Hydraulic Analysis at the Interface of the Yellowstone River and the Huntley, Montana Irrigation Diversion Fish Bypass

Andrew Johnson, Joel Cahoon, Al Zale, Katey Plymesser, and Matthew Blank

Hydraulic Analysis at the Interface of the Yellowstone River and the Huntley, Montana Irrigation Diversion Fish Bypass

Andrew Johnson, MS [1]
Joel Cahoon, PhD, PE [1]
Al Zale, PhD [2]
Katey Plymesser, PhD, PE [1]
Matthew Blank, PhD, PE [3]

[1] Civil Engineering Department, Montana State University
[2] Montana Cooperative Fishery Research Unit, Department of Ecology, Montana State University
[3] Western Transportation Institute, Montana State University

Abstract

The nature-like bypass channel built to allow fish to circumvent the Huntley Diversion Dam on the Yellowstone River was constructed in 2015. A project was commissioned in 2019 to determine the effectiveness of the bypass using hydraulic modeling and fish detection techniques. During the course of the study it was observed that there may be a localized zone of high water velocity at the interface between the upstream end of the bypass and the main channel of the river - an area just upstream of the low-head dam. The concern this raises is that some fish that successfully negotiate the bypass channel may be returned directly over the dam due a difficult hydraulic condition at the interface. That observation prompted a more focused hydraulic modeling exercise as reported herein. A detailed 2-D HEC-RAS model was developed to investigate the hydraulic conditions. The model predicts localized water velocities of up to 15 ft/sec. At low river flows there appears to be adequate pathways for fish to avoid this high-velocity region, but as river flow increases so does the area in which the velocity is high. From these results it is likely that, during higher river flow periods, the bypass channel may be passable, but fish may struggle to re-enter the river channel successfully. Suggested physical alterations to the site to help overcome this range from the addition of large riprap to rerouting the upstream end of the bypass channel.

Acknowledgement

Introduction

The Yellowstone River is nearly 700 miles long river with headwaters in Yellowstone National Park and flowing through much of southeastern Montana before joining the Missouri River. The Yellowstone is famously referred to as the "longest undammed river in the United States" but this is not entirely true. There are several low-head dams or diversions that span the Yellowstone but hold no storage allowing the river to flow freely over them (Figure 1).
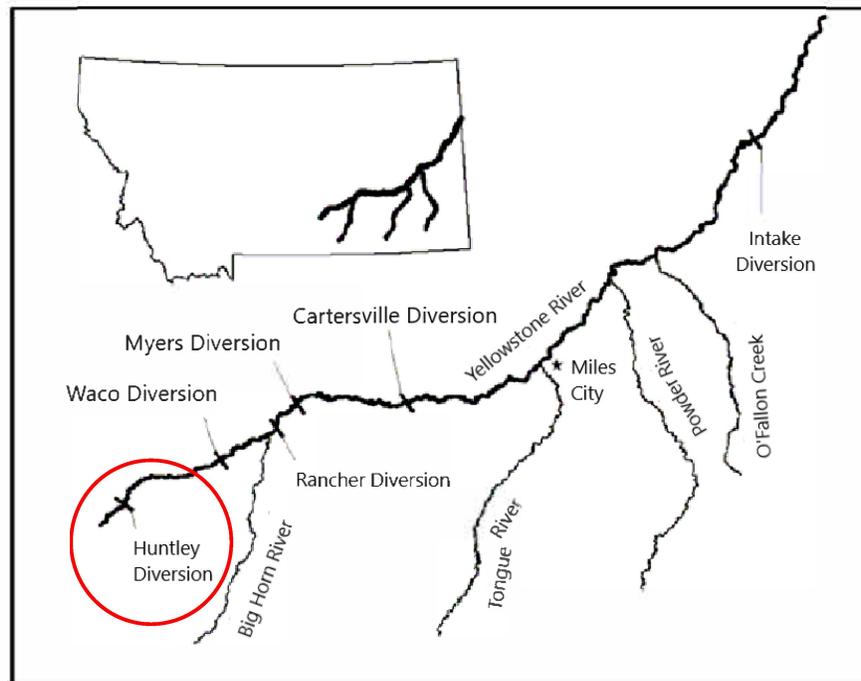
Figure 1 - Context map of the diversion dams along the Yellowstone River in Montana. (Atkinson & Dood, 2006).

The upstream-most of these low-head diversion dams is the Huntley Diversion. This diversion was built in 1934 as part of the Huntley Irrigation Project and is located just west of Huntley, MT which is about 15 miles east of Billings. The dam was built to provide irrigation and drinking water to the surrounding communities. The diversion is made of concrete, spans the width of the main channel, is approximately 10 ft in height on the downstream side, and provides enough upstream head to divert up to 730 cfs to the irrigation canal.

High spring (snow melt) river flows in 1996 and 1997 caused damage to the diversion dam. Repairs were made and a channel was cut around the diversion. The channel was lined

with riprap to make it into a nature-like bypass to help fish navigate around the impassible diversion. This "Old Bypass Channel" (Figure 2) was deemed ineffective as a pass way for upstream fish travel due to steep slope and high velocities (Zale, et al., 2018). In June of 2011, the Silvertip Pipeline ruptured by Laurel, MT upstream of the diversion. In the wake of the spill, plans were made to modify the bypass by making it longer and therefore less steep. The redesigned nature-like bypass (*New Bypass Channel* in Figure 2) was finished in 2015 and is the focus of this project.

Figure 2 - Huntley Diversion showing the old and new nature-like bypass channels. Image from Tupen (2020) and Google Earth.

Project Overview

There are three primary components of the current study - a fisheries experiment, a hydraulic modeling exercise to describe the conditions in the interior of the bypass channel, and the study documented herein, a focused hydraulic modeling exercise to describe the interface between the upstream end of the bypass and the main stem of the Yellowstone River. In this report, a brief tie-in between the two former components and the latter study is provided to give

context. The presentation herein relies heavily on Tupen (2020) and the forthcoming Montana State University MS thesis by Ian Anderson that will document the fisheries experiment.

<u>The Fisheries Experiment</u>

In the fisheries experiment (Anderson, forthcoming), 14 of the over 50 fish species that can be found in the Yellowstone River were included in a passive integrated transponder (PIT) based direct assessment of passage throughout the bypass. In order to determine if fish find and use the bypass, PIT tags were inserted into the abdominal cavity of nearly 4,000 individual fish. These fish were caught using electro-fishing in the vicinity of the diversion, measured, recorded, and fitted with a PIT tag before being released downstream of the bypass. A series of antennas that record the incidence of proximity of PIT tag were placed across the bypass in several locations as shown in Figure 3. Many useful analytics can be determined from recording the tagged fish at these antenna locations. Attraction to the bypass, passage to different points along the bypass, and occurrences of exiting the bypass can be determined and analyzed statistically. Many other interesting relationships can also be determined such as the size of the fish passing, and the temperature, flow rates, and time at which fish movements occur.
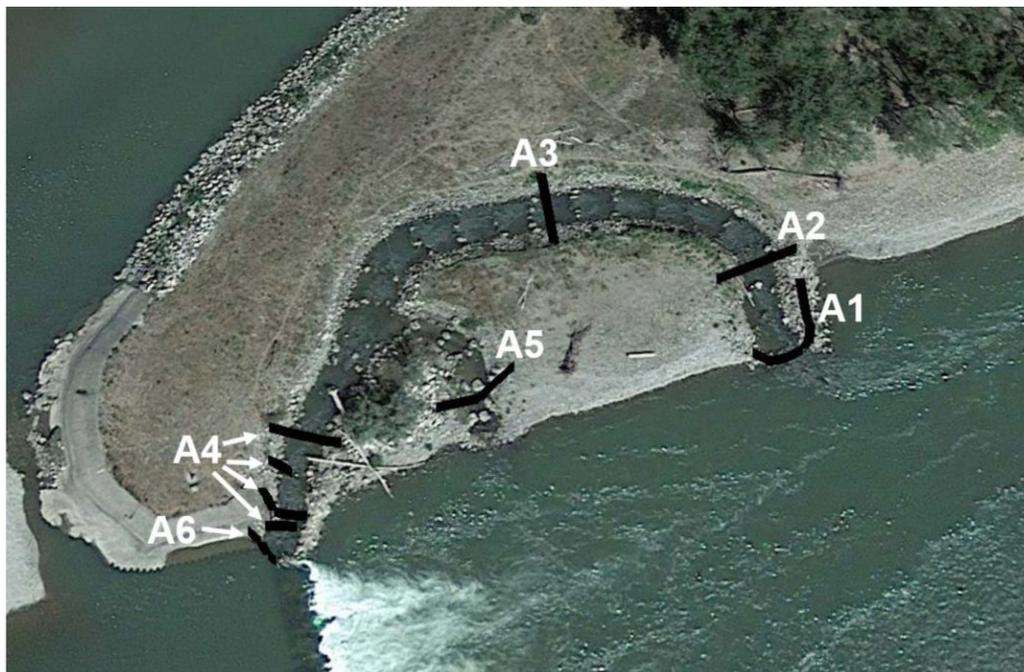
Figure 3 - PIT tag antenna locations. These record every occurrence of a tagged fish swimming over one of the buried cables. Image by Ian Anderson on Google Earth.

The fisheries experiment is still in progress as of this writing, but preliminary results indicated a possible concern. At some flow rates, fish successfully find and ascend the bypass to get upstream of the diversion but are then detected back at the downstream end of the bypass shortly thereafter. While this could mean that fish simply returned volitionally, it could also indicate that fish struggle to negotiate the interface between the upstream end of the bypass and the main stem of the Yellowstone just upstream of the dam. Given the close proximity of the upstream end of the bypass and the crest of the diversion (indicated in Figure 4) it is quite possible that fish are swept over the dam after successfully ascending the bypass channel. It was this observation that motivated the project team to add the analysis documented herein to the hydraulic assessment of Tupen, 2020.

Figure 4 - Study area for this project looking at the area around the bypass exit. Imagery from Google Earth (2021).

The In-Bypass Hydraulics Study

Much work has been done on this site to learn about the hydraulics and hydrology of this nature-like bypass. In her thesis work, Tupen (2020) produced a 2-dimensional hydraulic model of the bypass channel in HEC-RAS. Comparisons between the predicted water velocity in the bypass and literature-based swim capabilities indicated there were times when the bypass was

passable by most species and times when the bypass was a barrier to some species. The upstream portion of the bypass was noted as greatest barrier to passage. Readers are referred to Tupen, 2020 for details as this was an extensive study. Information developed by Tupen (2020) including bathymetry, topographic survey, and hydrologic flow estimates were used in the study documented herein.

The motivation to examine the hydraulic conditions more closely in the area shown in Figure 4 was a result of the observations of Anderson (forthcoming) and Tupen (2020). Anderson found some fish returning to the downstream end of the bypass after successful ascent, and Tupen found difficult velocity conditions at the upstream end of the bypass. In the study detailed herein, we have used an additional 2-D HEC-RAS model to explore the hydraulic conditions at that location more thoroughly.

Methods

The location of interest was modeled in HEC-RAS 5.0.7. The two-dimensional model was chosen for its ability to capture flow splitting, attain high resolution velocity data, and to complement previous bypass modeling. The general process for creating this model is as follows. The terrain was surveyed and brought into Civil3D to be exported to HEC-RAS as a raster. A 2-D flow area was drawn in RAS-Mapper to define the flow area and Manning's n was assigned spatially. Three boundary conditions were developed, one at the upstream end to have flow enter the model and two exits to allow water to leave over the dam and into the bypass. The model was then run over a range of flows.

Terrain Data and Bathymetry

To limit the amount of surveying and field work required, only a portion of the Yellowstone above the diversion was surveyed. The terrain was surveyed using a Leica GS14 rover and base station pair. The Billings, MT radio base was not used due to its limited range and proximity to the project site. All survey measurements on shore were taken by hand with the rover unit on a rod on an approximate 1foot square grid. The bathymetry was surveyed at low flows also utilizing the Leica GS14 rover and base pair. A Teledyne RDI StreamPro ADCP (acoustic doppler current profiler) was used to measure the depth. This device accurately and quickly measured flow rates in the bypass. The rover was installed above the ADCP sensor and

set to record a measurement at every 1 foot of movement. The ADCP was paired to a laptop separately from the GPS via a Parani-SD1000U Bluetooth adapter and recorded depth measurements at a much finer interval (Teledyne Marine, 2020). The clocks of both the GPS and ADCP devices were synchronized prior to recording measurements.

The two data strands were then combined using time as the common factor to accurately attain the bathymetry of the site. Some of the data was removed to eliminate noise from poor depth measurements. The survey data was combined in Civil3D and added to the previous topographical survey of the site to create a surface. The diversion itself was unsafe to deploy the equipment over the crest and was therefore described from historical construction photos and limited survey data and merged into the terrain surface. This surface was then exported from Civil3D as a raster file to be imported into HEC-RAS via RAS-Mapper using the NAD 1983 State Plane Montana FIPS 2500 Feet projection. This projection was also used in the previous modeling. The terrain can be seen above in Figure 5 as it can be viewed in RAS-Mapper.
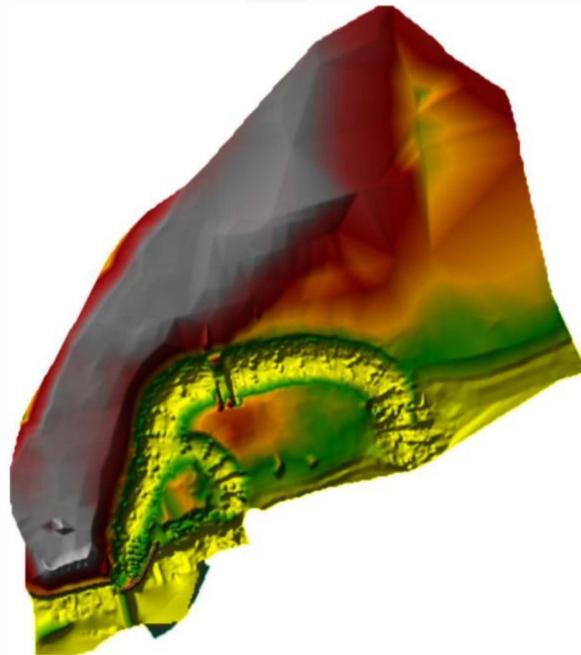
*Figure 5 - Terrain raster used in HEC-RAS.*

2-Dimensional Flow Area

A 2-D flow area was drawn in RAS-Mapper to establish the boundaries of the hydraulic model. A 1 foot square cell size was used. No mesh refinement study was performed as the mesh

was deemed adequately sized (Brunner, HEC-RAS River Analysis System 2D Modeling User's Manual, 2016). The 2-D flow area is also small leading to little consequences on computation time from the fine grid size. A layer built in ArcGIS Pro delineating different surface roughness areas was brought into the model. Since a calibration study was performed on previous modeling efforts (Tupen, 2020), the results from this work were used on this model.

Boundary Conditions

Boundary conditions are arguably the most important part of a model as the rest of the model needs to match these 'known' requirements at its extents. This model utilizes three, as shown in red in Figure 6. The upstream boundary condition (left) passes water into the model as a stage hydrograph. This stage was iteratively adjusted so that the flow rate into the bypass corresponded to previous modeling and field measurements at different flow rates in the Yellowstone. The first of the two exit boundary conditions seen over the diversion has a rating curve of stage vs discharge. This rating curve uses the standard HEC-RAS weir equation with a discharge coefficient of 3.5. This is within the recommended range for an ogee-crested weir (Brunner, HEC-RAS River Analysis System Hydraulic Reference Manual, 2016). The other exit is another stage hydrograph. This stage matched the results of the previous modeling results by using data from a cross section where measurement was taken within the bypass. At this line, both the stage and discharge were matched to accurately portray the interface of the bypass fish exit. At the site, water flows over the rock pile delineating the bypass from the main channel of the Yellowstone. This is a tricky situation to represent with boundary conditions, so an artificial 'wall' was built into the terrain at the flow area boundary to force this flow out of the model through the boundary condition in the bypass. The discharge measured at the boundary condition ignored this additional flow by only measuring the part of the flow that was in the bypass channel. This additional flow was easily identified at low flows because it never re-entered the bypass channel. At large flows when the bypass channel overfills, streamlines made the distinguishment possible.
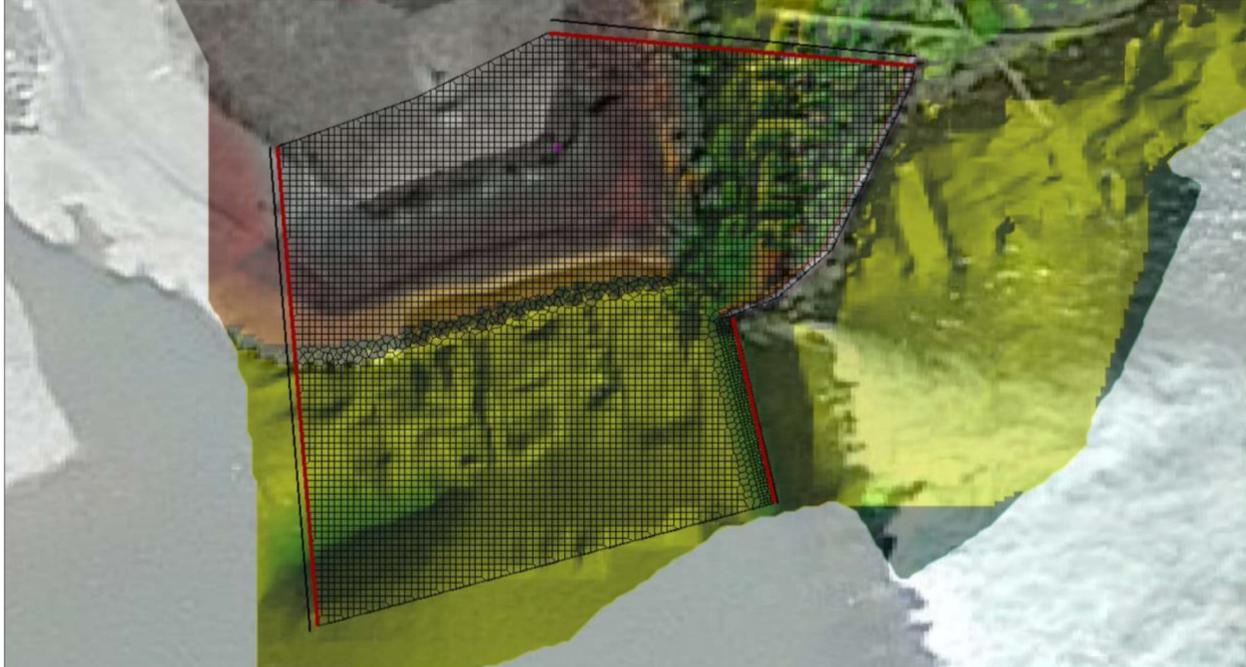
Figure 6 – Two dimensional flow area computational mesh and boundary conditions.

Simulation Runs

As mentioned in the previous section, each flow rate modeled must be iteratively solved by changing the upstream boundary to match the flow and stage across the downstream boundary within the bypass for each run. This requirement makes it impractical to run the entire hydrologic year through the model as in the previous models of the bypass itself. To capture as much of the hydrograph as possible, six flow rates in the Yellowstone were chosen to represent the curve. These flow rates were 3000, 5000, 10000, 20000, 35000 and 50000 cfs. More flow rates were chosen at the lower end of the hydrograph, which can be seen in Figure 7, as low flows occur frequently. The maximum flow was 50000 cfs even though the Yellowstone exceeds this discharge most years but typically only for a short duration. Additional flow rates were run between 10000 cfs and 20000 cfs to provide more resolution in this area where it is believed that fish may experience passage problems.
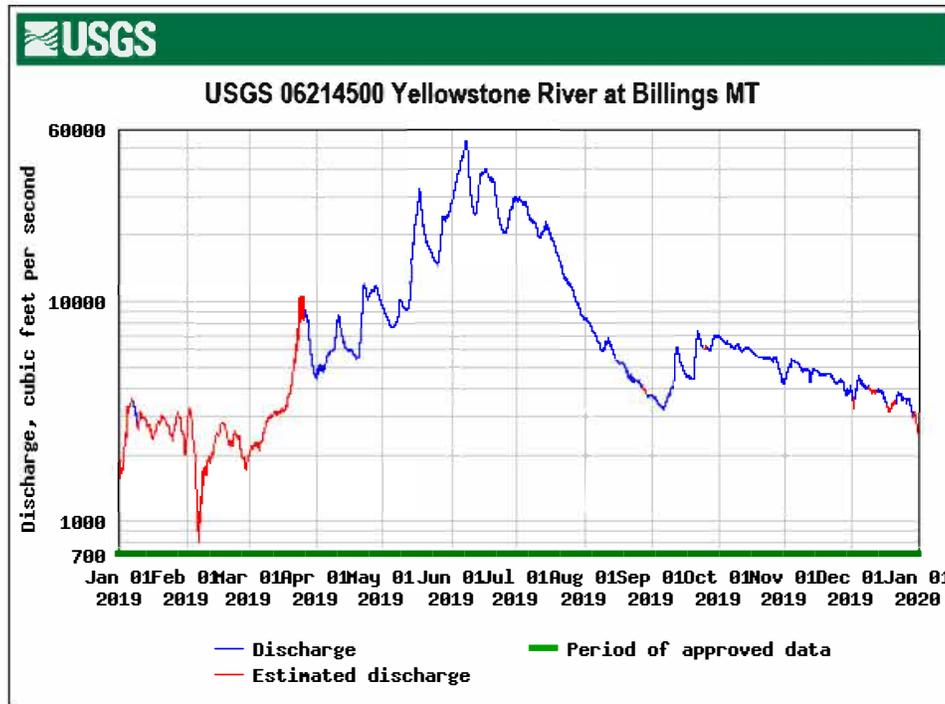
Figure 7 - Yellowstone River 2019 hydrograph.

<u>Computational Settings</u>

The default computational settings were used. The time step used was based on the Courant condition and was allowed to be varied by HEC-RAS to find the optimal step size within the following constraints. The maximum and minimum Courant condition allowed were 3 and 0.5 respectively. The number or steps below minimum before doubling was 4 along with the maximum number of doubling and halving the base time step. Solutions were run for 2 hours of simulation time to ensure the model was at steady state. An initial condition of the upstream stage was set throughout the model to reduce model errors and run time.

Results

Each of the six flow rates were run until steady and can be seen in the following figures. The velocity scale bars are in ft/s and flow is going from left to right. The flow rates listed are for the entire Yellowstone at the USGS Yellowstone River Gage 06214500, upstream of the diversion. The flow rate into the bypass was measured so that the offshoot of the bypass channel seen in Figure 8 below was not included.
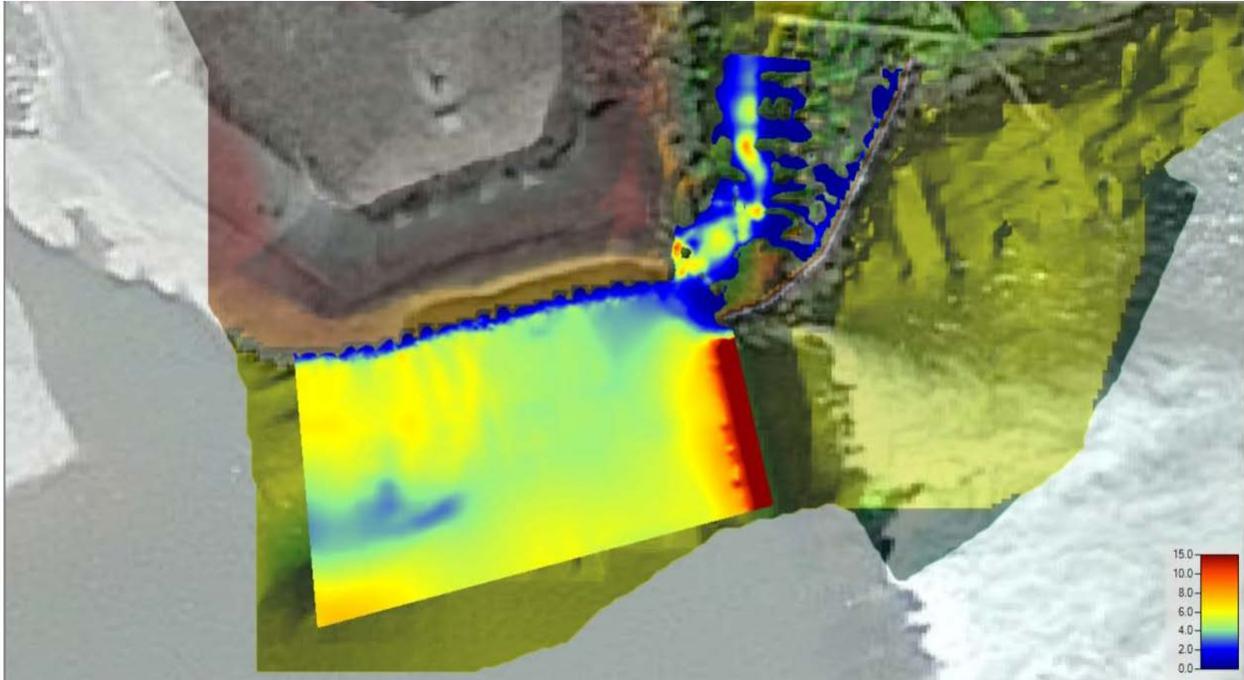
Figure 8 - 3,000 cfs in the Yellowstone.
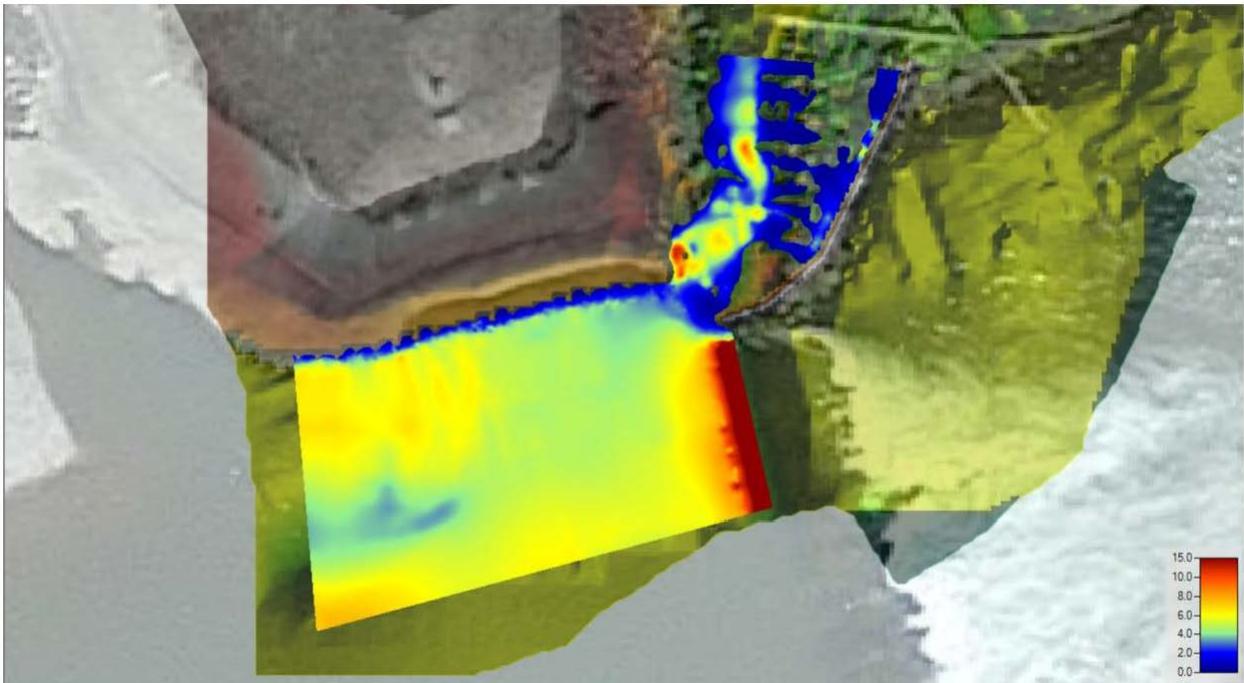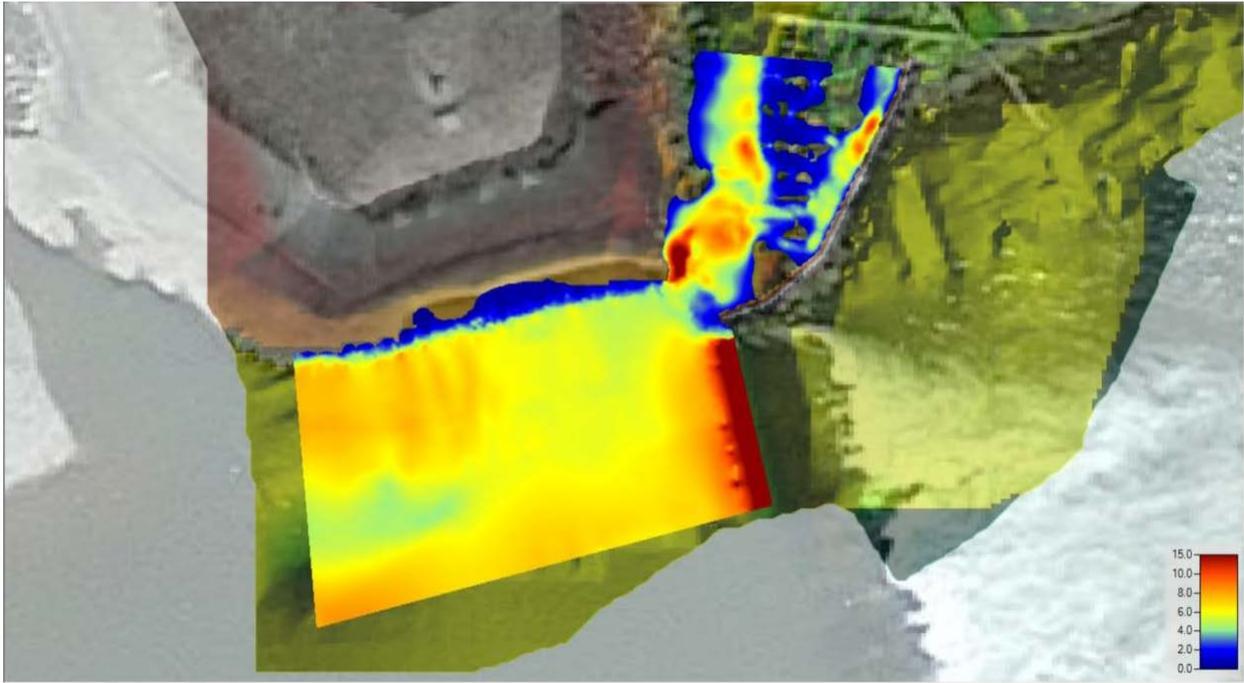

Figure 9 - 5,000 cfs in the Yellowstone.

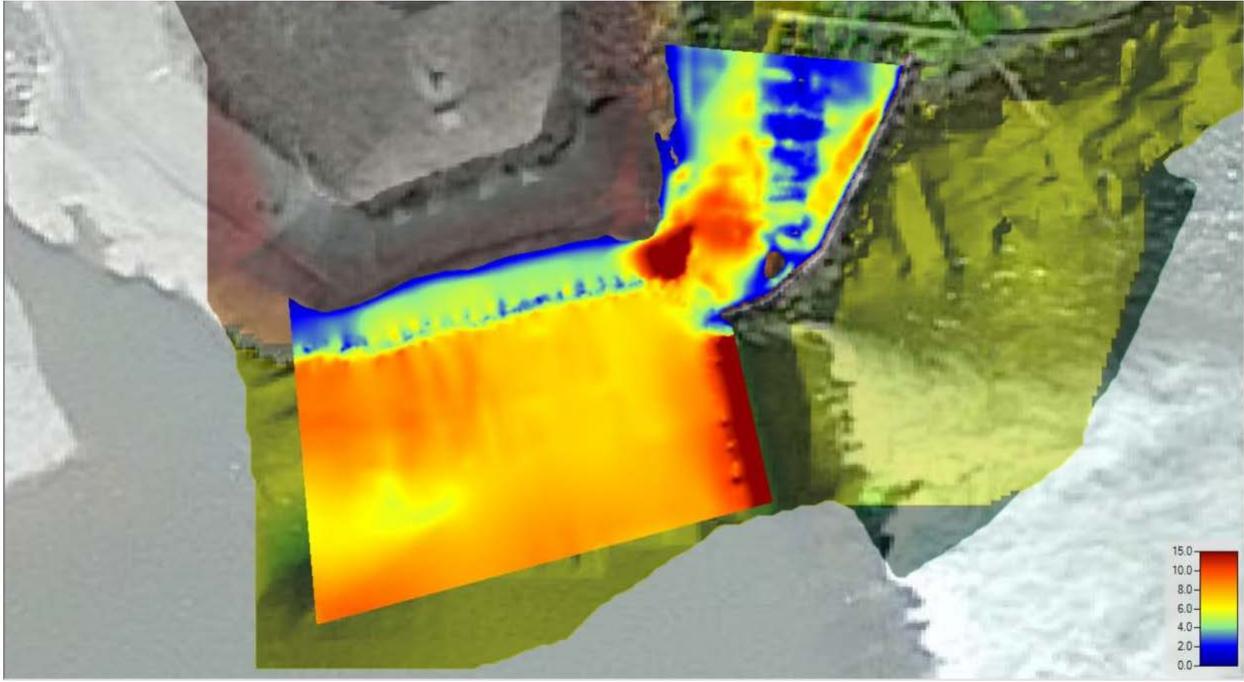*Figure 10 - 10,000 cfs in the Yellowstone.*
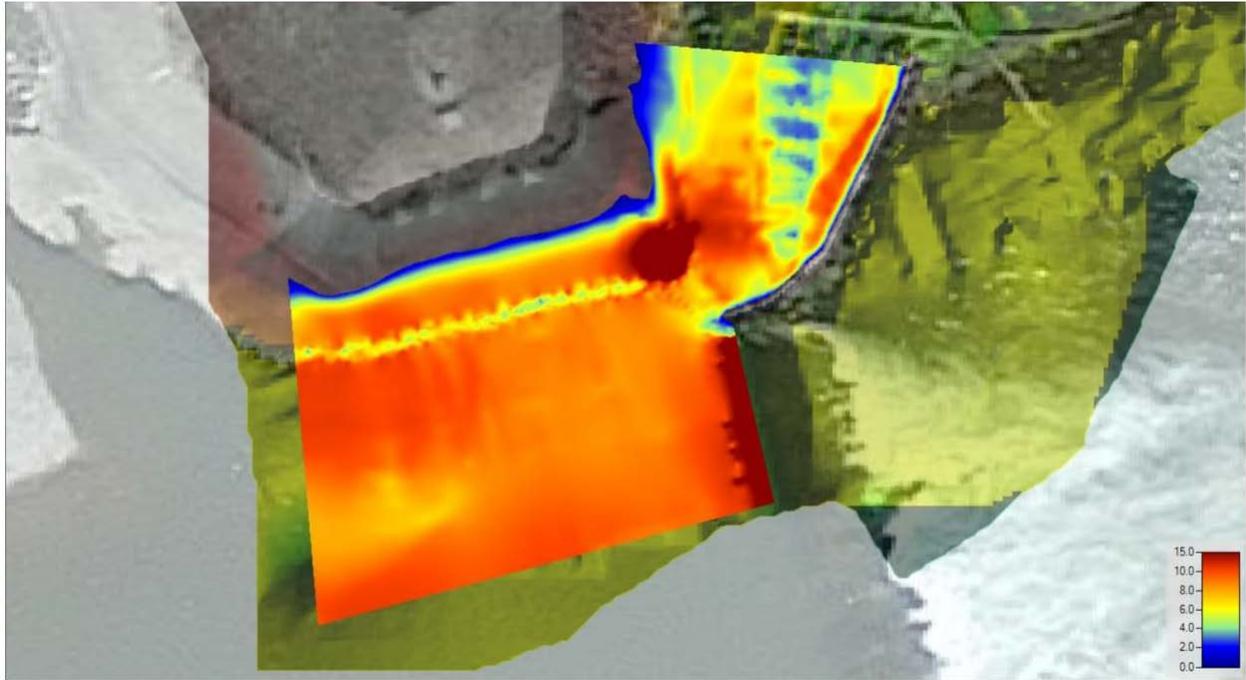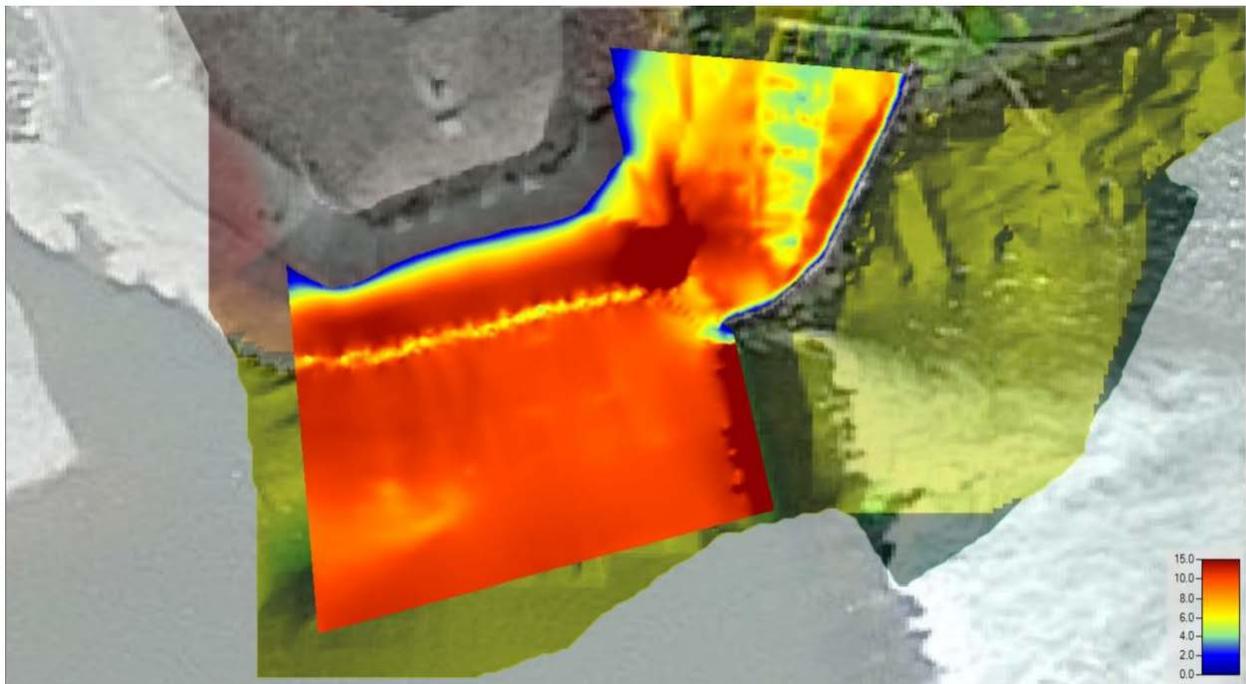

Figure 11 - 20,000 cfs in the Yellowstone.

Figure 12 - 35,000 cfs in the Yellowstone.

Figure 13 - 50,000 cfs in the Yellowstone.

Discussion

Figure 8 and Figure 9 show the bypass exit at base or low flows. While there are some higher velocity areas in the bypass, clear low-velocity routes are visible. Fish are expected to be able to navigate these velocities. The next two, Figure 10 and Figure 11, show the mid-range flow rates. Preliminary fisheries results indicate that in this range many species begin experiencing difficulties successfully passing the diversion and continuing upstream. Fish appear to make it to the upstream antennas and pass the bypass but may not completely navigate past the diversion. A high velocity spot appears on the river left of the bypass and grows in size and magnitude as the flows increase. Somewhere in this range a high velocity plume takes over much of the bypass. The clearest route around this plume is to the river right of the bypass which would put fish in a position to re-enter the Yellowstone just above the diversion. High flows, seen in Figure 12 and Figure 13 are dominated by high velocities and deep waters. Based on these model results it would be unlikely for many fish to pass the diversion.

To get a better view of the changes in flow patterns between 10000 and 20000 cfs, every 1000 cfs from 10000 to 18000 was also modeled. It is believed that in this range of flows fish experience difficulty fully passing the diversion and may be getting swept over the dam after successfully navigating the bypass. While the changes in each increment are quite small, a cut off at 15000 cfs was established as the flow at which if fish are seen at the upstream end of the bypass and then shortly after back at the downstream end, they would be considered having failed to pass the diversion. Figure 14 below shows this discharge. Figure 15 shows a profile line that was cut to expose velocities from the tip of rock pile at the bypass exit across to shore. This plot is shown as a fish swimming upstream would see it, the long stretch on the right side of the figure being the shore on the river left of the bypass. The depth averaged velocities are quite large on the river left of the bypass so fish trying to navigate around this barrier would choose to go left (river right) of the bypass into the slower flows. This action places these fish in a position to re-enter the Yellowstone nearly on top of the diversion which could be causing them to be swept downstream as the velocities over the diversion are quite large. This theory needs to be confirmed with the fisheries findings, but the preliminary results suggest this may be true.
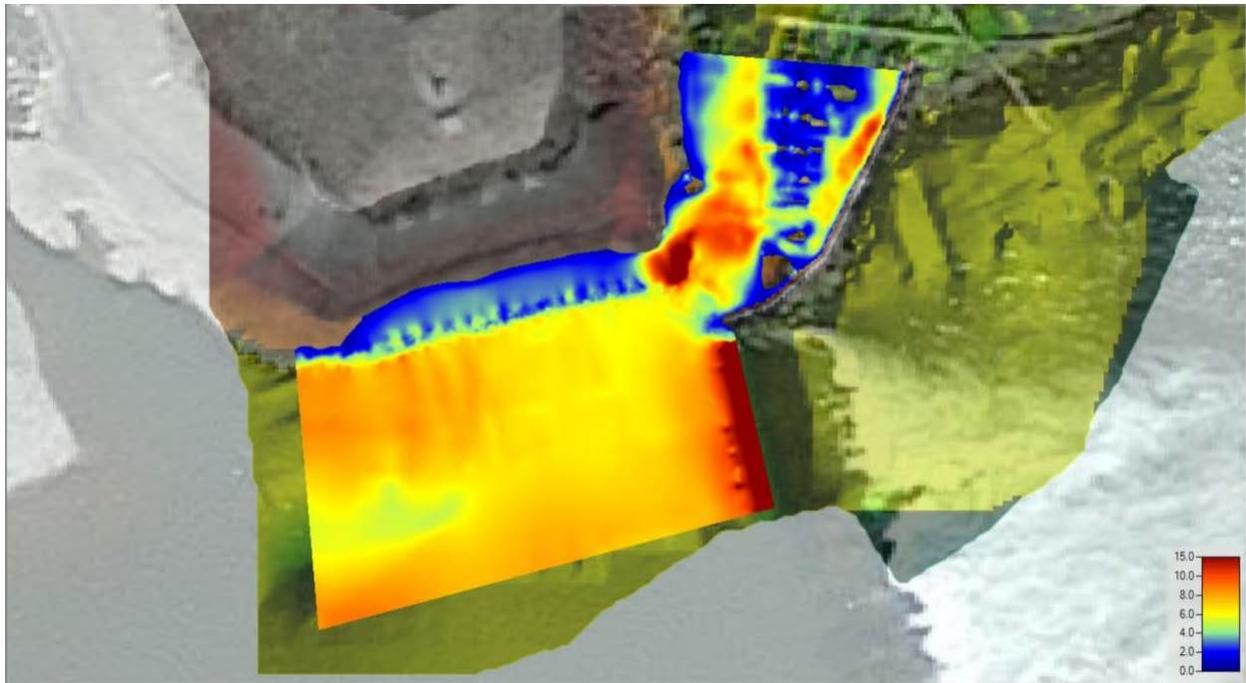
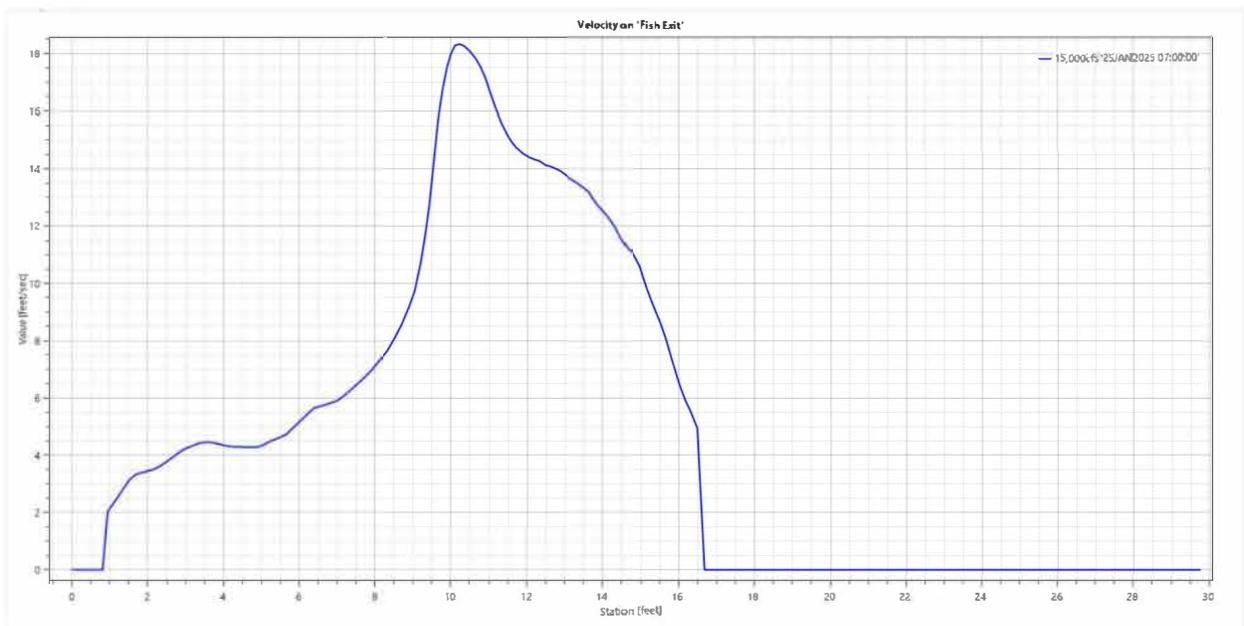*Figure 14 - 15,000 cfs in the Yellowstone*

Figure 15 - Velocity profile at the mouth of the bypass exit

Recommendations

The intersection between the fishway and the Yellowstone River may pose a threat to successful fish passage. This may not be a problem that needs to be solved but if it is we suggest a few possible solutions or improvements. These are simply ideas that would each need to be more thoroughly evaluated. They are not aimed at proposing any changes but are intended to provide a starting point for future discussions.

One solution could be to place a structural passage feature at the bypass exit. A Denil fish ladder (Figure 16) could be perched across the high velocity area to span this spot during the higher flows as shown in Figure 17. It may need to be placed such that it is only useful during parts of the year. This could help some of the stronger swimming species continue upriver when the flows are high (Katopodis, Kells, & Acharya, 2001) but may not provide passage to all species. This solution could also keep fish on the river left side of the bypass and away from the diversion itself and the accompanying faster velocities.

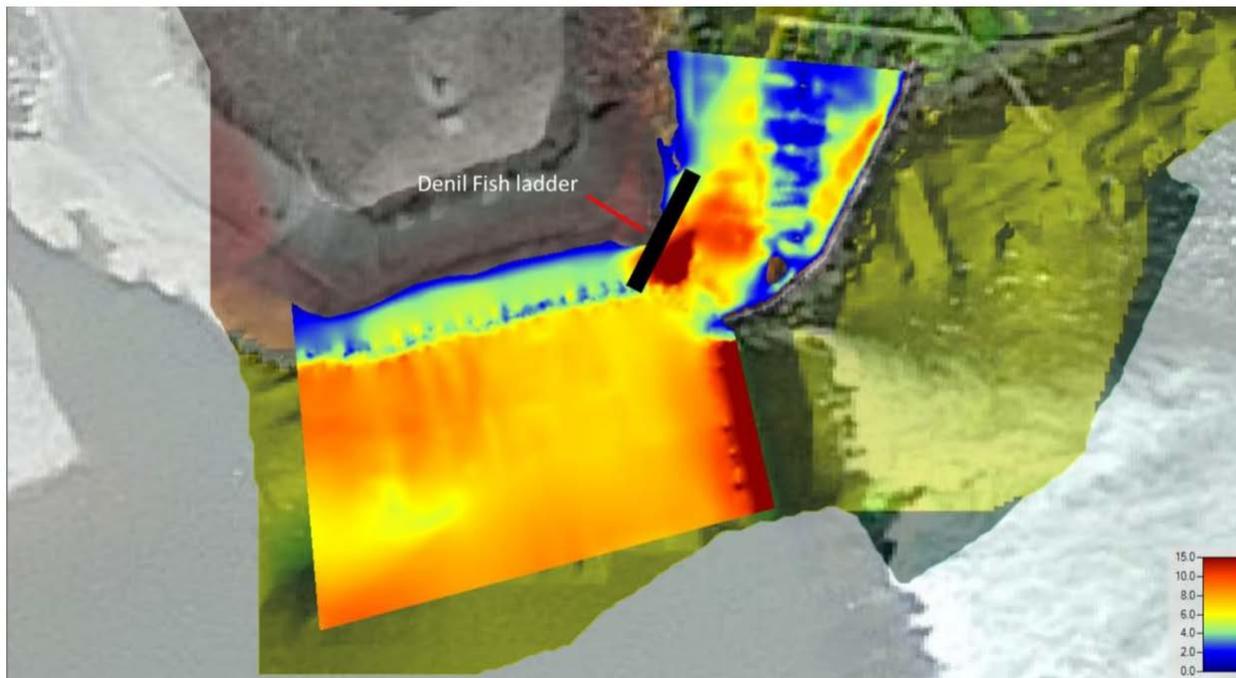*Figure 16 - Denil fish ladder. Photo by Matt Blank*

Figure 17 - Possible fish ladder location at the bypass exit

Another option, more alike to the nature-like bypass itself could be to modify the bypass exit into a rocky ramp style fishway, an example of which can be found in Figure 18. This ramp could be installed to span the bypass width such that it provides passage to fish throughout the hydrologic cycle. By strategically placing additional boulders, the fishway could provide resting places and a route of low velocity (Mooney, Holmquist-Johnson, & Broderick, 2007). An advantage to this type of passage structure is that it can be used successfully at a broad range of flow rates and by the diverse selection of species as it mimics natural stream hydraulic conditions (Calles & Greenberg, 2005). This solution could also be constructed in a way that would keep fish away from the diversion and release fish further upstream than at present.

More intensive alterations could also be investigated. Rerouting the upstream third of the bypass channel to run more parallel to the river channel could be an option. Doing so would deposit successfully passing fish into the river channel well away from the high water velocities apparent just upstream of the diversion dam. This portion of the channel could be sculpted to be active only at high flows with low flows using the current configuration, or it could be the sole pathway with the current confluence rendered inactive.

Figure 18 - Example of a rocky ramp style fish way. Photo by USBR.

References

Anderson, I. (forthcoming). *Effectiveness of the nature-like fishway at Huntley Diversion Dam, Montana.* Bozmeman, MT. MS Theisis, Montana State University.

Atkinson, S. J., & Dood, A. R. (2006). *Montana Piping Plover Management Plan.* Bozeman, MT: Montana Fish, Wildlife & Parks.

Brunner, G. W. (2016). *HEC-RAS River Analysis System 2D Modeling User's Manual.* Davis, CA: US Army Corps of Engineers.

Brunner, G. W. (2016). *HEC-RAS River Analysis System Hydraulic Reference Manual.* Davis, CA: US Army Corps of Engineers.

Calles, E., & Greenberg, L. (2005). Evaluation of nature-like fishways for restablishing connectivity in fragmented salmonid populations in River Eman. *River Research and Applications.*

Katopodis, C., Kells, J., & Acharya, M. (2001). Nature-Like and Conventional Fishways: Alternative Concepts? *Canadian Water Resources Journal,* 211-232.

Mooney, D. M., Holmquist-Johnson, C. L., & Broderick, S. (2007). *Rock Ramp Design Guidelines.* Denver, CO: US Department of the Interior Bureau of Reclemation.

Teledyne Marine, R. I. (2020). *WinRIver II Software User's Guide.* Poway, CA.

Tupen, H. (2020). *Hydraulics, Hydrology, and Resulting Fish Passage at the Huntley Diversion Nature-Like Bypass.* Bozeman, MT: Montana State University.

Zale, A. V., Lance, M. J., Plymesser, K., Blank, M., Cahoon, J., Frazer, K. J., & Ruggles, M. P. (2018). *Efficacy of the Nature-like Fish Bypass Channel at Huntley Diversion Dam.* Yellowstone River, MT.