# SEDIMENTATION ANALYSIS OF THE YELLOWSTONE RIVER AT INTAKE DIVERSION DAM, MONTANA

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## BACKGROUND

The Lower Yellowstone Project is a Bureau of Reclamation (Reclamation) irrigation project built in 1908 under the Reclamation Act of 1902. It is located on the Yellowstone River in eastern Montana approximately 70 miles upstream from the confluence with the Missouri River, and 15 miles northeast of Glendive. The project consists of a low-head diversion dam, a diversion headworks structure, and an irrigation canal system that delivers water to approximately 53,000 acres in eastern Montana and western North Dakota. The diversion dam has become a known barrier to native fish migration including the endangered pallid sturgeon. In addition, the canal has been documented to entrain hundreds of thousands of fish annually during diversion operations occurring from April through September. This entrainment issue was recently addressed through the construction in the spring of 2012 of a new screened headworks structure immediately upstream of the old headworks structure.

Reclamation has an obligation, under the Endangered Species Act, to modify the structure of this facility to address pallid sturgeon concerns raised by the Fish and Wildlife Service and the Montana Department of Fish, Wildlife, and Parks. The U.S. Army Corps of Engineers (USACE) received authority to proceed with the design of the Lower Yellowstone Project. Technical staff from both Reclamation and the USACE were brought together to form a multi-agency team tasked with the development and analysis of designs that would address the recovery goals for both agencies.

## INTRODUCTION

The proposed Yellowstone River Intake (YRI) Diversion Dam Modification Project includes the design of a large bypass channel around the diversion dam with the intent of improving upstream and downstream fish passage for adult pallid sturgeon and other native fish. The bypass channel will convey a significant portion of the river flow and sediment. Subsequently, the bed geometry of the reach may change as a result of the project. Reclamation conducted a sediment transport analysis utilizing a two-dimensional mobile bed hydraulics numerical model (SRH-2D; Lai, 2008) on a 5.5-mile reach of the Yellowstone River centered on the intake diversion dam and including the bypass channel. Figure 1 shows a project location map. This evaluation predicted the changes in bed elevations and stream geometry that would result from this project. The sedimentation analysis was further utilized to evaluate one of the other main goals of the proposed design; to minimize the operations and maintenance burden on the local irrigation district.

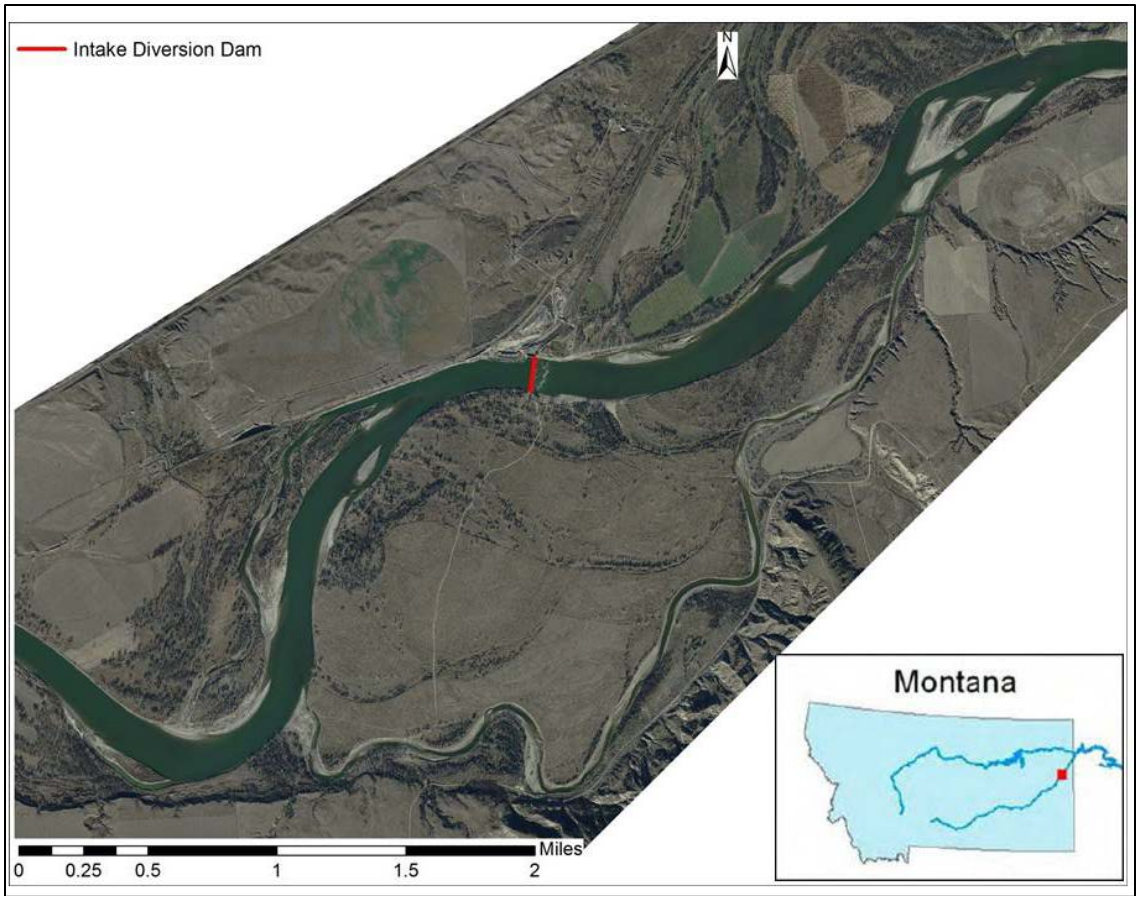


Figure 1 Lower Yellowstone Project location map (flow is from left-to-right).

## DESIGN ALTERNATIVES

Reclamation has, to date, numerically modeled and evaluated two (2) iterative bypass channel design alternatives that were at a 30% and 60% completion level. Several bypass channel alignments were evaluated by the USACE before choosing a preferred one for the 30% design. Model results of the 30% design showed low velocities and the potential for sediment deposition at the downstream end of the bypass channel, largely due to backwater effects from the main channel of the Yellowstone River. To compound the issue, the bypass channel was not capturing enough flow from the main stem. These observations prompted the design of a revised bypass channel alignment and geometry, which was included in the 60% design alternative. The 60% alignment had a reduced length that precluded the use of the existing high flow channel. The proposed 60% alignment takes advantage of existing swales and cut-off channels where feasible. In addition, changes in the entrance/exit angles to the Yellowstone River were included to alter the flow direction in these critical locations for both channel stability and fish passage. The proposed 60% bypass channel design is approximately 11,150 feet long with an average channel slope of 0.0007 feet/feet, and bottom and top width of 40 feet and 150-250 feet, respectively. Approximately 900,000 cubic yards of material will need to be excavated to construct the channel (USACE, 2014).

## MODELING METHODOLOGY

The model domain spans roughly 5.5 river miles on the Yellowstone River, centered on the intake diversion dam. The main goal of this project was to improve upstream and downstream fish passage for adult pallid sturgeon and other native fish by constructing a bypass channel around the diversion dam. A two-dimensional hydraulics and sediment transport mobile bed model was developed to assess the bypass channel functionality and stability as well as its effect on the main stem of the Yellowstone River. Model results were used to inform and iteratively refine project design concepts at various stages of development. Baseline hydraulic parameters, sediment transport rates, and amounts of erosion/deposition were compared through the design process.

Initially, hydraulic conditions with static channel geometry were simulated to calibrate the flow roughness, compute the quantity of flow entering the bypass, and assess mesh density sensitivity. Modeling of the mobile bed channel dynamics and sediment transport commenced after a satisfactory hydraulics model was constructed and calibrated. Model inputs, which are discussed in detail in this section, included a mesh with topographic information, bed material gradations, and flow-roughness parameters. Model boundary conditions included discharge hydrographs and sediment loads for the upstream domain boundary, while a rating curve specifying the water surface elevations over the range of modeled discharges was used at the downstream boundary.

**Model Selection:** All numerical models require simplifying assumptions and thus have limitations. The choice of model is often governed by time and budget constraints, knowledge of and access to existing models, and the availability of enough data with which to develop the model. It is important to understand the formulation of the selected model, recognize the model limitations, and apply the model in a manner that takes advantage of its strengths. Numerical model predictions will always include some uncertainty because the physical processes being modeled are not completely represented in the governing equations used in the model.

The numerical models utilized for this study were HEC-RAS (v 4.1.0) and SRH-2D (v 3.0). HEC-RAS is a one-dimensional (1D) step-backwater hydraulic model developed by the USACE. This model was utilized to simulate cross-section averaged river hydraulics for a series of steady flows. The basic computational procedure utilized in this model is based on the solution of the one-dimensional energy equation. Energy losses are represented through friction (Manning's equation) and contraction/expansion (coefficient multiplied by the change in velocity head). The USACE utilized HEC-RAS to develop design criteria, while Reclamation utilized it mainly to set the downstream boundary condition for the SRH-2D model simulations, which consisted of the development of a water surface elevation as a function of flow rate.

SRH-2D is a two-dimensional (2D) mobile-bed hydraulics and sediment transport model for river systems developed by Reclamation at the Technical Service Center in Denver, Colorado (Lai, 2008). SRH-2D solves the depth-averaged dynamic wave equations with a parabolic turbulence model using a finite-volume numerical scheme. The model adopts a zonal approach for coupled modeling of channels and floodplains; a river system is broken down into modeling zones (delineated based on natural features such as topography, vegetation, and bed roughness), each with unique parameters such as flow resistance. One of the major features of SRH-2D is the

adoption of an unstructured hybrid mixed element mesh, which is based on the arbitrarily shaped element method of Lai (2000) for geometric representation. This meshing strategy is flexible enough to facilitate the implementation of the zonal modeling concept; it allows for greater modeling detail in areas of interest that ultimately leads to increased modeling efficiency through a compromise between solution accuracy and computing demand.

**Model Topography:** To represent the model terrains, a multi-resolution three-dimensional surface was generated in a Geographic Information System (GIS) using a Triangulated Irregular Network (TIN). Topographic representations of the existing and proposed 30% and 60% design conditions were constructed. This was accomplished using a combination of bathymetric and land survey data collected through a joint effort between Reclamation and the USACE, along with Light Detection and Ranging (LiDAR) data. The type of LiDAR acquisition used does not have the ability to penetrate through water. Therefore, bathymetric survey data replaced the LiDAR data in wetted areas. Proposed design condition contours were generated by the USACE in AutoCAD that were subsequently brought into GIS for surface building. An example area from the model domain of the resulting terrain for the 60% design is shown in Figure 2.

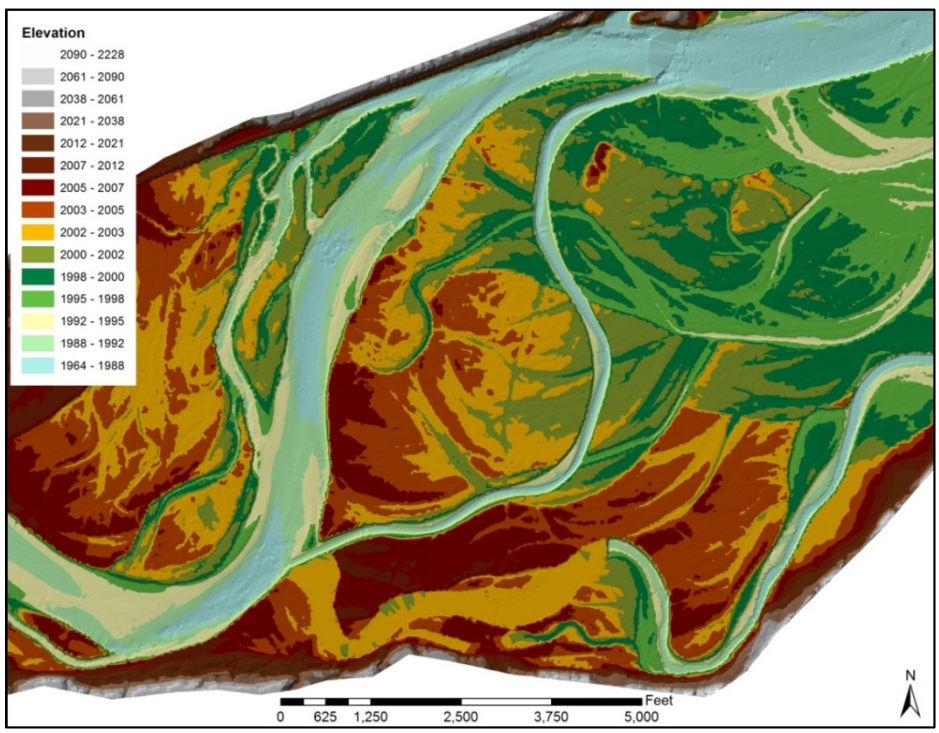


Figure 2 Example area showing the 60% design conditions surface used as input to the model. Elevation values are in feet.

**Model Mesh:** A 2D mesh defines the SRH-2D model topography and solution spacing. The mesh (nodes) stores ground elevation information from the model surface and consists of quadrilateral and triangular shaped elements. Surface-water Modeling System (SMS) software was used to construct flexible mixed element meshes that allowed for increased definition near areas of interest by using finer mesh cells. Coarser mesh cells were used elsewhere. A hydraulics only (fixed bed) module of SRH-2D was utilized to compare a relatively dense mesh (103,125

elements) to a much coarser mesh (25,350 elements) representing the existing conditions. This comparison was conducted using hydraulic outputs and showed the differences between the computed depths to be minimal. A coarser mesh relative to a fixed bed hydraulics model is needed for mobile bed simulations with sediment transport. This is due to the practical limitations of the number of mesh elements (and nodes) for the computationally intensive calculations in an effort to balance run time with model resolution. SMS was also utilized to delineate model roughness areas and assign model boundary conditions.

Each set of modeled design conditions (existing, 30%, and 60%) had its own computational mesh. The meshes consisted primarily of quadrilateral elements within channel areas and triangular elements in the floodplain/overbank areas. The element size varied based on location. In the main channel, the size of the quadrilateral elements was, on average, 65 feet in the lateral (cross stream) direction and 100 feet in the longitudinal (downstream) direction. The shorter dimension in the lateral direction was used to capture the more rapidly changing topography transverse to the stream flow with respect to horizontal distance. The triangular elements in the floodplain areas increased in coarseness as the model approached the domain boundary to a maximum size of 120 feet. An approximate total of 25,350 elements were used in the model domain to represent the existing topographic conditions. An increased mesh density along the proposed bypass channel alignments was incorporated into the preferred alternative meshes as it was a feature of focus. The 30% design bypass channel had an average element size of 25 by 35 feet while the 60% design bypass channel had an average element size of 20 by 35 feet. As a result the total number of mesh elements representing the proposed conditions model domain increased to roughly 30,450 for the 30% design and 39,000 for the 60% design. An example area of the model mesh for the 60% design conditions is shown in Figure 3.

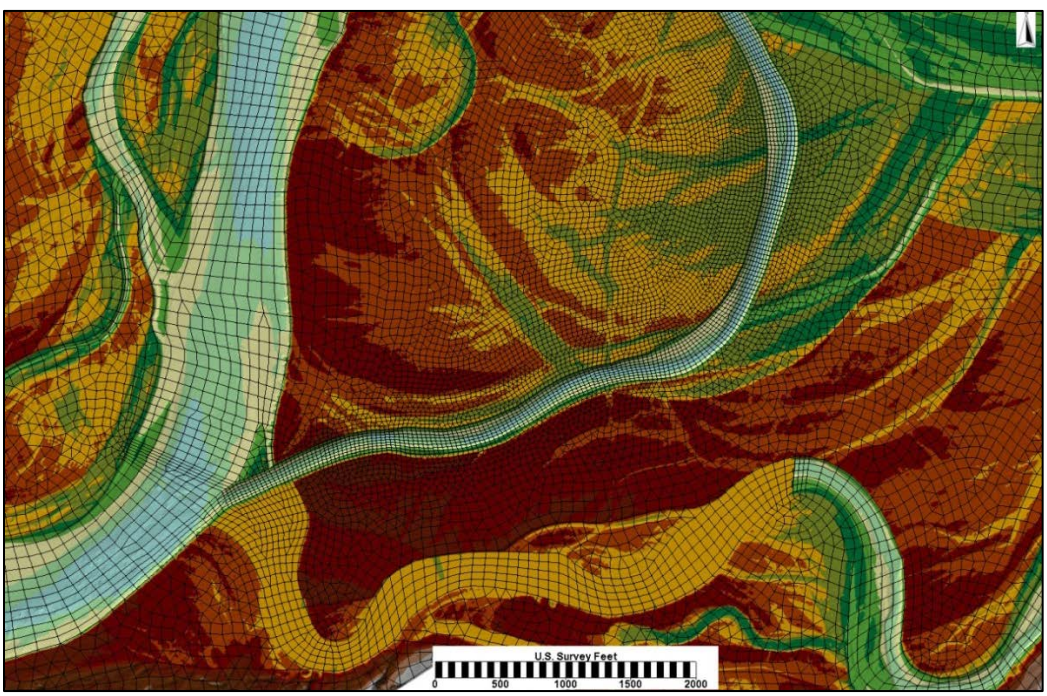


Figure 3 Example area of model mesh for 60% design conditions.

**<u>Model Boundary Conditions:</u>** Boundary conditions for the SRH-2D model were specified at the upstream and downstream model domain. The upstream boundary condition required both hydrologic (flow) and sediment data as inputs. Two average daily flow hydrographs representing particular events of interest were used for the flow input, while a rating curve relating flow to sediment discharge fluxes according to grain size was used for the sediment input. Another rating curve assigning a water surface elevation to the full range of flows from both hydrographs was used for the downstream boundary condition.

**Upstream Boundary Condition – Hydrology:** The closest USGS gages to the intake diversion dam are the Yellowstone River at Glendive MT Gage (06327500) which is located roughly 18 miles upstream, and the Yellowstone River near Sidney MT Gage (06329500) located roughly 36 miles downstream. For the SRH-2D sediment modeling, discharge data from only the Glendive Gage was used as it was upstream of the project site and closer in proximity. Average daily data representing two distinct hydrographs were selected to try and represent a range of flow conditions that the project design could encounter. A 2008 hydrograph was chosen as it appeared to roughly represent a typical wet year when looking at the most recent ten years of gage record. This hydrograph spans 107 days (5/19/08 - 9/2/08) with a peak flow of 63,200 cfs, which is roughly equivalent to the 5-year recurrence interval event according a flow frequency analysis conducted by the USACE (USACE, 2012). The other hydrograph used was from 2011 as it contains the flood of record. This hydrograph spans 206 days (3/1/11 - 9/22/11) and peaks at 122,000 cfs, which corresponds to a value above the 500-year event. The 2008 hydrograph is shown in Figure 4.

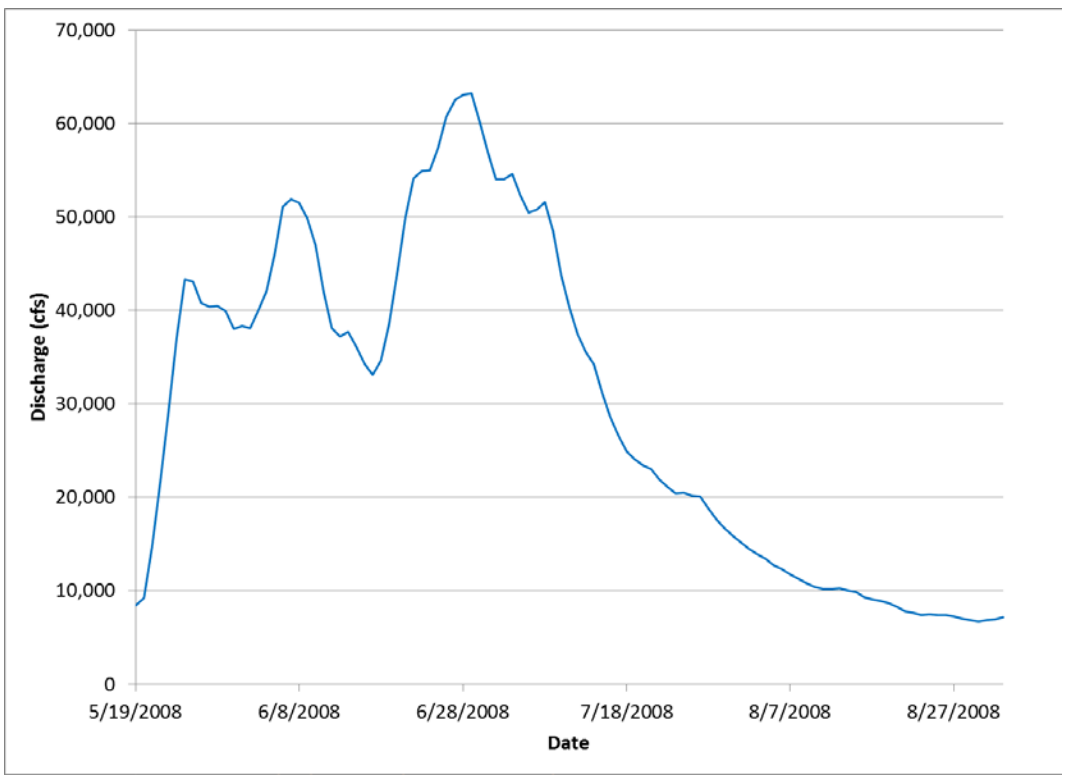


Figure 4 2008 input hydrograph.

**Upstream Boundary Condition – Sediment Loads:** The Yellowstone River has a mixed sand and gravel bed. Therefore, the consideration of bed load and suspended load sediment transport is necessary to quantify the passage of the total sediment load through the system. For the numerical sediment modeling, the relationship of total sediment load to the inflowing discharge is a necessary input.

To derive this total incoming sediment load relationship, Reclamation's in-house program SRH-Capacity (Huang and Bountry, 2009) was used. This model computes the sediment transport capacity using a specified transport equation for a given set of hydraulics and flow values. The required inputs for SRH-Capacity include 1D (cross section based) hydraulics, particle size gradation data, and hydrology data.

To compute the 1D hydraulics, Reclamation modified a HEC-RAS hydraulics model previously developed by the USACE. Additional cross sections were added to the HEC-RAS model to capture the pool-riffle sequence present in the morphology of the Yellowstone River channel. The geometry of the modified HEC-RAS model was then updated with the new topographic data collected in August 2012 by Reclamation and USACE staff.

Particle size gradation data were derived from gravel bar and bank sediment data collected by the USACE in August 2008 (USACE, 2008). The average of three and four grain size distributions was used in the model to represent the channel areas upstream and downstream of the intake diversion dam, respectively. These average distributions were binned into six different sediment size classes, two representing sand and the remaining four representing gravel.

Given the above input, the incoming sediment loads were calculated using the following three sediment transport equations, which are commonly used for rivers with both sand- and gravel-sized sediments:

1. Parker's (1990) bed load transport capacity equation combined with Engelund and Hansen (E/H, 1972), where the transport capacity of particle sizes greater than 2mm are computed with Parker, and the transport capacity of particle sizes less than 2mm are computed with E/H.
2. Wilcock and Crowe's (W/C, 2003) bed load transport capacity equation combined with Engelund and Hansen (E/H, 1972), where the transport capacity of particle sizes greater than 2mm are computed with W/C, and the transport capacity of particle sizes less than 2mm are computed with E/H.
3. Wu et al. (2000) total load sediment transport equation.

**Downstream Boundary Condition:** The downstream boundary condition consisted of a water surface elevation versus discharge rating curve. Discharge values encompassed both hydrographs. The associated water surface elevations were derived from the updated USACE HEC-RAS hydraulics model at a cross section whose location was at the downstream model domain boundary.

## MODEL RESULTS DISCUSSION

The main objective of the YRI hydraulics and sediment transport model was to evaluate the stability and effect of a proposed bypass channel around the intake diversion dam by quantitatively evaluating short term and long term changes in bed elevations. 2D sediment model runs were performed using topographic representations of the currently existing conditions along with the proposed 30% and 60% project designs. Erosion/deposition results from the 30% design showed the lower half of the bypass channel (downstream of the channel split) experiencing deposition. This led to a complete re-design of the bypass channel for the 60% design. Conversely, the 60% design showed small amounts of erosion throughout the bypass channel. Given the model uncertainties however, this was viewed as being in general equilibrium. A side-by-side comparison of the erosion/deposition results from the 2008 hydrograph for the 30% and 60% designs is shown in Figure 5.

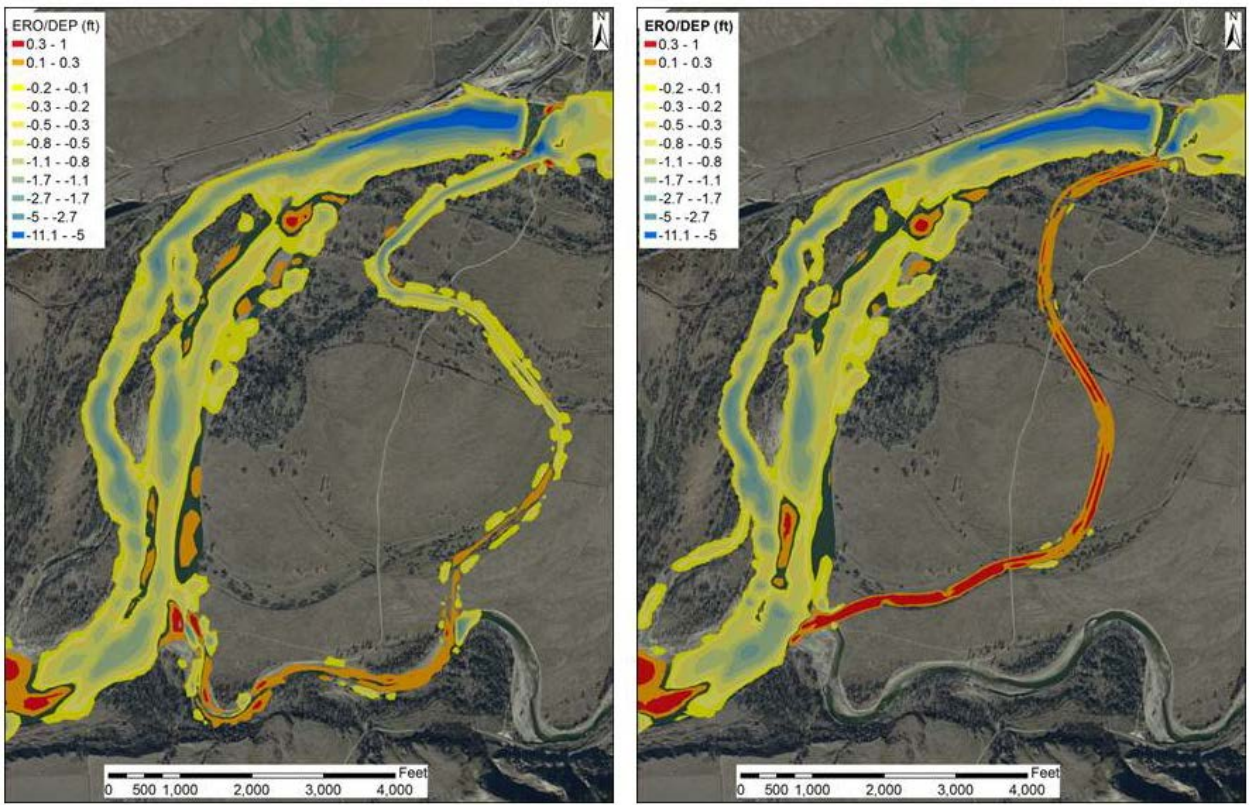


Figure 5 Erosion/Deposition results for the 2008 hydrograph using the Parker and E/H formulation for the 30% design (left) and 60% design (right). A positive (+) value indicates erosion while a negative (-) value indicates deposition.

In addition to evaluating erosion/deposition, monitoring lines were set up at areas of interest throughout the main and bypass channels to track sediment loads during the simulations. Sediment flux was measured at the upstream and downstream ends of both the main and bypass channels under all three modeled scenarios (existing conditions, 30% design, and 60% design).

Results showed the Parker, and Wilcock and Crowe formulations to be comparable, while the Wu formulation yielded noticeably lower sediment transport amounts. The average amount of main channel sediment captured by the bypass channel was roughly 8.5 to 9% for the 30% design and 11.5 to 12% for the 60% design. The relative amount of sediment being deposited in the 30% designed bypass channel is more than the amount of sediment being eroded in the 60% designed bypass channel. According to the Parker and Wilcock and Crowe formulations, an average of 12% and 17% of the incoming sediment load to the 30% design bypass channel is being deposited during the 2008 and 2011 hydrographs, respectively. Conversely, an average of 6% and 2% of the incoming sediment load to the 60% design bypass channel is being eroded during the 2008 and 2011 hydrographs, respectively. These results further indicate that the 60% design bypass channel is more stable with regards to sediment equilibrium during higher flow events. Lastly, sediment flux results showed that neither bypass channel design had a significant effect on the overall sediment balance in the reach. A sample set of sediment flux results are shown graphically in Figure 6 for the 60% design with the 2008 hydrograph that shows some of the above trends.

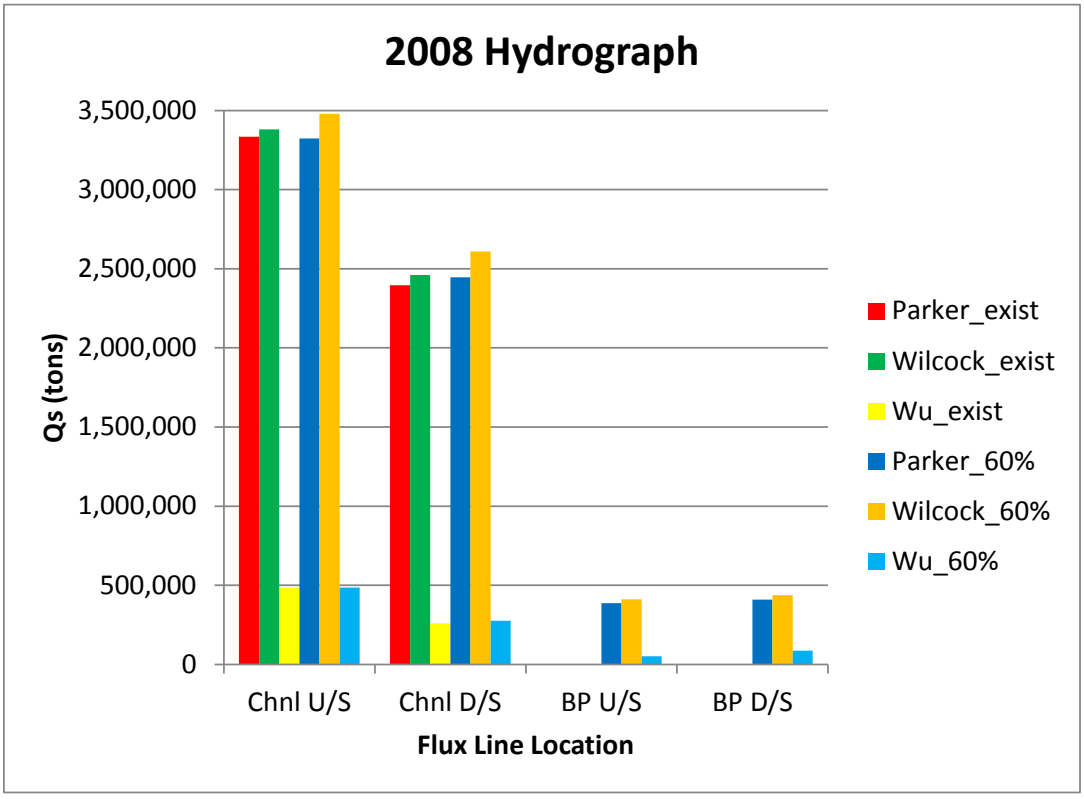


Figure 6 Sediment flux results for the 60% design under the 2008 hydrograph.
(Chnl – Main Channel; BP – Bypass Channel)

## SUMMARY AND CONCLUSIONS

The Lower Yellowstone Project consists, in part, of a diversion dam that has become a known barrier to migration of native fish, including the endangered pallid sturgeon. To address this, a diversion dam modification project is under design that includes a large bypass channel around the structure to improve the upstream and downstream fish passage. Reclamation evaluated the existing conditions as compared to the 30% and 60% proposed design through conducting a sediment transport analysis utilizing a two-dimensional hydraulics and sediment transport mobile bed model (SRH-2D) on the 5.5 miles of the Yellowstone River centering on the diversion dam and inclusive of the bypass channel. Model results were used iteratively through the design process, aiding the direction of future designs. The evaluation predicted the changes in bed elevations that would result from this project by looking at amounts of erosion/deposition along with overall reach affects.

Model results of the 30% design showed low velocities and corresponding deposition on the lower half of the bypass channel. As a result, the bypass channel was re-redesigned (60% design), which conversely showed small amounts of erosion throughout, but was deemed as being in approximate equilibrium. A sediment flux analysis revealed a significant difference between the Wu sediment transport formula as compared with the Parker, and Wilcock and Crowe formulations. The 30% design captured approximately 9% of the main channel sediment, while the 60% design captured roughly 12% during the 2008 hydrograph. The relative amount of sediment that was shown being deposited in the 30% bypass design was more than the amount of sediment being eroded in the 60% design. Lastly, neither bypass channel design was shown to have a significant effect on the overall sediment balance in the reach.

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