Two-and three-dimensional hydraulic modeling of innovative grade control structures project at Millbrook Exchange Park

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Introduction

Monitoring of the innovative grade control project at Millbrook Exchange Park indicated a substantially lower aggradation rate than originally anticipated (Doll et. al., 2020). In addition, some of the structures have failed (flow has cut around the structure arms, other structures have partially collapsed) and future failures appear to be a concern. The hydraulic model HEC-RAS 2D (V. 6.0) (USACE, 2020) was used to model the existing condition to identify vulnerable areas and components of the existing grade control structures and adjacent channel banks that need to be stabilized/retrofitted. Because two-dimensional hydraulic models calculate a depth-averaged velocity there are limitations when it comes to simulating recirculation and turbulence at structures. Therefore FLOW-3D® HYDRO (V. 1.0) (Flow Science, 2020), a three-dimensional hydraulic model was used to simulate the hydraulics at the structures in greater detail.

Model Input

HEC-RAS 2D version 6.0 was used to model the existing channel and structures. HEC-RAS 2D is a widely used two-dimensional hydraulic model that uses a Finite Volume Method approach. The as-built survey was used for the channel geometry and structure elevations and configuration were surveyed on 8-6-2020. A computational mesh spacing of 1 foot was used for the channel and overbank areas (Figure 1). The mesh was refined to a spacing of 0.25 feet surrounding the boulder structures (Figure 2). There was a total of 90,709 grid cells in the model. Manning n value was set to 0.035 for the channel and 0.06 for the overbank areas. The upstream boundary condition was set as an inflow hydrograph with constant flow and the downstream boundary condition was set at normal depth with a slope of 0.015 ft/ft measured from the topography.

The FLOW-3D® HYDRO mesh was set to 0.5 foot horizontal and vertical spacing for a total of 160,000 elements. The upstream boundary condition was set to constant inflow and the downstream boundary was based on the water level from the HEC-RAS 2D model output.

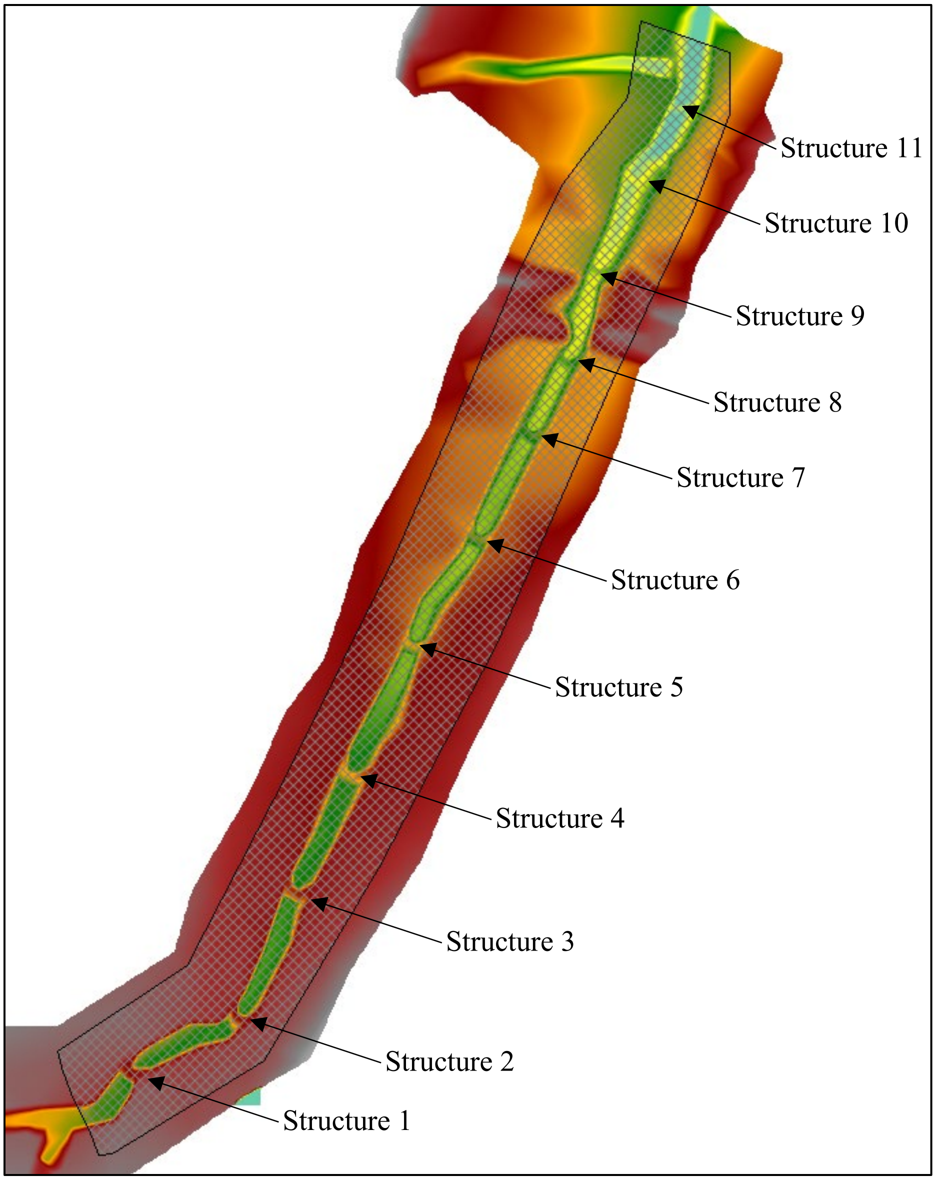

Figure 1. HEC-RAS 2D model mesh.

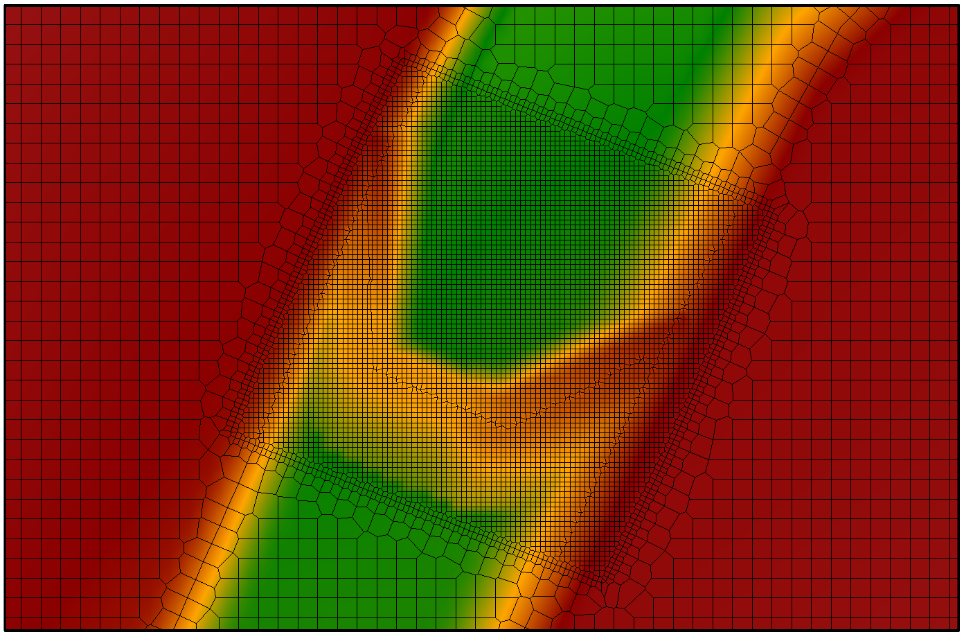

Figure 2. Refined mesh at boulder structure.

Model Scenarios

HEC-RAS 2D was run for discharges corresponding to the 1, 2, 5, 25 and 100 year storm events defined in the Basis of Design report (Table 1).

Table 1. Modeled Discharge Scenarios.

Storm Event	Discharge
1-year	30 cfs
2 year	60 cfs
5 year	107 cfs
25 year	200 cfs
100 year	300 cfs

Results and Discussion

Observed Storms

From March, 2019 and December, 2020 there were 10 events that exceeded the peak discharge of the 1 year storm. No event exceeded the discharge for the 5-yr storm during the monitoring period (Table 2).

Table 2. Discharge events during monitoring period.

Peak Flow (cfs)	Approximate Return Period	Number of Events
27-35	1-year	5
38-45	1- to 2-year	3
55	2-year	1
85	2- to 5-year	1

Modeling Discharge in the Range of Observed Storm Events

The velocity distributions for the 1-, 2-, and 5-year events are shown in Figure 3 through Figure 5. For the 1-year event the stream velocity in the channel was mostly below 2 ft/s, with the exception of areas at and just downstream of the boulder structures. The channel velocity increased to around 3-5 ft/s in the lower end of the project reach as the channel slope is much steeper in this area.

The 2- and 5-yr velocity distributions also show a similar pattern with higher velocity at and just downstream of the structures and low to moderate velocity in the upper half of the reach. The velocity increased in the lower half of the project reach, exceeding 10 ft/s for the 5-yr storm (Figure 6 and Figure 7).

Three-dimensional modeling showed that the change in elevation downstream of each structure created recirculating, turbulent flow paths (Figure 8). These results suggest that even where low depth-averaged velocity is indicated downstream of structures, hydraulic conditions that would prevent sediment accumulation may still occur.

Model output seems to explain how higher velocity and flow recirculation downstream of the structures results in the observed substantial scour at these locations. Similarly, deposition on the upstream side of the structures correspond to the drop in velocity and turbulence. Very high velocities (>~7-8 ft/s) in the lower part of the reach appears to be the cause of the substantial streambed erosion (3+ feet in some areas).

The modeling results indicate that deposition will not occur on the downstream side of the structures due to high velocity and flow recirculation; the footer boulder and structure arms will not be secured in place by sediment deposition as planned for in the initial design. The model results also indicate that for the 5-yr event flow is completely confined to the channel. The lack of floodplain-channel connection prevents energy dissipation and further exacerbates the high velocity and shear stress in the channel and around the structures.

While armoring the downstream side of the structures would prevent further streambed scour and undermining of the boulder structures, this approach would not, however, alter the hydraulics around the structures. Flow cutting around the structures and potential failure (which has already occurred on one of the structures) would remain a major concern, especially considering the project has not yet to be subjected to flow in excess the 5-yr discharge.

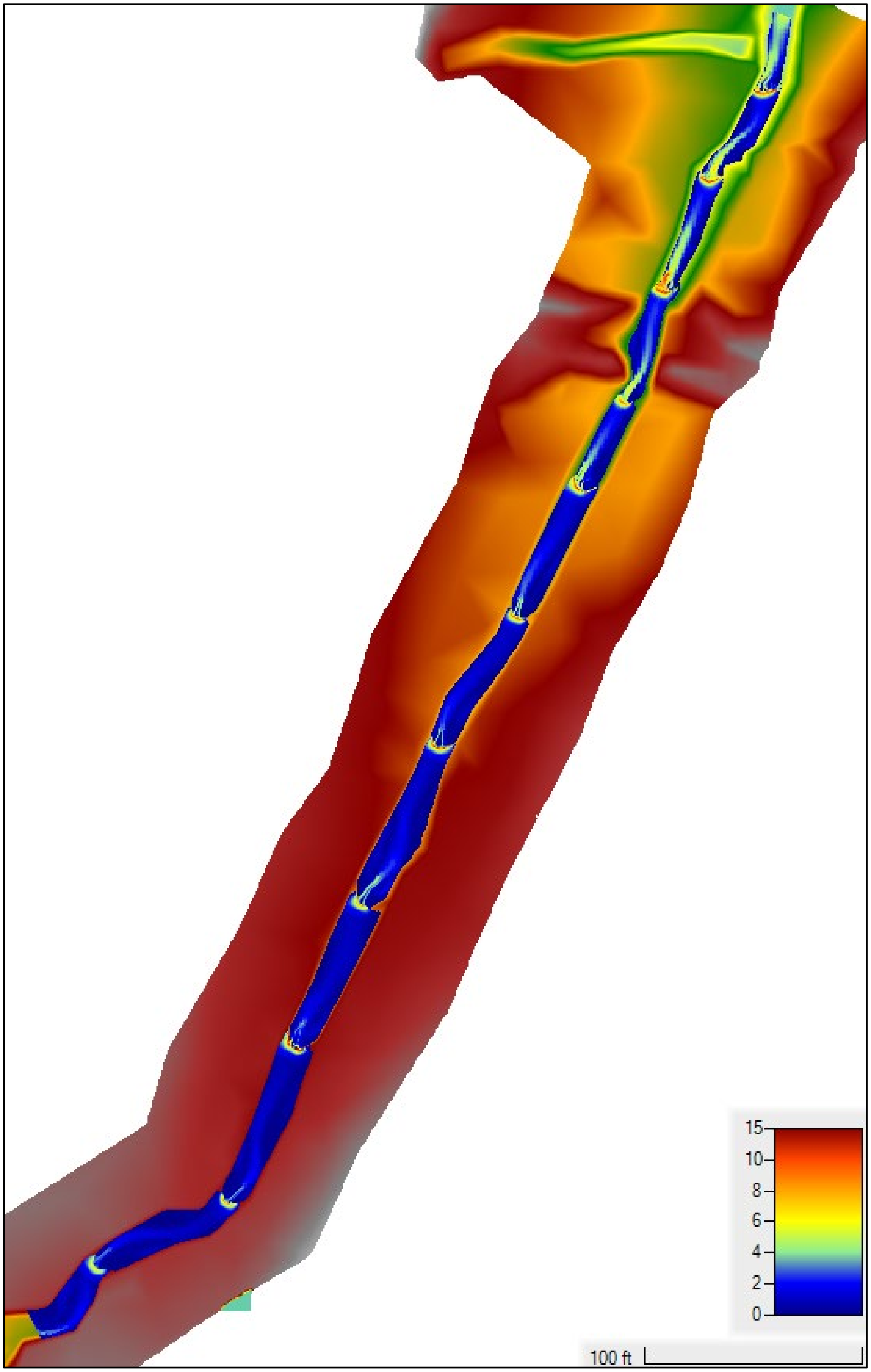

Figure 3. Quasi steady-state maximum velocity for the 1-yr event.

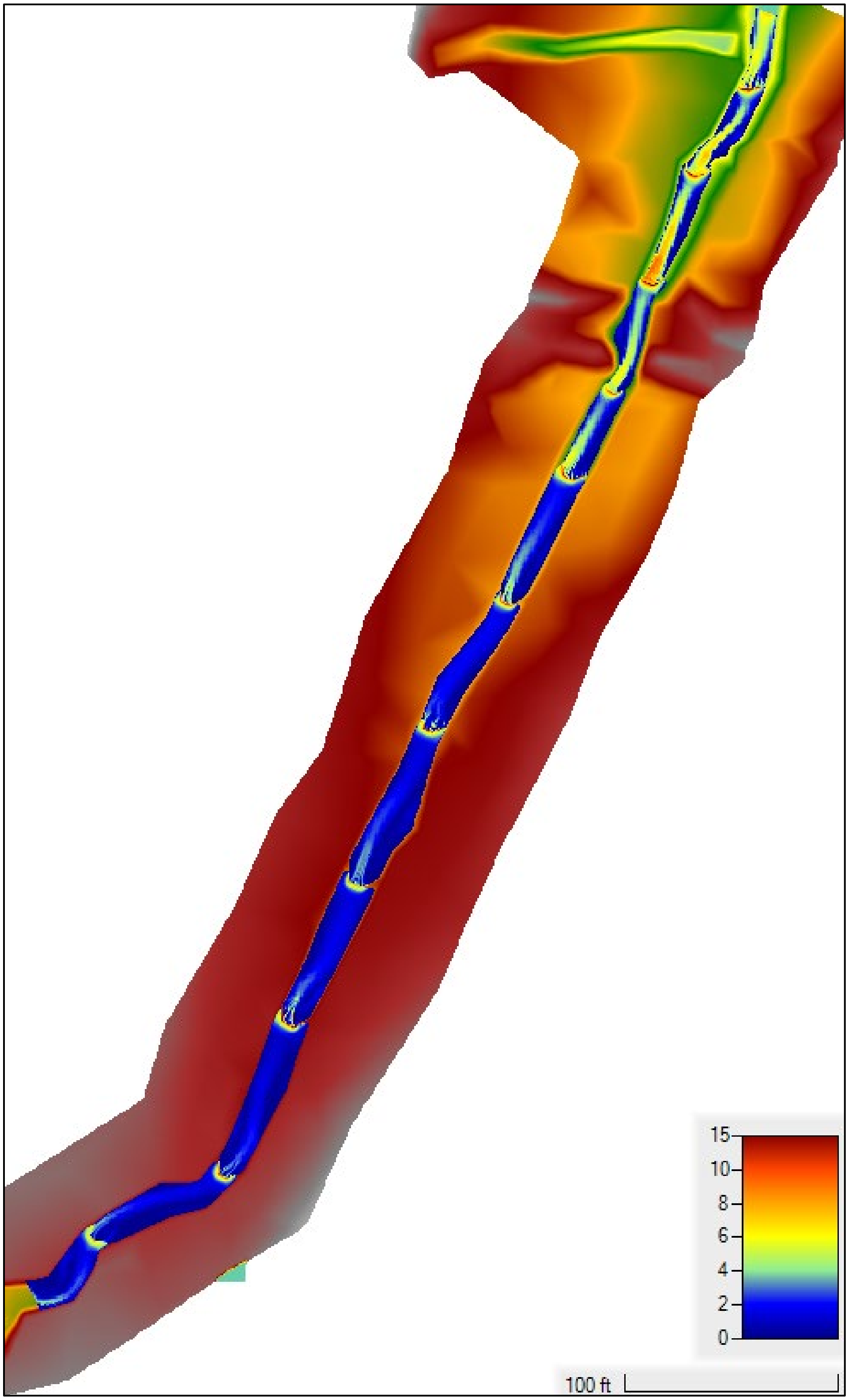

Figure 4. Quasi steady-state maximum velocity for the 2-yr event.

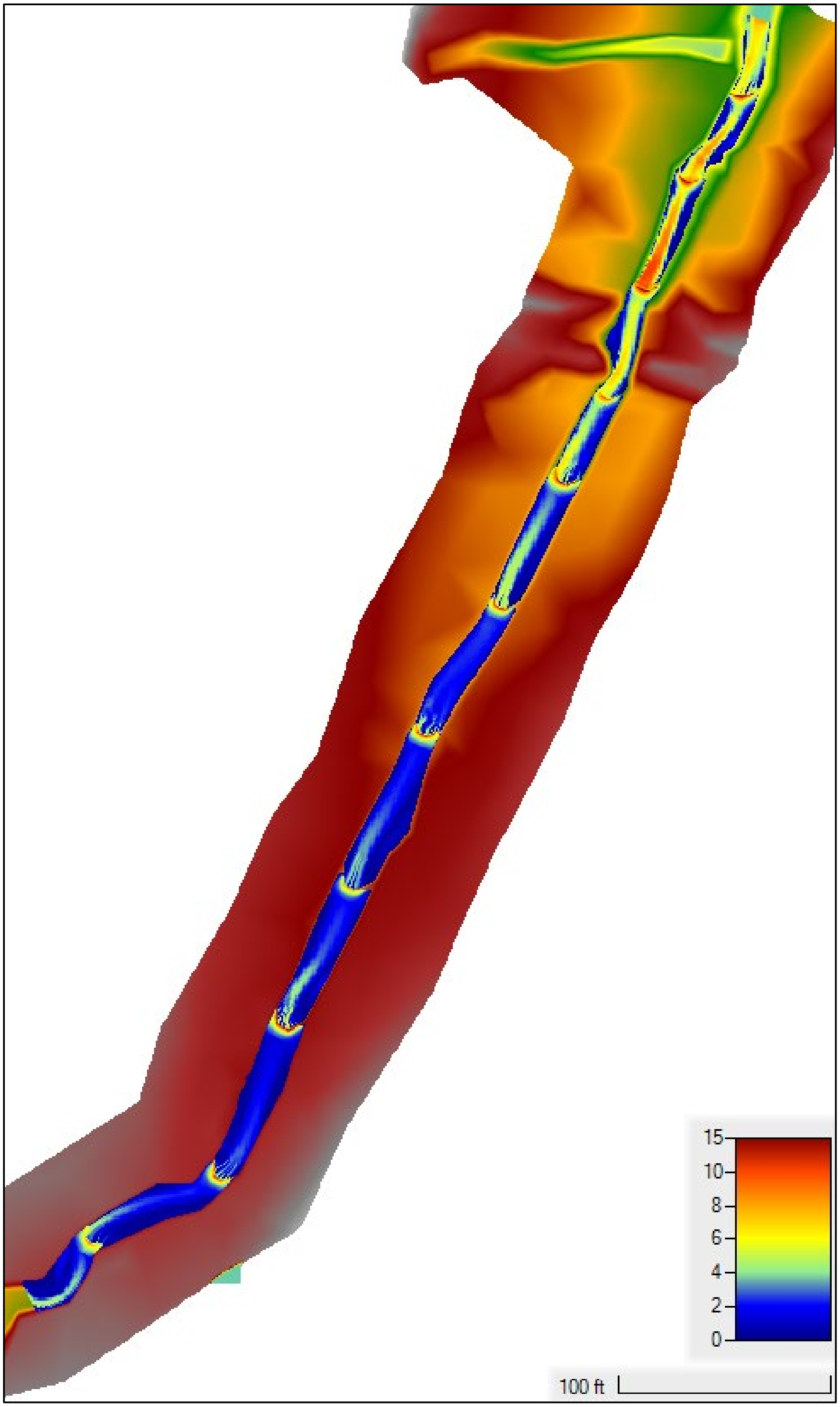

Figure 5. Quasi steady-state maximum velocity for the 5-yr event.

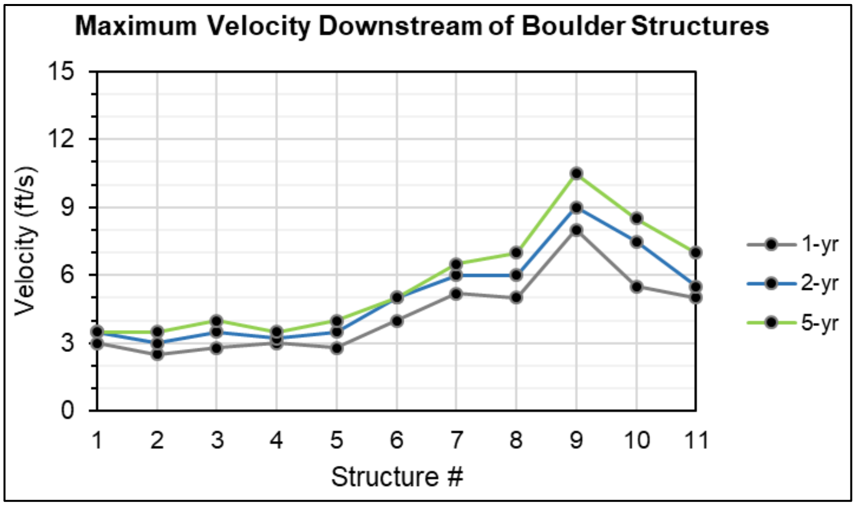

Figure 6. Quasi steady-state maximum velocity downstream of boulder structures.

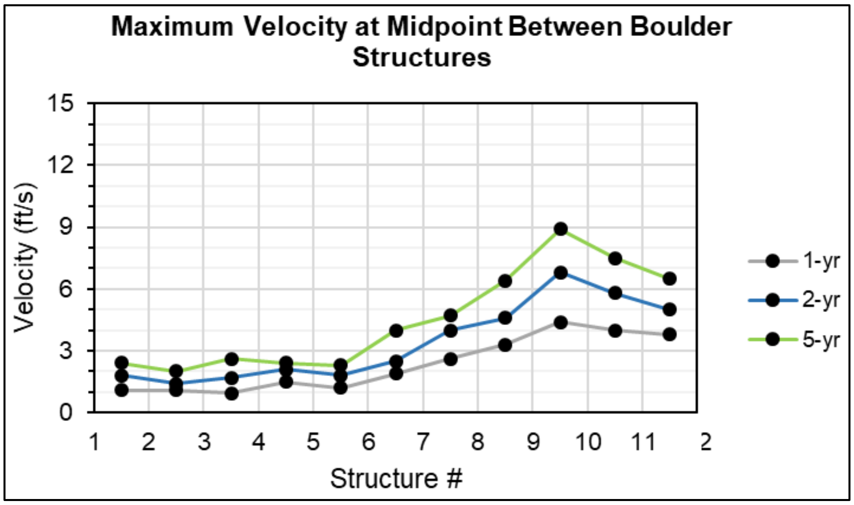

Figure 7. Quasi steady-state maximum velocity at midpoint between boulder structures.

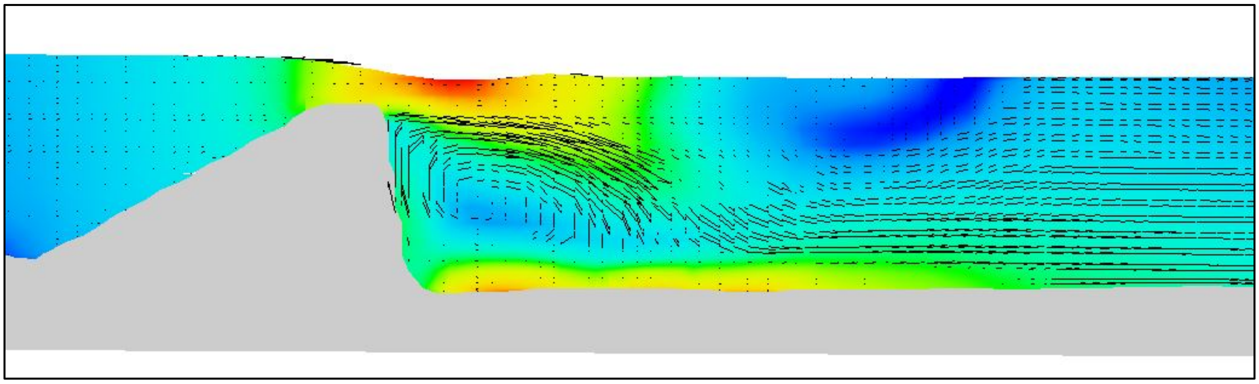

Figure 8. Quasi steady-state maximum velocity profile at structure 1 for the 2-yr discharge.

Simulating Larger Storm Events

While repeated sub-5-year peak discharge events caused several failures of the boulder structures and substantial erosion on the downstream side of the structures, particularly in the lower end of the project, model results indicate that larger storms pose an even greater risk. For events in excess of the 25-yr storm, the streamflow will be confined to the channel (Figure 9). The 100-yr event peak discharge will produce very limited overbank flow (depth < 0.3 ft.) in the upper half of the project reach, but the flow will remain confined to the channel for the lower half of the project reach (Figure 10). This lack of floodplain connection and confinement of flow to the channel will result in even higher velocity and shear that will further stress the structures and channel (Figure 11).

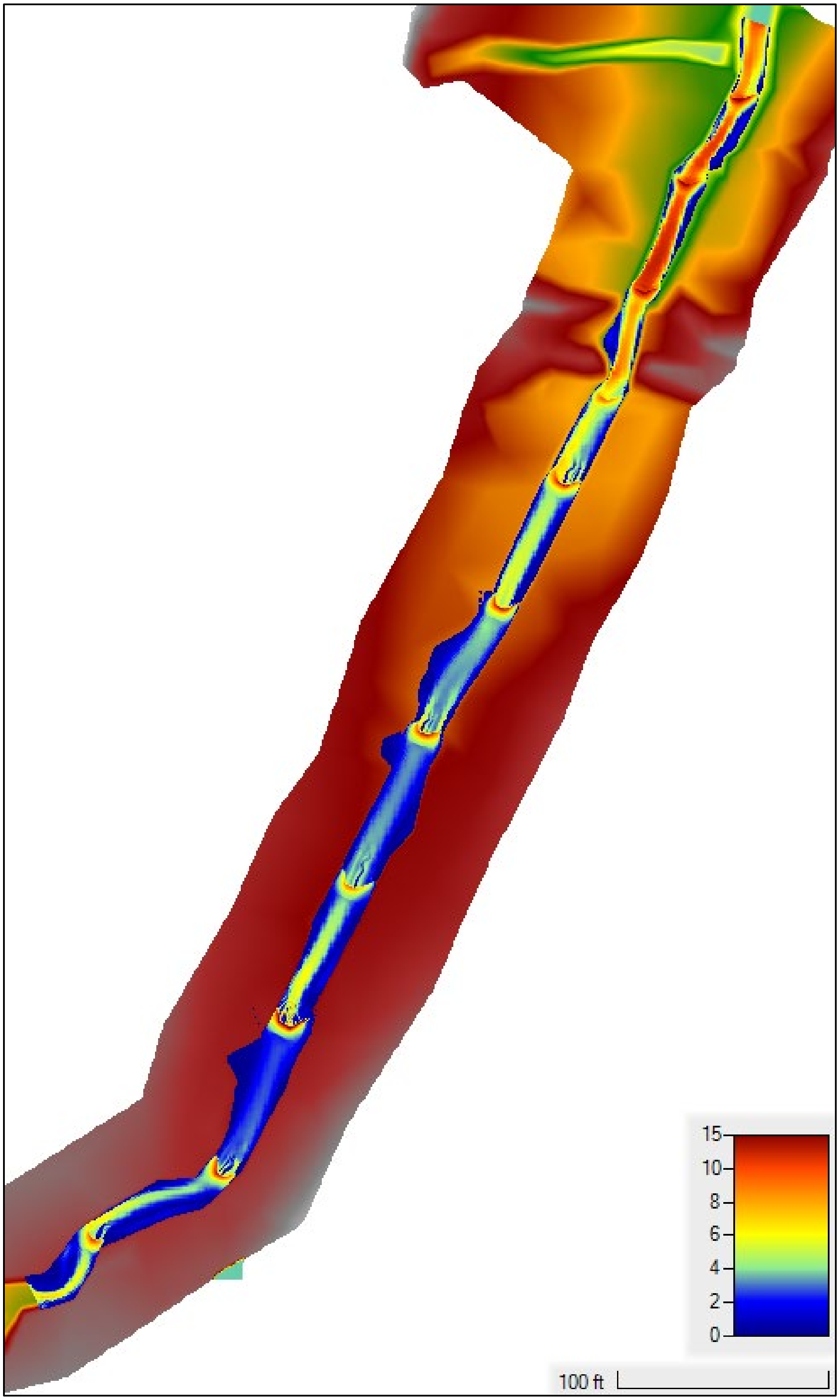

Figure 9. Quasi steady-state maximum velocity for the 25-yr event.

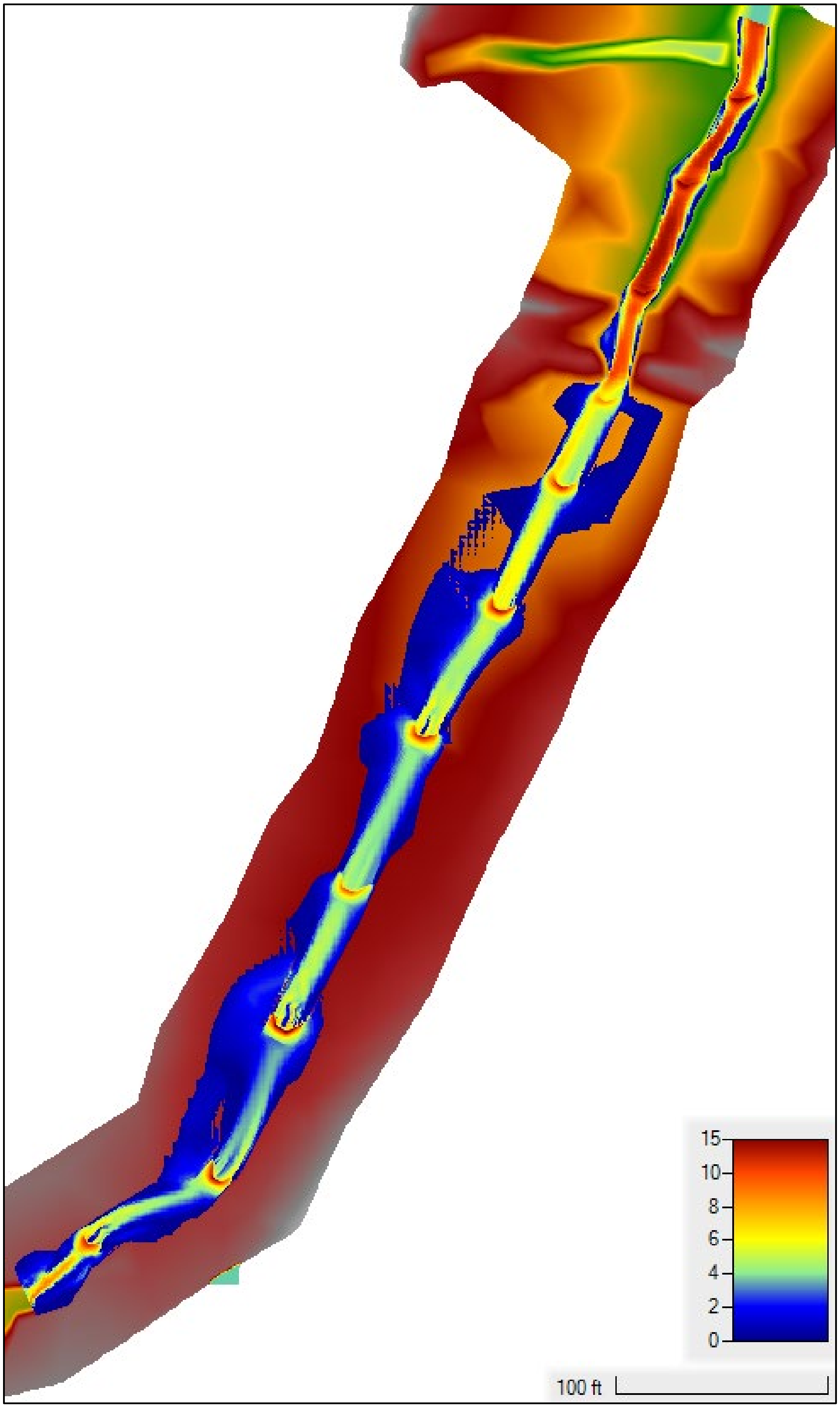

Figure 10. Quasi steady-state maximum velocity for the 100-yr event.

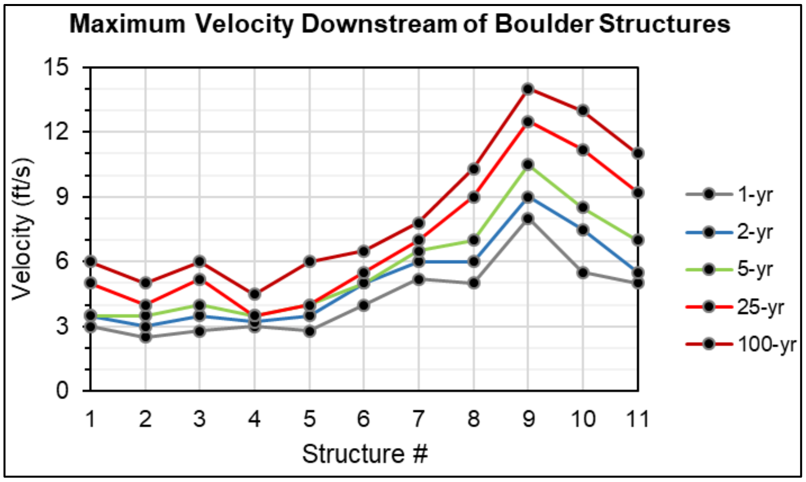

Figure 11. Quasi steady-state maximum velocity downstream of boulder grade control structures.

Conclusion and Recommendations

Very high velocity and turbulent recirculation have already resulted in excessive bed scour and erosion around several boulder structures and will continue to pose a substantial risk to future channel and structure stability at the Millbrook Exchange Park project. Based on the modeling results, the following conclusions and recommendations are provided:

- The model results appear to explain observed erosion and deposition accurately including:
  - Deposition in low velocity areas upstream of structures.
  - Erosion downstream of structures and along channel banks in lower half of project reach.
- Adding fill and stabilizing the downstream side of the structures with boulders will prevent the undermining of the structure footers; however, this will not reduce the risk of flow cutting around the structure arms. The lack of floodplain connection (overbank flow does not occur until discharge exceeds the 25-yr event) and the tendency for incised channels to widen will continue to threaten structure stability.
- Rather than repairing the existing structures, redesign of the project using a priority 2 restoration approach (Doll et al., 2003) with step pools, in which a new floodplain and stream channel is excavated at the elevation of the existing stream, is recommended. The channel and floodplain could be shifted to the left (looking downstream) from the existing channel to minimize impacts to existing trees. Rocks from the existing structures could be reused for new boulder steps. Simply repairing the structures will not guarantee long-term stability. The high risk of failure due to water cutting around the structures and channel widening will only be resolved by addressing the lack of floodplain connection.

References

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