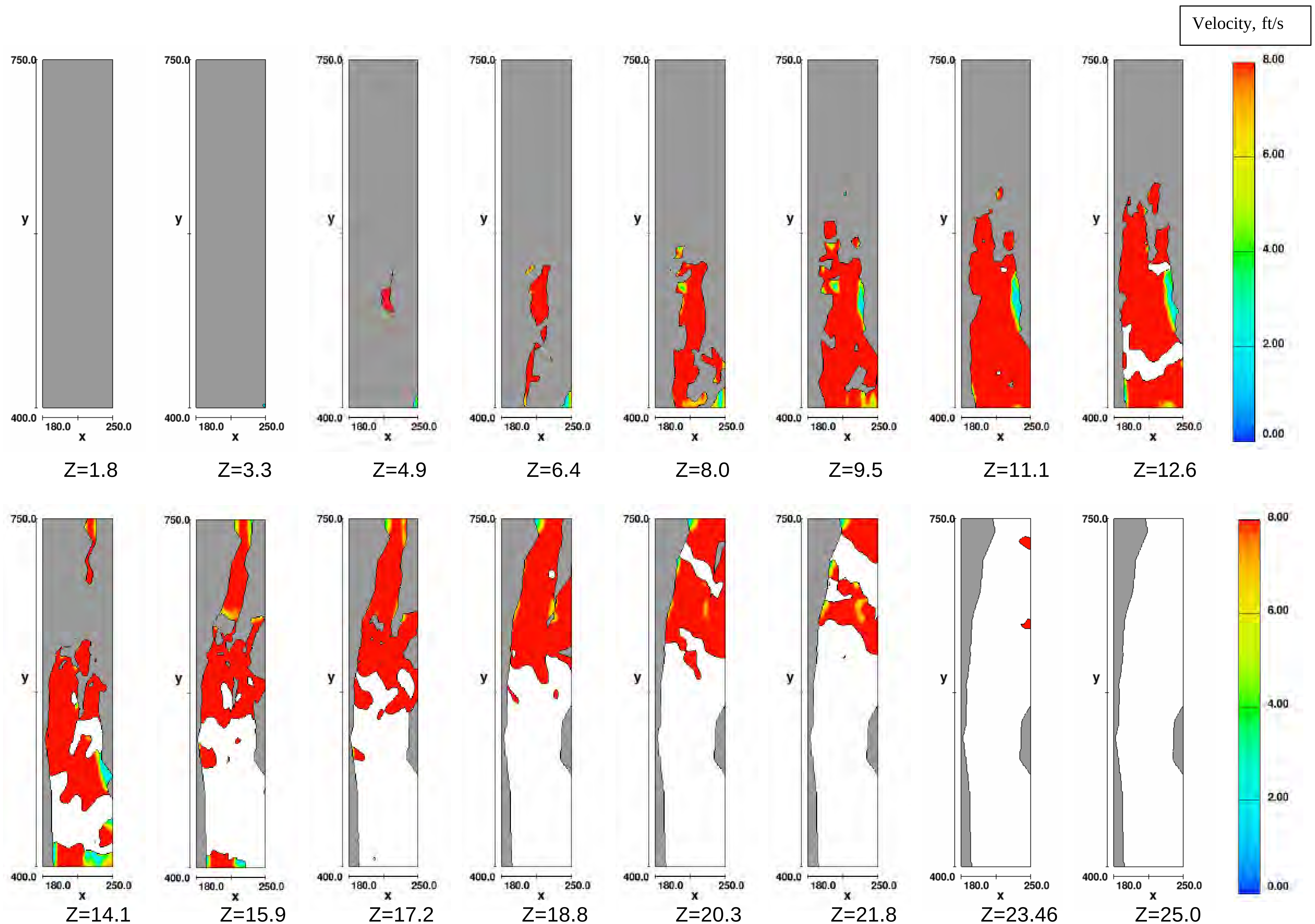


Figure 20 – Total flow velocities for 4,000 ft^3/s river flow simulation with all velocities > 8 ft/s shown in red. The color contours are horizontal slices through the falls at elevation Z above the model datum.