NUMERICAL MODELING OF ISLETA DIVERSION DAM GATE OPERATION HYDRAULICS TO MINIMIZE SEDIMENT EFFECTS

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INTRODUCTION

Isleta Diversion Dam was constructed in 1934 by the Middle Rio Grande Conservancy District (MRGCD) as part of their irrigation system, and is located on the Rio Grande about 10 miles south of Albuquerque, New Mexico, immediately downstream from the Highway 147 Bridge (Figure 1). The diversion dam was rehabilitated by Reclamation in 1955 as part of the Middle Rio Grande Project, authorized by Congress in the 1948 and 1950 Flood Control Acts. The Middle Rio Grande (MRG) has long been recognized for its characteristics of high sediment loads and dynamic channel conditions (Happ, 1948; Lagasse, 1980; Makar, 2010). The Isleta Diversion Dam consists of 30 river gates, three headworks gates on the Peralta Main canal (east side), and four headworks gates on the Belen Highline canal (west side) of the dam (Figure 2). The headworks gates are located in a sluiceway with a downstream gate used to maintain a maximum diversion head. Gate operations are used to provide water to downstream irrigators, meet downstream flow requirements of the 2003 Endangered Species Biological Opinion (USFWS, 2003), and manage sediment. Within the context of these multiple water use needs, a one-dimensional (1D) and two-dimensional (2D) fixed bed hydraulic models, sluiceway hydraulics, and sediment incipient motion analysis has been completed to provide recommendations on gate operations that would help reduce sediment impacts. The objectives of these recommendations are to reduce sediment diversion through the headworks gates into the irrigation system, reduce the potential for downstream formation of vegetated islands, maintain an open channel as much as possible along the right bank of the river downstream of the diversion dam, and minimize upstream sediment accumulation. This analysis does not evaluate the effects of sediment supply and sediment transport capacity. Documentation of historical channel characteristics and changes, local knowledge and observation by the staff of the Isleta Pueblo, and the MRGCD is coupled with modeling and incipient motion analysis to interpret results.

CHANNEL DESCRIPTION

The MRG has historically had a high sediment load, causing the channel to fill, especially during hydrograph recession periods, resulting in over bank flooding during subsequent high flow events and avulsing to lower areas of the valley, leading to aggradation (raising of the river bed and floodplain due to sediment accumulation) across the floodplain (Scurlock, 1998; Lagasse, 1980; Happ, 1948). This condition is believed to have existed prior to the 1500s (Scurlock, 1998). The resulting river channel was wide and shallow and generally sand bedded with small pockets of gravel (Scurlock, 1998; Lagasse, 1980). The MRG has changed significantly over the last century as a result of human activities such as irrigation diversions, levee and riverside drain construction, channel rehabilitation (channelization) and maintenance, upstream sediment and flood control reservoirs, trans-mountain diversion, and urbanization. There have also been diminished flood peaks and sediment supply from large tributaries to the Rio Grande since the 1940s (Lagasse, 1980). The following reach descriptions are summarized from Makar (2010), and Baird and Strand (2013) and provide a context of channel conditions and sediment supply into Isleta Diversion Dam. The Albuquerque Reach, extending from Angostura Diversion Dam downstream to the Isleta Diversion Dam (see Figure 1) narrowed from about 600 feet wide in 1972 to about 390 feet in 2002, and the plan form is transitioning from a wide, low-flow braided channel to a single thread channel with vegetated bank-attached bars. Bed material is changing from sand to areas of gravel bed. It is expected that the existing trends of incision, narrowing, and bed coarsening will most likely continue. The suspended sediment load has reduced by about 75 percent. The Belen Reach extends from Isleta Diversion Dam to the mouth of the Rio Puerco (Figure 1) and was about 550 feet wide prior to 1972. This reach currently averages about 350 feet wide, and the channel is continuing to narrow through island and bar development and is transitioning to a single thread channel. The historic sand bed is coarsening to areas of gravel bed. Both the Albuquerque and Belen Reaches appear to have a sediment transport capacity greater than the amount of sediment being supplied, whereas historically the sediment transport capacity appeared to be less than supply. These reaches will likely continue to experience channel slope reduction, through bed degradation and lateral migration. This means there is less sediment being supplied to Isleta Diversion Dam by the river than historically.

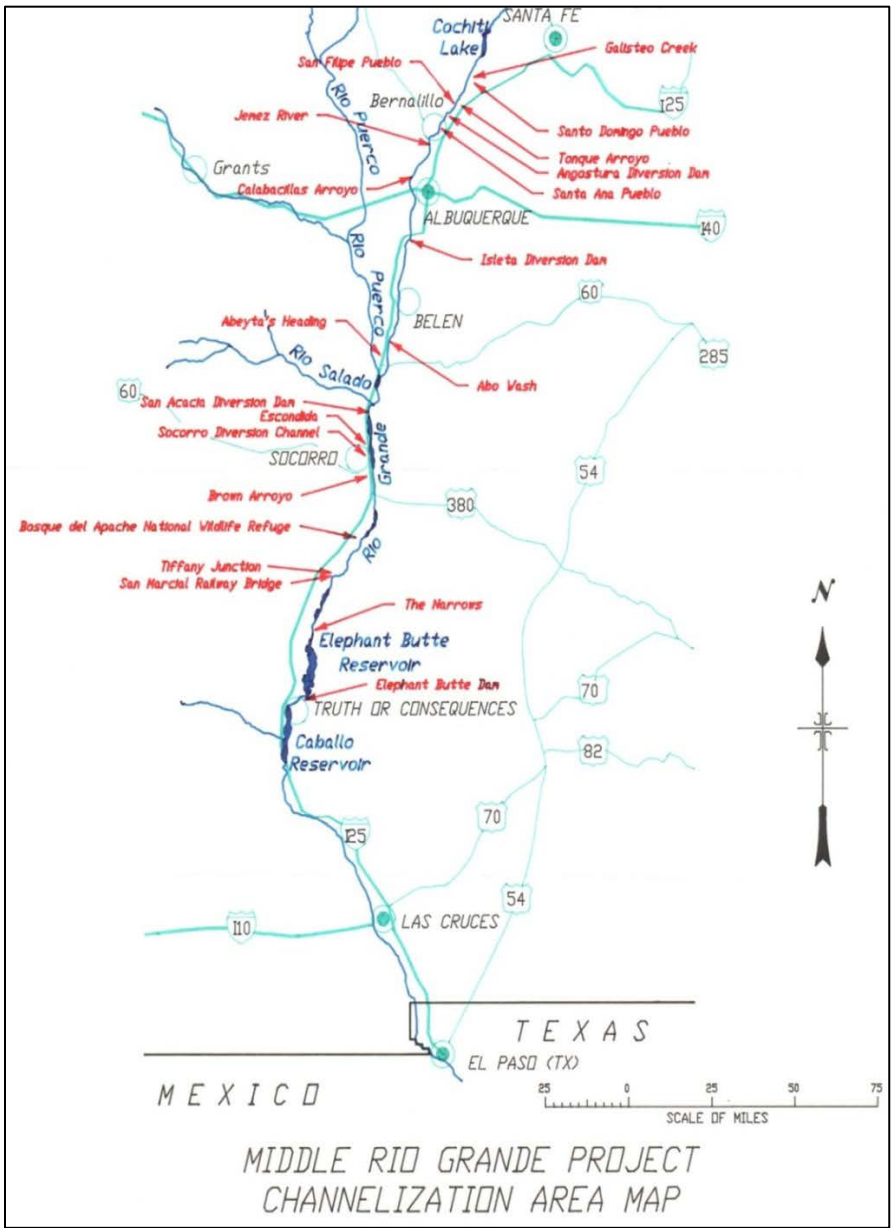

Figure 1. Location map.

MODEL SELECTION AND APPLICATIONS

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) backwater step hydraulic model developed by the U.S. Army Corps of Engineers (USACE, 2008). This model simulated cross section averaged river hydraulics for a series of steady, gradually varied flows. The SRH-2D model utilized for this study is a two-dimensional (2D) fixed-bed hydraulic model specifically focused on the flow hydraulics of river systems (Lai, 2008). SRH-2D solves the depth-averaged dynamic wave equations with a depth-averaged 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

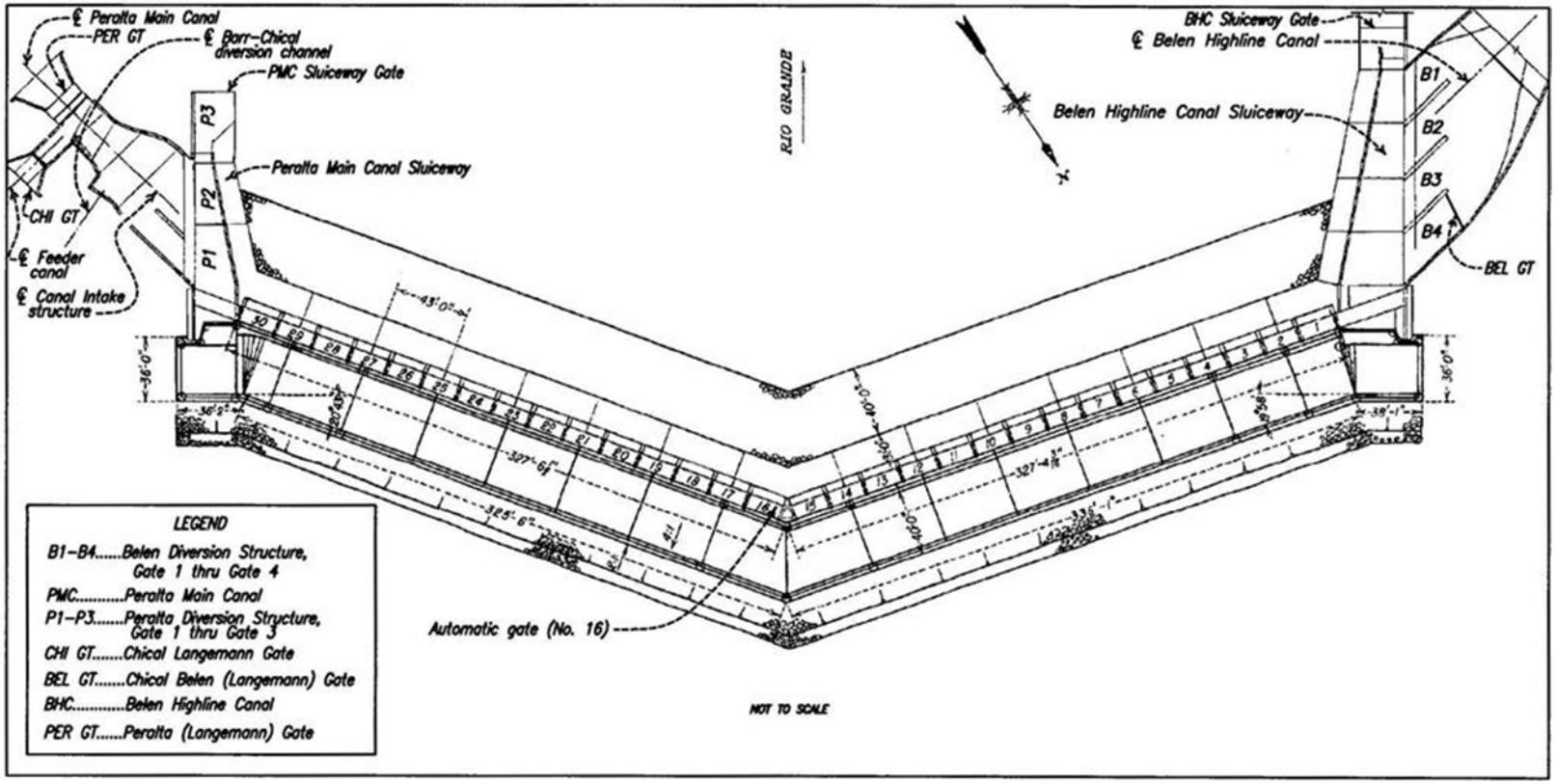

Figure 2. Isleta Diversion Dam plan view.

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, and ultimately leads to increased modeling efficiency through a compromise between solution accuracy and computing demand. HEC-RAS was utilized to set the downstream boundary in the SRH-2D model simulations, which consisted of a water surface elevation. At the time of this study, SRH-2D did not have the ability to model gates, while HEC-RAS did, so the HEC-RAS model was also utilized to formulate gate operations that made up a set of scenarios modeled in SRH-2D.

Topography Development: A combination of several data sets was utilized to construct the existing conditions topography of the study area. In-channel ground survey data were collected upstream and downstream of the diversion dam in 2005 and 2012 (exact dates are unknown) and supplemented with a more recent data set collected immediately upstream of the dam in June, 2013. These data were primarily used to represent the wetted portion of the channel (bathymetry). To supplement the survey data in the floodplain areas, a Digital Terrain Model (DTM) generated from Light Detection and Ranging (LiDAR) data collected in 2012 was utilized. By combining the interpolated survey data with the LiDAR data, a representative topographic surface was created in ArcGIS using a Triangulated Irregular Network (TIN) methodology. It is important to note that the channel bed near/around the diversion dam is extremely dynamic and based on river flows and operational strategy of the diversion dam gates; comparison of the 2012 and 2013 survey data showed that gate operations have a significant influence on the bed elevation upstream of the dam. During the data collection period in June 2013 all diversions were through the Peralta Main side of the dam, and sediment deposition was observed upstream of the Belen Highline headworks. The 2012 survey data upstream of the Belen Highline side was several feet lower than the 2013 data. Most likely during high flows, with both sluiceways open, both sides of the dam would have a lower bed elevation than when no diversion of flow through the gates adjoining the sluiceways is occurring. The lowest measured bed elevation on each side of the diversion dam was used in this study. A project was implemented to remove islands and widen the channel downstream of Isleta Diversion Dam. The topography downstream was based on the project design while the upstream topography remained the same for both the pre-project and post-project cases. The existing and post-island removal project topographic surfaces are shown in Figures 3 and 4.

Modeling to Establish and Evaluate Effects of Gate Operations: The HEC-RAS model was used to establish gate operations and resulting water stage at Isleta Diversion Dam. The diversion dam was represented through a series of radial gates. The sluiceway and accompanying canal diversions were not represented in the model. The 1D downstream boundary condition was set to a normal depth slope determined by the average bed slope near the lower end of the model domain dictated by the 2012 survey data. The 1Dupstream boundary condition consisted of various discharges related to the gate operational scenarios that were evaluated.

A SRH-2D fixed bed model was used to evaluate channel hydraulics for selected gate operations. Surface-water Modeling System (SMS) software was used to generate the 2D mesh which contains finer mesh cells near areas of interest, such as the diversion dam, and coarser mesh cells elsewhere. The mesh stores bed elevation information based on the topographic surface and consists of quadrilateral and triangular shaped elements. SMS was also utilized to delineate model roughness areas and assign model boundary conditions. Hydraulic roughness is the primary calibration parameter for hydraulic modeling assuming the channel and floodplain geometry is accurate. Roughness assignments included ‘main channel’, ‘vegetated overbanks-islands’, and ‘concrete’ (diversion dam and sluiceways). Lacking any new data to calibrate to the main channel and overbank roughness in the HEC-RAS model were set at 0.028 and 0.045, respectively based on prior modeling effort (Tetra Tech, 2012). The ‘concrete’ roughness value was assigned to be 0.015 according to values found in literature for a float finish (Sturn, 2001). Roughness values in a 2D model are often lower than those in a 1D model because the 2D model solves for eddy losses independently, as opposed to these losses being lumped into the roughness value or expansion/contraction loss coefficients. Therefore, roughness values were set slightly lower in the 2D model at 0.025, 0.045, and 0.015 for ‘main channel’, ‘vegetated overbanks/islands’, and ‘concrete’, respectively.

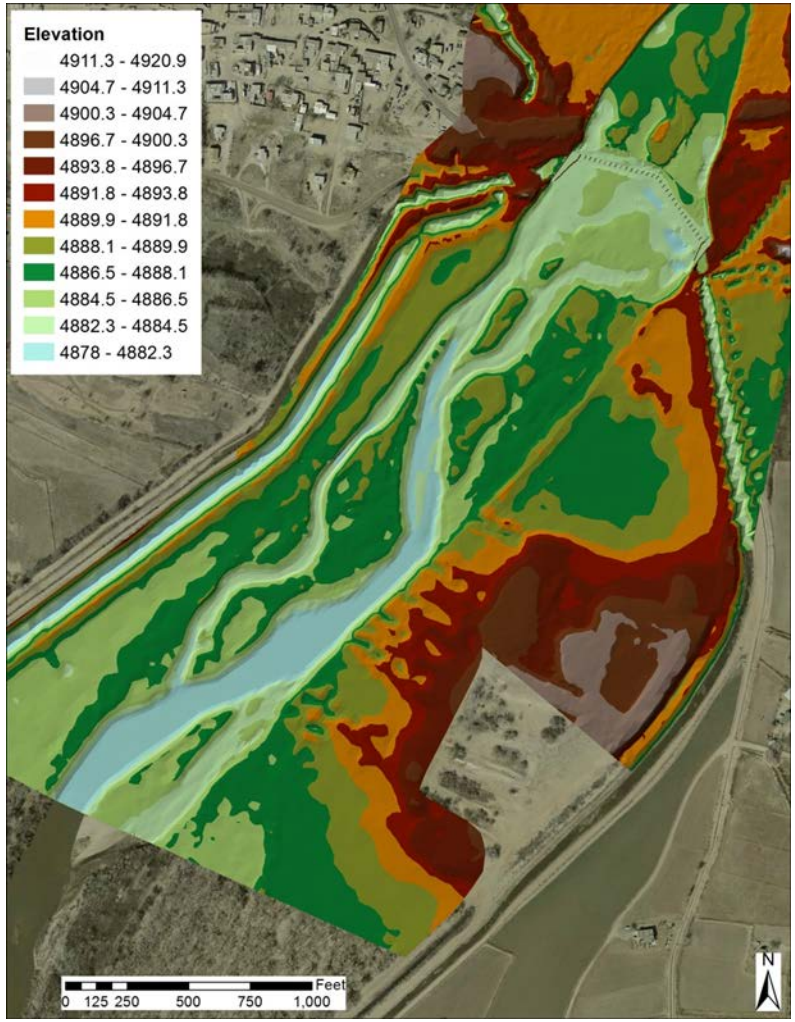

Figure 3. Existing conditions digital topographic surface.

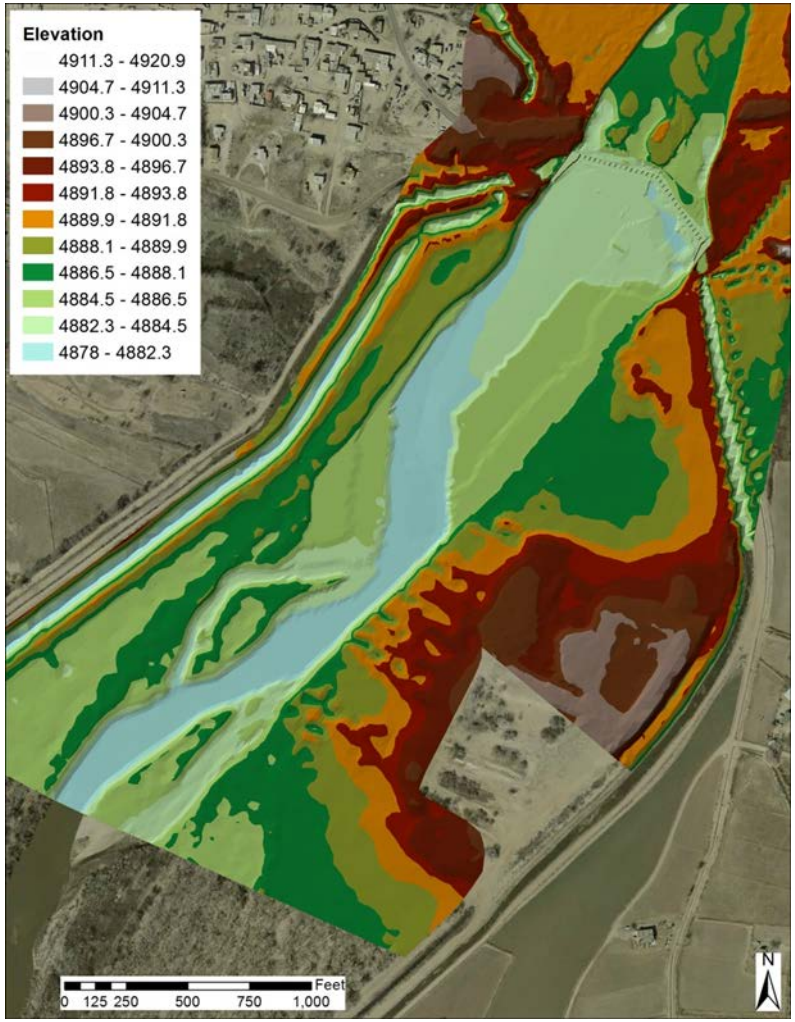

Figure 4. Post-project conditions digital topographic surface.

The 2D upstream boundary condition was specified as a steady flow input rate ranging from 500 to 5,000 cfs. The 2D downstream boundary condition was set to a corresponding water surface elevation based on output from the 1D model. Internal boundary conditions were also used to represent flow through each diversion dam and sluiceway gate as well as the sluiceway diversions. Maximum sluiceway diversions were 250 and 300 cfs down the Belen Highline and Peralta Main Canals, respectively. To ensure flow continuity, there were also a set of internal boundary conditions set up at the entrance to each sluiceway that controlled how much flow passed through each structure.

Sluiceway Hydraulics Methodology: The water surface elevation in both sluiceways predicted by SRH-2D for many of the flow scenarios was lower than required for full diversion head because the 2D model does not include hydraulic computations for pressurized flow through gates. Instead, local sluiceway velocity was evaluated using flow cross sectional area and discharge to solve the continuity equation (discharge= cross sectional area multiplied by the mean cross sectional velocity). For the Peralta Main sluiceway, diversions were equally divided for each headworks gate or bay (see Figure 2). For the Belen Highline sluiceway, all flows were diverted through the first and fourth headworks gate. The first headworks radial gate has been replaced by an automated Langaman gate which is used for all diversions (pers. communication David Gensler, 2013).

Sediment Incipient Motion Methodology: Incipient motion of sediment was computed to analyze the areas of potential sediment deposition, and sediment mobility. Incipient motion occurs when the shear stress (critical shear stress) acting on a particle of sediment overcomes the stabilizing force due to particle weight and size and the particle begins to move. The Shields Diagram (Shields, 1936) was used in this study to determine the critical shear which initiates sediment particle motion. Vanoni (1977) criterion was used to illustrate the velocity at which particles begin to move based upon extensive field and laboratory surveys. Bed sediment sizes upstream and downstream of Isleta Diversion Dam have coarsened from predominantly medium sand to coarse sand with some fine gravel, over time since about 1975 (Bauer, 2009). The most recent bed sediment sizes from the decade of the 2000s are shown in Table 1 which illustrates the median bed material size in the reach containing Isleta Diversion Dam is 0.6 mm (Bauer, 2009). Visual estimates from a recent field visit in 2013 validate similar sand sizes are present near Isleta Dam. One of the bed material measurements in Table 1 can be classified as fine gravel (4-8 mm). Visual observations of the downstream river bed indicate that gravel transport through the diversion dam delta is not likely at present. The upstream channel has degraded (bed lowered) but the delta length of about 2 miles has remained approximately the same between 1936 and 2002 (Baird and Strand, 2013). Because this study focus is mainly on sediment mobility in the island removal and channel widening area downstream of the Isleta Diversion Dam, only sand sizes were considered in this assessment.

Table 1 Median Bed Material Sizes (Bauer, 2009), Critical Velocity and Shear Stress for Incipient Motion Upstream and Downstream of Isleta Diversion Dam.

Direction from Isleta Diversion Dam	Distance from Isleta Diversion Dam (Miles)	Median Bed Material Size (mm)	Critical Velocity Hjulstrom (1935) ft/s	Critical Velocity (Vanoni, 1977) ft/s	Critical Shear Stress (Shields, 1936) lb/ft^2
Upstream	6.23	0.63	0.15	0.50	0.047
Upstream	3.54	5.72	N/A	N/A	N/A
Upstream	3.52	0.40	0.10	0.47	0.047
Upstream	3.53	0.40	0.10	0.47	0.047
Downstream	3.22	0.58	0.14	0.50	0.047
Downstream	3.23	0.80	0.20	0.55	0.047
Average		0.575 (Excluding Upstream Gravel Sizes)	0.14	0.50	0.05

Flow Scenario Gate Operations: Many different combinations of dam, sluiceway and headworks gate operations are used to meet water user, and Rio Grande Silvery Minnow flow requirements. Having 10-15 percent of the diverted flow pass through each sluiceway gate creates enough velocity and shear stress to nearly always eliminate sediment deposition in the Peralta Main and Belen Highline Canal headworks sluiceways. In this paper "sluicing" refers to having 10-15 percent of the diverted flow amount pass through each sluiceway gate (sluiceway outflow) and be released into the downstream river channel. Maximum sluiceway flows has been observed to maintain an open channel along the banks, especially the west (Belen Highline Canal) side. Opening every other gate has also been observed to minimize the propensity for downstream sediment bar deposition. Flow scenarios were selected to include representative peak diversions with maximum sluicing, representative minimum diversions with minimum sluicing (less than 10 percent), spring runoff peak river flows with maximum diversion, an inflow resulting in opening about ½ of the river gates, and maximum flows in each sluiceway. A summary of the above scenarios showing the magnitude of flows modeled in each scenario is shown in Table 2 followed by an example schematic of scenario #1 (Figure 5).

Table 2 Summary of modeled flow scenario gate operations.

Scenario ID	Scenario summary	Total flow upstream of the dam (cfs)	River gates flow (cfs)	Sluiceways	Sluiceway inflow (cfs)	Sluiceway diversion (cfs)	Sluiceway outflow (cfs)	Total flow downstream of the dam (cfs)
1	Maximum diversion with maximum sluicing	680	30 (Gate #16)	Peralta Main	345	300	45	130
				Belen Highline	305	250	55	
2	Minimum diversion (summer) with minimum sluicing	529	91 (Gate #16)	Peralta Main	235	220	15	124
				Belen Highline	203	185	18	
3	Typical spring runoff peak (non-drought) - all open gates	5,000	variable (all open)	Peralta Main	400	300	100	4,450
				Belen Highline	350	250	100	
4	Typical spring runoff peak (non-drought) - select open gates	2,820	1780 (10 gates at 178 each)	Peralta Main	520	300	220	2,270
				Belen Highline	520	250	270	
5	Maximum diversion - no open gates	1,565	0 (all gates closed)	Peralta Main	760	300	460	1,015
				Belen Highline	805	250	555	

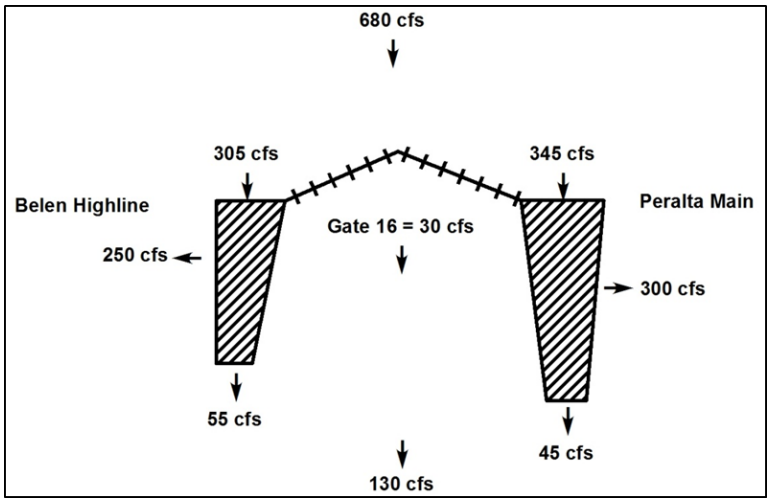

Figure 5 Schematic of scenario #1.

RESULTS AND DISCUSSION

This section compares and contrasts differences between each scenario for project topography. Also presented are sluiceway velocity and sediment incipient motion results for each scenario and the smallest sluiceway outflow volume which minimizes sediment deposition for all operations. Results and discussion for each scenario are presented first for scenarios with low likelihood, and second with high likelihood of bed change due to sediment deposition or transport. A qualitative evaluation of potential channel response to the island/attached bar lowering and channel widening project is also provided.

Potential for Deposition in Sluiceways: Flow velocity in the Peralta Main sluiceway is less than critical velocity, for median (0.6 mm) and larger sediment sizes, downstream of the third gate (P3 in Figure 2) in scenario #2, and in the Belen Highline sluiceway in front of gate #2 (B3 in Figure 2) and downstream of the fourth gate (B1 in Figure 2) for scenario #2. These results indicate a high likelihood of sediment deposition in both sluiceways when the operation has minimum summer diversions with minimum flow to pass through the sluiceway. The velocities were evaluated as being sufficient to transport sediment through the sluiceway in all other scenarios. For any diversion operation, the minimum sluiceway outflow discharge most likely to prevent sediment deposition in the Belen Highline sluiceway is 35 cfs, and 30 cfs in the Peralta Main sluiceway..

Gate Operation Effects on Potential Sediment Deposition and Erosion: This section provides results from the 2D model to evaluate the potential for sediment deposition versus erosion downstream of the dam for the proposed case where islands were removed and the channel widened (see Figures 3 and 4). The modeled water surface upstream of the diversion dam for all but scenario #3 was lower than needed to provide full diversion head. This resulted in larger velocities in the model results than actual field velocity. Therefore, this paper describes and uses model results downstream of the diversion dam for all scenarios except scenario #3. For scenario #3, all of the gates are open and upstream water surface elevations are accurate and consistent with field observations and HEC-RAS model results, and both upstream and downstream results are described. Model and incipient motion results are divided into two categories. Category 1 has a low likelihood for sediment erosion or deposition except in the immediate downstream vicinity of open gates. Category 1 includes scenario #1 and 2. Category 2 includes scenarios #3, 4, and 5 which have a high likelihood for sediment erosion or deposition. The proposed project topography results are shown and discussed for scenarios in each category with a qualitative discussion of likely channel response.

Category 1, scenarios #1 and 2 have a low likelihood of appreciable sediment deposition, due to the upstream sediment supply being low for this discharge. While there is low likelihood of erosion or deposition, if there was sediment supply from upstream tributaries this section describes potential areas change. Since scenario #1 and #2 have very similar hydraulic results, scenario #1 model results are used to represent both scenarios. The dark blue color in Figure 6 represents flow velocities which are up to the critical velocity of 0.5 ft/s for scenario #1 with the proposed channel widening downstream of the dam, and shows areas of potential sediment deposition. Zones of

potential sediment deposition are found in the first 400 ft. downstream of the dam between gates 16 and the Peralta left bank looking downstream of the left sluiceway (Figure 6). In the widened channel area there is a potential zone of deposition between about 1,000 ft. to about 1,900 ft. downstream of the dam apex, indicating a likelihood of sediment deposition which would potentially result in channel narrowing or areas where sediment would need to be excavated to maintain the channel width. Likely zones with small scour potential would be downstream of gate 16, downstream of the left sluiceway, between the right sluiceway and in the channel downstream of the right side sluiceway, and in the downstream channel center until the second bend (Figure 6).

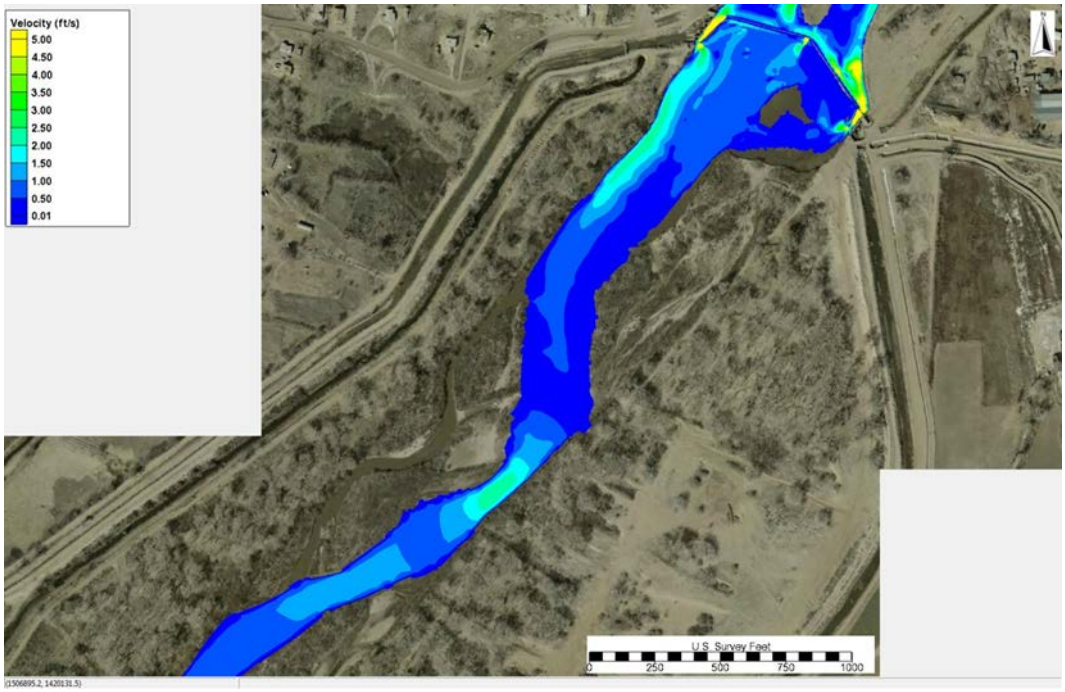

Figure 6 Proposed topography depth-averaged velocity contours for scenario #1.

Category 2 scenarios, #3, 4 and 5, each have a high likelihood of sediment deposition due to the sediment supply being relatively higher than for inflows to the diversion dam ranging from 1,565 to 5,000 cfs. Each of these scenarios has very different inflows and gate operations and results will be summarized separately. For Scenario #3, all river gates are open with 100 cfs flowing through each sluiceway; 4,450 cfs passes through the dam. Potential erosional areas would be around the upstream island (Figure 4). Flows near 4,450 cfs would provide the maximum opportunity for the widened channel to remain near the design width according to the SRH-2D model results and incipient motion criteria. The bank attached bars between 400 and 1500 ft. downstream of the Peralta Main sluiceway were lowered (Figures 3 and 4), and have velocities indicating potential for sediment deposition.

Scenario #4 has 1,780 cfs passing through 10 open river gates, and 220 cfs and 270 cfs flowing out the Peralta Main and Belen Highline sluiceways, respectively. One-to-three gates are closed between each open gate. The open gates are clearly shown in the velocity results (Figures 7 and 8). Flow velocity accelerates through the open gate contractions. Between open gates there are zones of low velocity and eddies (Figure 8). Deposition between open gates has been observed in the field. Downstream of each open gate there is high velocity with the potential for erosion. Zones of high velocity are found downstream of each sluicegate, and along the right main channel. The inundated portion of the east side bank attached lowered bar shows potential for sediment deposition. Flows near 1,780 cfs would provide opportunity for the widened channel to remain near the design width according to SRH-2D model results and incipient motion criteria. But not as much opportunity as 4,450 cfs flows in scenario #3. The bank attached bar on the left side between 400 and 1500 ft. downstream of the Peralta Main sluiceway was lowered (Figure 7 and 8) and made into two surfaces. These lowered surfaces are inundated at 1,780 cfs, and have velocities indicating potential for sediment deposition.

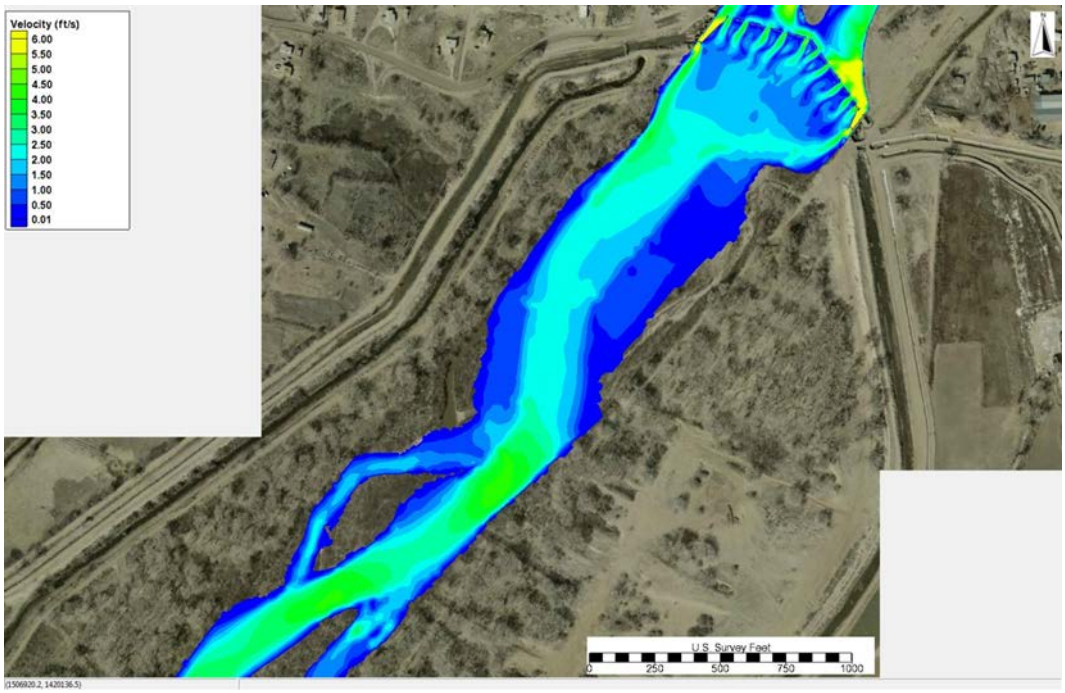

Figure 7 Project design topography depth-averaged velocity contours for scenario #4.

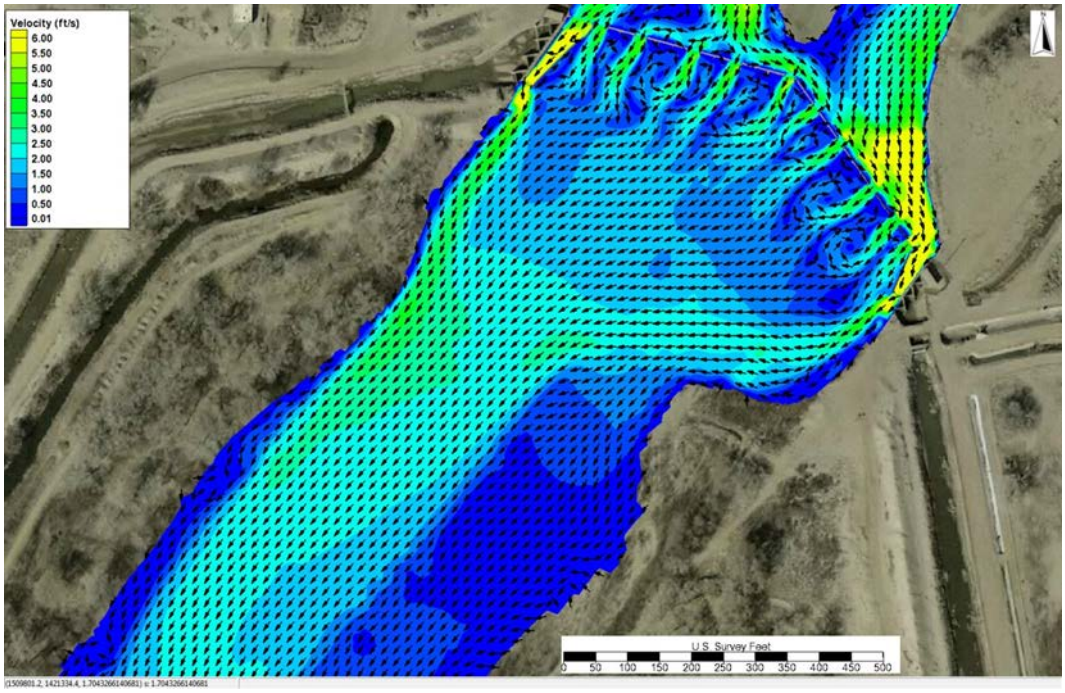

Figure 8 Project design topography depth-averaged velocity contours and vectors for scenario #4.

All river gates are closed in Scenario #5. Flow is maximized through each sluiceway in the amount of 460 cfs in the Peralta Main canal sluiceway, and 555 cfs in the Belen highline canal sluiceway. Maximum flow discharging through each sluiceway results in very high shear stress and velocity downstream of each sluiceway, especially the Belen Highline sluiceway. Downstream of the Belen Highline sluiceway the high velocity zone extends downstream about 600 ft. The majority of the zone downstream of the diversion dam between the sluiceways is depositional as a result of the formation of a slow velocity zone until the flow paths reconnect into the relatively

narrower downstream channel. Flow on the east abutment downstream of the sluiceway has the potential to cause scour extending across the east third of the distance across the channel below the dam. Scouring velocities also occur along the west bank downstream of the Belen Highline sluiceway downstream through the widened proposed topography reach. Flow in the left channel around the island shows potential for scour, while flow around the right side channel path shows potential for deposition and slight erosional tendencies.

These results are based upon the median sand sediment size of 0.6 mm requiring a velocity of 0.5 ft/s or larger to limit deposition (Table 1). Larger sediment particles could deposit in areas where velocity is between 0.5 and 1.0 ft/s, resulting in more areas of sediment deposition than described above. Results are also based upon fixed bed topography without potential bed elevation changes which would develop when considering sediment supply and sediment transport capacity.

SUMMARY AND CONCLUSIONS

A fixed bed two-dimensional hydraulic model was developed for Isleta Diversion Dam and the upstream and downstream channel. In addition a sluiceway hydraulic analysis was completed for the Belen Highline and Peralta Main canal sluiceways. Using the upstream and downstream median sand bed sediment sizes, the velocity which initiates sediment transport was estimated using the Vanoni, (1977) method. These results provide a quantitative basis for recommending gate operations to reduce sedimentation impacts.

Headworks sluiceway hydraulics and critical velocity analysis results indicate which scenario's result in sediment deposition or transportation through both headworks sluiceways. When the sluiceway outflow in the Peralta Main Canal is less than 30 cfs there is potential for sediment deposition. The Belen Highline Canal sluiceway velocity shows potential for sediment transport when sluiceway flows are 35 cfs or larger.

The SRH-2D model results and incipient motion analysis provided results to show velocity patterns and potential zones of sediment deposition or erosion for five flow scenarios ranging from 124 to 4,450 cfs river flows downstream of the diversion dam. In general maximizing flow volume in each sluiceway provides for potential erosion and high velocity flow along each bank downstream of each sluiceway and particularly along the west bank (Scenario #5). Opening every other or every third gate results in eddy currents and zones of potential deposition between gates. Operating only the sluiceways causes eddy currents near the downstream apex of the dam between sluiceways which indicates a potential for sediment deposition. The flow scenarios with river discharges equal to or greater than 1,780 cfs show potential for maintaining the widened channel. All flows inundating the lowered bank attached bars and islands showed potential for sediment deposition. Given the variable nature of Rio Grande hydrology, it is likely that the widened channel can be partially maintained with river flows, but supplemental mechanical widening may be needed to maintain the excavated hydraulic geometry.

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REFERENCES

Baird, D.C., and Strand, R.I., (2013). "Channel Characteristics of the Middle Rio Grande, near Isleta Diversion Dam and Sediment Management Gate Operations," U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, Denver, CO. Report No. SRH-2013-10.

Bauer, T. (2009). "Draft Sediment Effects on the Middle Rio Grande, NM," U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, Denver, CO.

Happ, S.C. (1948). "Sedimentation in the Middle Rio Grande Valley, NM," Geological Society of America Bulletin 59(12):1191-1216.

Gensler, D. 2013. Hydrologist, Middle Rio Grande Conservancy District, Albuquerque, New Mexico.

Lagasse, P.F. (1980). "An Assessment of the Response of the Rio Grande to Dam Construction-Cochiti to Isleta Reach," Technical Report for United States Army Corps of Engineers, Albuquerque District, Albuquerque, NM.

Lai, Y.G. (2000). "Unstructured Grid Arbitrarily Shaped Element Method for Fluid Flow Simulation,) *AIAA Journal*. 38(12), 2246-2252.

Lai, Y.G. (2008), "SRH-2D version 2: Theory and User's Manual," U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, Denver, CO.

Makar, P.W. (2010). "Channel Characteristics of the Middle Rio Grande, NM," U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, Denver, CO. Report No. SRH-2011-05.

Scurlock, D. (1998). "From the Rio to the Sierra: An Environmental History of the Middle Rio Grande Basin," General Technical Report RMRS-GTR-5. : U.S. Department of Agriculture, U.S. Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Shields, A, 1936, Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung, Mitt. Preuss. Versuchsanst.

Sturm, T.W. (2001). Open Channel Hydraulics. McGraw-Hill Series in Water Resources and Environmental Engineering. New York, NY. 493 pp.

Tetra Tech Inc., (2012), HEC-RAS model of the Rio Grande, Albuquerque, NM.

U.S. Army Corps of Engineers (USACE), (2008), "HEC-RAS River Analysis System User's Manual," Version 4.0, Hydrologic Engineering Center, Davis CA.

U.S. Fish and Wildlife Service (USFWS), (2003). "Programmatic Biological Assessment of Bureau of Reclamation's Water and River Maintenance Operations, Army Corps of Engineers' Flood Control Operation, and Non-Federal Actions on the Middle Rio Grande, New Mexico March 1, 2003-February 28, 2013," *U.S.* Department of the Interior, Fish and Wildlife Service, New Mexico Ecological Services Office, Albuquerque NM.

Vanoni, V.*A.*, ed., (1975). Sedimentation Engineering. ASEC Task Committee for the Preparation of the Manual on Sedimentation of the Sedimentation Committee of the Hydraulics Division (reprinted 1977) Manual 54, American Society of Civil Engineers.