Defining Discharge Required for Effective and Appropriate Sluicing at Oso and Blanco Diversions

San Juan-Chama Project
Colorado Upper Colorado Basin Region

U.S. Department of the Interior

February 2025

Mission Statements

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Cover Image – Blanco Diversion Dam gauge flood (Brian Leavesley/Colorado Department of Water Resources).

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Acronyms and Abbreviations

1D	one-dimensional
2D	two-dimensional
cm	centimeters
CODWR	Colorado Department of Water Resources
DOC	Designer's Operating Criteria
DPR ERC	Definite Plan Report - Reclamation Engineering and Research Center (renamed Technical Service Center)
ft/s	foot/feet per second
ft^3/s	cubic feet per second
HEC-RAS	Hydrologic Engineering Center River Analysis System
m	meters
mi2	square miles
mm	millimeters
MCSA	Monte-Carlo Simulation and Analysis
MPM	Meter-Peter Mueller
NOAA	National Oceanic and Atmospheric Association
Project	San Juan-Chama Project
RAS Mapper	River Analysis System Mapper
Reclamation	Bureau of Reclamation
RMRS	Rock Mountain Research Station
RMSEz	root mean squared error in z-direction (i.e., vertical)
$tons/yds^3$	tons per cubic yard
USFS	United States Forest Service
WSE	water surface elevation
yds^3	cubic yards

Symbols

=	equal to
≤	less than or equal to

%	percent
±	plus or minus
§	Section

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Executive Summary

The San Juan-Chama Project (Project) includes diversion dams on the Blanco and Navajo Rivers of southern Colorado. These diversion facilities require active trash and sediment management during flood operations and sediment removal each year due to the amount of trash and sediment load delivered by the rivers and upstream watersheds. Project diversion dams are equipped with sluiceway gates. As opposed to sluiceways in flood and irrigation storage reservoirs that are intended to pass large quantities of sediment to restore reservoir storage, diversion dam sluiceways are located next to diversion tunnels, and are meant to evacuate debris and sediment from in front of the diversion tunnel or channel to restore maximum diversion capacity. Sluicing operations are not intended to evacuate all the material from the operating pool behind the diversion dam.

Due to issues associated with sluicing in the initial years of Project operation, the decision was made to cease sluicing operations. The sluiceways are currently used only to deliver bypass flows. Both the 1972 Designers' Operating Criteria and the 2009 Standard Operating Procedures make clear that sluicing should be carried out during "floodflows," but do not define a specific threshold. This investigation took the first step to providing guidance on how to use these sluiceways effectively by finding that 200 ft^3/s at Blanco and 300 ft^3/s at Oso Diversion Dam is required for bypass flows to minimize the likelihood of negative impacts downstream. This conclusion is the result of sediment transport modeling that showed these values to represent bankfull conditions when deposition of fine material is minimized.

This finding indicates that total flows of 720 ft^3/s at Blanco and 950 ft^3/s at Oso are required for the diversion tunnels to be full and to have sufficient bypass flows. The defining of floodflows for these systems is a critical step to developing specific guidelines and procedures for effective and appropriate sluicing operations. In addition to defining floodflows, this investigation produced several recommendations for future to help inform sediment and debris management decision making.

Recommendation 1: Develop a Testing Plan to Optimize Sluicing Operations

With the knowledge of what are floodflows needed to implement a sluicing operation, the next step is to optimize the operations of the sluiceway and tunnel headworks gates. A testing regime, including data collection on efficacy and impact, should be planned, and implemented. The results of this sluiceway testing should inform future decisions about standard operating procedures or opportunities for automation. The conditions in which this testing can occur may not exist for several years, given the restriction to those flood conditions outlined above. Testing should occur in conjunction with downstream users and aquatic resource partners, including development of monitoring sites and protocols.

Recommendation 2: Analyze Historical Record of Diversion and Bypass Data to Characterize Extent of Diversion Losses Associated with Flood Conditions

This investigation compiled and analyzed the available stream gage data. Appendices A and B are plots of the combined bypass and diversion annual hydrographs. These plots allow a visual inspection of flood flows and how the diversion and bypass flows are divided. This inspection highlights that when flood flows occur, there are many cases when diversions decrease, and bypass flows increase. However, this relationship is not well known. No effort was done to quantify this dynamic, nor characterize of the extent of lost capacity due to floodflows through the life of the Project. Characterizing the extent of the problem is critical to assessing the benefit/cost of any proposed solutions.

Recommendation 3: Develop Debris and Sediment Transport Data Collection Plan

The data compilation and analysis for this report highlighted several things. Firstly, there is a serious dearth of debris and sediment transport data associated with the Project streams and diversions. The sediment rating curves developed for the Definite Plan Report were derived from a data set collected in 1962 and used to calculate the change in storage in Heron Reservoir. The data includes only suspended sediment, as design engineers assumed all bedload would be bypassed through the sluiceway. No effort was ever done to characterize the bedload component of sediment transport. Having robust and reliable sediment rating curves will provide valuable information for any future modeling efforts and help characterize the extent of sedimentation arriving at the diversion dams under a variety of conditions.

Given the extent of debris collected from the trash racks during floodflows in the past, it clearly plays an important role in blockage of the tunnel. Appendices B and C are a sample of inspection photos at Blanco and Oso Diversion Dams, respectively. While these photos show significant sediment deposition in front of and behind the trash racks, the dynamics between debris and sediment deposition is unknown. It is possible that a small change in operation of debris management will ameliorate much of the tunnel blockage.

Recommendation 4: Investigate Structural Solutions to Improve Facility Sediment and Debris Management

This investigation found that the Project facilities are in areas with a high potential for debris and sediment yield from the upstream watershed. The Blanco Dam is higher in the watershed and closer to sediment and debris sources, resulting in greater transport capacity and a higher proportion of gravel. In addition, there are no private homes or agricultural lands downstream of

Blanco until downstream of Highway 84. In contrast, Oso, is lower in the watershed, resulting in more total flow, but a high proportion of sands and lower transport capacity, with many homes and agricultural diversions immediately downstream on the Navajo River, making it a poorer candidate for sluicing operations.

The costs and impacts associated with current operations should be assessed in comparison to possible facility improvements. Numerical and physical models should be used to assess alternatives. Physical models can also be used to optimize gate and trashrack raking operations for sediment and debris management. Numerical models are very limited in their ability to represent sediment transport around complex hydraulic structures like the diversion dam. Reclamation uses planning structures such as the Value Planning Study to implement these kinds of high-level analyses.

1.0 Introduction

The San Juan – Chama Project (Project) is, in part, a trans-boundary diversion that diverts water from the Blanco, Little Navajo, and Navajo River headwaters in the San Juan Mountains of southern Colorado, through the 27-mile-long Blanco, Oso, and Azotea Tunnels and into Willow Creek, where it is eventually stored in Heron Reservoir (figure 1). Congress authorized the Project in 1962 under Public Law 87–483, 76 Stat. 96, 43 U.S.C. § 96 615ii–615yy. However, planning began in 1935 when stream gages were installed at Rio Blanco near Pagosa Springs and Navajo River at Banded Creek Ranch. After more than 20 years of data collection on both water availability and usage, a Plan for Development was issued November 1955. Upon completion of the Definite Plan Report (Bureau of Reclamation 1964) construction began in 1964 and was completed at the end of 1970. The first continuous diversions occurred in the spring of 1971.

The diversions are meant to function continuously so long as bypass flows are met. Bypass flows vary seasonally, requiring a maximum of 40 ft^3/s and 80 ft^3/s in May and minimums of 15 ft^3/s and 30 ft^3/s in January at Blanco and Oso, respectively. The fact that these watersheds are primarily snowmelt driven, with occasional monsoons, results in those months between the beginning and end snowmelt runoff having often little to no diversions possible as all existing flows are required for downstream bypass. Most diversions occur between April and July, with occasional monsoons also diverted.

After bypass flows are met, the remainder of the flow is to be diverted into Project tunnels. Diversion is limited to the tunnel capacities of 520 ft^3/s and 650 ft^3/s at Blanco and Oso, respectively. When flows exceed the tunnel capacities and bypass requirements, these flows travel over dam spillways through rivers eventually connecting with the San Juan River downstream. During high flows, debris and sediment partially block the tunnel entrance resulting in diversions less than the tunnel capacities, and large bypass flows. Trash racks in front of tunnel entrances and sluicegates in diversion dam spillways are features used to mitigate the impact of sediment and debris tunnel blockage during high flows to maintain diversion capacity.

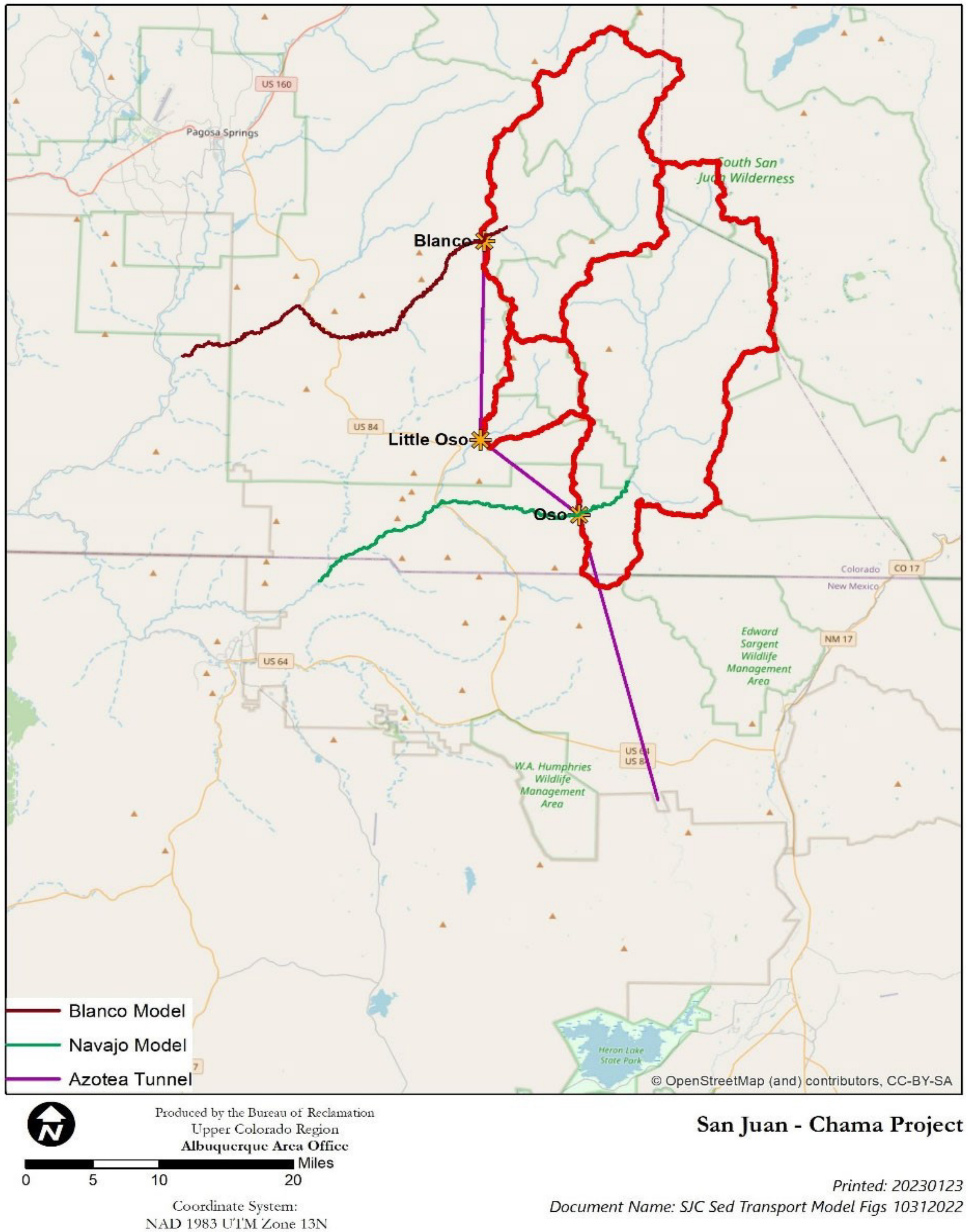


Figure 1.—Site Map of San Juan - Chama Project Transboundary Diversion, with dam watersheds and Blanco and Navajo River sediment transport model domains.

1.1 Dam Operations and Sluicing at Blanco and Oso Diversion Dams

The following narrative is a summary of communications between Reclamation operators of the newly finished diversion dams, the Southwest Regional Director, and engineers from the Engineering and Research Center in Denver, Colorado. Information is also derived from Inspection Reports during the early years of Project operation. All these materials are Sensitive but Unclassified Information. Lastly, quotes and information are also taken from the Schutz v. Stamm decision that was published in 1977.

With diversion beginning in 1971, by the fall of 1972 it was clear to the operators that the dams were getting overwhelmed with debris and sediment and thus could not be operated as intended. The bypass slot behind the trash racks were clogged immediately, and the sluicegate was required to release bypass flows. On November 15, 1972, Bureau of Reclamation

(Reclamation)'s Southwest Region Director wrote to the Director of Design and Construction at the Reclamation Engineering and Research Center (ERC) to request help. The operators of the dams noted the two basic problems that all similar facilities face, sediment, and trash. With respect to trash, the operators noted that:

> "During storm flows, trash will almost completely seal off flow through the trash rack, creating head differential downstream of the trashrack of up to 5 feet. With the floatwell downstream of the trashrack, this condition results in the automatic controls being completely useless as stream flow will be going over the ogee spillway; yet the controls are closing the gate as a result of the dropping water surface behind the trashrack."

Dam operators also noted issues associated with sediment at the dams, stating that:

> "Sediment creates two major problems; one affecting operation of the diversion dam when it fills with silt, and the other by potentially increasing the turbidity of downstream releases during sluicing operations. Comments from the fish and wildlife interests are to the effect that sluicing and turbidity are causing untold harm to fishing below the dam, and local interests are stating that sluicing of the sediment is causing wells to become inoperative.
>
> The basic argument against sluicing is that water is diverted and the sediment is left in the pool above the diversion dam. Later, this sediment would have to be flushed downstream at lower flows thereby increasing turbidity. An arbitrary decision for no sluicing would require the project to resort to manually cleaning each reservoir…"

The letter concludes that "sluicing operations could be carried out if approached objectively." Chief of the Division of Water Operation and Maintenance responded in February 1973 to address the trash and sediment management issues. He offers to design some motorized drag bars to remove debris from the trashrack, as operators were removing trash manually. Lastly, the Division Chief concurs that an evaluation should be made of potential revisions to the sluicing operations and iterated that "In accordance with the Designers' Operating Criteria (DOC), the sluicing operation was intended to be accomplished during periods of floodflow to remove sediment deposits from in front of the headworks and not during low flows as indicated in your letter." Finally, the Division Chief recommends physically removing the sediment from the pool and **automating the sluicegate to respond to flood flows**.

After a very wet 1973 runoff season, concerns about operation of the project led to a site visit by the ERC Director of Design and Construction on June 27–29, 1973. Figure 2 shows that bypass flows during the spring runoff of 1973 exceeded 500 ft^3/s for several days and exceeded 200 ft^3/s for much of the season. Diversion data is not available for 1973. All available hydrographs at both Blanco and Navajo/Oso diversions can be seen in appendix A.

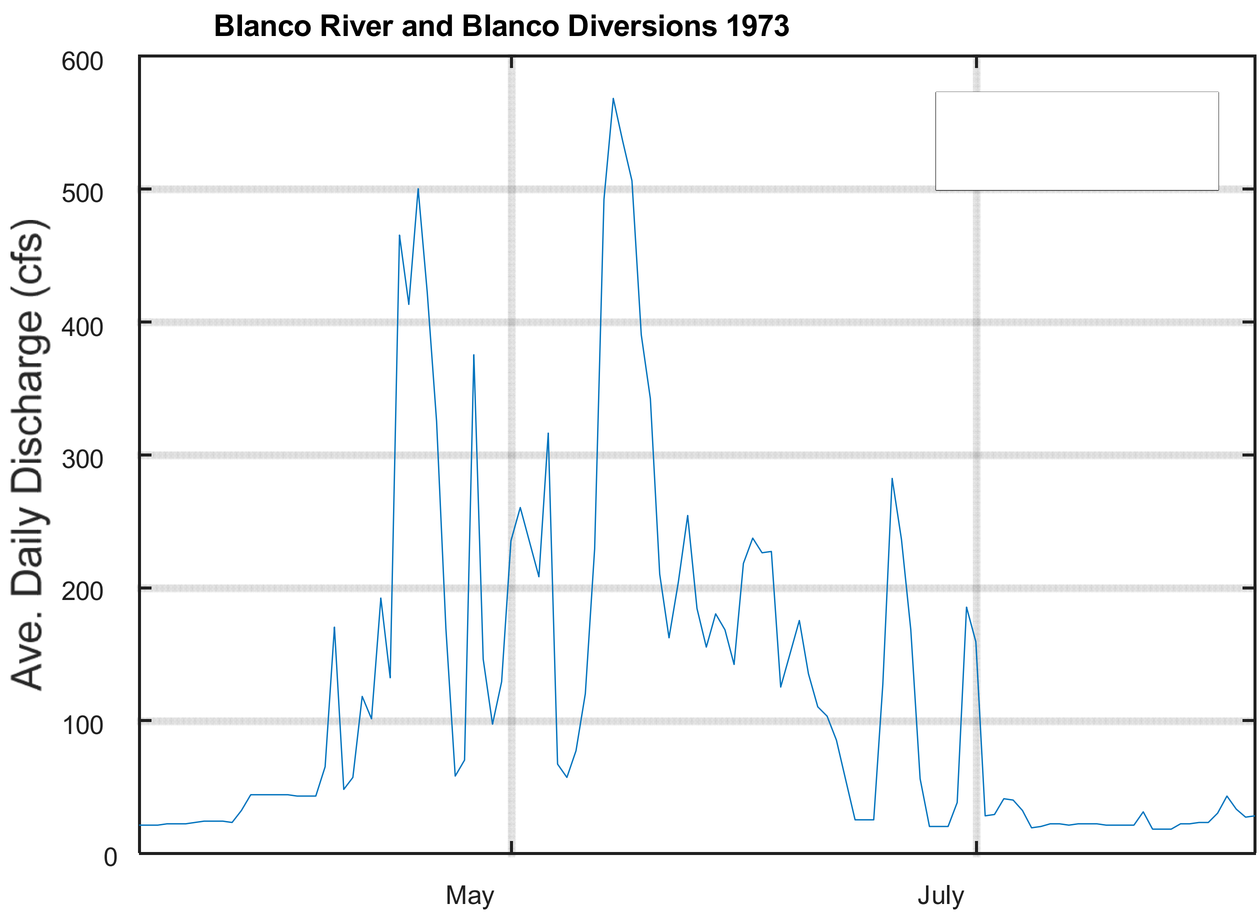


Figure 2.—Hydrograph of bypass flows in 1973 at Blanco Diversion Dam.

During the site visit, the dam operators indicated that:

1. Not using the sluicegate improves management the trash problem, as flows can carry logs over the Ogee weir.

2. Even if they would operate the sluicegate continuously, they do not believe the sediment could be sluiced from in front of the trashrack.

3. Sluicing is done periodically, which was daily at Blanco during the unusually high runoff of 1973, and weekly or more at Oso and Little Oso.

4. A headcutting channel cannot be developed upstream from the sluice gates because discharge through the sluice gate is inadequate to bring the water level below the top of the Ogee weir.

On the day of the site visit at Blanco Dam, a sluicing operation was carried out, and ERC notes state that:

> "Some floating trash had collected in front of the radial sluice gate which was open a few inches to help maintain downstream flow. Water was being diverted and flowing over the Ogee weir spillway. At 6 a.m. on June 28, the trash racks had been plugged with about 2.3 feet of drawdown through the trash racks. During our inspection the diversion gates were closed and the radial sluicegate opened to approximately 8 feet. Trash could be seen coming off the trash racks as the sluicing began. Some hand raking was required to loosen some of the trash from the racks. This reservoir was also nearly full of sediment. There was considerable gravel material in the upstream deposits. This gravel material could be heard banging against the trash racks during the sluicing and appeared to be controlling the head cutting through the upstream sediment deposits."

This account suggests that under certain conditions, the sluiceway at Blanco can pass sufficient flow to develop a head cut channel through the sediments deposited in the operating pool. However, operator experience also suggests that during higher flows, the sluiceway size is insufficient.

Additionally, the dams are designed with a slot vortex tube just behind the trashrack. This 3-inch slot in the floor is designed to entrain fine bed load and divert it into a 30-inch bypass pipe that outlets into the sluicebox. The ERC found in their 1973 inspection that:

> "The 30-inch bypass pipe that acts as a vortex tube, located between the trashrack and the radial gate to the tunnel, was completely plugged with small limbs and trash. They noted that nothing would go through the 3-inch slot in the floor and that anything making through the 6-inch bar spacing is going through the tunnel."

The team also visited Oso Diversion Dam. At the time about 500 ft^3/s was being diverted and there was approximately 1.1-foot depth going over the Ogee spillway and 50 ft^3/s through the sluicegate. A sluicing operation was not performed. The 48-inch bypass pipe was not in operation due to a motor failure.

Many of the conclusions made by the Design and Construction Group from their observations in the summer of 1973 are still relevant today:

1. The trash problem has placed a great burden on limited personnel during spring runoff.

2. No measurements of sediment transport are available.

3. The sluice gates were designed to sluice the coarser sediments downstream and maintain a relatively clean channel immediately in front of the trash racks. For Blanco and Oso Diversion Dams any coarse sediment moving through the trash racks would normally settle to the bottom and be flushed back to the river through the bypass pipe. In actual operation, the sluice gates are apparently unable to provide the velocity necessary in front of the trash racks to sluice sediment downstream. This, combined with the inoperable bypass pipes, is allowing coarser sediment to enter the tunnels.

4. If tunnel inspections show excessive abrasion, then some remedial measures to provide more effective sluicing will be investigated. Ideas discussed on-site included a training wall in front of the trash racks.

5. There is an immediate need to take whatever action is necessary to assure the bypass slot, pipes, and gate be operated at all times. This was to ensure that bypass flows are not interrupted.

6. The practice of sluicing of trash and sediment this year has apparently been accomplished without too many downstream complaints. This situation could become even more critical in future years because of fishery and irrigators' interests.

The team's immediate recommendations were:

1. The design and construction of a mechanized trash raking system should be investigated, along with costs.

2. The extent of sediment control will depend on the inspection of tunnels for abrasion from sediments.

3. The bypass pipes should be increased from 3 inches to 6inches, which is the opening between the trashrack bars.
4.

In addition, the field operator from Chama, Darrell Summers, had three suggestions:

1. A need to try different sluicing methods.
2. A skim wall or log boom.
3. A training wall in front of the trashrack.

The following summer in June of 1974 the ERC responded to the Regional Office request for ideas about how to remedy the trash and sediment issues with four proposed modifications, including drawings and cost estimates:

1. Open the vortex tube slot to 6 inches. This is not completed as of this writing.

2. Provide a vehicle ramp to the raking platform. This will necessitate cutting through the headworks transition wall. Heavy equipment cannot access the debris collected from the trashrack.

3. Remove the Ogee section and install radial gates. Maximum water surface will now be the diversion water surface. This proposal was meant to be tested in a scaled model. This model was never constructed as of this writing.

4. Change the location of the trashrack structure. The initial trashrack at Blanco Diversion Dam was half vertical bars and half winged walls meant to direct debris into the sluicegate and over the ogee weir (see first photo in Appendix C). In the early 1990s all the trashrack systems were upgraded and mechanized, not relocated.

As these proposed modifications represented a radical departure from the original design, they recommended that 1:16 mobile bed model studies be done to optimize proposed features and develop new Designer's Operating Criteria for the rebuilt structures. The Director notes that:

> "… Selection of the model option required field data obtained during an extensive sluicing operation. Detailed photographs, discharge readings, operation records, and elevations, and samples of sediment in front of the diversion would be needed."

In fact, suspended sediment data was collected above and below Blanco and Oso Diversion Dams between May 1972 and October 1974 and reported by the ERC. We were able to locate the report in draft form, as it was never finalized. The decision to not finalize the report was in part due to the conclusion that the data they collected was entirely insufficient to draw any appropriate conclusions. They collected only suspended sediment and the few samples where size distribution was determined, found that their samples contained only size fractions less than 1 millimeters (mm). The author of that unpublished report acknowledges that the bedload, or unmeasured load, is likely greater than the measured sediment load. Additionally, sampling was done in coordination with sluicing events, rather than taken to represent a variety of conditions. The draft report highlights the lack of sediment transport data with which to make conclusions.

Also in 1974, Ernest W. Schutz, Herman C. Hartong, and the Southwest Conservation District of Colorado sued the Federal government, specifically Gilbert Stamm, then Commissioner of the Bureau of Reclamation, A. Darrel Summers Project Superintendent, and Cecil D. Andrus Secretary of the Interior. The Jicarilla Apache Tribe was an Intervenor in the case. A decision was not rendered until three years later, on November 16, 1977 (Schutz v. Stamm 1977). The ruling finds that there are two separate and distinct duties placed on the Secretary by Public Law 87-483. Firstly, that “the facilities be operated without injury, impairment, or depletion of existing or future beneficial uses of water within the State of Colorado.” The second and separate duty is to avoid depletion of the flows of the Navajo and Blanco Rivers below the minimum bypass values. Judge Matsch found that operation of the Project did not impact existing or future beneficial uses of the water and that disputes related to how bypass flows were measured were beyond the expertise of the court. Judge Matsch also found that with respect to the sluicing, the duty to operate the Project without injury, impairment, or depletion of existing or future beneficial uses were violated. This finding was due to a variety of evidence and points of fact presented at trial.

According to the ruling, the effective use of sluicing requires “the level of the pool to be reduced to the top of the sediment before the sluicegate is opened so that when sluicing occurs there will be sufficient turbulence to cut into the accumulated deposits. The result is, necessarily, a high volume of sediment in a low flow of water going downstream to the detriment of downstream lands and users. In late 1971, an effort was made to remove sediment from the forebay (i.e., operating pool) at the Blanco Diversion Dam through mechanical dredging operations. That proved to be expensive and ecologically undesirable. There were complaints from downstream users about the turbidity and sedimentation of the stream from sluicing in 1971 and 1972.” And in 1973, a high-water year, the ruling states:

> “Without advanced warning, large surges of water went downstream with heavy loads of sediment. They occurred while the downstream users were irrigating, resulting in significant and substantial damage by inundation of the water users’ diversion structures and ditch headings, as well as the spread of sediment through irrigation ditches and across hay meadows.
>
> Another consequence of the 1973 operation was the deposit of significant amounts of sediment in the downstream channels of these rivers. The configuration of the streambeds was altered and many holes were filled. Those holes had given significant protection to fish, enabling them to avoid the adverse effect of high ambient air temperatures during the summer.
>
> It is inescapable…that the fish and aquatic life in the Navajo and Blanco Rivers has been adversely affected by the dams and their operation. Since 1973, there has been less effect from the sluicing operation; but it remains true that the sediment is carried by the by-pass flows with the diversion flows are relatively sediment free.”

Judge Matsch confesses that his ruling was delayed, "by an effort to reach a result which could be constructive in the future operations of the project." However, no result could be reached, and Judge Matsch was left stating that, "I am unable to do more that declare the statutory duties of the defendants." With respect to the sluicing operations, Judge Matsch clearly states the limit of his ruling as:

> "The technology of sluicing operations is also not a matter within the court's competence. The Congress has told the Secretary not to damage the water users in the operation of the project. They have been damaged by sluicing operations. This is not an action to determine the amount of the damage claims for operations consistent with those directions. I do not presume to such authority for this Court, and I am unable to accept the approach taken in Pyramid Lake Paiute Tribe of Indians v. Morton, 354 F. Supp. 252 (D.D.C. 1972). There are many downstream users and landowners who are not parties in this suit and those who are present here cannot represent them. If I were to mandate operating criteria and procedures which resulted in damage to those users and owners and if compliance with my orders provided a defense to their claims, the result would be a depravation of their property rights without due process of law. It would not be different if I were to direct the Secretary to formulate new operating procedures because the possible effect of my acceptance or approval of them would be the same as a mandate."

It appears there were several contributing factors that led to the downstream users' lawsuit. The first few years of operation of the dam did not go as planned. While the designers assumed the sluicing would occur during floodflows, when the greatest amount of sediment is being transported, in operation the dams were overwhelmed with both debris and sediment, the trash racks were clogged as was the vortex tube and bypass tunnel that comprise the low flow bypass system. All the material in the operating pool made the sluiceway ineffective, as insufficient flow was going through the sluiceway to create a headcut channel through the pool. Instead, after high flows had receded, dam operators attempted a sluicing operation where much of the sediment was in the finer size classes and little flow was available to transport those sediments, yielding high turbidity downstream. The high flows of 1973 really put the Project to the test. Figure 2 shows multiple peaks and low flow periods during the duration of the summer. Low flows would result in the trapping of sediments in the operating pool, some grain size sorting would occur in the quiescent pool, then another peak would come downstream and mobilize high concentrations of those deposited materials. The plaintiffs appealed Judge Matsch's decision the day after it was filed. However, the next spring on March 6, 1978, the court accepted their motion to dismiss their appeal, and the decision stands.

The sequence of photos in figure 3 were taken by the ERC at Blanco Diversion Dam on August 17, 1977, and show a before and after the operating pool was drained for tunnel inspection and provide a sense for how these sequences might occur. On the left of figure 3 the report states that, "the diversion pool is normally maintained about this elevation by automatic operation of the top seal radial gate which regulates flow into the Blanco Tunnel. Flow through the sluicegate was 20 cfs [ft^3/s], over the Ogee Wier was 69 cfs, and through the tunnel was

125 cfs." The photo on the right was taken after the operating pool was drained. Figure 3 shows that there is a large amount of sediment deposition and accumulation in the operating pool occupying most of the pool volume. In addition, little to no gravel can be seen in the photo, it appears to be mostly fine sediment. At the dam spillway, the sediment deposit can be seen to reach nearly the crest elevation on the opposite side from the headworks. After draining, a scoured channel can be seen along the dam headworks. No significant head cutting through the sediment deposit appears to have occurred with a total flow of 214 ft^3/s. It also does not appear as though the radial sluice gate is open very far.

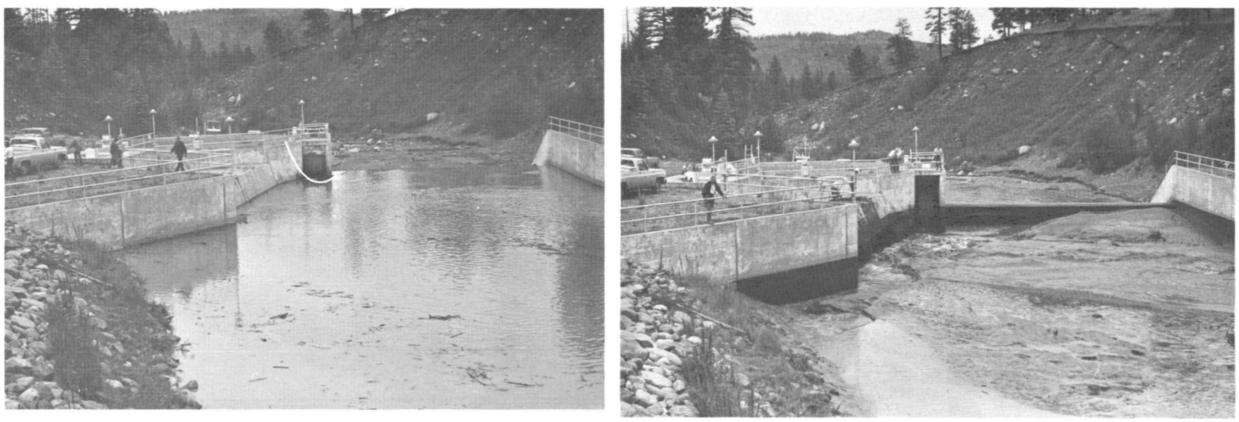


Figure 3.—Site visit photos from August 17, 1977, showing the operating pool full under normal operations (left), and after the operating pool was drained for tunnel invert inspection (right).

This operating condition at Blanco Diversion Dam diverges from those described in the Designers' Operating Criteria. The design drawings and description in the Designer's Operating Criteria indicate that the normal operating pool level is 6 inches below the crest of the spillway. This recommendation includes the assumption that regular sluicing operations are maintaining the trashrack and tunnel entrance clear of debris and sediment. Maintaining flow over the spillway could be an effort at trash management, as this would encourage floating debris to go over the spillway. This sequence of photos also illustrates how significant deposition of fine material may occur in the operating pool and low flows do not have the shear force to mobilize enough material to develop a headcut through those fine deposits.

In a February 16, 1978, letter from Reclamation's former Southwest Regional Office in Amarillo, Texas to Frank Maynes (one of the attorneys in the Schutz v. Stamm case), the statement was made, "That operation is to sluice only the bare minimum necessary to keep the structure in operation. The downstream users will be advised at least 48 hours in advance of such sluicing operations." On October 13 of the same year, a letter attempting to resolve the sluicing issues states that historically the Rio Blanco was heavily laden with silt and other natural materials during rapid thaws or rainstorms and that all natural materials could not be expected to be strained from the bypassed waters, and that Reclamation will continue to refine sluicing operations to reduce problems of downstream users.

By 1980 several improvements had occurred at the diversion dams. The inspection report from August of that year indicates that a new trashrack with chevrons was constructed at Blanco and was helpful but did not solve sediment and trash issues. The Chama personnel constructed trash removal system at Oso was effective. The v-notch bypass measurement weir was replaced with a Parshall flume to improve accuracy, as the v-notch weir was easily compromised by debris. While the radial diversion gates at both dams were in good condition, the 3-foot square low flow diversion slide gates could not be used due to rocks and had not been used since 1973 at Oso and 1974 at Blanco (figure 4). In addition, the bypass gates/vortex tubes were not in use and the sluicegates had been automated to facilitate bypass flows. Recommendation 80-2-B states:

> "Tests operate each gate at each structure at intervals in accordance with DOC, change DOC, or remove gates where appropriate and place gates in storage. (Operations restrictions per the 1974 lawsuit and subsequent instruction from Regional Director have resulted in limiting some gate operations.)"

Figure 4.—Low flow diversion slide gate blocked by rocks (October 18, 1994).

The next inspection occurs in October 1984. The 1984 Inspection Report mentions that the Upper Rio Grande Basin Projects Office is studying alternatives of sediment handling. These documents have not yet been located. The trash removal system at Oso was no longer safe to operate. The new dragbar system would be installed at the end of the 1985 diversion season.

The photo shown in figure 5 was taken during the 1987 inspection and shows a significant amount of sediment deposited behind the trash racks.

Figure 5.—Oso Diversion Dam inspection photo on October 22, 1987, from behind trash rack just upstream of the 10-foot x 13-foot radial gate.

While sluicing of sediments is minimized, the sluicegates are currently used to deliver bypass flows; therefore, the sluicegate is in regular use and some additional opening is often required to clear sediment and trash from in front of the sluicegate. In addition, the sluicegates are used to drain the operating pools for facility inspections and maintenance. A bypass channel and gate were constructed and installed at the Oso Diversion Dam in 1994, the channel, gate, and pipe opening are at a higher elevation and permits the bypass of required flows without using the sluicegate or bypass gate in the dam headworks.

When the sluicegate is closed during floodflows, the bedload quickly aggrades to the level of the headworks sill. This allows bedload, which represents the coarsest materials in transport, directly into the diversion tunnels. Facilitating bedload transport into the headworks has two significant impacts, 1) larger bedload material is very erosive and the ball-mill effect damages Project tunnels, and 2) aggradation and debris in the headworks forebays and trash racks may interrupt ideal operations, leading to loss of diversion capacity.

This phenomenon can be seen in figure 6. It shows that in 2019, a relatively wet year, that during the floodflows of spring runoff, diversions decrease while bypass flows increase. This same phenomenon can be seen in most wet years or during large monsoon events and can be inspected in appendix 1 of this report, showing all available paired diversion and bypass hydrographs at Blanco and Oso Diversion dams.

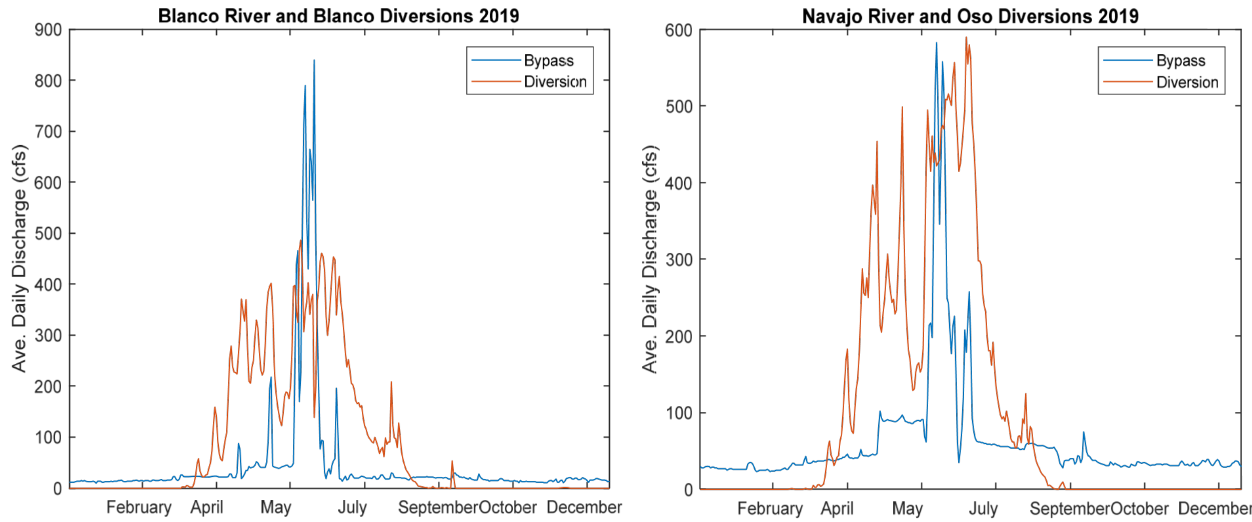


Figure 6.—Diversion and Bypass hydrographs for 2019 at Blanco (a) and Oso/Navajo (b) Rivers.

As high flows recede, under these operations, sorting occurs among the sediment grains in the operating pool, resulting in thick layers of silts and clays near the surface of the deposited material. Photos indicate that this sorting is much more prominent at Oso diversion. The sluicegates being open under these conditions, with limited bypass flows, is what led to high levels of turbidity and fine material deposition downstream, damaging fisheries habitat. This material is removed regularly by Reclamation to staff to reset the channel, clear the headworks and provide as much space as possible for the incoming material, and maintain diversion efficiencies as long as possible when floodflows occur again.

Project sluicing became a problem again in 2007, when two landowners downstream of Oso Diversion Dam complained after a larger than usual amount of sediment was deposited on their properties. The incident that produced this pulse of high sediment concentration, was the result of the need for tunnel maintenance, gates that were frozen, and an early runoff pulse. Flow had been directed to the open bypass gate (see figure 15) by building a temporary dike through the operating pool. As flow increased, a slush blockage occurred in the bypass gate, allowing flows to back up and eventually break through the dike. This directed flows across the operating pools, over a sheet pile weir, and the flow entrained a high concentration of fine materials. This highly concentrated water flowed through the sluicegate, that was frozen in the open condition. After several days, the sluicegate thawed and was closed to allow only the required bypass flows. This abrupt flow reduction resulted in the settling of those fine materials in the private landowners' stream channels where fishery habitat was being developed.

After this event, Reclamation staff discussed several scenarios to alleviate and minimize problems associated with normal sluicing operations. In 2009, the 35-year-old DOC was updated based on the actual operation of the dam as the Standard Operating Procedures. Included in the updates was the outcome of these conversations, where the following plan for sluicing was recommended:

> "Continue to remove sediment mechanically as regulated and permitted under Reclamation's Section 404 permit for the facility. However, to reduce the amount of fine sediments deposited against and near the diversion dam, increased sluicing energy would be used when high flows are available (this would occur when the diversion tunnel is already full, meeting all project diversion obligations). As flows in excess of diversion capacity start to flow over the diversion spillway, the sluicegate would be opened to pass those excess flows from the reservoir bottom to mobilize the finer sediments dropped out near the diversion dam, and to pass them downstream with sufficient flow volume to provide a more natural transport event. This action would mimic the natural hydrograph and provide additional sand substrate to benefit the downstream fishery. It would also reduce the amount of sediment requiring mechanical removal. The diversion pool's coarser-grained sediment could be removed mechanically and delivered to the managers of the downstream fishery for reintroduction and their 404 permit if they so desired."

The project described herein is an effort to quantify these recommendations through an analysis of available data, hydraulic, and sediment transport modeling.

1.2 The Tunnels

In addition to the challenges associated with sediment and trash management, the tunnels presented their own set of surprises. On August 6, 1973, a portion of the tunnels were inspected, including a mile of the Blanco Inlet, and a half mile of the Blanco Outlet, Oso Inlet and Outlet, and Azotea Inlet and Outlet. The following findings and conclusions were made:

1. All sections have lost about an average of one-half inch with holes of up to 3 inches over the lower two feet of the invert.

2. Oso tunnel appears to be in the worst conditions overall; however, Blanco Inlet and Azotea Outlet are almost as bad.

3. The outlet of Oso Siphon has large rock visible concluding that the siphon is at least partially plugged.

4. The first three items after only one good runoff year (fall 1972 and spring 1973) would conclude that there is a major problem with erosion of the tunnel inverts.

Figure 7.—Tunnel invert erosion at the edges of the repaired patch, (right) Oso Tunnel 2022 inspection photos, and (left) Oso Tunnel concrete invert repair made in 1983 showing a small amount of erosion after one year of diversions.

Tunnel erosion is an on-going issue, and inspections are currently done annually. After testing a variety of patching methods and materials, replacing the concrete invert with new concrete was determined to be the most durable and cost-effective solution. However, this does not stop erosion entirely, as the seam between the two concrete sections now erodes (figure 7). In addition, there are several locations where neoprene belting is found to be effective at retarding erosion. This solution is also not perfect, as erosion continues at the periphery of the belt material (figure 8).

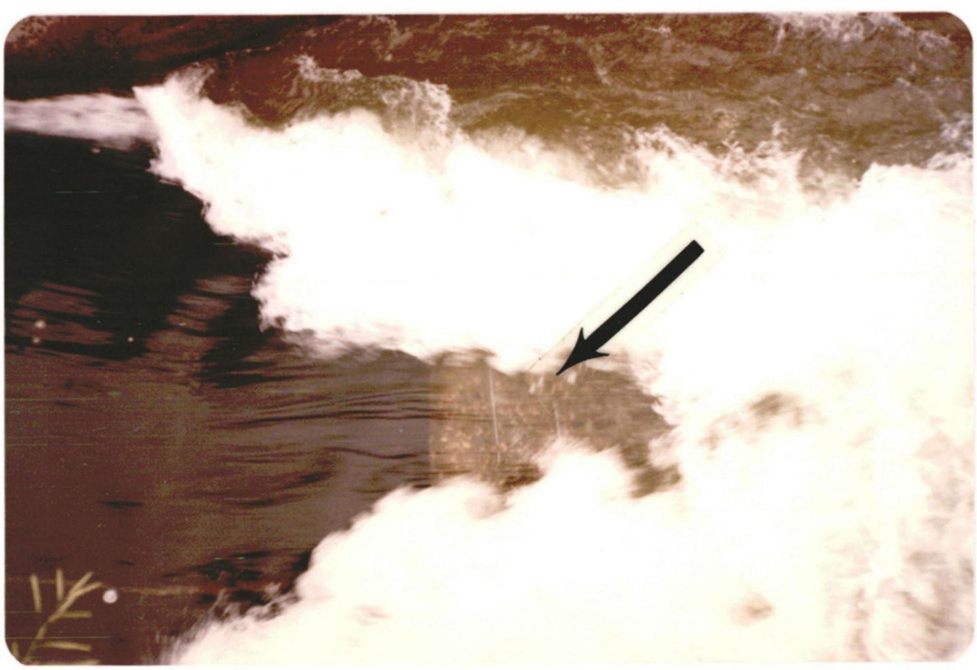


Figure 8.—Azotea Tunnel outlet structure. Exposed rebar directly below neoprene belting (1984).

Lastly, the tunnels must go under both the Little Navajo and Navajo Rivers at Little Oso and Oso Diversion Dams, respectively. The siphons that go under the river accumulate materials that can increase erosion and reduce conveyance capacity. Figure 9 shows that a significant amount of fine material is deposited during the drawdown of diversions (left), and that boulder and cobble size materials may also be present (right).

Figure 9.—Oso Siphon showing fine material deposition (left) and large size material at Oso Siphon outlet (right).

1.3 Blanco Diversion Dam

This dam sits at the downstream portion of a 90-degree bend (figures 10 and 11). The 5 x 17-foot radial gate in the sluiceway can be seen in the slot on left hand side of figure 10 and right of figure 11. The Blanco Dam is 13 feet high from apron to crest with a 5-foot headworks sill. Details about the dam and operating pool can be found in several sources (Reclamation 1964, 1972, 2019).

San Juan-Chama Project, Colorado-New Mexico
Upstream view of Blanco Diversion Dam

1. Blanco Feeder Conduit Headworks.
2. 5'x17'Sluiceway Radial Gate.
3. Ogee Weir.

Figure 10.—Looking downstream at the Blanco Diversion Dam, illustrating the dam components.

The Blanco Diversion Dam can experience large hydrologic events that carry significant debris and sediment loads. The sediment yield study (Reclamation 2019) found that on average the volume available below the headworks sill is likely to fill with sediment more than three times per year on average, suggesting that a significant portion of sediment is transported into the tunnel, where some fraction remains with the rest traveling to the tunnel exit in Willow Creek, where dredging operations are implemented. The degree of sedimentation is not well documented and data available is very sparce. An examination of the hydrographs in appendix A suggests that there are many years where debris and sediment overwhelmed the trash racks and headworks, resulting in high bypass flows. Reclamation does regular inspections of the Project components and in some cases those inspections occurred after high flow events.

A selection of photos can be seen in appendix C of sediment build up in the operating pool, inside the forebay, along with degradation in the system tunnels. It is worth noting that the report, corresponding to the photos in appendix C from the 2007 Review of Operations and Maintenance Report claims that 6,000 cubic yards (yds^3) of material was removed from the Blanco operating pool in 2007. Surveys of the dam operating pool indicate that this volume is greater than the pool volume as defined by the dam crest. This means that sediment accumulation was at a higher elevation than the dam crest.

San Juan-Chama Project, Colorado-New Mexico
Blanco Diversion Dam

Figure 11.—Looking upstream and downstream on Blanco Diversion Dam.

The spoils at Blanco Dam are stored in three areas that can be seen on figure 12. The two smaller areas are where most of the spoil stockpiling occurs. The larger 4.5-acre area is only used for overflow or transitional piles.

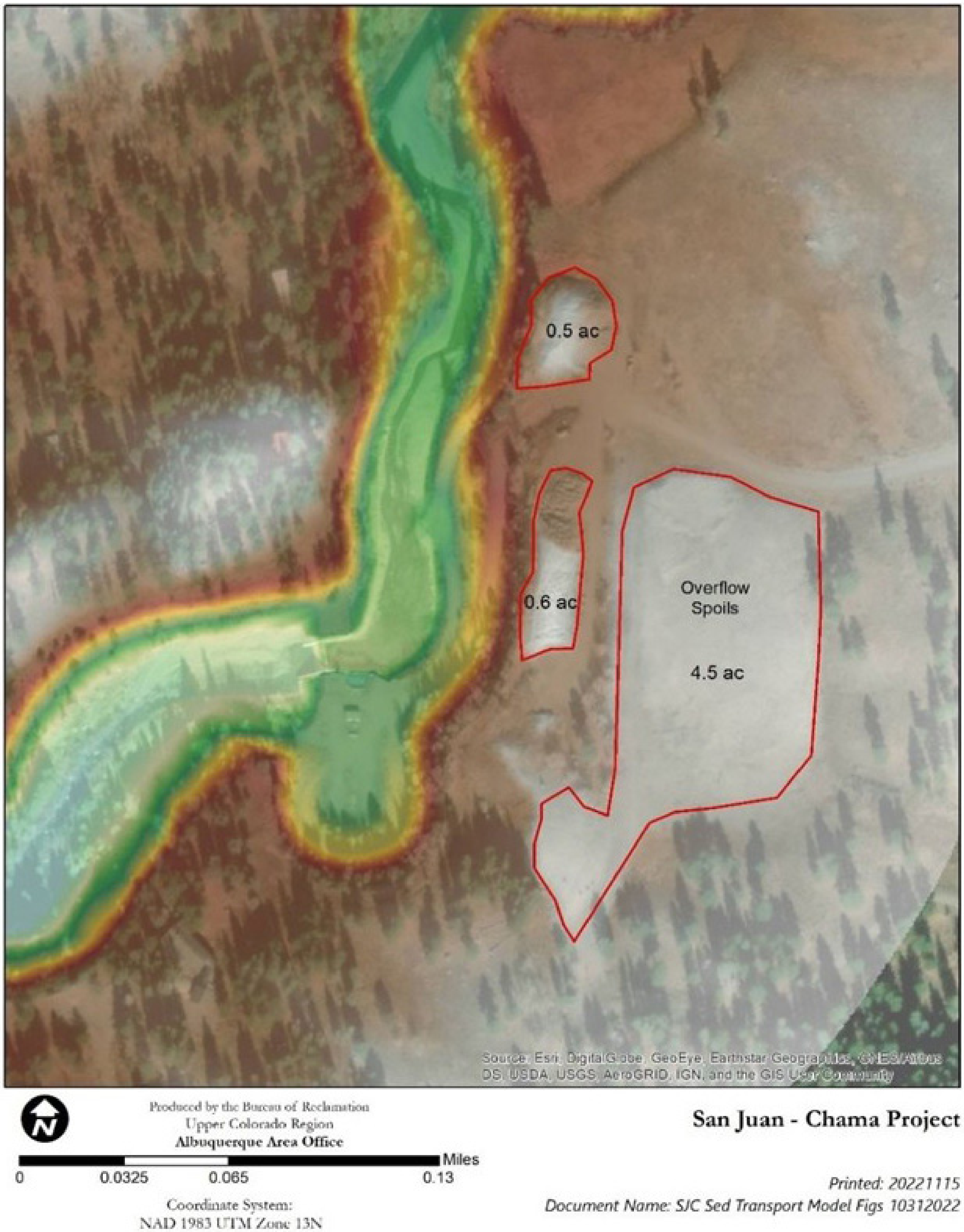


Figure 12.—Blanco Diversion Dam spoil stockpile locations.

1.4 Oso Diversion Dam

Oso Diversion Dam transects the Navajo River. Oso Diversion can be distinguished from Blanco in two significant ways, 1) the dam is 4.5 feet taller, and 2) the slope of channel is less than Blanco with a much larger operating pool. Figures 13 and 14 show the front and back facing sides of the dam, respectively.

Figure 13.—Upstream facing side of Oso Dam showing sluicebox and gate, as well as headworks trashrack. Dam forebay is behind this trashrack. A portion of the headworks sill can also be seen.

Figure 14.—Downstream side of Oso Dam showing spillway and sluiceway slot.

The impact of the higher crest and lower slope is the wider operating pool and the degree to which fine materials can deposit over a large area in the immediate vicinity of the dam. Photos of the dam during Project inspections can be seen in appendix D. These photos illustrate the great degree to which fine material and sands deposit near the dam and inside the forebay to the tunnel conduits. These photos indicate that the low flow slide gate is often buried in sediment. The photos indicate that regular dredging to maintain a channel to the diversion headworks is required, including excavation within the forebay where a small skid steer is used. Photos suggest that during floodflows the bed of the channel is at a higher elevation than the headworks sill. This condition will impair diversion capacity, and those diversion interruptions can be observed in the hydrographs in appendix A.

Figure 15 shows the spoil stockpile areas and indicates that significantly more material is stockpiled at this location. This finding is commensurate with the larger operating pool area.

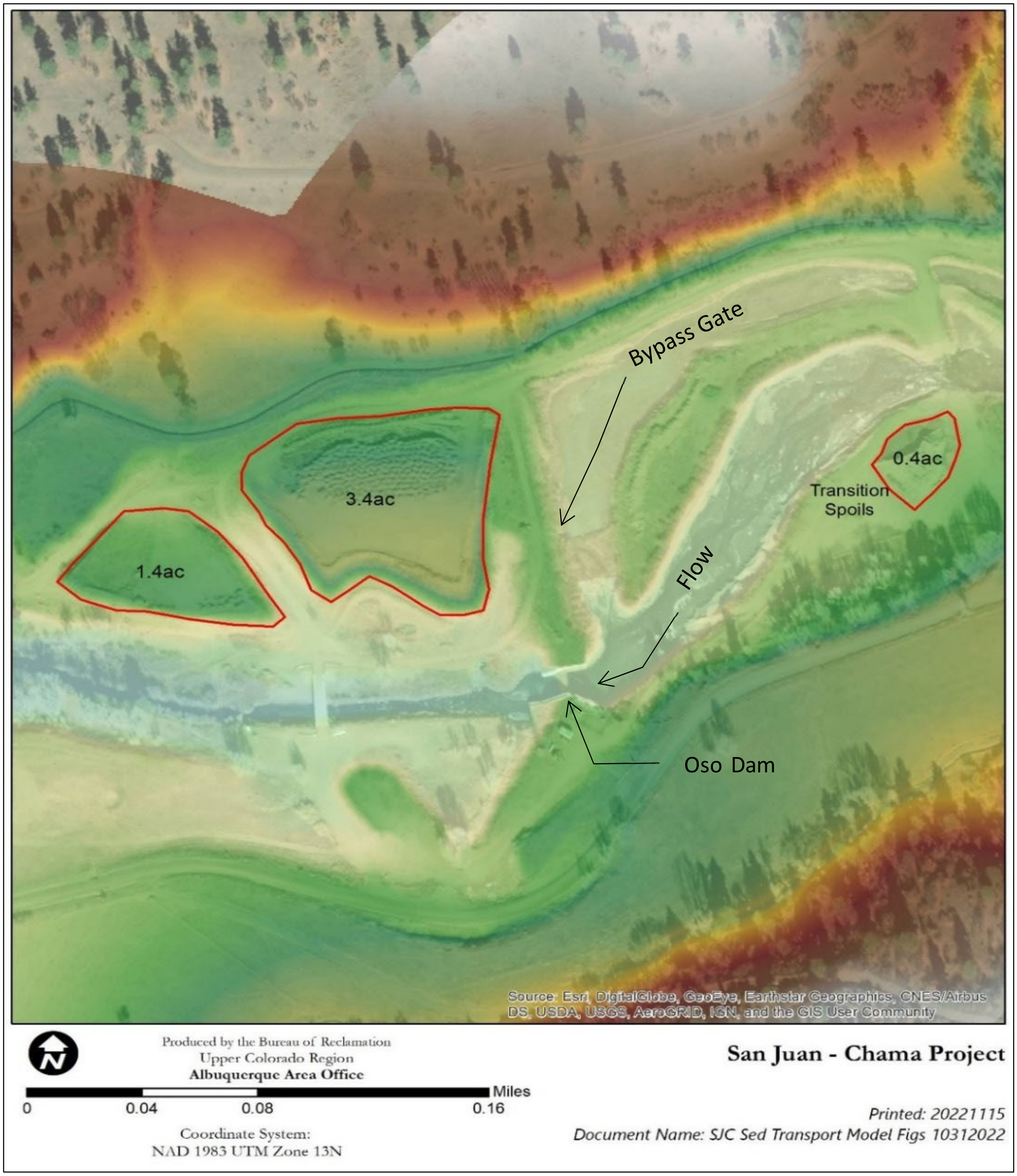


Figure 15.—Oso Diversion Dam spoil stockpile locations.

1.5 Aquatic Habitat and Restoration

The impoundment of the sediment transported in the Blanco and Navajo Rivers has significant consequences to the downstream morphology. The dearth of gravels and sands has created a very homogenous river with a high width:depth ratio and poorly sorted (i.e., narrowly distributed) cobble, boulder, and bedrock channel bed. In 2005, Reclamation surveyed habitat up and downstream of the Blanco Diversion Dam to investigate the status of Brown Trout (*Salmo trutta*) habitat and the potential for deposition of fine sediments that can degrade suitable habitat (Massong and Porter 2006). Their survey found that the upstream reach (the 500m section downstream of the diversion dam) has a very high sediment transport potential, where the channel has a steep cascade/step pool planform, dominated by large boulders and few gravel deposits in the low flow channel. Between the Blanco Campground and Hwy 84, they found less transport potential, with a pool/riffle plain bed channel planform. Downstream of the dam to Hwy 84, they found virtually no fine sediments, but large volumes of gravel derived from some mass wasting events on the river banks through this reach and deposited in log jams created from those same events. The survey indicated that the substrate varied from bedrock to boulder/large cobble.

The cutoff of both coarse and fine sediments to the downstream channels creates a threshold channel versus and alluvial channel. A threshold channel is defined by a channel that has no bedload transport occurring and the bed is either bedrock or fossilized with no bed forms. An alluvial channel has a dynamic bed with varying bedforms and in-channel complexities. The lack of gravel beds, deep polls, and shallow riffles makes for degraded trout habitat. This condition can be seen in figure 16. This photo comes from a report by Wildland Hydrology regarding a habitat restoration project on the Blanco River just downstream of Highway 84 (Kurz and Rosgen 2002).

Figure 16.—Photo of Blanco River illustrating homogeneity of stream habitats and absence of gravel and sand.

The habitat restoration solution that many have turned to is the creation of artificial step-pool sequences, mostly created using large rocks in some combination of j-hook and cross vane configuration. These check structures are often paired with placement of gravel in a bar configuration (figure 17; Kurz and Rosgen 2002).

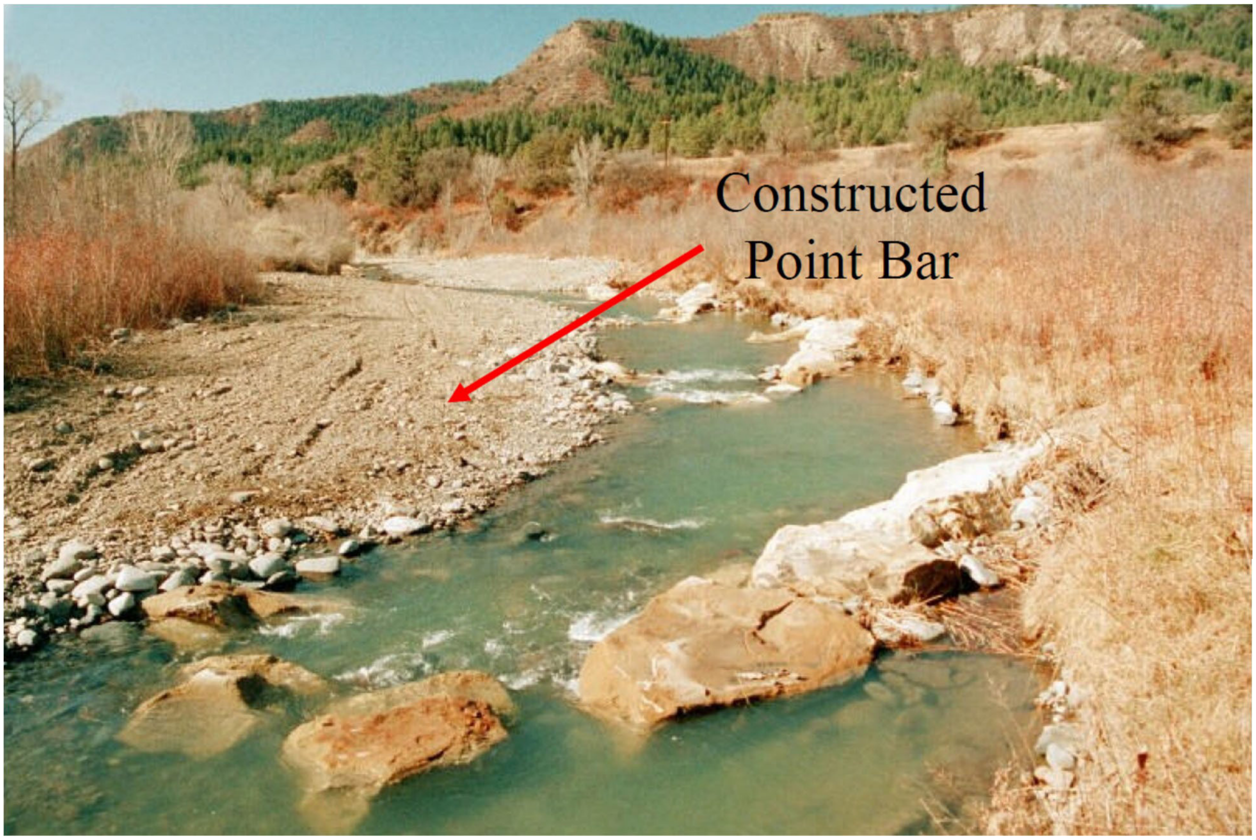


Figure 17.—Post-construction photo of J-hook vane and imported gravel point bar.

The success of these efforts varies greatly and depends on several factors including the sequence and magnitude of monsoonal and spring runoff flooding that occurs post-construction, and the appropriate siting, design, and construction of the features. Many of these features can be seen in the aerial imagery downstream of the Blanco and Oso Project diversions.

2.0 Problem Definition and Hypothesis Development

The investigation thus far has led to the following conclusions:

- Not using the sluiceway during floodflows impacts diversion capacity.
- Not using the sluiceway during floodflows results in emergency dredging, sediment, and debris removal to maintain diversion capacity.
- Diversion of bedload results in accelerated tunnel invert erosion and damages.

- Willow Creek outfall and Heron Reservoir storage design based on assumption that no bedload is diverted.

- Downstream river channel aquatic habitat is degraded by removal of sands and gravels at the diversions.

These conditions illustrate the value in being able to use the sluiceway during floodflows. This project sets out to test the following hypotheses:

1. There is a minimum threshold discharge value that is required to mobilize sands and gravels in each river system.

2. There is a minimum duration, or volume of flow, of this threshold discharge that will transport sands and gravels through the reach of interest.

3. The dam sluiceways are sufficient to bypass some portion of the sands and gravels through the Blanco and Oso diversion dams.

3.0 Data Availability

3.1 Elevation Data

This investigation benefitted greatly from the recent LiDAR acquisition by the U.S. Geological Service in 2018 and 2019 (Quantum Spatial 2020). This project collected data across a large portion of southwest Colorado at a 1 meter (m) horizontal resolution. In the vertical, their Quality Assurance/Quality Control report found the root mean squared error in z-direction (RMSEz) ≤ 10 centimeters (cm) (0.33 feet). Acquisition of this data is directly through the Colorado GIS Coordination and Development Program.

The data was collected over two time periods, October 5–November 10, 2018, and July 27–September 24, 2019. The 2018 data collection occurred during low flows and therefore LiDAR points gathered much of the stream bed. In addition, a water body layer was used in the data processing to adjust elevations or screen out areas with surface water. The acquired LiDAR can be seen in figure 18. The area resulted in the following model domains:

- Blanco: Upstream 4.5 miles, Downstream 67.7 miles; Total = 72.2 miles

- Navajo: Upstream 11.1 miles, Downstream 47.1 miles; Total = 58.2 miles

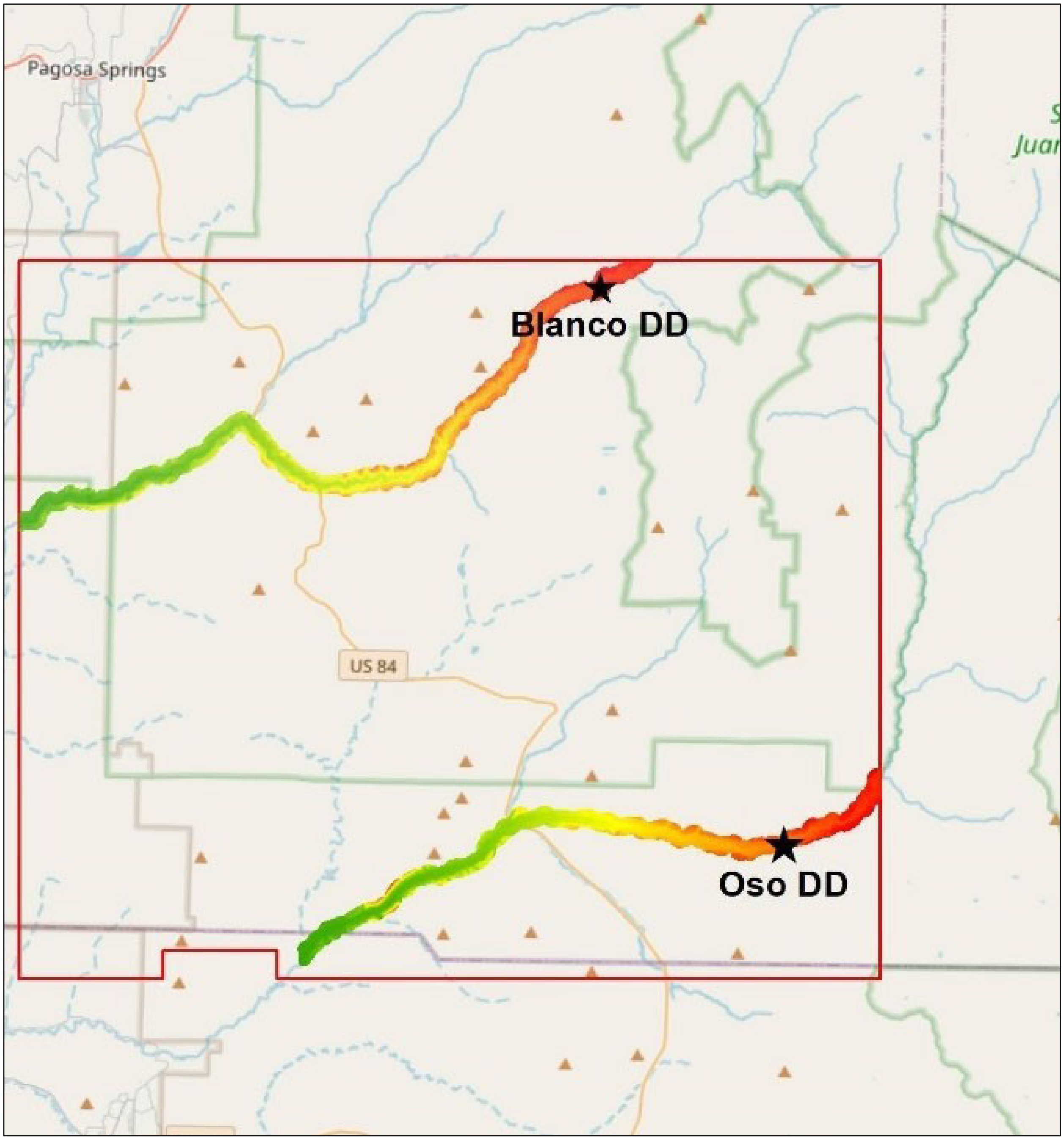


Figure 18.—Southwest LiDAR Project area representing Blanco and Navajo model domain.

Hydraulic model results were compared with aerial imagery to locate pools, riffles, and other features and determine the validity of channel bathymetry in the LiDAR. Rather than try and adjust specific locations, other than the operating pool bathymetry, the developed data surfaces were used as-is.

3.2 Hydrologic Data

3.2.1 Colorado Department of Water Resources

The Colorado Department of Water Resources (CODWR) operates and maintains the stream gages downstream of the Project diversions. Stream gages are a combination of two features, a long weir for high flows with a Parshall flume cut into the weir for low flows. Flow measurements from the Parshall flume are more reliable than those from the high flow weir. At Blanco and Navajo/Oso a 4-foot and 8-foot Parshall flume, respectively, is used to measure low flows. Parshall flumes at Blanco measure flows up to 56 ft^3/s and at Oso up to 140 ft^3/s. At higher flows a 60-foot weir with 12-foot sidewalls at a 2:1 slope is used at both locations. These weirs often collect debris, making it difficult to make high quality measurements (figures 19 and 20). Staff at the CODWR office that maintains the gages were very helpful in this project.

Figure 19.—Blanco River 4-foot Parshall Flume (left) and 60-foot weir at floodflow showing debris buildup (right). (photo by CODWR).

Figure 20.—Navajo River bypass gage 8-foot Parshall flume (left) and 60-foot weir at floodflow (photo by CODWR).

Gage data from these locations are available beginning March 1971 at Blanco and Navajo bypass. At flows that stay within the Parshall flumes, measurements are considered good, except during periods of ice which occurs most winter. Records from periods of flow above the Parshall flumes are considered fair.

3.2.2 Definite Plan Report

The Bureau of Reclamation set up stream gaging stations during planning for the Project and were maintained for just over 25 years. These values were used to both design the dams, but also to determine the resource availability relative to the downstream demands. The gages and their maintenance were:

- Rio Blanco near Pagosa Springs: May 24, 1935–September 30, 1961.
- Navajo River at Banded Peak Ranch: April 1, 1937–September 30, 1961.

3.2.3 Blanco River Bypass at Blanco Diversion

The mean hydrograph of the 30-yr record, between 1971 and 2021, along with several statistical metrics are seen in figure 21 and show an incredible amount of variability. The mean value represents the average of all the daily average values available (n = 30), and barely makes it to 100 ft^3/s, indicating the large number of low flow days in the historical record. However, with a maximum over 1200 ft^3/s, the record also indicates the potential for flow events more than 12 times the mean. In addition, the data show the extreme variability associated with the summer monsoons, where max values are over 800 ft^3/s. During the monsoon season mean daily discharge values represent the required bypass flow.

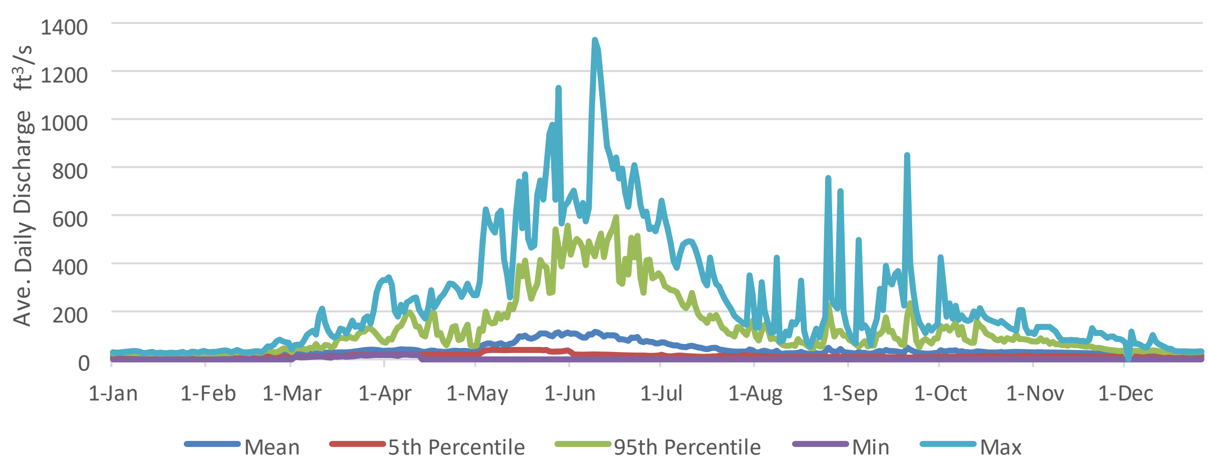


Figure 21.—Blanco River bypass 30-yr mean hydrograph, along with other statistical metrics.

This variability can also be seen in figure 22, that shows the cumulative annual volume, average annual daily peak discharge and the instantaneous annual peak discharges. Instantaneous peaks recorded were often well more than double the daily average discharges recorded at the gages.

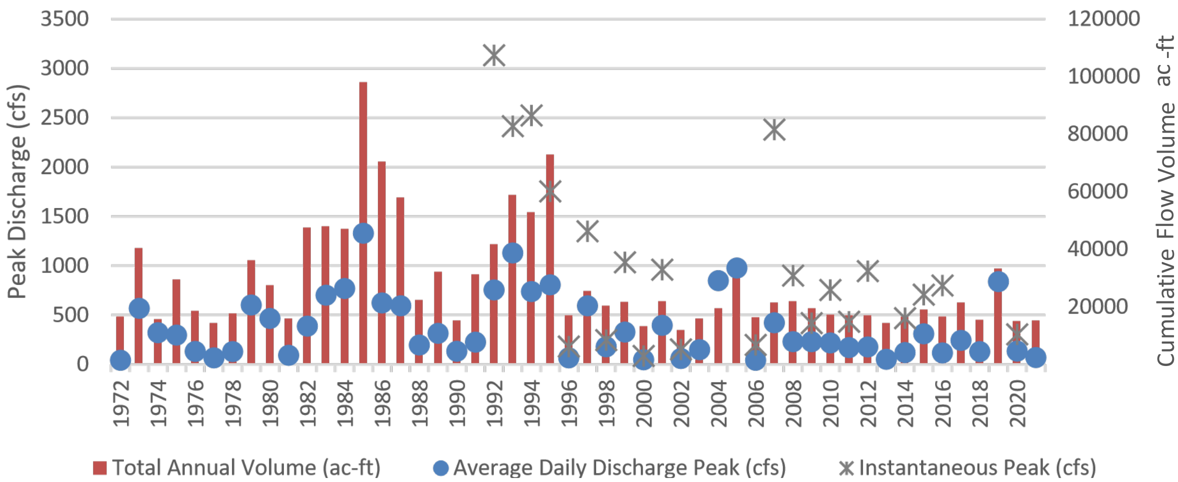


Figure 22.—Blanco River bypass gage annual flow volumes, daily average, and instantaneous peaks (1971–2021).

The Definite Plan Report includes a flow duration curve developed at the time of the report to estimate average conditions. The historic flow duration curve is compared with the flows observed in the CODWR record in figure 23. Figure 23 suggests that the bypass flows match up very well with the flows observed pre-Project development.

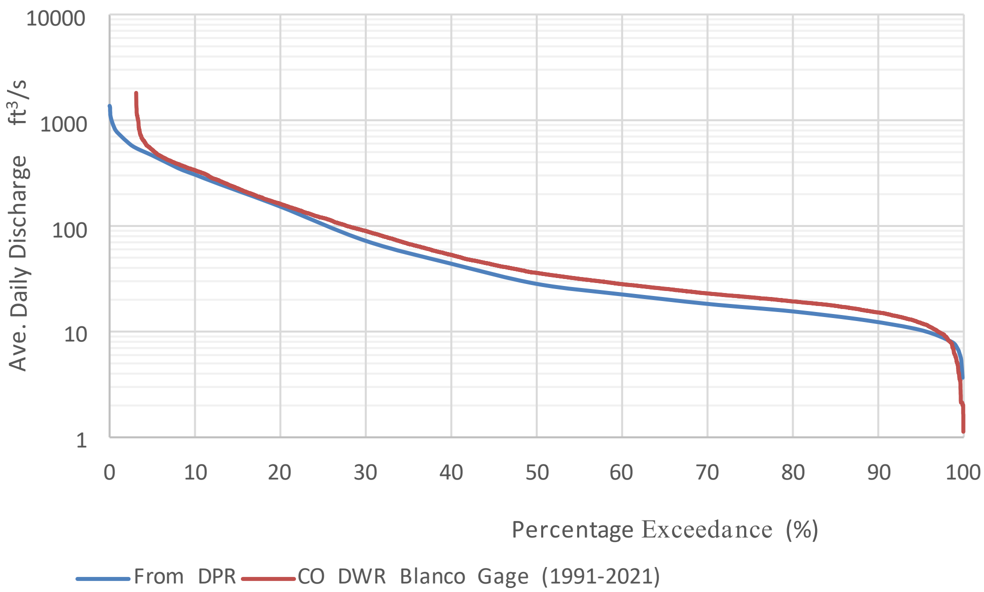
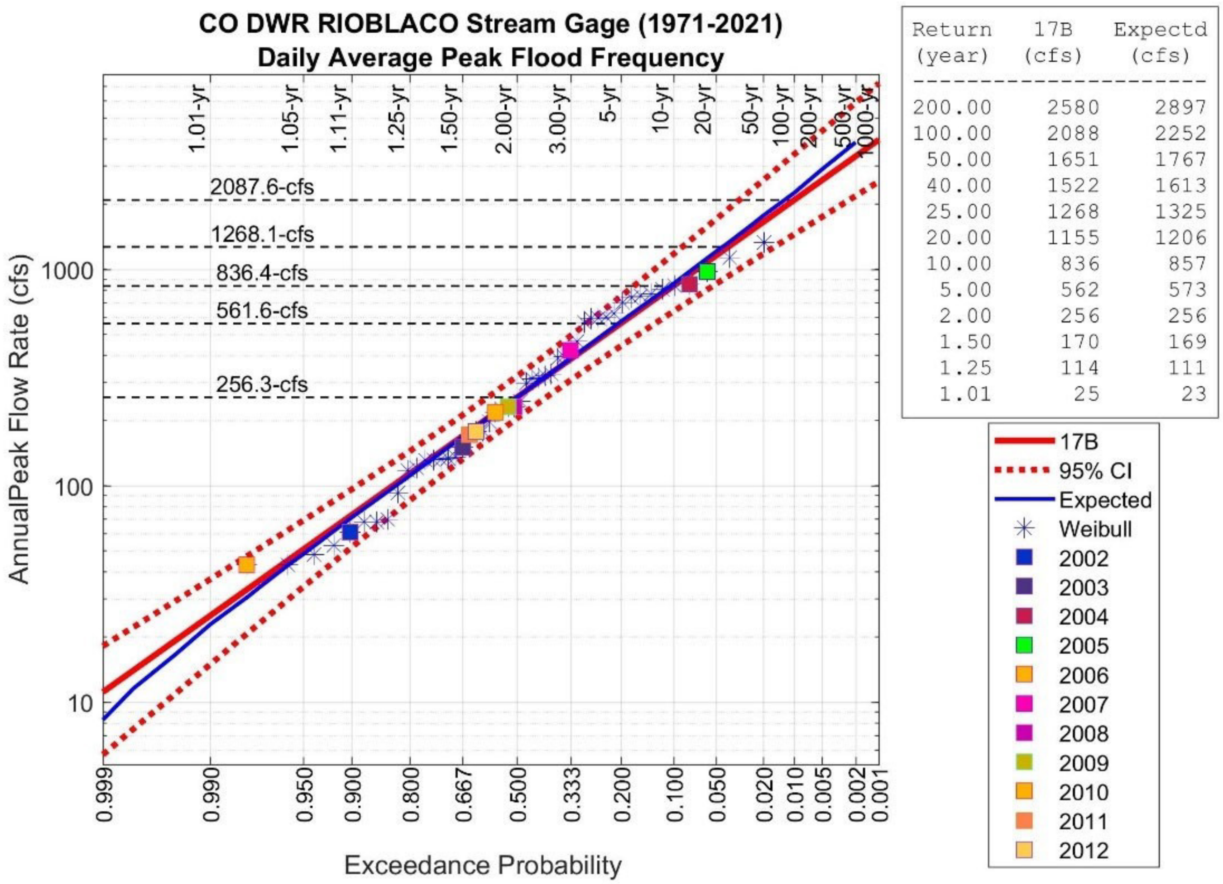


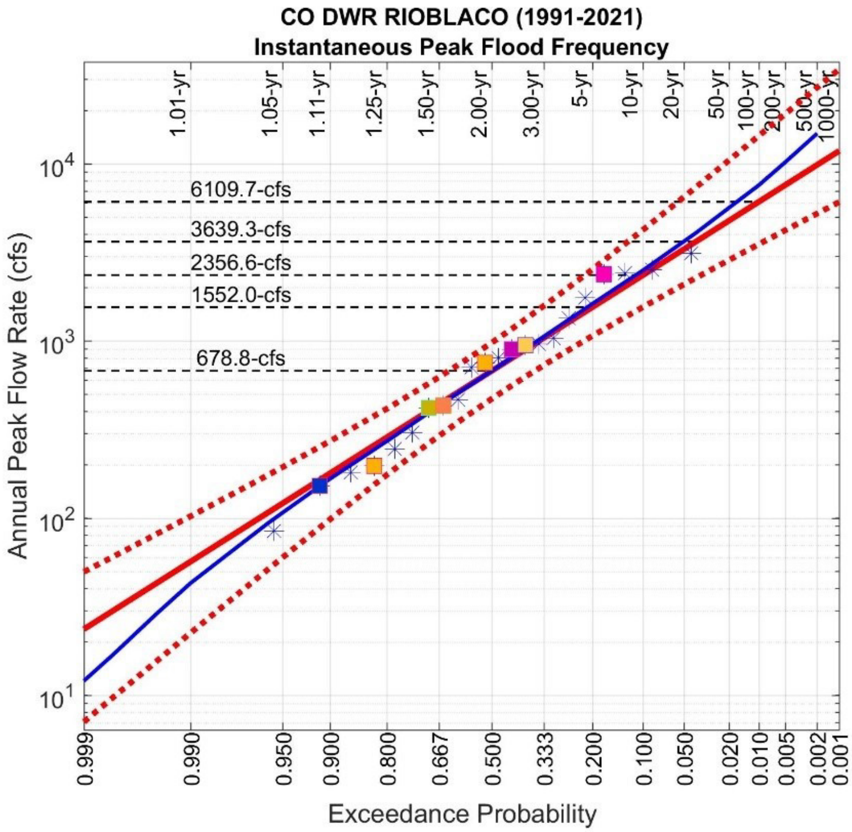
Figure 23.—Flow Duration curves from CODWR Blanco River bypass (1991–2021) and Definite Plan Report (1935–1961).

To better characterize the Blanco bypass flows, it is useful to look at the peak discharge flood frequency. Both the daily average and the instantaneous annual peaks were used to derive flood frequencies. Figures 24 and 25 plot the most recent events, the expected annual flood peaks, and include tables of the flood frequency values at common intervals, with the 17B value representing the USGS strategy and the Expected column representing the value determined directly from the Weibull distribution. These plots indicate that in any given year there is a 50 percent chance (2-yr flood) of an instantaneous peak of 679 ft^3/s, with a daily average of 256 ft^3/s.



Return (year)	17B (cfs)	Expectd (cfs)
200.00	2580	2897
100.00	2088	2252
50.00	1651	1767
40.00	1522	1613
25.00	1268	1325
20.00	1155	1206
10.00	836	857
5.00	562	573
2.00	256	256
1.50	170	169
1.25	114	111
1.01	25	23

Figure 24.—Blanco bypass annual instantaneous flood peak frequency plot and table.



Return (year)	17B (cfs)	Expectd (cfs)
200.00	7608	10246
100.00	6110	7582
50.00	4790	5664
40.00	4402	5117
25.00	3639	4074
20.00	3303	3656
10.00	2357	2510
5.00	1552	1622
2.00	679	679
1.50	439	430
1.25	286	272
1.01	57	43

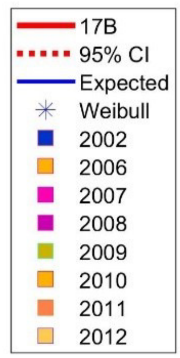


Figure 25.—CODWR Blanco bypass gage average daily discharge annual peak flood frequency and table.

3.2.4 Navajo River Bypass at Oso Diversion

The Navajo River below the Oso Diversion dam displays much of the same variability observed at the Blanco River. Figure 26 illustrates the mean, min, max, 5th and 95th percentile daily average flows for the 30-year period of record from 1971 to 2021. Figures 26 to 29 tell a similar story to the observations at the Blanco River with one important exception. While the 2-yr daily average flood peak for both the Blanco and Navajo Rivers is approximately 255 ft^3/s, the instantaneous peaks are much smaller at the Oso Diversion Dam bypass, resulting in an instantaneous peak of only 429 ft^3/s to Blanco's 657 ft^3/s.

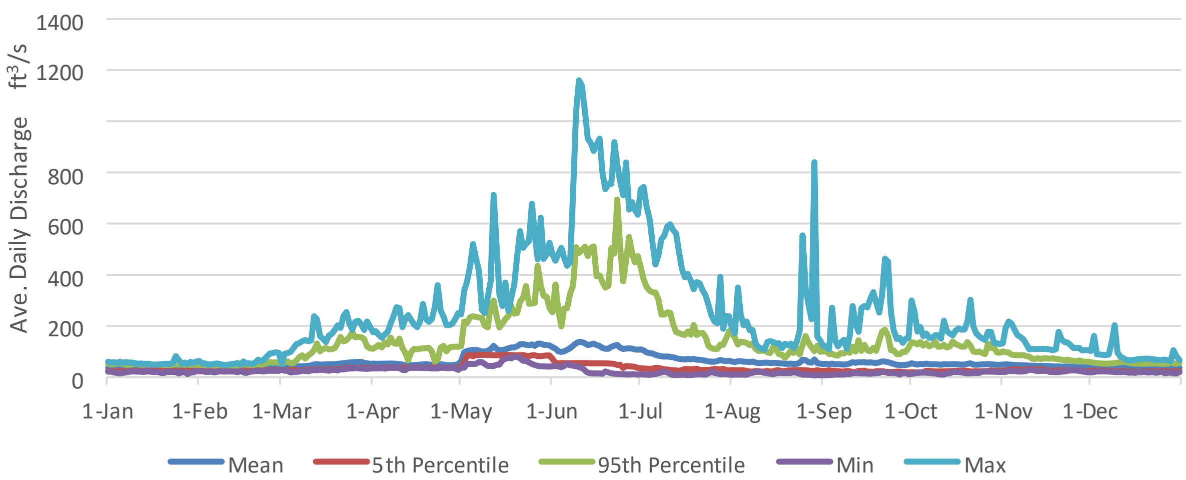


Figure 26.—CODWR Navajo River below Oso Diversion Dam average annual hydrograph and other statistical metrics.

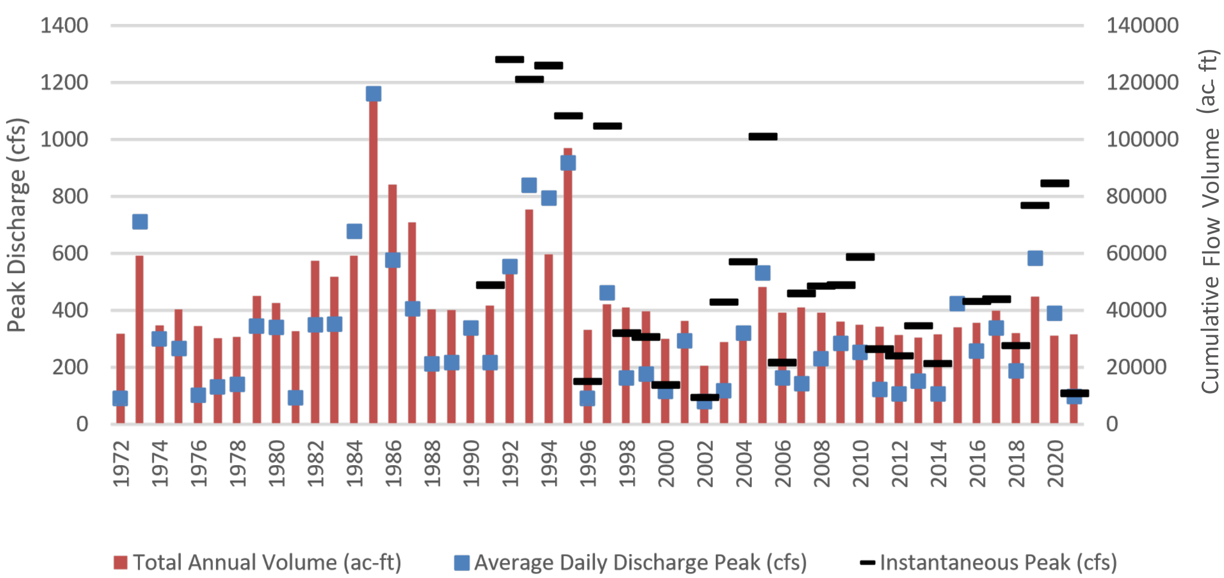
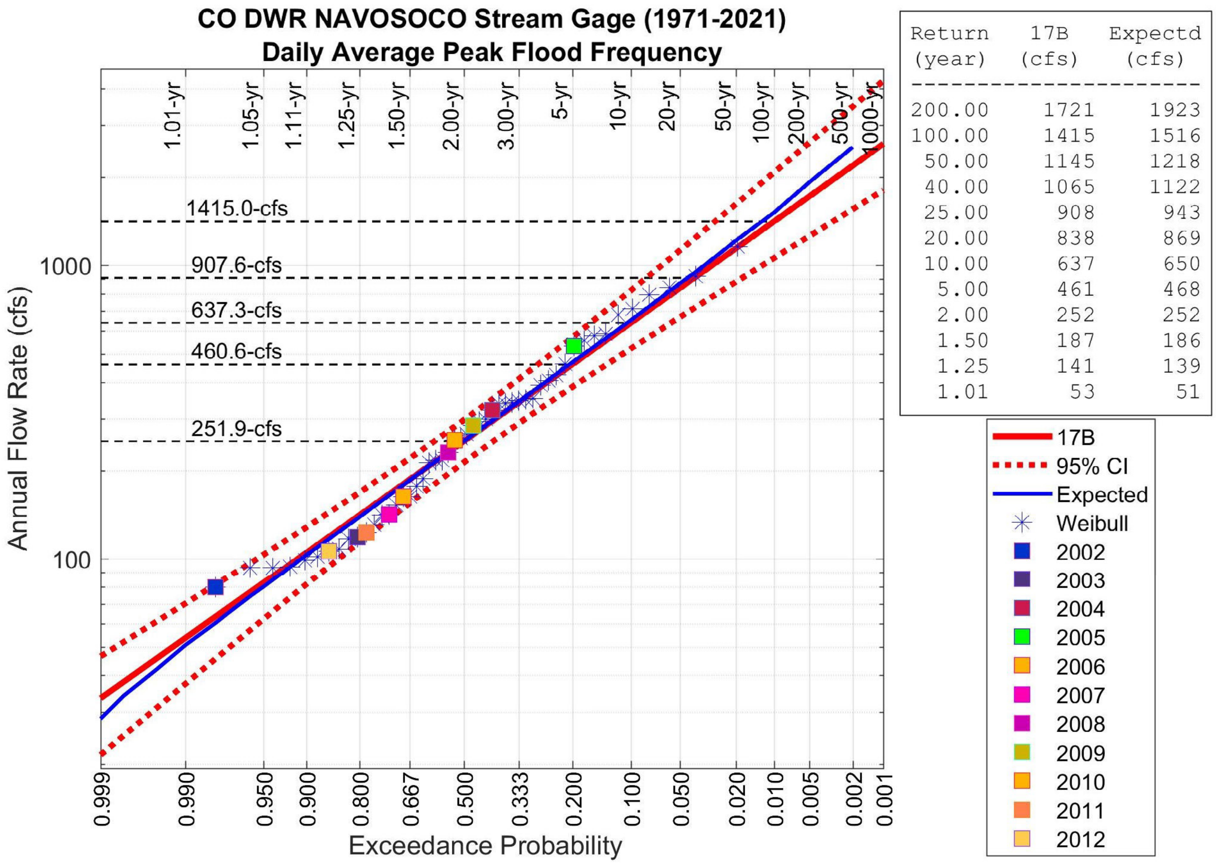
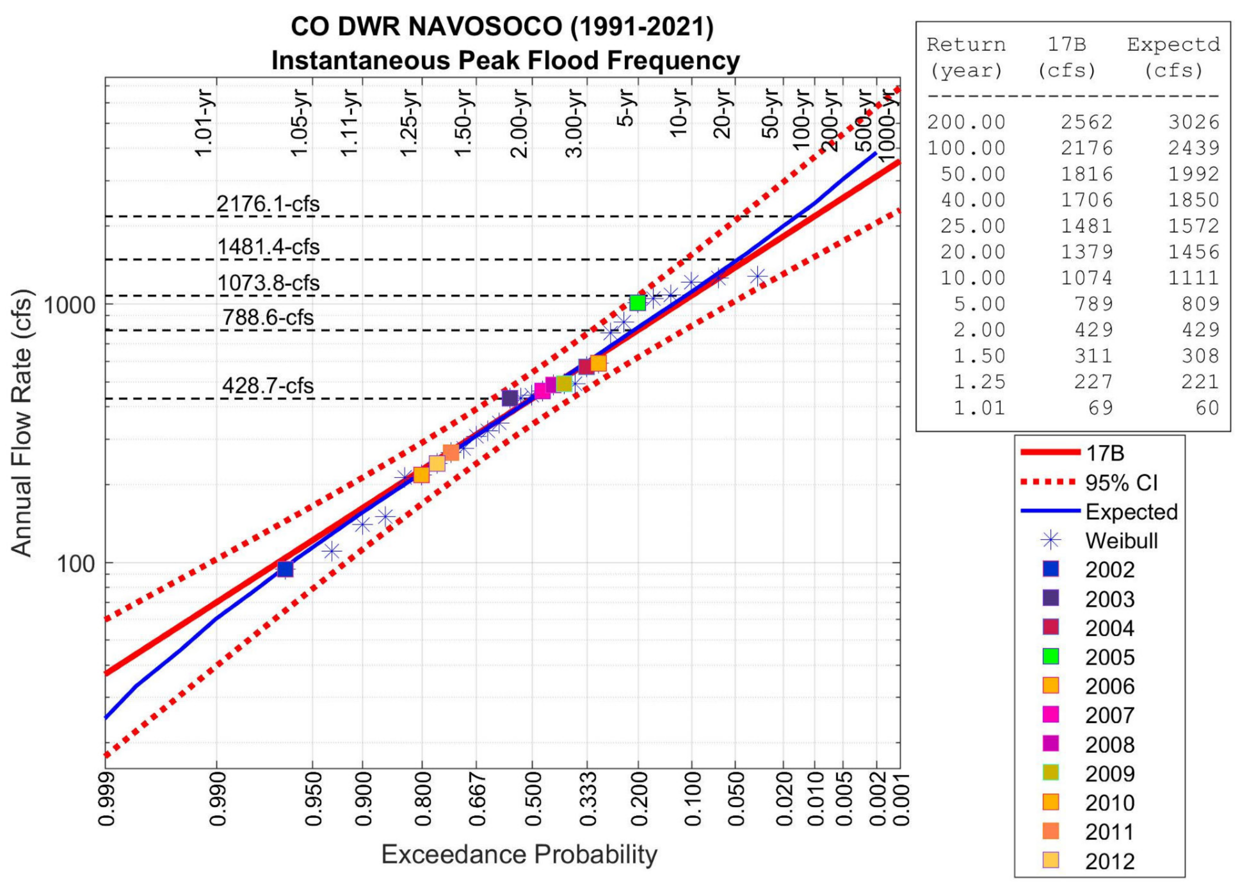


Figure 27.—CODWR Navajo River below Oso Diversion Dam annual volume, daily average peak, and instantaneous peak.



Return (year)	17B (cfs)	Expectd (cfs)
200.00	1721	1923
100.00	1415	1516
50.00	1145	1218
40.00	1065	1122
25.00	908	943
20.00	838	869
10.00	637	650
5.00	461	468
2.00	252	252
1.50	187	186
1.25	141	139
1.01	53	51

Figure 28.—CODWR Navajo River below Oso Diversion Dam daily average peak flood frequency graph and table.



Return (year)	17B (cfs)	Expectd (cfs)
200.00	2562	3026
100.00	2176	2439
50.00	1816	1992
40.00	1706	1850
25.00	1481	1572
20.00	1379	1456
10.00	1074	1111
5.00	789	809
2.00	429	429
1.50	311	308
1.25	227	221
1.01	69	60

Figure 29.—CODWR Navajo River below Oso Diversion Dam instantaneous peak discharge flood frequency graph and table.

3.3 Bed Material Data

The bed material distribution and associated metrics such as the D50, that represents corresponding particle size when the cumulative percentage reaches 50 percent, often referred to as the median particle size, were assessed through a variety of sources.

Bed material samples were collected and analyzed for the sediment yield study and were also used herein. These samples represent the incoming bed material and a portion of the upstream bed material. Larger size classes are likely to reach the operating pool in much smaller proportions than their representation in the upstream bed; therefore, other sources of data were sought out. A thorough discussion of the bed material sampling is in Reclamation (2019).

3.3.1 Bureau of Reclamation 2013 Navajo River Gravel Augmentation

In 2013 the Bureau of Reclamation implemented a Gravel Augmentation Project downstream of the Oso Diversion Dam in the Navajo River. To assess the project impact, Wolman Pebble Counts were completed post-project and then again in each year to 2019. This strategy involves wading the river and collecting a bed material sample at the toe of your boot during each step, then determining the particle diameter. Due to the nature of this strategy, smaller particle sizes are poorly represented, with often no sand or smaller size particles and few gravel sizes. Nevertheless, Reclamation staff indicate that little to know sand or gravel was found during their surveys. The bed material distribution at the sampling locations for the gravel augmentation monitoring, as well as the material distribution from the spoil material piles and upstream channel are plotted in figure 30. This figure suggests that median grain size (50th percentile, D50) of the sampling done in the spoil pile and upstream are near those values observed at the FS Road, center of channel monitoring location.

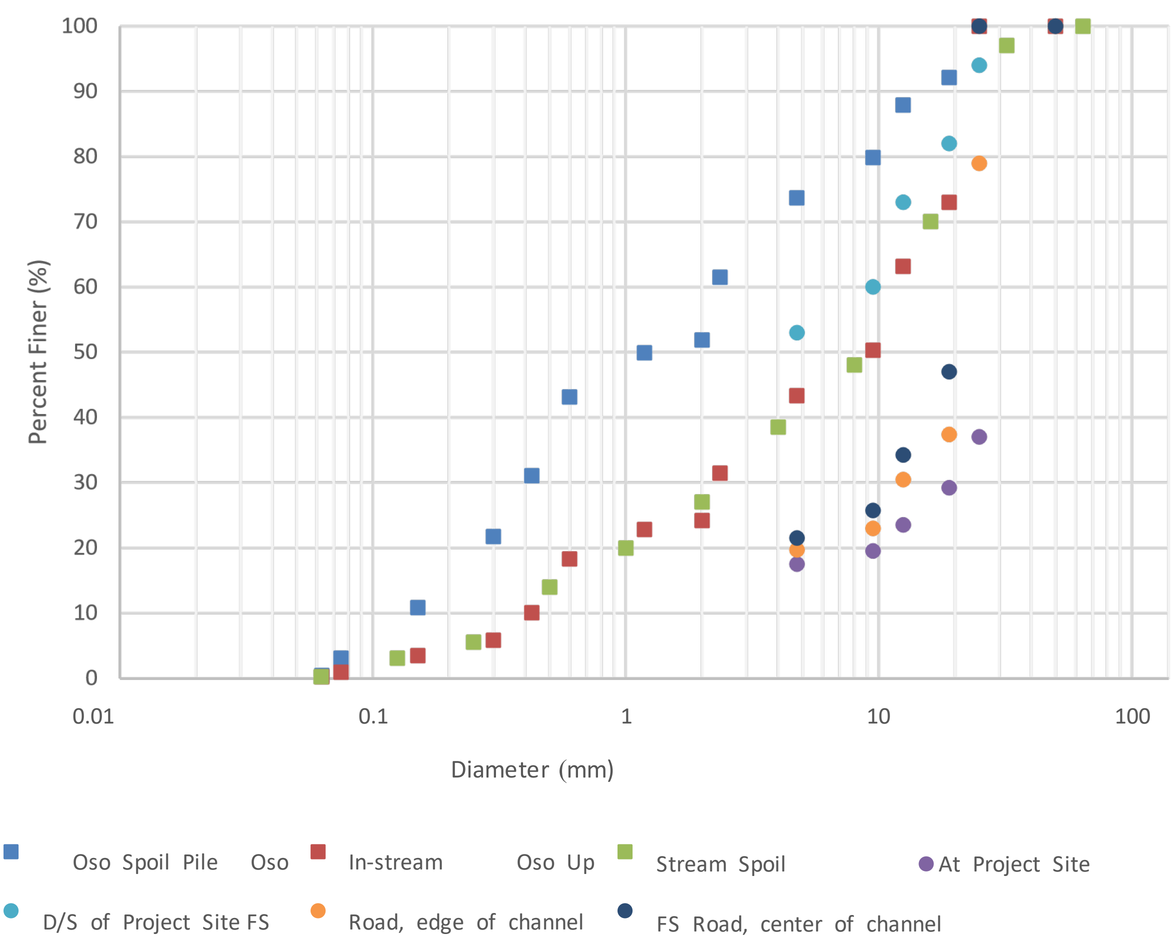


Figure 30.—Sediment size distribution for samples collected upstream and in the spoil pile, along with the Gravel Augmentation Project monitoring sites.

This dataset also extends over more than 6 years from April 2013 to September 2019. Figure 31 displays the bed material distributions for each of the monitoring visits, with successive visits having a wider line. By following the 50th percentile over the duration of the monitoring, a few trends can be seen. During the runoff of 2013, first runoff post-project, fining occurred, that was likely deposition of the material placed upstream. In the fall of 2014 coarsening had occurred, indicating a depletion of the augmented gravel. Coarsening continued over 2015. In 2017, the site showed a return to fining and continued to fine through the fall of 2018. The last monitoring occurred in 2019, that brought some coarsening. Figure 27 illustrates the peak flows over this period and shows 2014 and 2018 to be lower and 2017 and 2019 as higher flow years. Conventional geomorphic wisdom would suggest that high flows would transport higher fluxes and larger grain classes, resulting in an overall coarsening of the bed. The fining that occurred over various time periods suggests that the augmented gravel is continuing to be transported downstream and/or other upstream sources of sands and gravels are reaching this site.

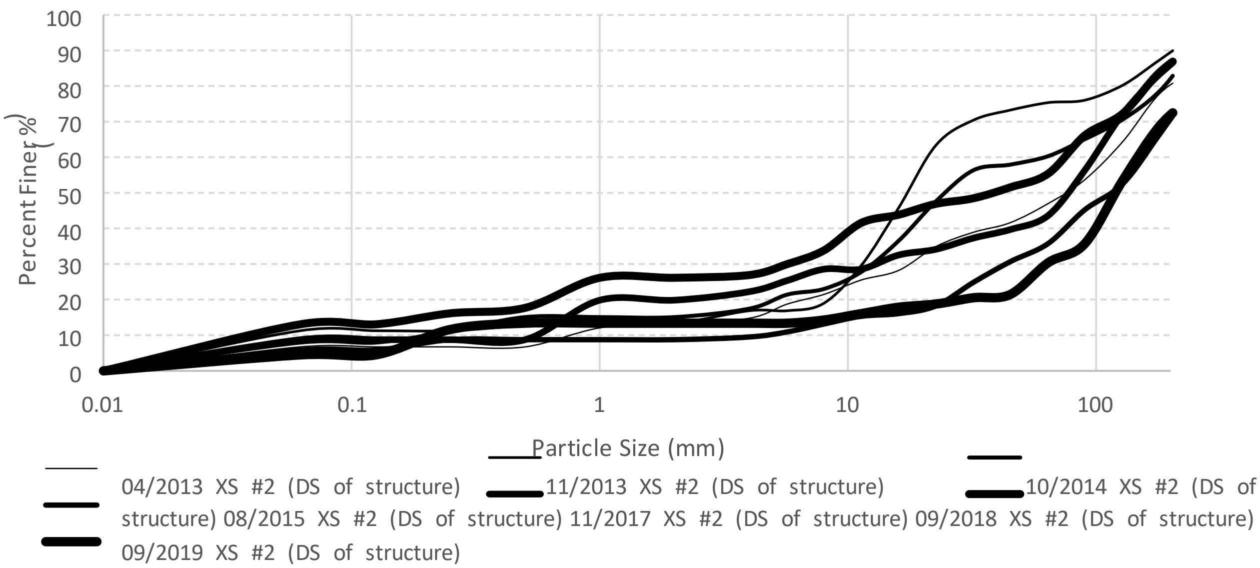


Figure 31.—Bed material size distribution downstream of Gravel Augmentation Project structure at series of monitoring visits between 2013 and 2019.

3.3.2 USFS Rocky Mountain Research Station San Juan Mountain Stream Sampling

The U.S. Forest Service (USFS) Rocky Mountain Research Station (RMRS) collected streamflow, bed material, and sediment transport data in the San Juan Mountains of southwest Colorado in 1999 (U.S. Forest Service 1999). This dataset was used to inform this investigation. Figure 32 shows the locations of the RMRS sampling locations in relation to the Project dam locations. Figure 32 also illustrates a broad geological classification of the area. Many of the RMRS locations represent first order streams with very small drainage areas (see table 1). The geology upstream of the Project dams is also distinguishable from the RMRS sites in

Figure 32 suggests that there is a considerably higher proportion of Unconsolidated, Undifferentiated material in the Project locations. The larger proportion of this material would produce more and perhaps finer material than would be expected at the RMRS sites.

Table 1.—USFS Rocky Mountain Research Station San Juan Mountain sampling site characteristics

	Barlow Creek	East Fork San Juan River	Florida River	Junction Creek	Middle Fork Piedra River	Red Creek	Scotch Creek	Silver Creek	Taylor Creek
Channel Topography	Plane	Riffle - braided	Plane Bed to Steppool	Plane with Steps	Plane to Riffle (some steps upstream)	Plane	Steppool	Plane to Steppool	Plane
Discharge (ft^3/s)	98	553	512	240	355	28	140	46	90
Water surface slope (feet [ft]/ft)	0.024	0.008	0.013	0.028	0.018	0.250	0.040	0.045	0.023
Q1.5 width (ft)	22	56	39	24	44	10	16	14	18
Mean Q1.5 depth (ft)	1.1	1.7	2.5	1.7	1.6	0.8	1.1	1.0	1.0
Mean Q1.5 velocity (feet per second [ft/s])	3.9	5.7	4.3	5.8	4.9	3.3	5.1	3.1	4.8
D50 (millimeters [mm])	62	50	210	50	79	15	47	29	
Drainage area (square miles [mi^2])	7.5	64.1	44.4	24.7	33.2	6.9	12.0	6.1	11.3
Years sampled	2001	1999	1999	2001	2001	2001	2001	1999	2001

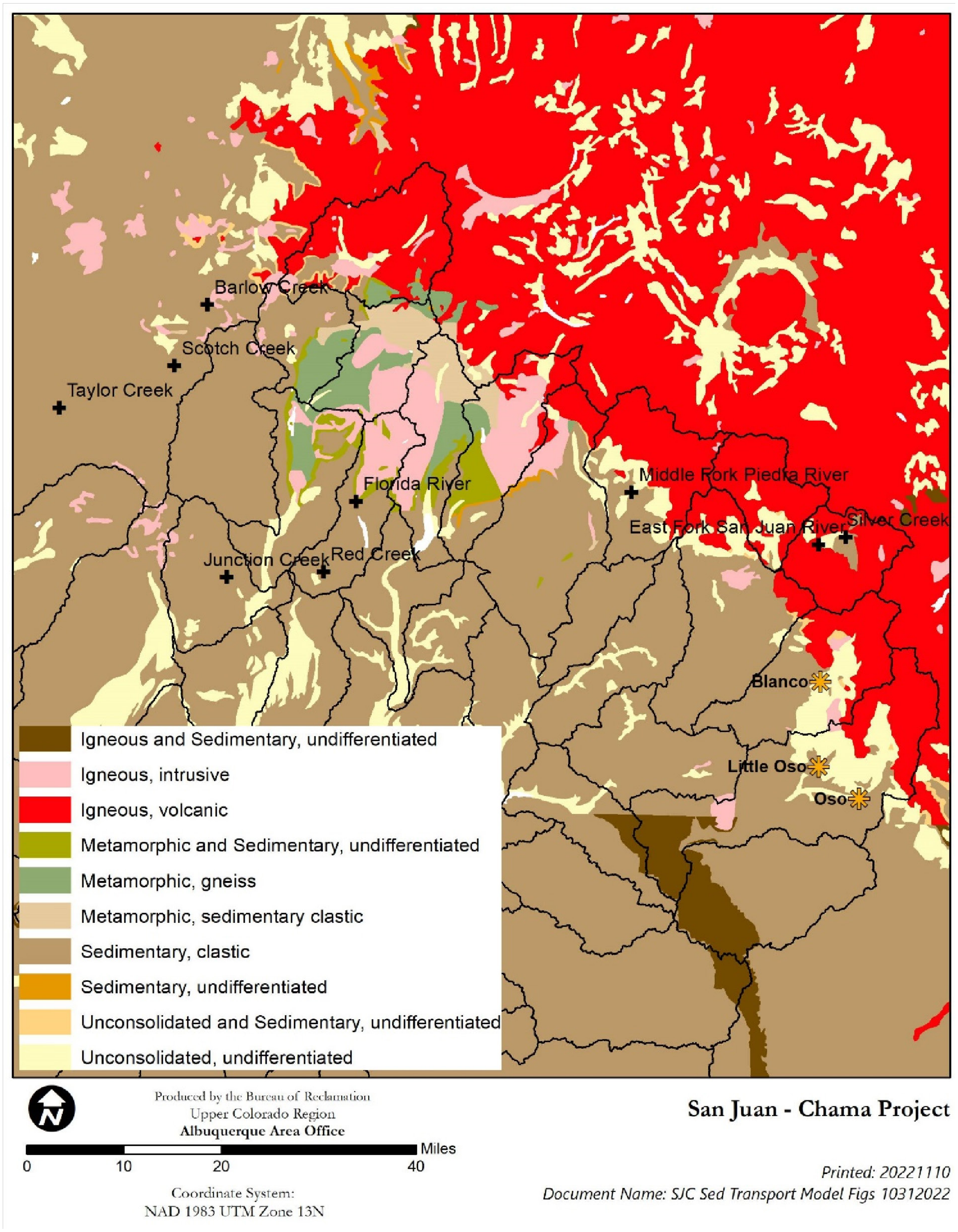


Figure 32.—USFS Rocky Mountain Research Station sampling sites in relation to Project diversion dam locations with geology basemap.

An understanding between the RMRS and Project sites can also be had by comparing their width and drainage areas. The width of a channel is strongly correlated with the amount of flow the channel receives, however, other characteristics such as geology also play a major role. Figure 33 shows that the Project streams represent larger drainage areas than the RMRS stream sites. The Navajo River, along with being the lowest in the watershed and having the largest drainage area, also is narrower than would be predicted by this dataset. The Blanco River looks to follow the predicted trendline.

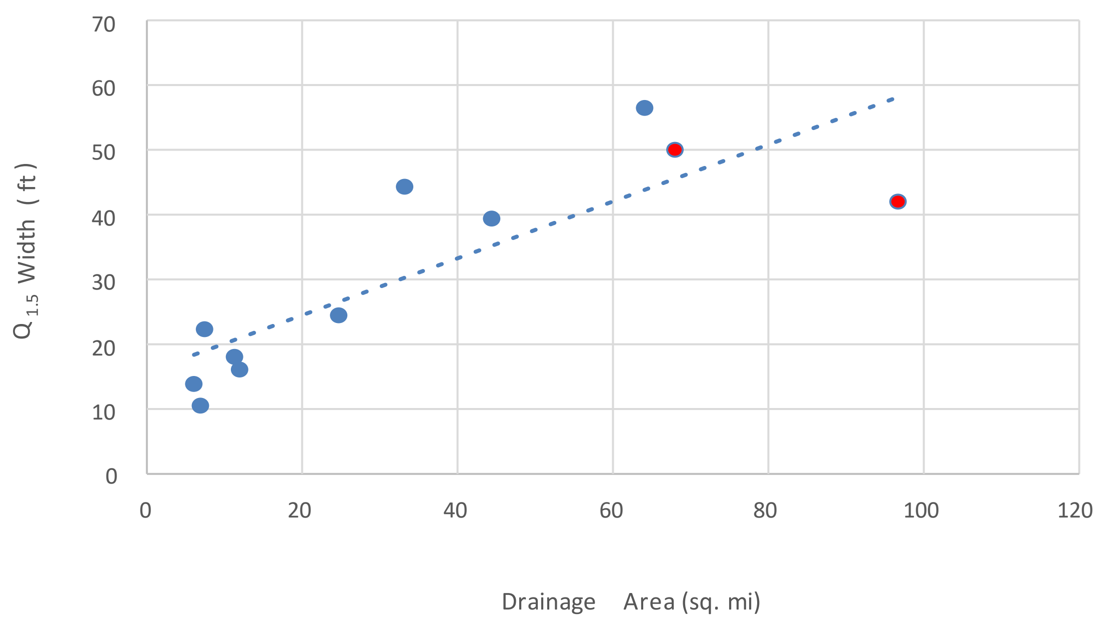


Figure 33.—Graphic relationship between drainage area and width at the 1.5-yr flow recurrence interval for RMRS streams (blue) and Project sites (red).

3.4 Sediment Transport

The understanding of the quantity of material being transported passed a particular point, as a function of flow, is useful in predicting geomorphic changes to the downstream and geomorphic trends upstream. This relationship is known as a sediment rating curve. While discharge measurements are common and relatively reliable, sediment transport measurements are relatively rare and notoriously unreliable. Many experts agree that measurements are generally within an order of magnitude of the actual value. This is in part due to measurement limitations but is also related to the high degree of variability in sediment transport. Like discharge measurements, the higher the flow and sediment transport, the less reliable the measurement.

The RMRS sampling locations also collected sufficient data to develop rating curves for each of the sites. Sediment bedload rating curves were developed from bed load traps, thus not capturing sand and finer material. Figure 34 shows the bedload rating curves for all the RMRS locations.

Figure 34 shows that only three sites had measurements with discharges greater than 200 ft^3/s, these are East Fork of the San Juan River, the Middle Fork of the Piedra River, and the Florida River.

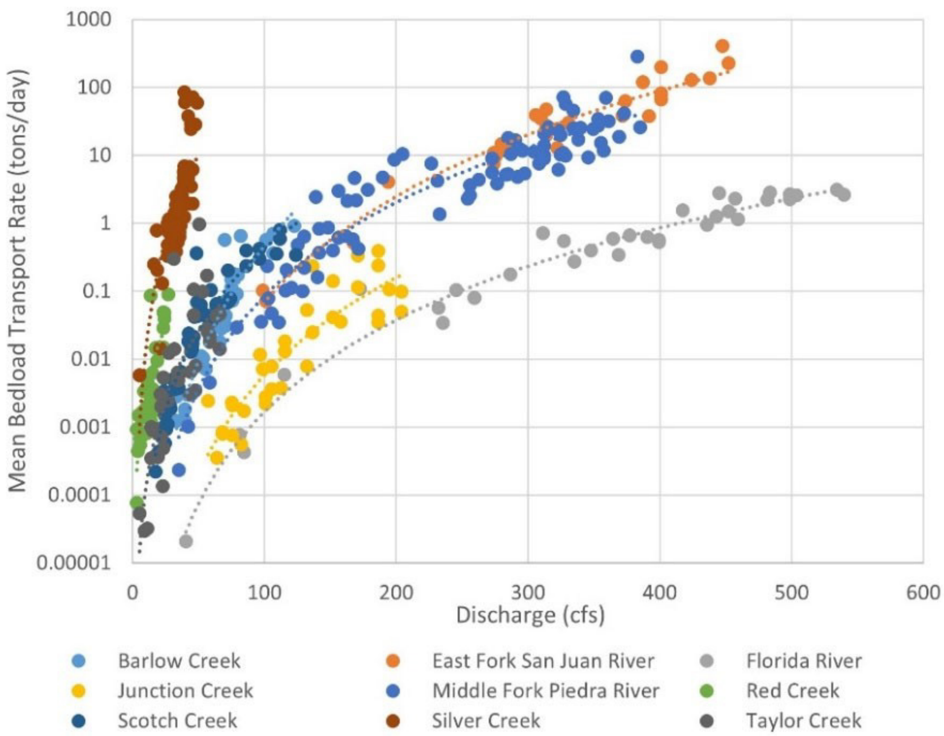


Figure 34.—RMRS site sediment rating curves. Mean bedload transport rate indicates average of all sediment sizes measured over a fixed duration.

3.4.1 Definite Plan Report

In the development and planning of the Project, designers collected suspended sediment samples during discharge measurements at the Rio Blanco near Pagosa Springs, Navajo River above Chromo, and Willow Creek near Parkview from November 1961 to October 1962 (Reclamation, 1964). Bedload was not included in their assessment, as they assumed that 100 percent (%) of the bedload would be sluiced downstream. Designers also assumed that the concentration of suspended sediments in the river would be the same in the tunnels and therefore the same in Willow and Azotea Creeks and were used to derive the 100-yr sediment accumulation and conservation pool estimates for Heron Reservoir. Figure 35 illustrates the rating curves developed from the Definite Plan Report, along with the rating curve from the RMRS dataset with larger discharges. The large discrepancy at lower flows is a result of the method by which the rating curves were developed. An order of magnitude in measurement can be seen in the data collected at the Blanco River, where at a discharge of 520 ft^3/s between 1000 and 10000 tons per day were observed. Figure 35 also shows that the Blanco and Navajo rivers were found to have similar suspended sediment transport rates.

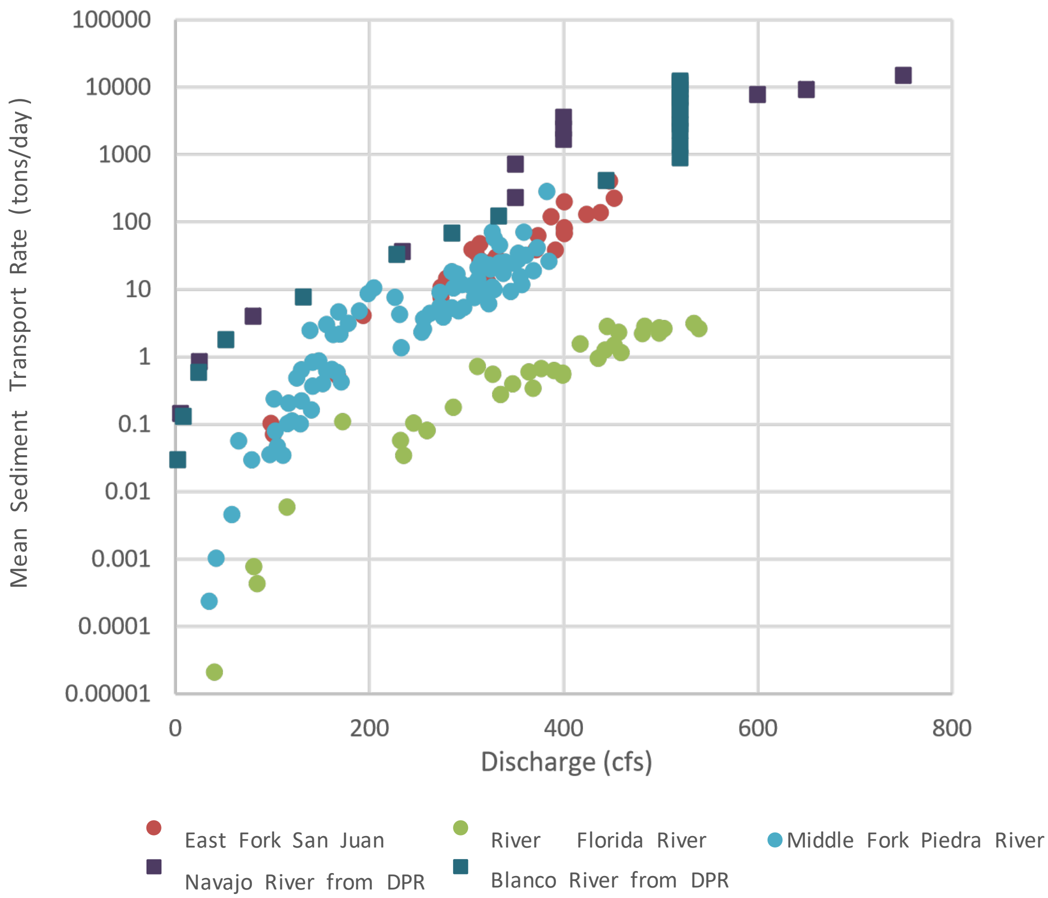


Figure 35.—Sediment rating curves from the Definite Plan Report, as well as at three selected rivers from the RMRS dataset. Data from DPR is suspended and RMRS data is bedload only.

4.0 Model Development

To properly represent the systems of interest in a numerical computational model, the model must be properly constructed, some of the system elements that must be properly characterized include:

- Hydrologic inputs, representing the peak and duration of flows experienced at the model boundaries.

- Sediment load inputs, representing the amount of sediment likely to be input to system, based on discharge and other conditions.
- Bed material size distribution up- and downstream of the dams.
- Channel and floodplain elevations.
- Structures that impact flow and sediment transport including diversion dams and stream gages.

Given the importance of sediment transport modeling and the desire to simulate many miles of river, the decision was made to simulate the system in 1-dimension. This name is somewhat of a misnomer, as the model is 3-dimensional, in that the model simulates the downstream, the depth, and changes over time. Nevertheless, the model does not simulate the secondary currents associated with channel bends and other channel features. Two-dimensional (2D) hydraulic and sediment transport models can simulate these secondary currents and have an overall lower error due to their coverage of the entire channel. 2D models have increased in use since the availability of data such as LiDAR; however, large model domains may make 2D modeling prohibitive due to computational demands.

4.1 Geometry

Channel geometry was derived from the available LiDAR data, as well as satellite imagery from Google. River centerline and banklines must be digitized, after which River Analysis System (RAS) Mapper in Hydrologic Engineering Center-River Analysis System (HEC-RAS) version 5.0.9. was used to develop cross section geometry, including distance between cross sections. Figure 36 illustrates these components over a portion of the Navajo River. The Blanco hydraulic and sediment transport model represented 0.4 miles upstream and 6.4 miles downstream. The Blanco Dam and River model included 960 cross sections with average 37 feet between cross sections. The Oso Diversion Dam and Navajo River model includes 2796 cross sections, with spacing of approximately 10 feet. The Navajo River is modeled 1 mile upstream and 4.2 miles downstream of the Oso Diversion Dam.

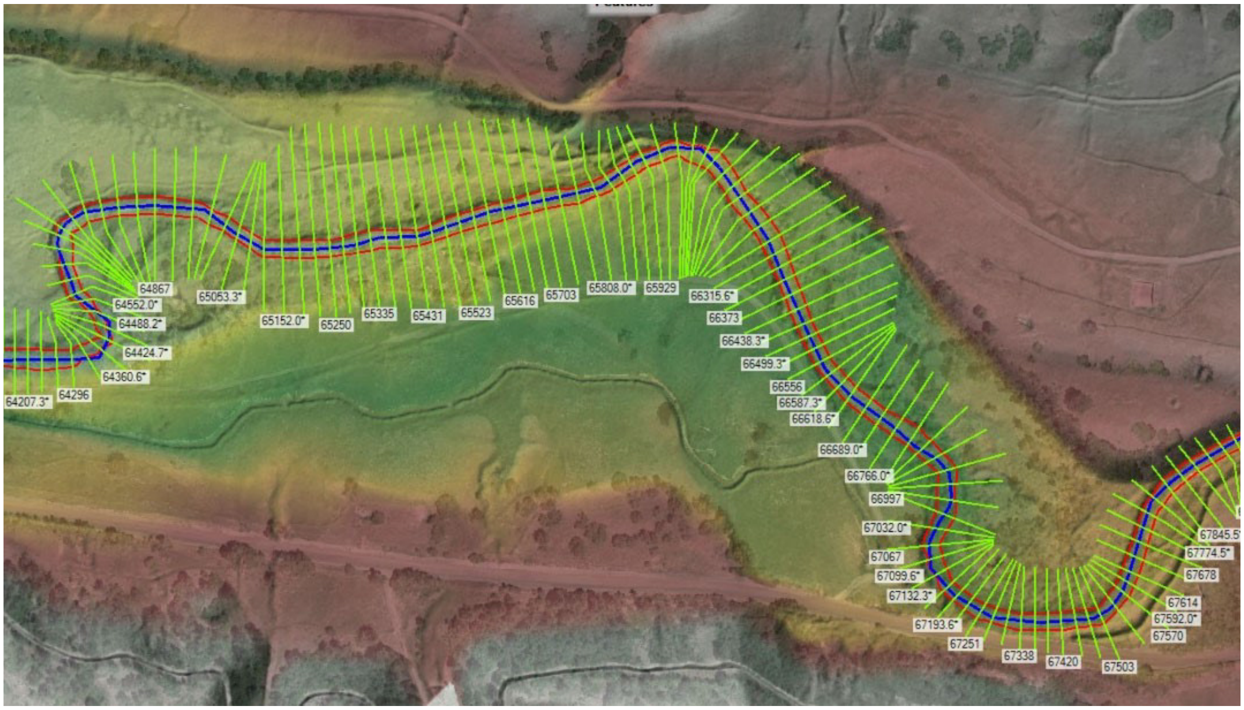


Figure 36.—Section of Navajo River model geometry, illustrating digitized channel centerline and banklines, model derived cross sections, LiDAR and satellite imagery.

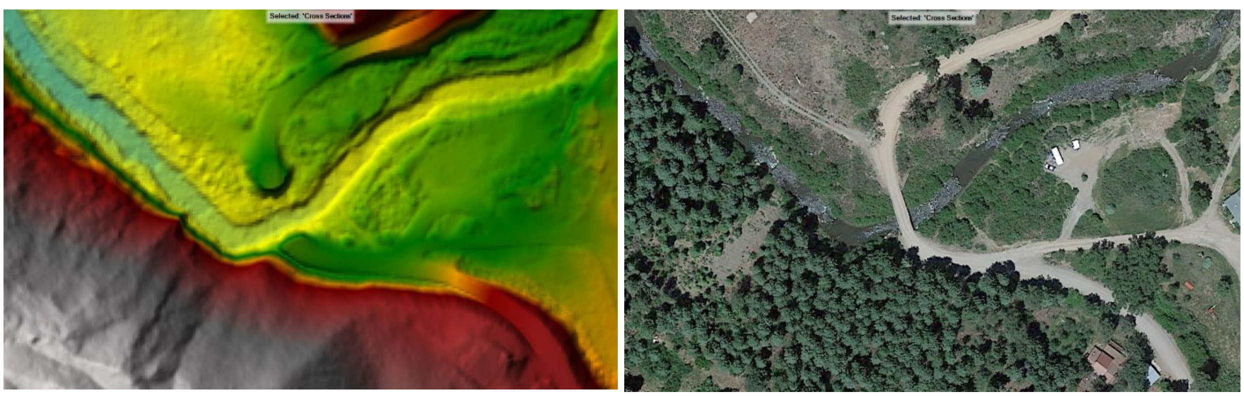


Figure 37.—Location of bridge crossing the Blanco River in the LiDAR data (left) and Google satellite imagery (right).

Quality control and assessment were done primarily by comparing LiDAR elevations and satellite imagery. Figure 37 is an example of a location where the post-processing of the LiDAR removed a bridge and capturing the elevation of the terrain below. Other features such as rock obstructions, pool/riffle complexes, sharp bends, and habitat restoration project features, were used to verify project geometries. Rather than surveying any particular location to adjust LiDAR elevations, the decision was made to use the LiDAR as-is, rather than adjust a specific location or the entire bathymetry based on a few particular locations. Adjustments to the LiDAR were done in the vicinity of the dam, the dam operating pools, the stream gages, and the approach channel between the dam and stream gage. If specific locations of interest are identified in the future, field verification of LiDAR elevations should be carried out.

4.2 Structures

Within each of the models there are two structures that span the channel (figure 38). The diversion dams were modeled as inline structures. Design drawings were used to size the ogee spillway weirs and sluicegate opening (figure 39). The model permitted the testing of the gate opening under different flow conditions. Dam design drawings were used to input the dam apron, crest, and sluicebox elevations. Elevation transformations from National Geodetic Vertical Datum 1929 to the North American Vertical Datum 88 were done using the National Oceanic and Atmospheric Administration (NOAA)'s VDATUM tool (https://vdatum.noaa.gov/vdatumweb/).

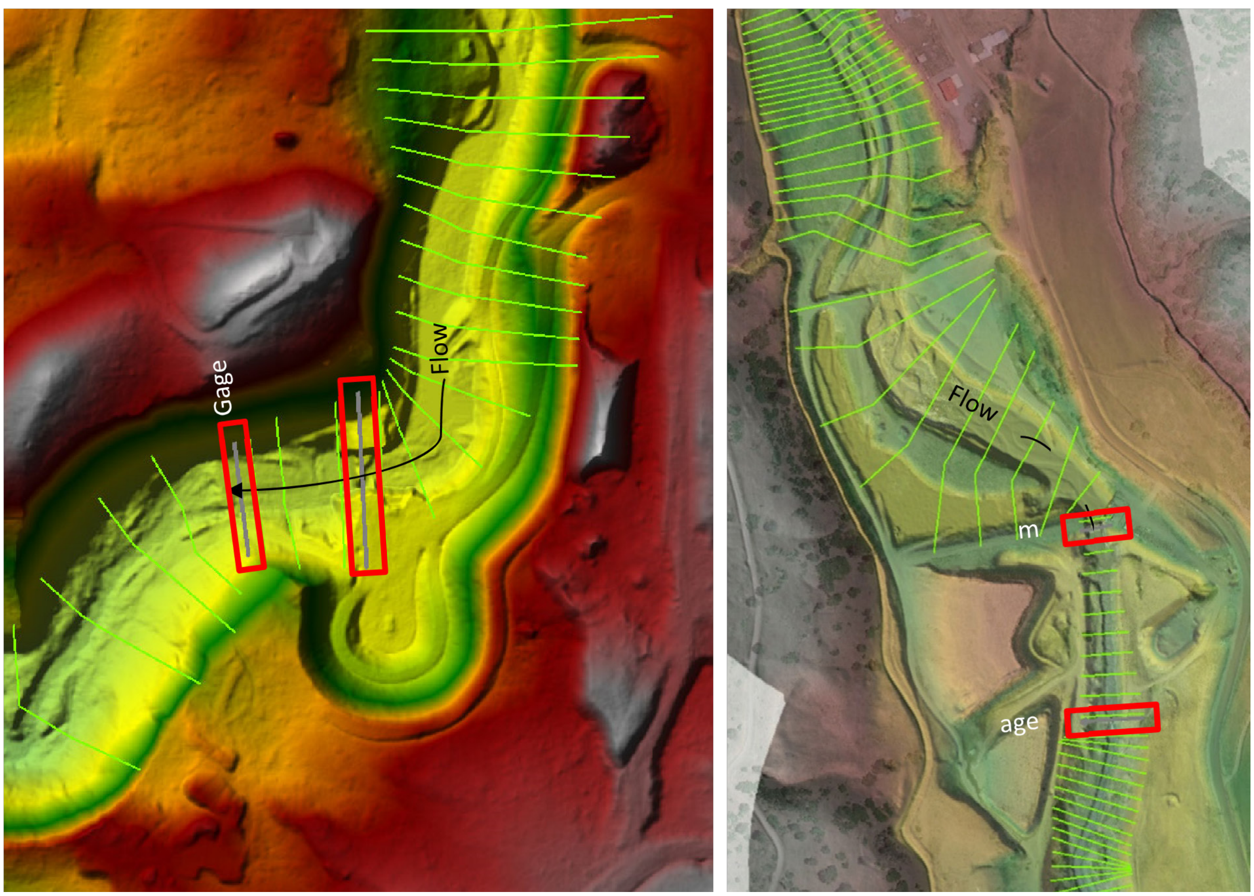
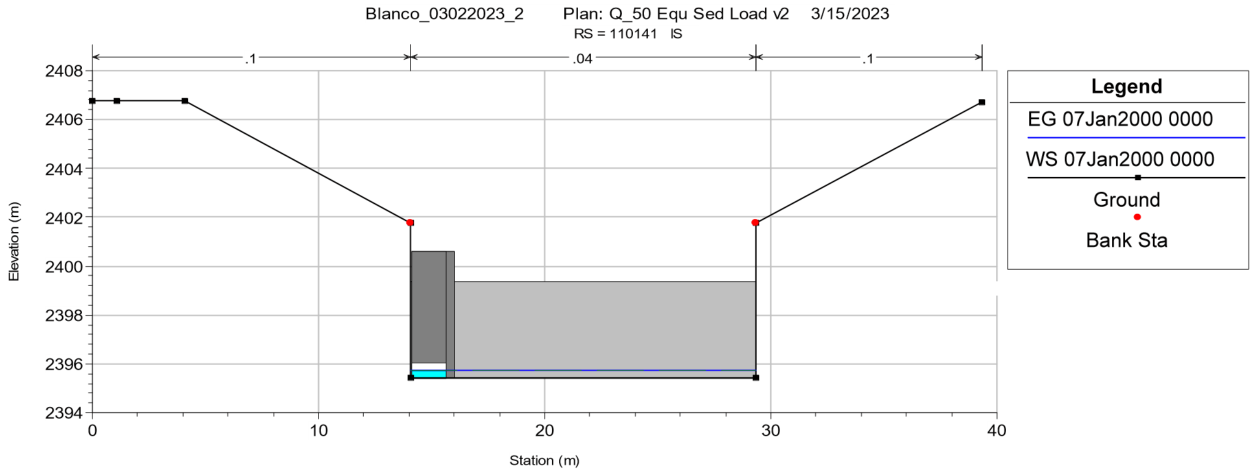


Figure 38.—Blanco River (left) and Navajo River (right) terrain data showing cross section layout and location of model structures (grey) representing diversion dams and stream gages.



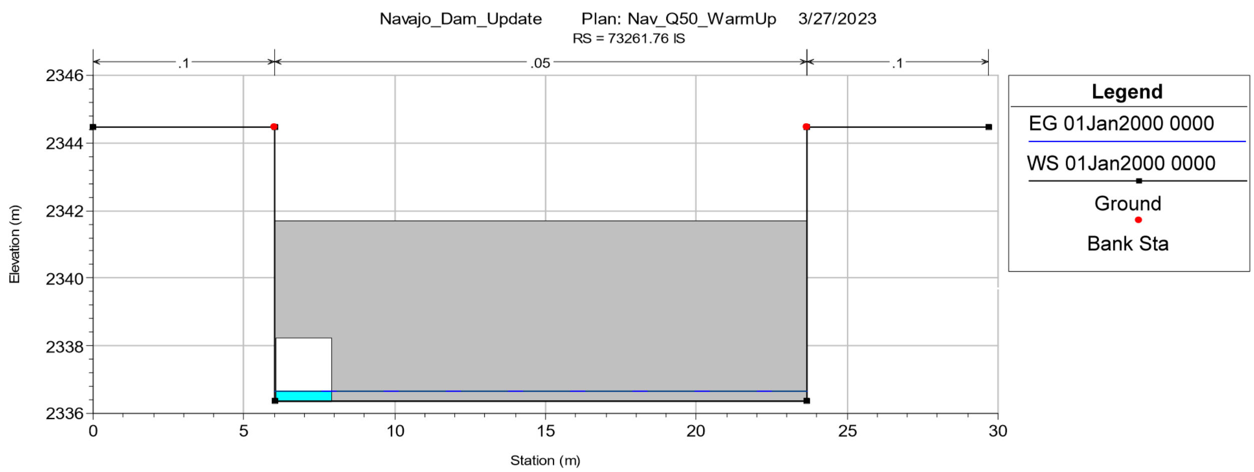
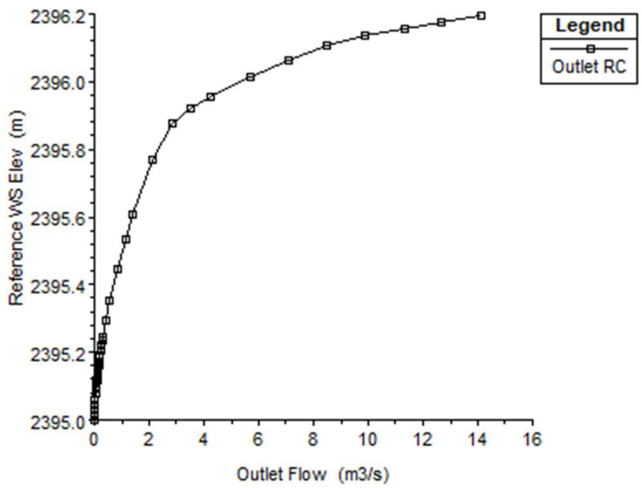


Figure 39.—Model representation of Blanco (top) and Oso (bottom) gated spillway structures with gate openings.

The stream gages were modeled as weirs with a known rating curve. Working directly with the CO DWR, modelers were able to translate the datum used in their records to the North American Vertical Datum 88, used in the LiDAR data (figure 40). The ability to input a known rating curve within the model domain is a significant control in determining the associated water surface elevations. The importance of this hydraulic structure in the model accuracy cannot be overstated.



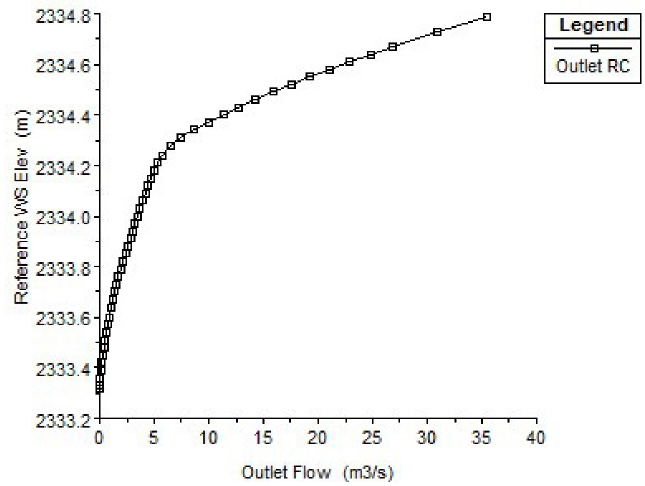


Figure 40.—Stage-Discharge Rating Curves representing the stream gages and built into the model as weirs for the Blanco (left) and Navajo (right) Rivers.

4.3 Hydraulic Parameters and Boundary Conditions

Roughness in the model was represented with Manning's Equation in n-values of 0.05 in the main channel and 0.1 in the floodplain. These values are based on guidance from Chow (1959). Some sensitivity analyses were performed on these parameters.

Upstream boundary conditions were simulated as a constant discharge of varying values, with a warm-up period of 7 days. For the first 7 days of the simulation a flow of 20 ft^3/s was run through the model, allowing an equilibrium bed to form in the channel. After this 7-day warm-up period, the flow was increased to values between 50 ft^3/s and 1000 ft^3/s. With 2-year flows of 679 and 429 at Blanco and Oso bypass, respectively, this range represents flows likely experienced at the dam locations.

In addition, the high flow modeling was done of different durations from 1 to 4 days. This variety of input conditions allows for the identification of possible hydraulic threshold conditions for both the quantity and distance sediment, of a certain size class, may be transported. Downstream hydraulic boundary of normal water surface was used for both rivers.

4.4 Sediment Transport Parameters

Deposition of sediments was permitted outside of movable bed limits. In addition, the channel was permitted to only erode the top 1 meter (3.3 ft) of bed material, assuming that bedrock is met at that depth. Given that this modeling effort is limited to relatively short durations and the finding of mostly large boulders and bed rock during river surveys, including in the Blanco River by Massong and Porter (2006), this depth of erosion is highly unlikely to be exceeded.

The bed material distribution of each cross section must be defined in the model. Available data includes a few samples of the spoil material dredged from the dam operating pools, some Wolman pebble counts from the gravel augmentation project, the RMRS data from other San Juan rivers (table 1), observations from Massong and Porter (2006), and observations from various site visits. With this data, some extrapolation, estimation, and professional judgement were required to characterize the stream bed material distribution. The small number of samples available indicate that the Navajo river is slightly coarser than the Blanco River. Although the Blanco River has a larger overall stream gradient, the greater discharge values experienced in the Navajo River may explain these larger sizes.

The cross sections up- and downstream of the diversion structure were modeled with slightly different bed material distributions. Due to the entrainment of sediment at the dams, it was inferred that the bed material downstream would be slightly coarser than upstream. The up and downstream discrepancy can also be interpreted by the large number of sand and gravel bars observed in the upstream reaches with few to none downstream of the diversion dams. In the Navajo River, the Gravel Augmentation project provided a wealth of data with which to estimate the downstream bed material. These samples represent only the subreach in the first 1500 feet post-gravel augmentation project and show a significant amount of median grain size variability (figure 31).

The upstream reach bed uses a coarser than average of the material distributions measured in the upstream spoils, with a D50 of 2.8 mm in Blanco and 8.7 mm in the Navajo River, representing very fine gravel and fine gravel, respectively. Fine material is likely over represented in the spoil pile relative to the upstream stream bed. The downstream distributions were estimated using the data listed above and represent a D50 of 23.1 mm in Blanco and 40.9 mm in the Navajo River, representing coarse gravel and very coarse gravel, respectively (figure 41). It is likely that downstream conditions have a higher proportion of coarse materials. The decision to represent gravels in the downstream bed results in more conservative estimates of changes to median grain size.

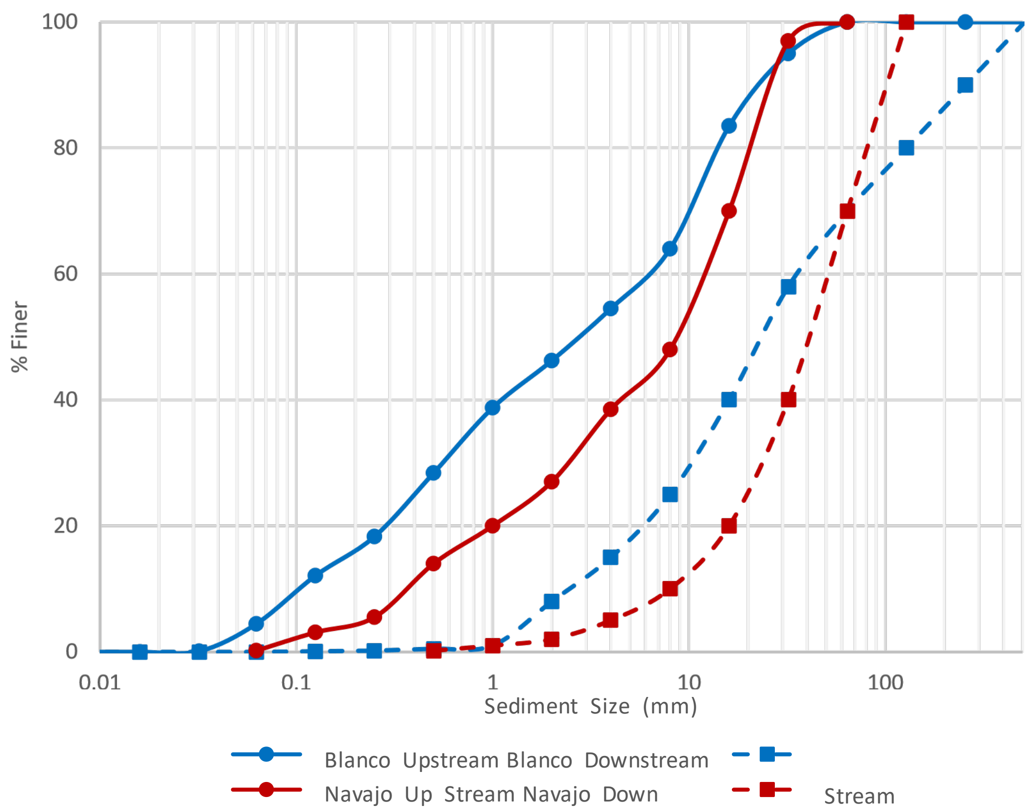


Figure 41.—Up and downstream bed material distributions for Blanco (blue) and Navajo (red) Rivers.

4.5 Sediment Transport Model Boundary Conditions

The model boundary condition is comprised of both flow and sediment transport conditions. The ideal modeling strategy dictates that a sediment rating curve be developed based on a robust set of observed data measured at the location of interest. The data collected in development of the Definite Plan Report is the only data set available for this purpose.

A sediment rating curve derived from the data collected during development of the Definite Plan Report were used to represent the incoming sediment load as a function of the discharge (figure 42). Additionally, an alternative to defining a sediment transport rating curve, model equilibrium conditions can be used to represent model sediment transport boundary conditions. Five different bedload transport equations were tested, as a sensitivity analysis to best represent the limited conditions known about the system.

HEC-RAS requires that the size distribution of the sediment being transported under different discharge conditions be defined. There are few cases in which this data is readily available, and a specific data collection campaign is required to obtain this data. Figure 43 represents a best estimate of these parameters, whereby the sands and gravels make up the bulk of the material transported (50–400 ft^3/s), with some coarsening of the distribution for larger flows.

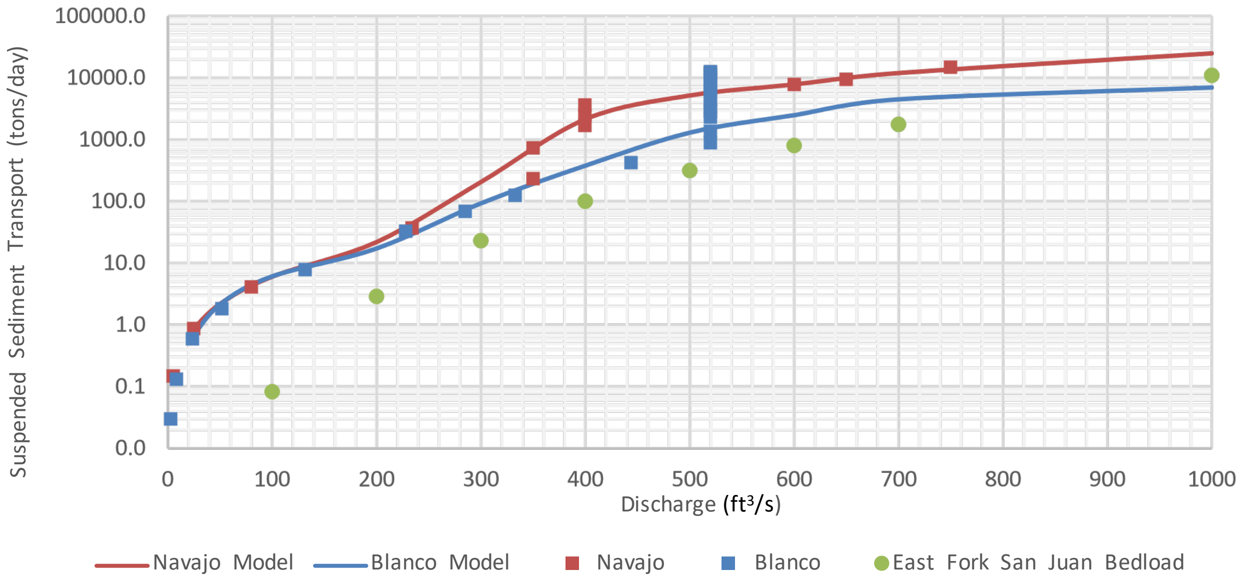


Figure 42.—Sediment transport model sediment rating curves.

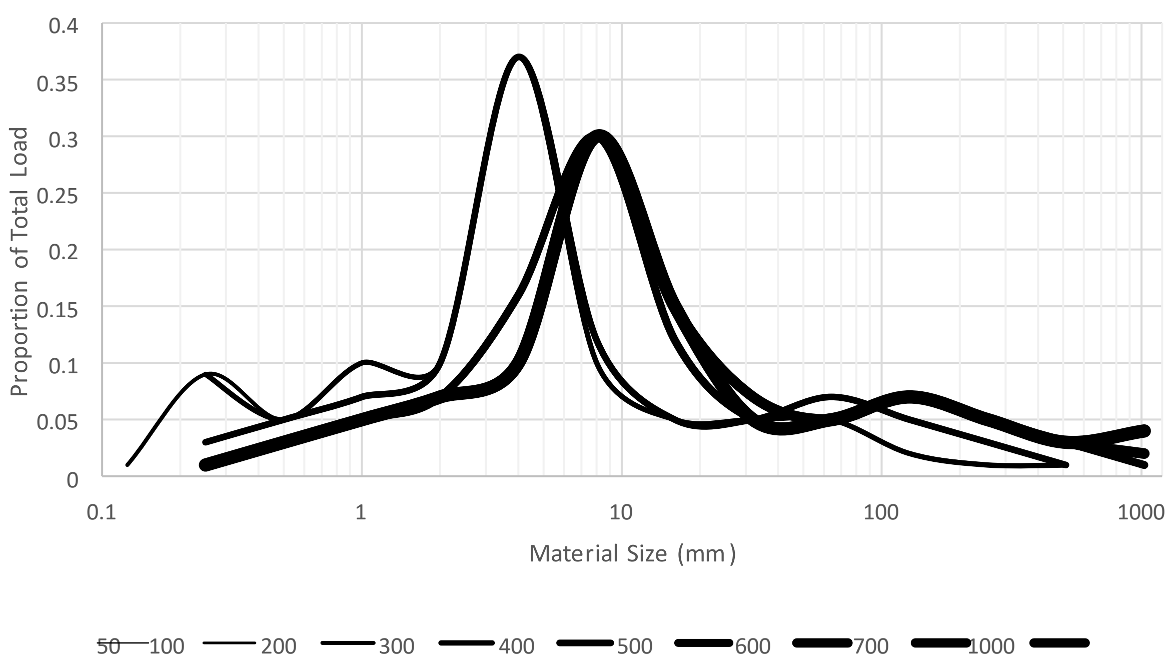


Figure 43.—Sediment transport model sediment size class gradation curves for range of discharges.

5.0 Model Results and Discussion

The model runs that were implemented, and whose results follow, were organized to test the model under a variety of conditions, thereby improving the likelihood that threshold conditions would be identified. Model sensitivity to both magnitude and duration of discharge was tested. Additionally, some geometric changes, transport function, and parameterization of the sediment transport model were tested. Sediment transport modeling has a high degree of uncertainty, made greater by an absence of calibration data and confidence in boundary conditions. Attempting to characterize the range of results based on unknown inputs aids in interpreting any particular model result.

Sediment transport model outputs include several variables. Based on the questions under investigation herein, the primary variables of interest include invert change, D50 cover, mass change, and width:depth ratio. Tracking the change in invert elevation with changing discharge magnitude and duration helps to identify potential monitoring areas should sluicing operations occur. Additionally, if large amounts of accretion are found in model results, the discharge conditions that allow this accretion would be excluded from appropriate sluicing conditions.

The D50 represents the median grain size of the cross section. The initial cross section value is given by figure 41, and how that value changes with discharge magnitude and duration provides insight into the likelihood that a location will experience fining. The reduction of the D50, especially below 0.125 mm representing sizes smaller than sand, would represent a threshold condition where sluicing would not be recommended for the discharge condition that produces those results.

The longitudinal cumulative mass change variable is similar to the invert elevation change; however, this variable represents changes in mass. This variable also helps understand where sediment is being evacuated and where it is accumulating. This variable can also be useful in identifying threshold conditions when sediment transport increases or decreases rapidly.

The width:depth ratio of the model is a surrogate for the geometry of a channel cross section. A wide and shallow cross section has a high value, a deep and narrow cross section has a low ratio. This ratio can be used to identify bankfull conditions, as the width increases with increasing discharge until bankfull is reached. After this point increasing discharge increases only depth and the ratio begins to decrease.

5.1 Sediment Transport Function Sensitivity

The first step in sediment transport modeling is to have a stable and robust hydraulic model. Next, the model is to be parameterized, calibrated and boundary conditions chosen based on the best available information. Sediment transport modeling requires the definition of a Fall Velocity Method, Sorting Method, and Transport Function. For this investigation the Ruby Fall Velocity and Thomas (Exner 5) Sorting Method are used. Lastly, an appropriate Transport Function should be selected based on the available data, model stability, and the model representation of known geomorphic trends. HEC-RAS has several transport function options. Functions are derived using different data sets, representing unique conditions based on grain size distribution and hydraulic parameters (U.S. Army Corps of Engineers 2016). These functions represent the sediment transport potential and can be used as an equilibrium boundary condition. The sediment transport data available in the Definite Plan Report and Engineering Research Center investigations were limited to suspended sediment, and there is an acknowledgement that bedload is in fact most of the sediment transport and is referred to as the unmeasured load. Transport potential functions used for the input boundary condition represents the results if a system were in equilibrium, meaning that the sediment load and the ability of the stream to transport that load are in equilibrium. In many cases, there is either more or less sediment available for transport than the transport capacity of the stream.

Sensitivity to these equilibrium boundary conditions was determined for the Blanco River. Five different transport functions were tested and rating curves for each were developed and compared to the rating curve derived from the DPR suspended sediment investigations. The suspended sediment transport measurement with the highest discharge at Blanco was taken at 520 ft^3/s. Figure 42 illustrates that at a measured discharge of 520 ft^3/s, suspended sediment transport rates varied between 890 and 12,423 tons/day. Figure 44 suggests that at high flows the measured suspended load was very close to the equilibrium load. The one exception being Yang's equation that predicts an order of magnitude more sediment transport than the other functions. The other commonality among the results is the finding that at flows less than approximately 500 ft^3/s the sediment load is likely much greater than what was measured. Figure 44 also shows the averaged transport potential for the subreaches from the model boundary to the dam, from the dam to Highway 84, and from Highway 84 to the downstream model boundary near the confluence with the San Juan River (figure 1). The functions are most consistent in finding that the greatest transport potential is in the upstream subreach, followed by the middle subreach, with the downstream subreach having the least sediment transport potential.

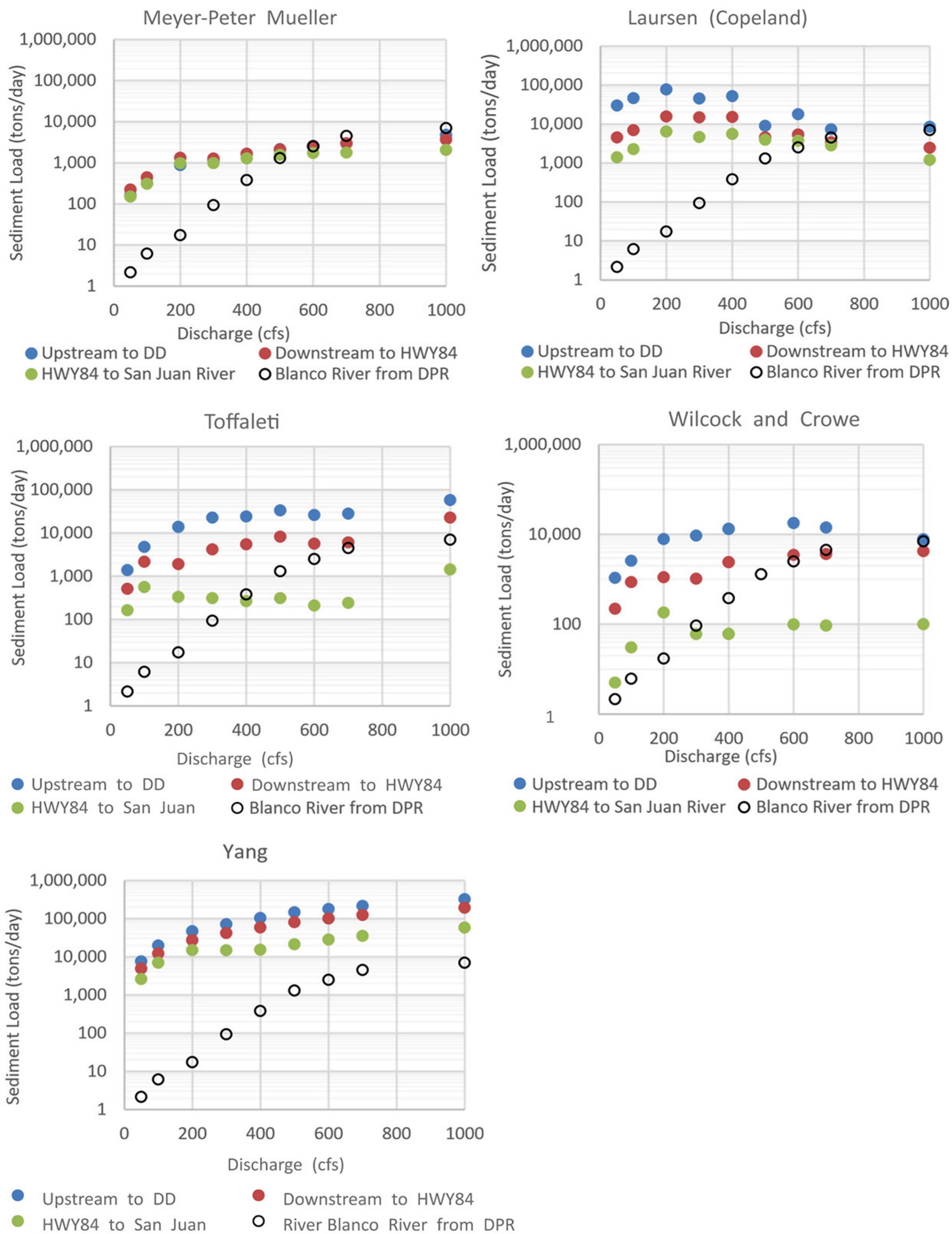


Figure 44.—Sediment rating curves from model results of equilibrium boundary conditions for five transport potential functions.

The longitudinal change in transport potential at 1000 ft^3/s for three of the bedload functions are seen in figure 45. This figure shows that both the Toffaleti and Wilcock-Crowe functions have very large transport potentials upstream of the dam that reduces quickly at the dam, with a gradual reduction in the downstream direction. The Meter-Peter Mueller (MPM) function has a relatively low transport potential upstream, dropping to zero at the dam, and then varying downstream based on local hydraulics.

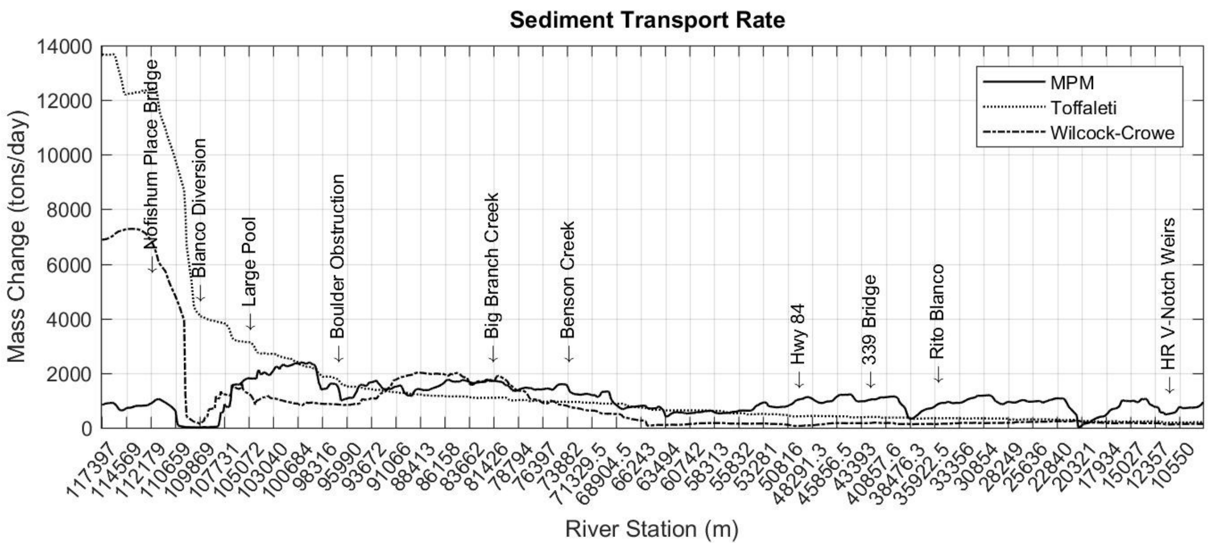


Figure 45.—Sediment transport potential values for three functions at Blanco River.

5.1.1 Estimating Annual Sediment Load at the Dam Sites

The sediment rating curves from both the DPR and the transport potential represented by the equilibrium condition of the MPM were used, along with the daily average flow records, to estimate the total annual load diverted and bypassed at the Blanco and Oso Dams. The difference in estimated annual transport is largely a function of the difference in sediment transport at low flows. For some context, the operating pool at Blanco has a volume of approximately 6000 cubic yards (yds^3), with a unit weight of sand and gravel of 1.215 tons per cubic yard ($tons/yd^3$), indicates that the Blanco operating pool has a capacity of 7290 tons of material. Figure 46 suggests that based on the MPM rating curve tens of thousands of tons of sediment are likely being entrained into Project tunnels. On the other hand, the DPR rating curve suggests that almost no sediment is transported downstream and material transported to Blanco Diversion Dam is on the order of just thousands of tons and may be largely captured in dam operating pool.

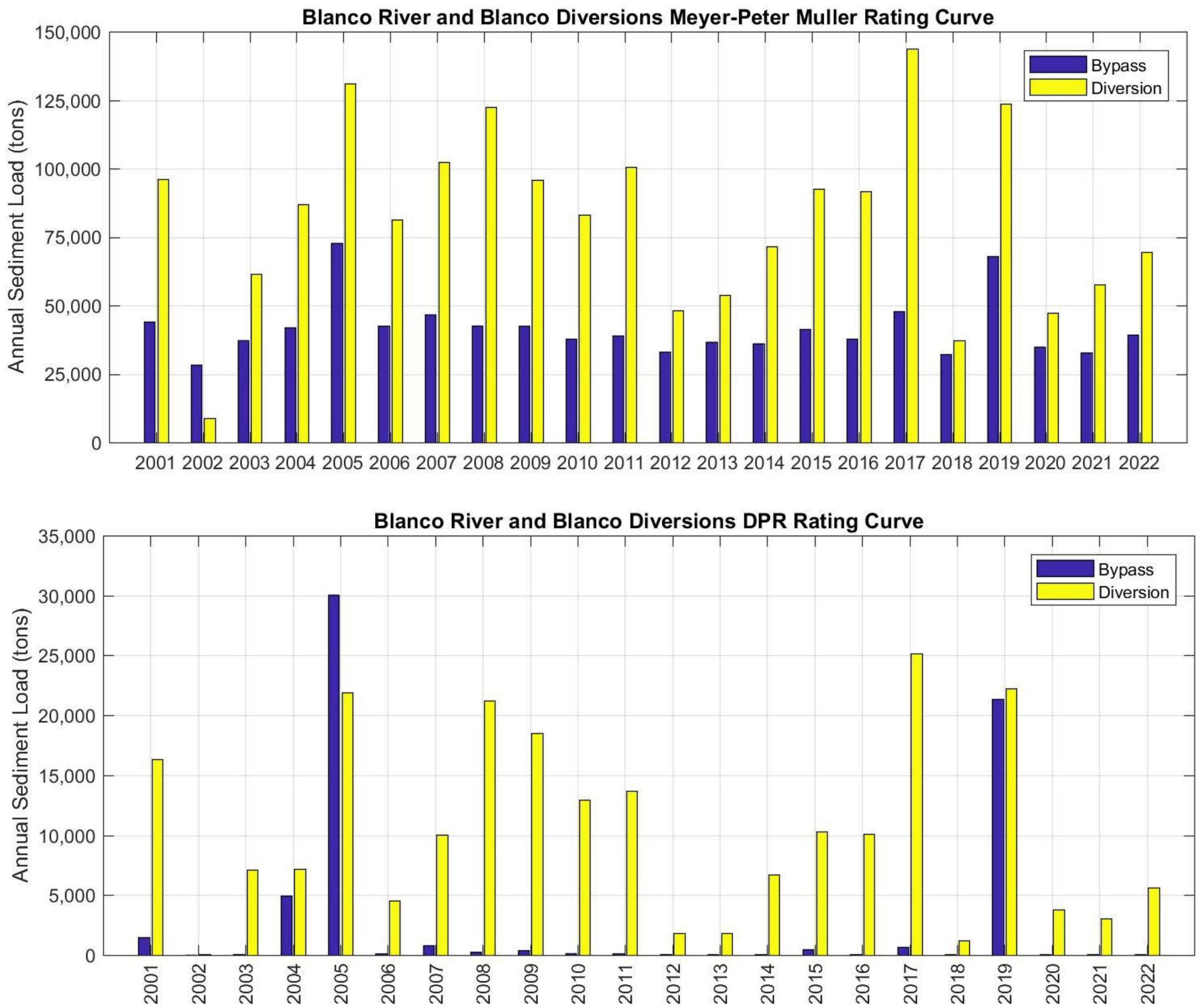


Figure 46.—Total annual sediment load bypassed and diverted at Blanco Dam, based on and MeyerPeter Mueller (top) and Definite Plan Report (bottom) rating curves.

A similar trend is seen in the Navajo River at Oso Diversion Dam; however, the larger flow volumes in the Navajo translate to larger sediment loads (figure 47). The Oso operating pool is significantly larger than Blanco's, with a total volume of 51,000 yds^3 that translates to approximately 62,000 tons of material. Like Blanco, if the MPM transport capacity function is a suitable representation of the system, tens of thousands of tons of material is diverted into the Oso tunnel on a regular basis. If the DPR rating curve is a better estimate, nearly all the material transported to the operating pool is captured. This discrepancy highlights the need for measured data to properly represent sediment transport conditions.

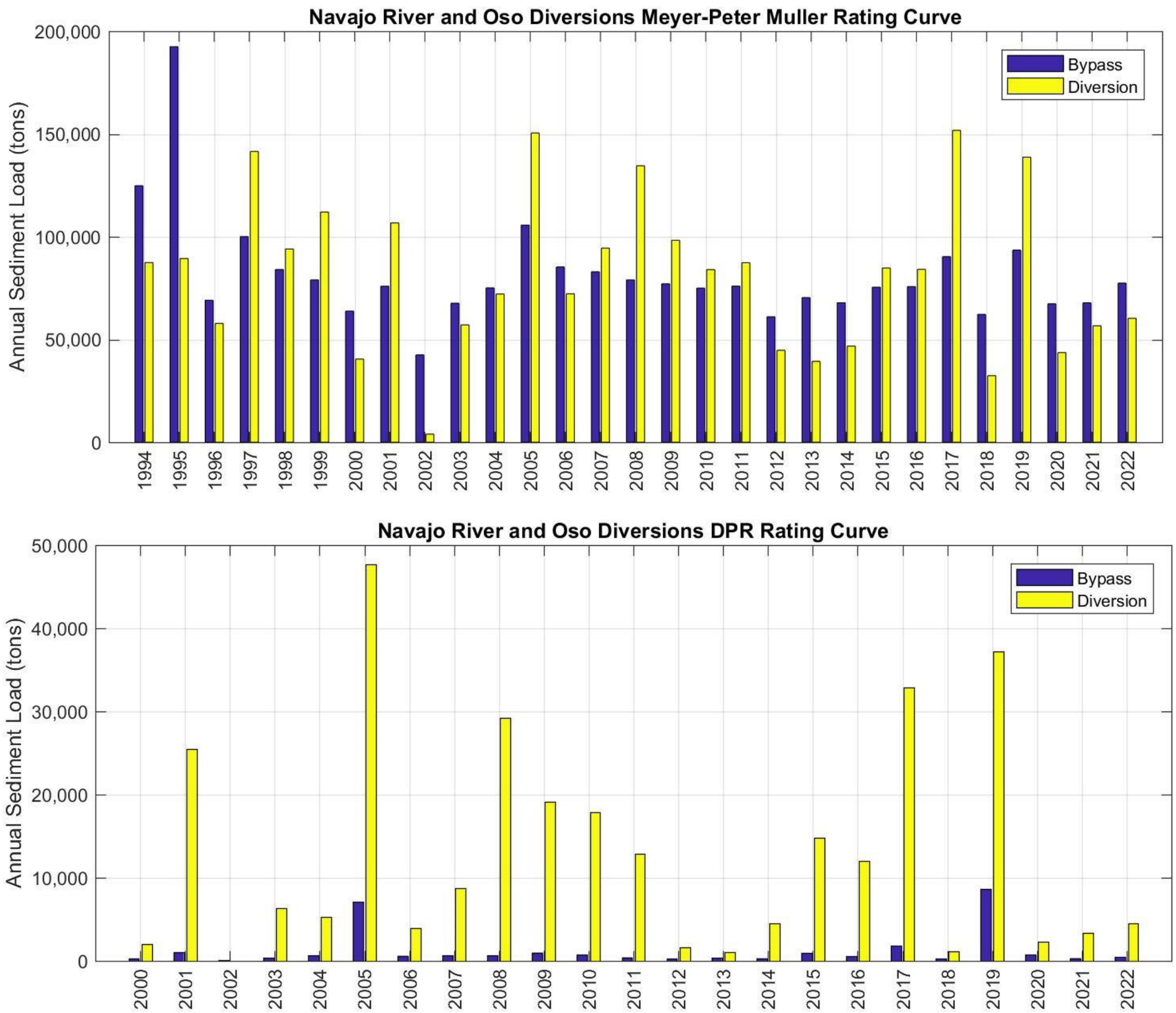


Figure 47.—Total annual sediment load bypassed and diverted at Oso Dam, based on and Meyer-Peter Mueller (top) and Definite Plan Report (bottom) rating curves.

5.2 Operating Pool Geometry

During model development a discrepancy was seen between the apron elevation or invert elevation of the dam and sluiceway, as determined from converted design drawing elevations, and the elevation reported in the LiDAR. This discrepancy was somewhat expected due to the regular sedimentation of this area and the inability of LiDAR to penetrate through deep water. To fix this discrepancy, first the dam approach channel was created in the few cross sections immediately upstream of the dam, based on the design drawings. The LiDAR derived topography of the operating pool was then modeled.

The model predicts a significant amount of deposition in the operating pools at Oso Diversion Dam. Fluvial geomorphic first principles suggest that a wide and low slope channel will have lower depths and therefore less shear force than a narrow channel with a steep slope. This principle was tested in the Oso Dam operating pool. A channel from above the operating pool to the dam approach cross sections was modeled using a straight reach that will create the steepest slope possible. This modeled channel was iteratively narrowed using manual techniques to update the approach channel of the model geometry. Figure 48 is an example of the original cross section through the operating pool, with the pink line representing the new geometry with a 40 ft (12m) bottom width and 3:1 side slope. The ideal bottom width was determined by looking at the upstream reach and matching the operating pool channel to the upstream width.

Figure 49 illustrates the invert elevations in the vicinity of the Oso Diversion Dam for both the original geometry and the 40 ft (12m) wide channel through the operating pool. This figure shows that with the original operating pool geometry, a significant amount of deposition or aggradation occurs well upstream of the dam. The deposition of material well upstream of the diversion dams is a significant problem for sluicing operations. As we know the larger materials, such as gravels, are likely to settle out of the water column before the finer material. Therefore, a condition in the operating pool that induces setline near the operating pool delta (where quiescent operating pool water meets the flowing river) results in fewer gravels reaching the dam vicinity and more sands.

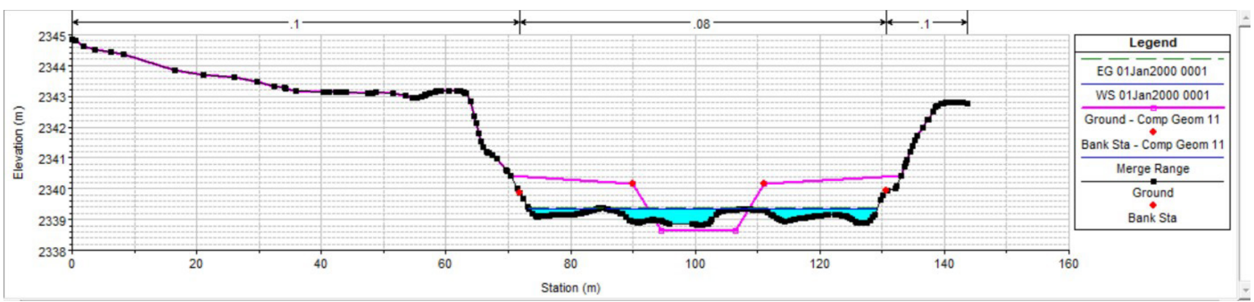


Figure 48.—Cross section displaying original operating pool geometry and simulated 12m channel.

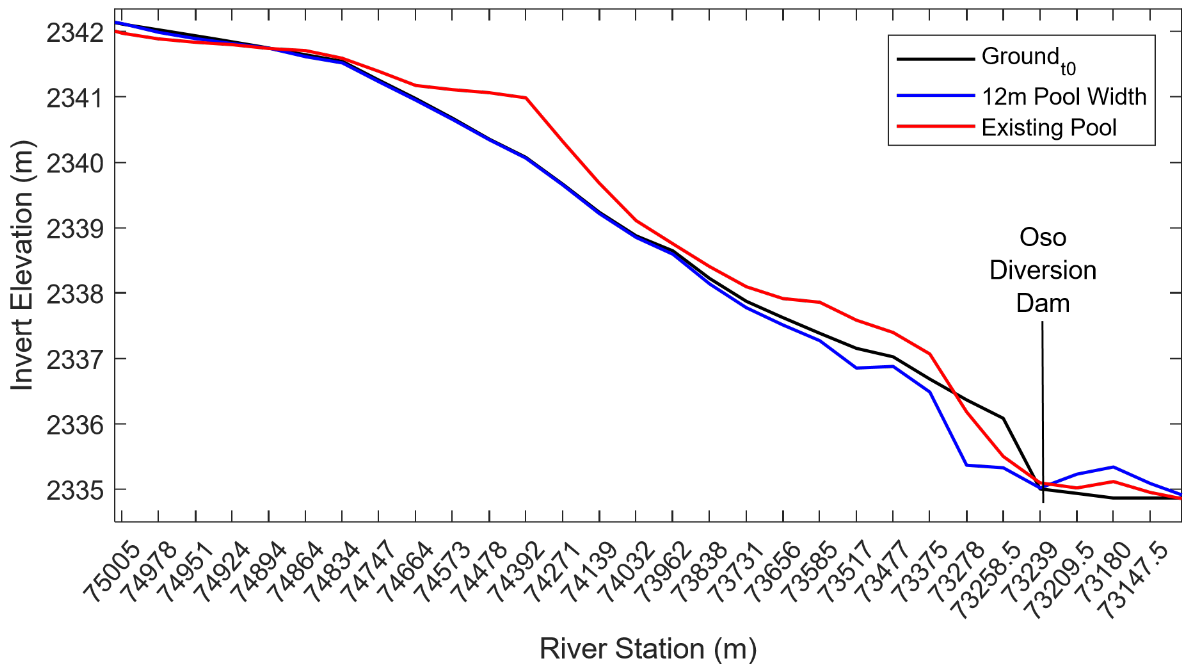


Figure 49.—Model results from 300 ft^3/s for two days displaying invert elevations in the vicinity of the Oso Diversion Dam for the initial ground, with the original operating pool and with a 12 m channel.

5.3 Discharge Sensitivity

The sensitivity of the models to changes in discharge was implemented for a 3-day duration, after a 7-day 20 ft^3/s warm-up period, with discharge rates ranging from 50 ft^3/s to 1000 ft^3/s. This range was decided upon based upon the hydrologic analysis findings, with the hope in identifying trends, processes, and possible thresholds to inform operational decision-making. The results for the variables of interest, Invert Change (figure 50), D50 Median Grain Size (figure 51), Longitudinal Cumulative Mass Change (figure 52), and the Width:Depth ratio (figure 53). These figures combined reveal several things about the communalities and differences between the two river systems.

5.3.1 Invert Elevation

The first thing that stands out is the aggradation occurring upstream of the diversion dams. In the case of Blanco, flows of 200 ft^3/s and greater, and 300 ft^3/s and greater at Oso, result in significant deposition in the operating pools. Some degradation occurs downstream of the dams and increases with increasing discharge. Blanco results suggest that the rifle-pool complexes downstream of the dam to Highway 84 will become better developed with deeper pool and shallower riffles. Downstream of Highway 84 little invert change occurs.

In the Navajo River a similar result occurs with the possibility of significant aggradation in the dam operating pool and some degradation downstream. While the Navajo sediment transport model does show some sensitivity to local channel characteristics, these results suggest that any degradation will occur withing the first 2.4 miles of stream, which includes the first two private properties downstream of the dam.

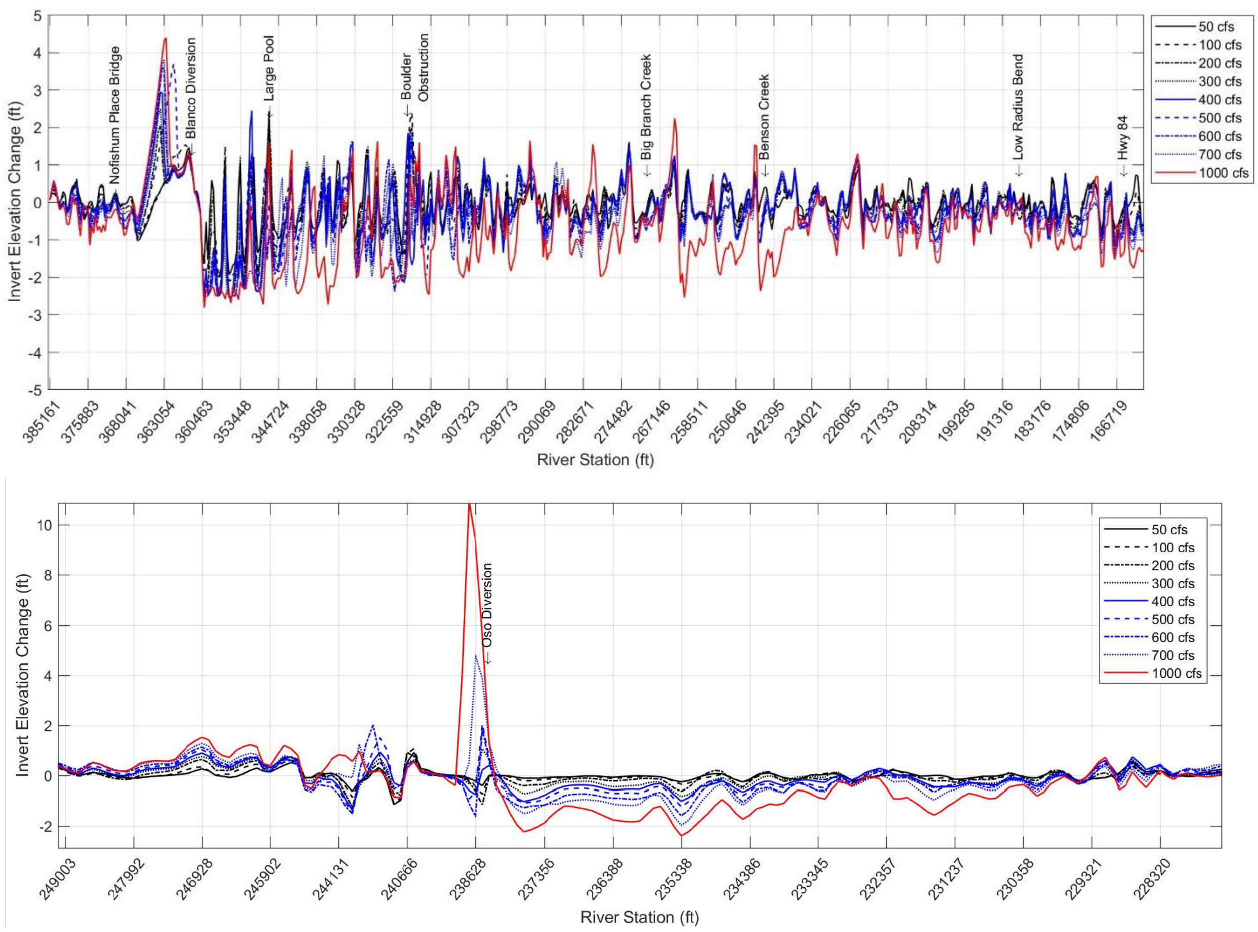


Figure 50.—Invert elevation change discharge sensitivity for the Blanco (top) and Navajo (bottom) River models.

5.3.2 D50

Model results for D50 represent the median grain size that begins from the input conditions (figures 41) and after the transport capacity is calculated for each cross section based on the class size differentiation estimated in figure 43. The results at t=0 represent the post-warmup period results, with the remainder based on discharge magnitude over a fixed 3-day duration.

Discharge to sediment transport relationships are corroborated by looking at the sensitivity of the D50 to changing discharge rates, with a very important exception. The sinusoidal pattern seen in the figure indicates the riffle/pool sequences associated with the meandering streams of the San Juan Mountains. Figure 51 shows that the Blanco River is coarsening, even with relatively little discharge upstream of the dam. Downstream of the dam, the Blanco River D50 shows a small amount or coarsening for discharges of 50 ft^3/s and 100 ft^3/s, with a jump in coarsening beginning at 200 ft^3/s. There is no fining that occurs in the Blanco Model. This suggests that there is a very high transport capacity, and that any sediment size will be transported through the modeled reach.

In the Navajo River model, a very distinct signal can be seen. Figure 51 shows that while the upstream D50 is fairly stable, with some slight coarsening with larger flows. Downstream of the Oso Diversion Dam, the median grain size is increasing slightly from the initial condition for flows between 50 ft^3/s and 200 ft^3/s. At 300 ft^3/s a marked increase in median grain size is seen. The coarser locations represent riffles and are predicted to coarsen with 3-days with flows of 300 ft^3/s and greater. The pool locations are represented by the finer material and the model predicts that little change will occur there.

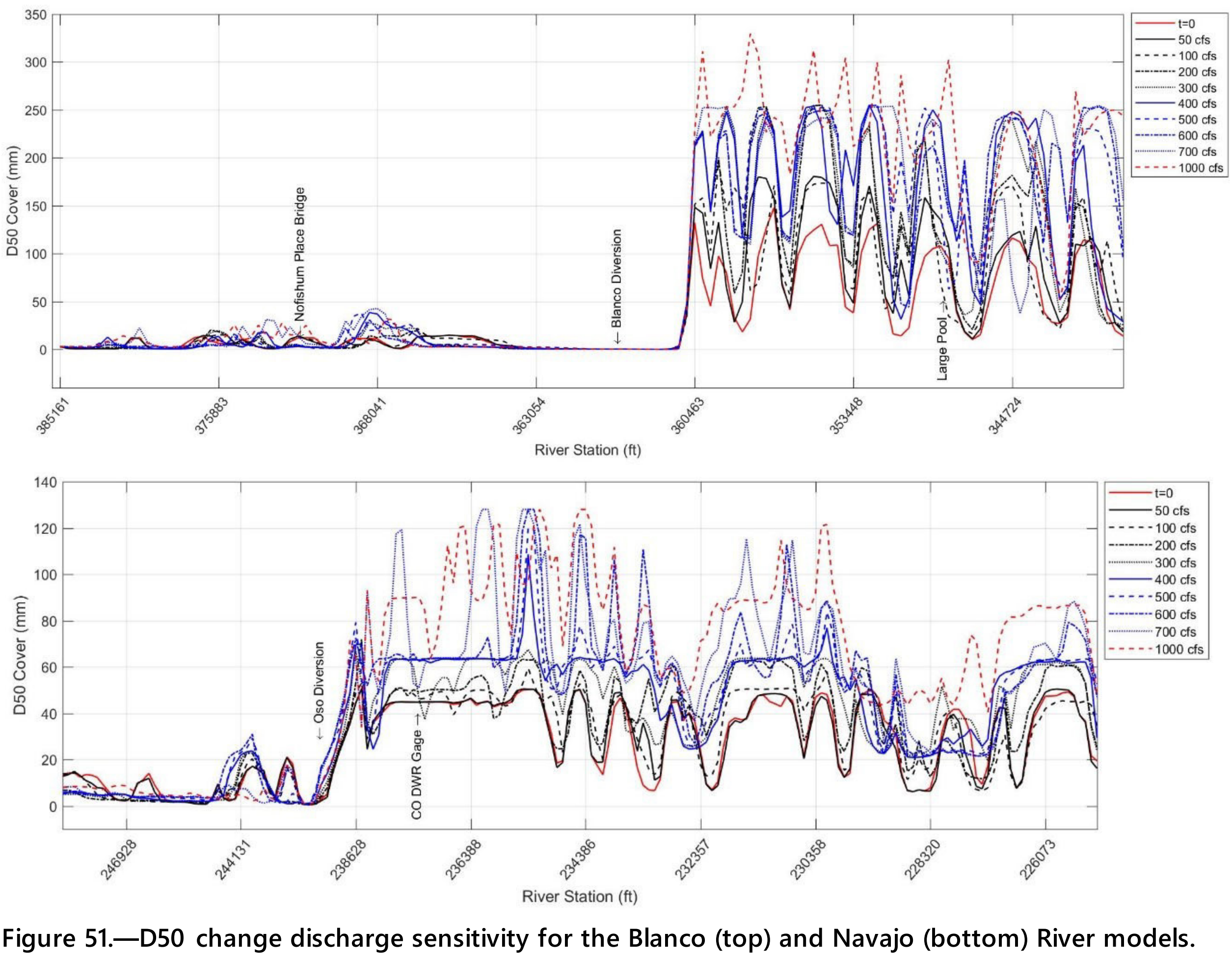


Figure 51.—D50 change discharge sensitivity for the Blanco (top) and Navajo (bottom) River models.

5.3.3 Longitudinal Cumulative Mass Change

The Longitudinal Cumulative Mass Change plot represents the total change in mass, cumulatively in space and time. Spatial accumulation is from the current cross section to the upstream boundary. This variable is informative in understanding the system dynamics with respect to where sediment sources and sinks occur in the model domain. A positively sloping line indicates that mass was accumulated in that location, a negative slope indicates mass was lost in that location, and flat slope that little change occurred. Figure 52 highlights the very different dynamics of the Blanco and Navajo Rivers within this model domain.

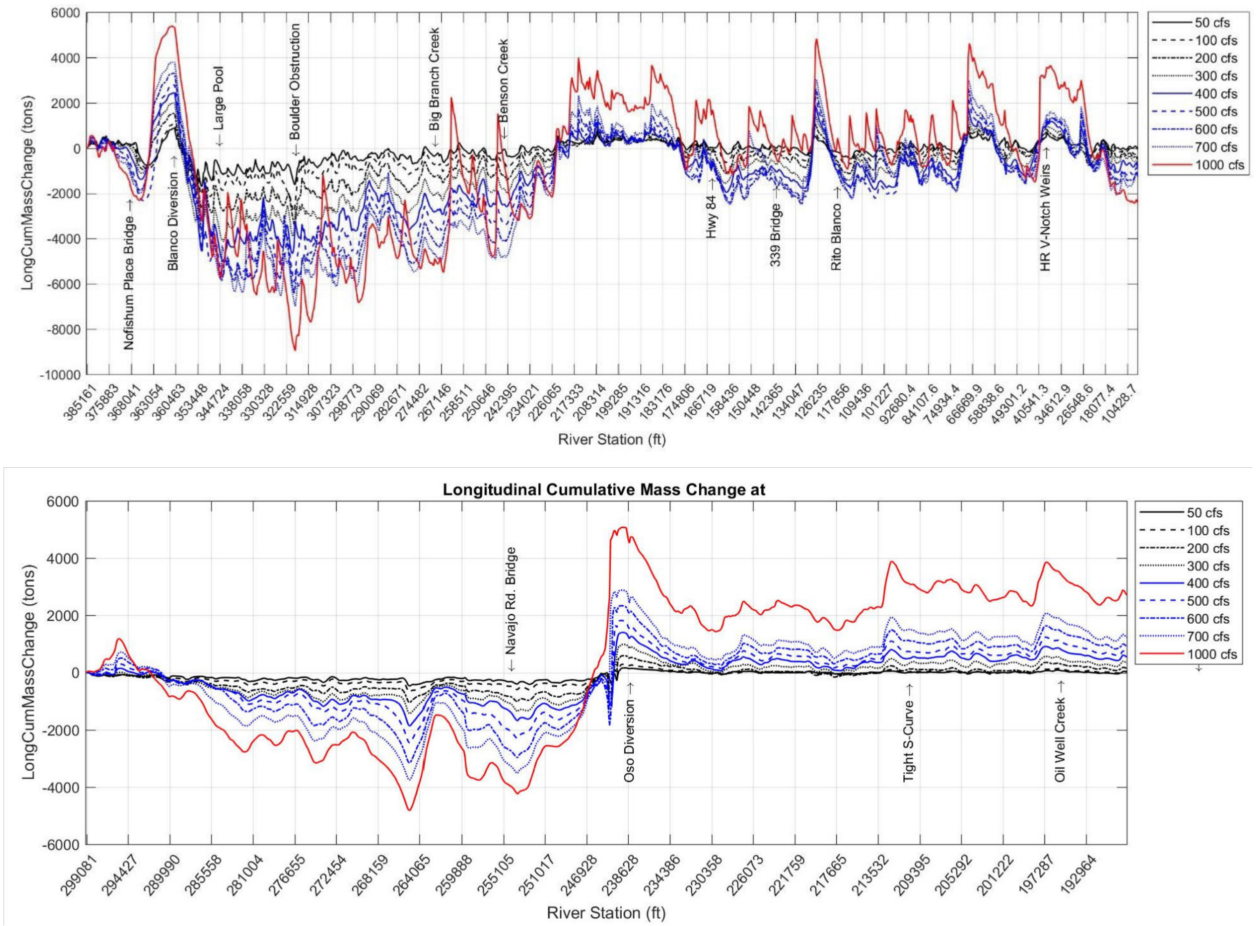


Figure 52.—Longitudinal cumulative mass change discharge sensitivity for the Blanco (top) and Navajo (bottom) River models.

The Blanco River model results indicate that the mass evacuated in the first approximately 4 miles of modeled river is deposited behind the Blanco Diversion Dam, in addition to material derived from the stream bed. Downstream of Blanco Diversion Dam material continues to be sourced from this subreach until the approximate location of a large boulder obstruction (River station 320000). Downstream of the large boulder obstruction, derived material begins to deposit. The material deposited is derived from the subreach immediately downstream of Blanco Diversion. Material continues to deposit until the approximate location of the Blanco River Campground (River station 228000). From just upstream of Hwy 84 (River station 190000) to the downstream model boundary, results suggest that sediment sources and sinks vary between riffles and pools, with a net loss of material mass. Locations with positive slope indicate the possibility of deposition of material and coincide with pool locations. Beginning just upstream of Hwy 84 and continuing for the next approximately 5 miles and in near the confluence with the San Juan River, several man-made habitat restoration features and diversion structures are in place and should be monitored for pre- and post-sluicing operation conditions (see Section 1.5). With respect to discharge magnitude, results suggest that flows of at least 200 ft^3/s are required for sediment transport throughout the model domain, and that transport capacity generally increases with increasing magnitude. This finding is consistent with other assessed variable results.

The Navajo River model results suggest that the subreach upstream of the dam is generally degradational with local areas of aggradation. Aggradation of the operating pool begins approximately half the distance from the Oso dam to the Navajo Bridge. Downstream of the Oso Diversion Dam, the accumulated material deposits in the first 1.5 miles downstream of the dam at most flows less than 1000 ft^3/s. Little to know aggradation/degradation occurs with less than 300 ft^3/s in the river.

The mass accumulated in these short duration and high flow simulations can also provide some insight into operating pool accumulation. At the Blanco Diversion Dam if 1000 ft^3/s were to flow for 3 days, or 72 hours, approximately 5000 tons of material is accumulated. With a unit weight of sand and gravel of 1.215 $tons/yd^3$, this value translates to ~4100 cubic yards, which is less than the operating pool volume of ~6000 cubic yards. At the Oso Diversion Dam, the same conditions result in a similar mass accumulation of ~5000 tons or ~4100 cubic yards. This volume is significantly less than the ~51,000 cubic yards of storage in the Oso operating pool.

5.3.4 Width:Depth Ratio

This ratio is displayed in figure 53 for both river systems. Figure 53 suggests a threshold condition that occurs in the Blanco River at 200 ft^3/s and in the Navajo River at 300 ft^3/s. At the lower flows large changes in width: depth ratio are seen, and then the values of this ratio nearly converge upon reaching the above mentioned discharge values. The fact that the values converge suggests this discharge represents the bankfull conditions, as increases in discharge have small changes in width relative to depth.

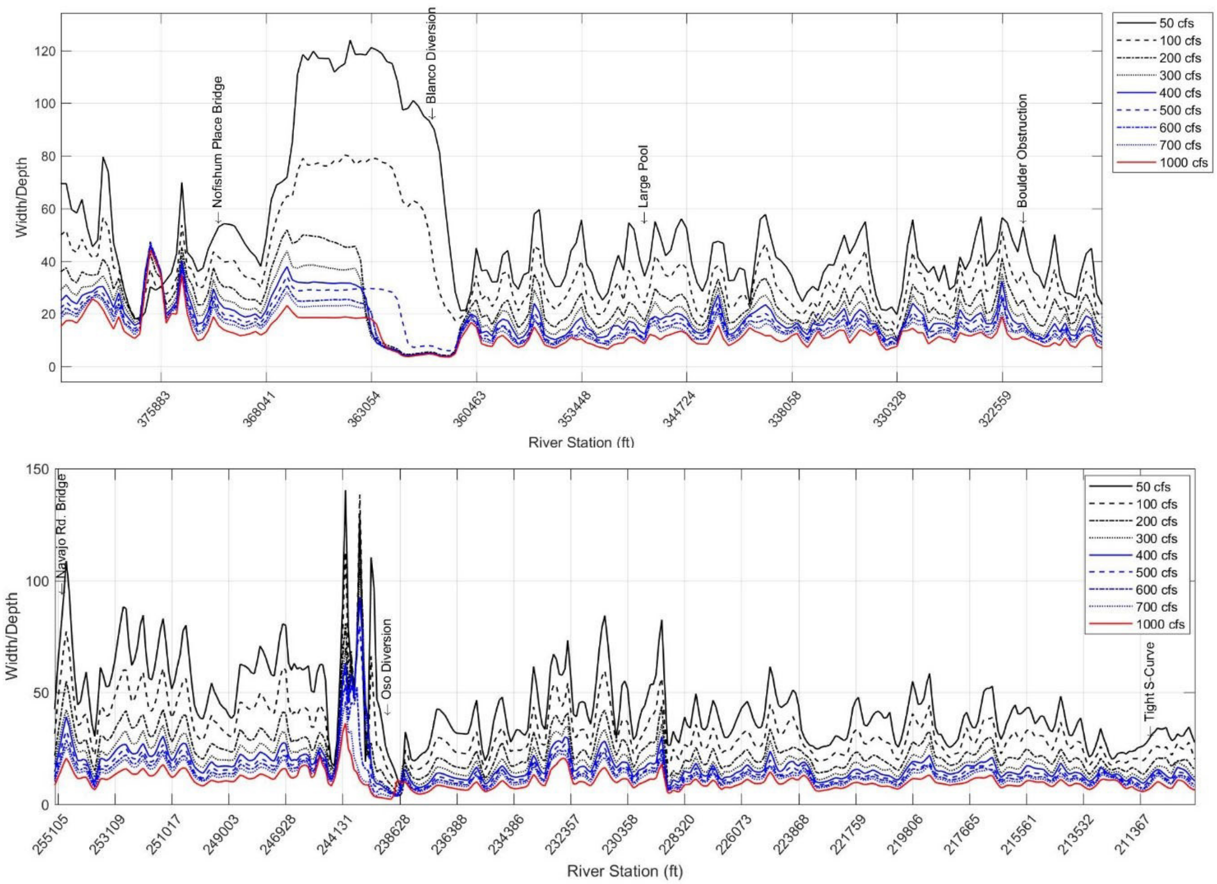


Figure 53.—Width:depth ratio discharge sensitivity for the Blanco (top) and Navajo (bottom) Rivers.

5.4 Duration Sensitivity

Upon reviewing the results of the discharge sensitivity analysis, the logical extension is to investigate the sensitivity of model results to the duration of the simulation. The following is the results of those analysis. For the Blanco and Navajo River models 200 ft^3/s and 300 ft^3/s were used, respectively, as these were determined to be bankfull conditions. Durations of 1 to 3 days were output. These results were output after a 7-day 20 ft^3/s warm-up period. The changes to the invert elevation are not reported here, as little change was found to occur in the duration sensitivity, except for the dam operating pools. The width:depth ratio for a single discharge also not change significantly with duration and is not reported herein. The finding that little change is occurring to the invert elevation and width depth ratio during the 1, 2, or 3-day durations suggests that the model is reaching an equilibrium condition quite quickly. This is especially true when little degradation/aggradation is occurring.

5.4.1 D50

The results from the duration sensitivity analysis for the median grain size variable is displayed in figure 54. This figure shows two very distinct signals from the two different river systems. However, in both systems the warm-up period results in changes to median grain size based on cross section characteristics. In the Blanco River coarsening occurs downstream of the dam during the first day of high flows, virtually no coarsening occurs after the first day. Conversely, in the Navajo River system, the model suggests that very little change to the median grain size in the bed material with additional time at higher flows.

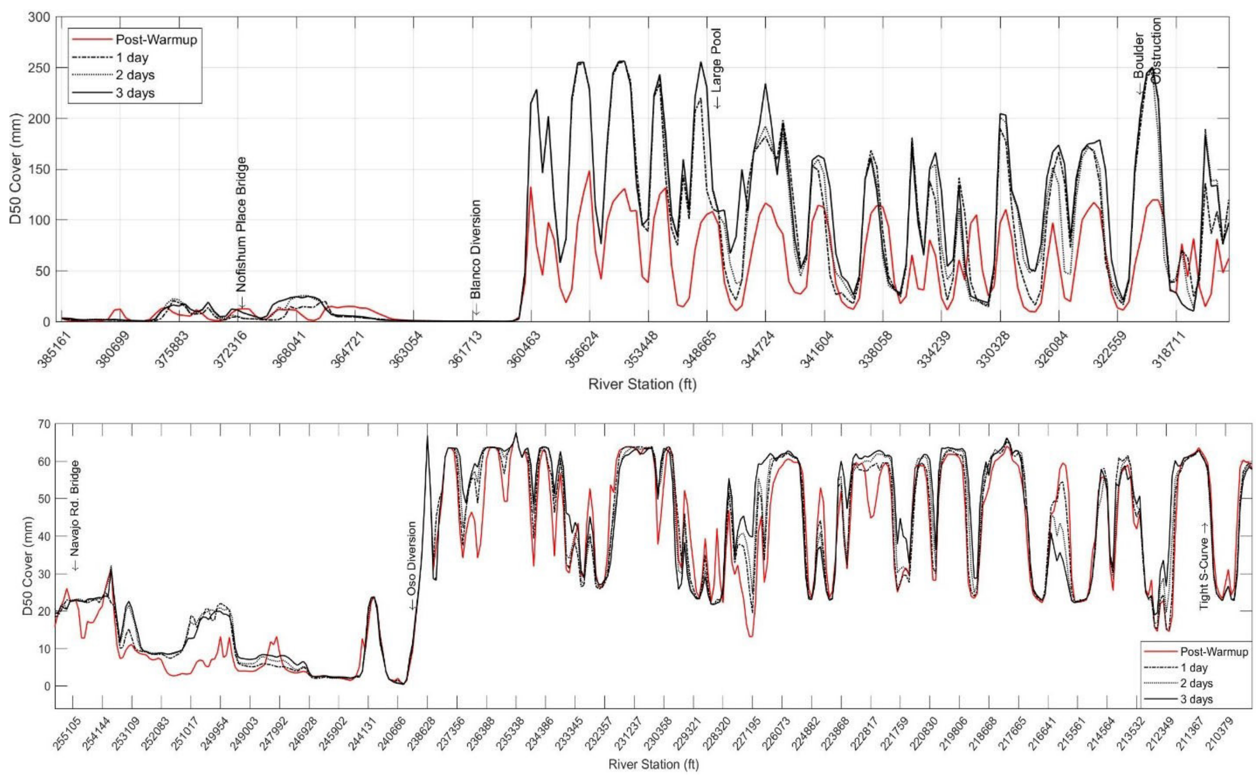


Figure 54.—D50 change duration sensitivity for the Blanco (top) and Navajo (bottom) River models.

5.4.2 Longitudinal Cumulative Mass Change

The changes in cumulative longitudinal mass in the two river systems, as a function of the duration of discharge suggests that the changes occur relatively linearly with time (figure 55). In the Blanco River model, the subreach trends identified in the discharge magnitude sensitivity continue with discharge duration. The subreach between the dam and Highway 84 continues to aggrade with longer duration flows. However, features upstream of Highway 84 arrest that aggradation, and the channel downstream is relatively stable over time. The subreach that begins at the outlet of the canyon and near the Blanco River Campground (River station 228000) is not predicted to accumulate significant mass of material with longer duration high flows.

The Navajo River model displays similar relationships for duration sensitivity as the discharge sensitivity, in that most of the change occurs upstream of the dam and immediately downstream. The remained of the modeled reach is quite stable.

Another noteworthy result shown in figure 55 is that after 3 days of high flows approximately 3000 tons at Blanco and 2000 tons at Oso are accumulated. These values are significantly less than the available storage in the operating pools.

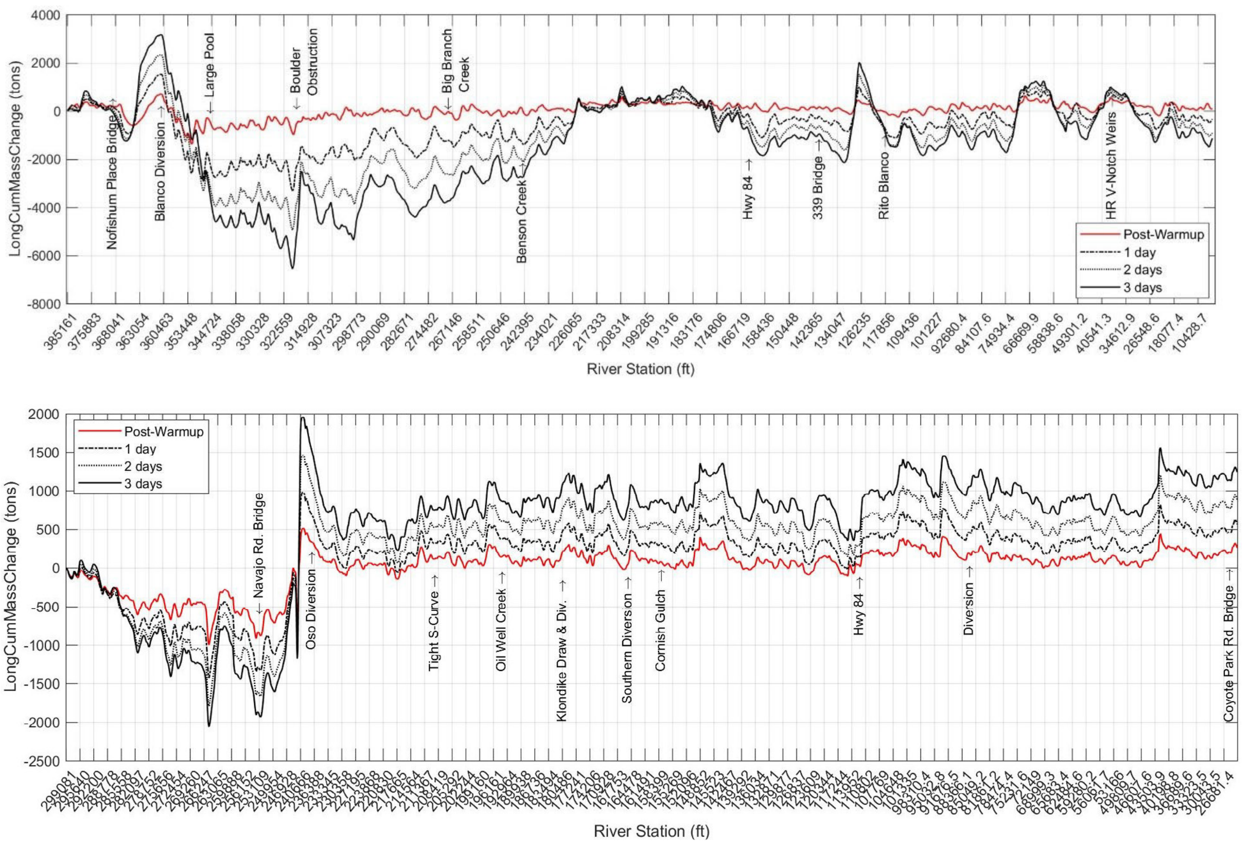


Figure 55.—Longitudinal cumulative mass change duration sensitivity for the Blanco (top) and Navajo (bottom) River models.

6.0 Dam Spillway and Sluiceway Hydraulics

Model geometry was built to include the dam spillway and gates based on the design drawings and elevations (figure 39). The model does not include sediment transport. This representation allows for the opening and closing of the dam gates, which was done with a range of discharge conditions. The results of this analysis are very illuminating and shed light on some of the observations made by Chama operational staff in the early years of Project operations. The physical principles behind sluicing require that concentrating flow through the sluicegate will increase velocities, indicated by lowering the WSE. This high velocity thread within the channel can produce a headcut through the material below, that will be carried downstream.

The water surface elevation (WSE) upstream of the dam is plotted in figure 56, as a function of the gate opening and the discharge. This plot suggests that at Blanco Diversion Dam for flows as great as 1000 ft^3/s, with the gate open to 10 feet, a drop in the water surface elevation occurs to below the level of the spillway crest, indicating that all flow is going through the sluicegate. Although not tested, the sluicegate at Blanco opens to 17 feet, suggesting that greater than 1000 ft^3/s discharge can be conveyed through the sluicegate.

At the Oso Diversion Dam, with all 6 feet of the sluiceway open, a WSE drop below the dam crest, can be seen in all flows except for 1000 ft^3/s. This indicates that for flows of 1000 ft^3/s and greater not all the water will be able to go through the sluiceway. If a significant amount of water is also going over the spillway, the downstream boundary of the sluiceway may be inundated, reducing sluicing efficacy. This supports the observations made by the operating personnel who observed that the sluicegate was not big enough to use for sluicing under high flows, as no distinct high flow thread is created upstream of the dam.

These flow, gate, water surface elevation relationships are hypothetical and assume the area in front of the sluicegate is entirely clear. In the absence of sluicing or between sluicing operations, these relationships are not applicable. However, the result of a sluicing operation would be to evacuate the material in the immediate vicinity of the sluicegate and dam spillway. The accuracy of these relationships, given changing operating pool conditions, in unknown.

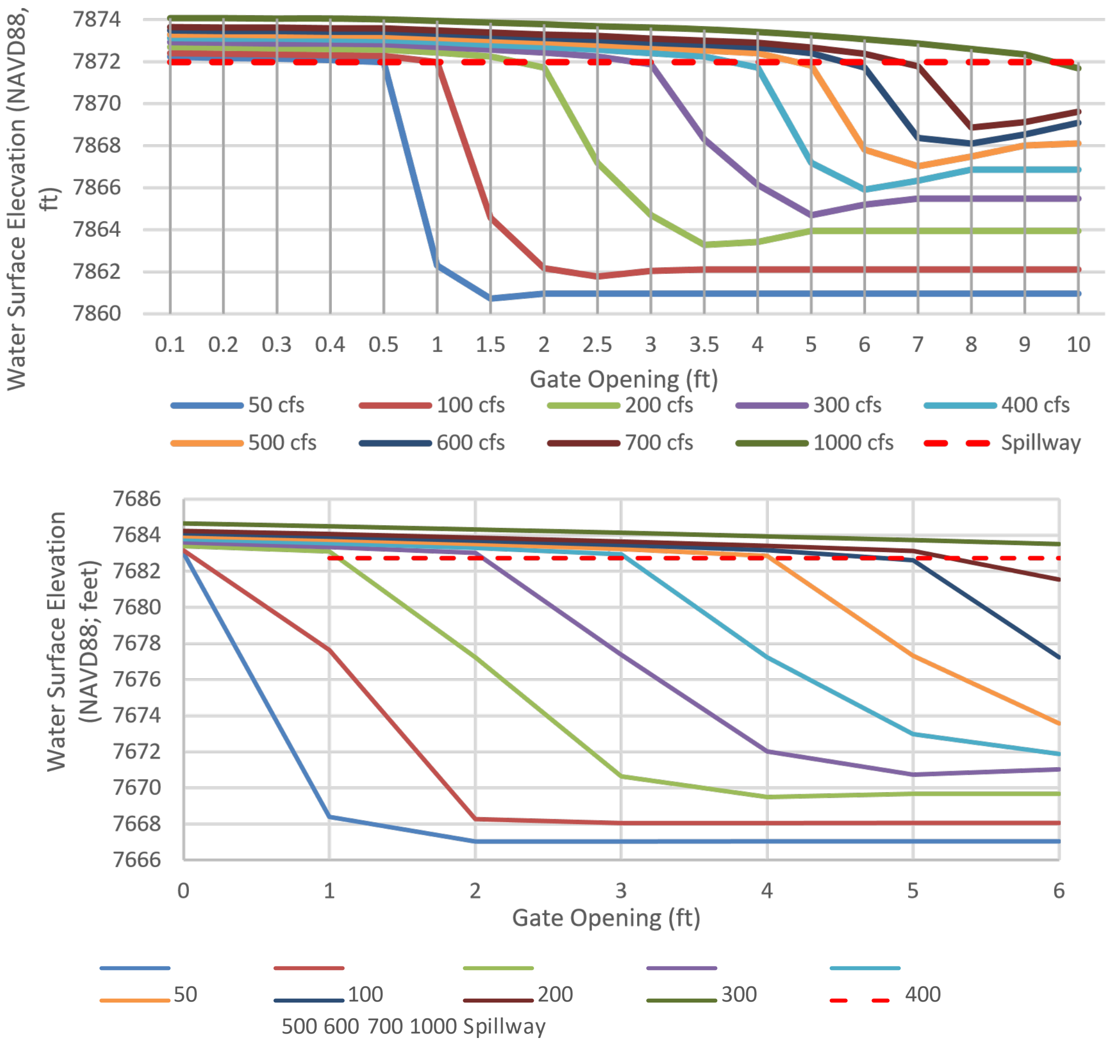


Figure 56.—Blanco (top) and Oso (bottom) dam upstream water surface elevation as a function of gate opening and discharge.

Another set of figures that can be developed for the Blanco and Oso Dams are gate curves for the sluicegates. Gate curves predict the flow through the gate given the gate opening and the upstream WSE. Figure 57 illustrates the gate curves for each dam. An interesting pattern emerges from these theoretical gate curves. At Blanco Dam, when the WSE is at the spillway crest elevation and the sluicegate is open 1 foot, 100 ft^3/s is going through the gate. With a 2-foot opening, and the WSE at the dam crest, 200 ft^3/s is being conveyed through the gate. This relationship, 1 foot to 100 ft^3/s, with the WSE at the spillway, is consistent up to a 7-foot gate opening. While similar, at the Oso Dam, the sluicegate discharge starts with 200 ft^3/s with a 1-foot opening and an additional 100 ft^3/s is conveyed with each foot of opening. Although derived theoretically from the hydraulic model and dam geometry, these relationships were made to facilitate dam operations.

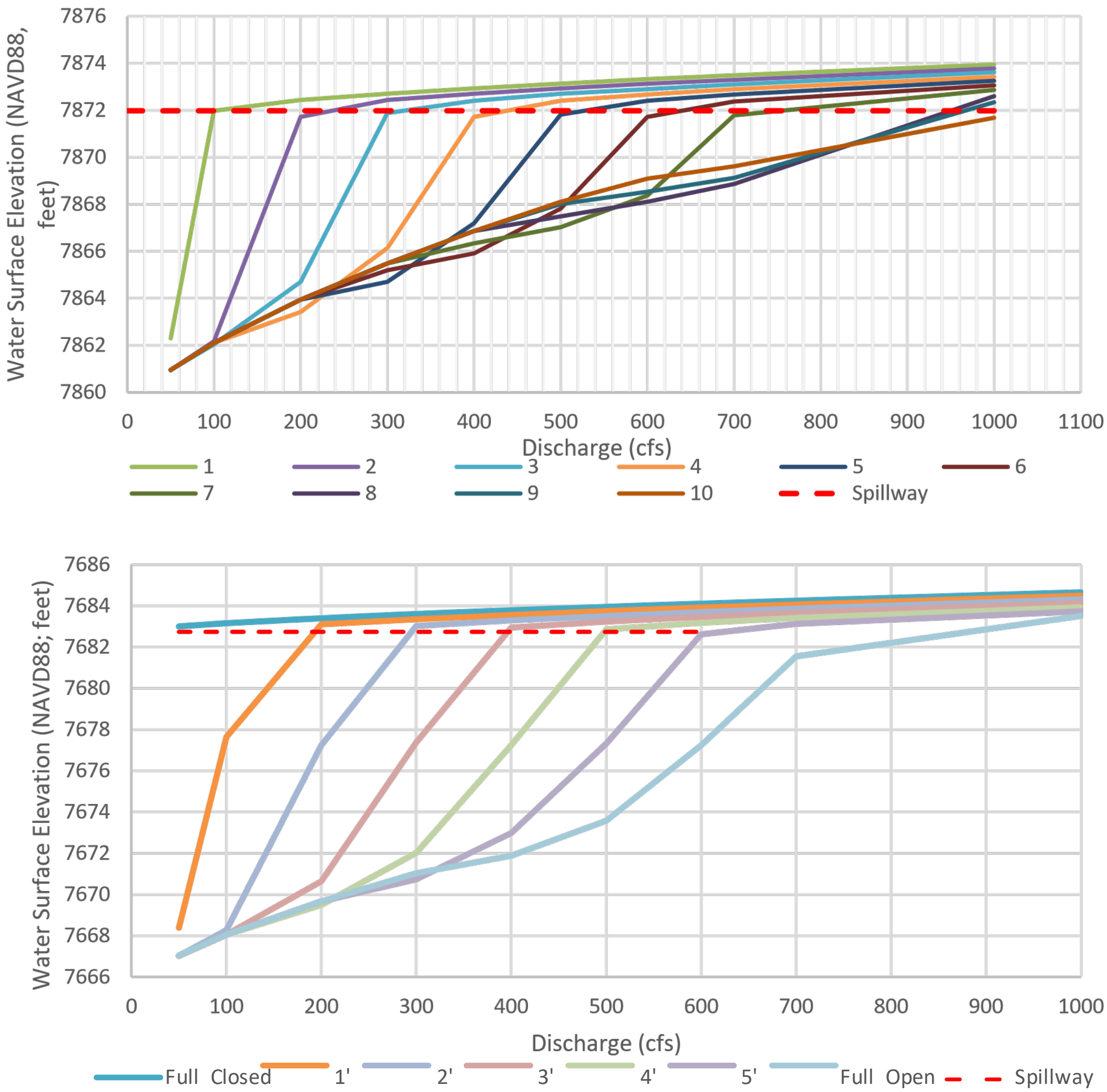


Figure 57.—Sluice gate curves at Blanco (top) and Oso (bottom).

7.0 Conclusions and Recommendations

This investigation represents an appraisal level analysis of the hydraulic and sediment transport conditions of the Blanco and Navajo Rivers, including the Blanco and Oso Diversion Dams. The result of this investigation is intended to provide some guidance with respect to what constitutes "floodflows" when a sluicing operation would be appropriate and effective. A sluicing operation is meant only to occur when debris and sediment are blocking the tunnel entrance, thereby reducing diversion. The efficacy of a sluicing operation is measured by the ability to restore the tunnel to full diversion capacity. The function of a sluicing operation at a diversion dam is not intended evacuate all the material from the diversion dam operating pool, the function is to restore diversions. This is accomplished through a combination of trashrack, sluice gate, and headworks gate management.

The introduction of this report attempts to synthesize the Reclamation Inspection Reports, communications between dam operators and designers, and the decision of Judge Matsch in the 1974 lawsuit. That synthesis highlights that sediment and debris management can be very challenging during high flow events. The synthesis also documents that early efforts to use the dam sluiceways were done during low flows, resulting in large concentrations of sediment with little discharge to transport it. Current guidance for use of the sluiceways is lacking, with the sole statement that it should be carried out during “floodflows” with no further guidance.

The essence of Judge Matsch’s decision is to reiterate Reclamation’s legal requirement that “the facilities be operated without injury, impairment, or depletion of existing or future beneficial uses of water within the State of Colorado.” Given this requirement, the study presented herein set out to determine what downstream flows are required to minimize the likelihood of those undesirable impacts. To accomplish this a one dimensional hydraulic and sediment transport model was developed, boundary conditions were tested and sensitivity analyses to flow magnitude and duration were implemented.

Gravel and sand deposition in the downstream reach is desirable for aquatic habitat, the deposition of silts and clays represents a degradation in aquatic habitat and a risk to irrigation infrastructure. This investigation sought to estimate a flow rate at which silts and clays are least likely to settle into existing and new sand and gravel beds, and irrigation diversions. These conclusions are from analysis of modeled changes to variables such as invert elevation and bed material size changes, as well as the source and sink locations of sediment in the rivers modeled. These flow rates represent approximate bankfull conditions on the respective systems, reducing the likelihood that fine materials settle into aquatic habitats and diversions.

Model results suggest that a flow of 200 ft^3/s through the Blanco River and 300 ft^3/s though the Navajo River for 1 day, is required to minimize the likelihood of negative impacts. Both models suggest all changes to median grain size occur in the first day of modeling, implying that the model reaches equilibrium quickly. The Blanco model results show that a significant portion of the sediment is trapped by the diversion dam and that very limited aggradation will occur near the Blanco Campground upstream of Hwy 84. The Navajo River model results suggest nearly all the sediment derived from upstream is deposited behind the Oso Diversion, with each day of high flow resulting in additional deposition. Within three days of modeling the operating pool did not fill with sediment. Downstream of the dam, model results suggest that sands and gravels will travel a relatively short distance with sediment accumulating in the first 1000 feet downstream of Oso Diversion Dam in the Navajo River. Longer duration modeling also showed very small levels of aggradation beyond the first 1000 feet below the dam. These findings suggest that Navajo River has low transport capacity of sands and gravels and that if those materials are sluiced through the diversion dam at high flows, they are unlikely to travel much distance downstream. However, fining of the bed material distribution at individual cross sections is also unlikely to occur with 300 ft^3/s in the river. Gravel augmentation programs downstream of Oso Diversion Dam suggest that gravel size particles move quickly downstream.

For the Blanco River 200 ft^3/s and the Navajo River 300 ft^3/s represent the Project bypass flows; therefore, with a full tunnel of 520 and 650 ft^3/s, at Blanco and Oso respectively, a total of 720 ft^3/s at Blanco and 950 ft^3/s at Oso total river discharge is recommended as a minimum threshold representing floodflow in each system. The definition of "floodflow" represents the first step toward developing guidance on effective and appropriate sluicing.

The investigation also set out to determine if dam sluiceways are sufficient to bypass some portion of the sands and gravels that are transported to the dam structures. A sluicing operation is not intended to evacuate all the material that has deposited in the dam operating pool. Rather, a sluicing operation is intended to reestablish the maximum diversion capacity of the tunnel. Both the sluicegate and the diversion gate settings impact the efficacy of a sluicing operation. Sluicing is maximized when the sluicegate is fully open and the diversion gate is fully closed; however, sluicing efficacy may not require this maximization. Sluiceway gate curves suggest that at Blanco dam greater than 1000 ft^3/s can be conveyed through the sluiceway with no overtopping of the dam spillway. The diversion of water was not simulated at the structure. The gate opening was modeled up to a 10-foot opening, but the gate is a total of 17 feet in height and the dam spillway crest is 13 feet tall. Modeling suggests that a significant draw down in the operating pool will occur with the Blanco sluicegate open. That drawdown represents a high likelihood of sluicing efficacy. The Oso Dam has a 6 ft x 6 ft sluiceway with a much smaller capacity. At flows over 700 ft^3/s little drawdown occurs with maximum sluicegate opening and some water is going over the dam spillway. The inability to drawdown the water surface and the likelihood that the sluiceway exit is inundated, suggests that sluicing efficacy at high flows at Oso Dam may be ineffective. In addition, sediment transport modeling indicates that a minimum of 950 ft^3/s (300 ft^3/s bypass and 650 ft^3/s diversion) should be available in the Navajo River to minimize downstream risk of fine materials settling into aquatic habitats and irrigation diversions. With this guidance threshold, the likelihood of sluicing efficacy is further reduced at Oso Dam.

Sediment transport modeling involves several assumptions and reliance on empirically derived formulas. When measurements and modeling occur simultaneously, total daily volumes of sediment within one order of magnitude are the norm. While suspended sediment transport measurements are available for these river systems, no bedload transport data is available, representing an unknown portion of the total load. Several bed load functions were assessed for transport modeling. The Meyer-Peter Mueller (MPM) equation was used due to its stability and sensitivity to downstream geometry given that the investigation focus is on downstream impacts. The MPM is a bedload equation derived from flume experiments in a sand and gravel flume and experiments mostly examined gravel. The MPM tends to under predict finer materials (USACE, 2024). Sand comprises a significant portion of the material dredged from the dam operating pools; therefore, these estimates may under predict bed load at high flows. With respect to low flows, these empirical functions appear to over predict bedload.

Although not within the scope of this analysis, sediment bedload transport rating curves from modeling discharge sensitivity and suspended sediment rating curves from the DPR data collection effort, were developed and could easily be used to derive total annual volumes of sediment based on the flow time series. This value is of interest due to potential downstream impacts, tunnel impacts, and dredging and sediment management operations. The MPM rating curves suggest that even in a very low flow year tens of thousands of cubic yards of material are being transported. Given that the operating pool volumes are significantly less that these values, this finding suggests that this material is either going into the tunnels or through the bypass, or that the model is overestimating bedload. Given, the conditions downstream and the dam operations and maintenance experience, it is highly unlikely that these results accurately represent conditions at the dams. It appears that the model is most likely over-predicting bedload sediment transport rates, particularly at low flows. While this provides less confidence in total annual volumes, it also provides a more conservative result with respect to potential downstream impacts of sluicing.

The suspended sediment rating curve developed from the DPR was also used to estimate total annual volumes. The annual volumes estimated with from this data set suggest that in low water years all the sediment arriving at the dams is entrained behind the dams, as the volumes are less than the operating pool total available volumes. The suspended sediment rating curve also suggests that during high flow years, the sediment arriving at the dams can be greater than the pool volumes. This finding is more consistent with dam operation and maintenance activities. This suggests that the proportion of bedload in the total transport is relatively small, particularly being true in low water years.

Dam debris and sediment management operations occur in two distinct time periods. After diversion season is over, generally in fall or early winter, as all available flows are required for bypass, Reclamation staff excavates the material that was deposited over the spring runoff. Excavation activities may also be required after large monsoon events. The reestablishment of the maximum dam operating pool volume allows for maximum adaptability to maintain the ideal height for diversion with changing discharge conditions. The other period when sediment and debris management occur is during high spring flow runoff events.

One of the distinct features of the Navajo, and especially the Blanco Rivers, is the strong diurnal signal that occurs when snow is melting. A typical hydrograph will show that flows approximately double from a minimum at 12 p.m. to a maximum at 12 a.m., ±3 hrs, especially true during high flow years. When staff arrive to the dams in the morning, they see the result of overnight high flows. Depending on hydrologic conditions, anything from a small amount of debris on the trashrack and no sediment build up, to layers of large trees and feet of sediment deposition may be encountered. Likewise, the diversion capacity of the tunnel may be reduced to less than a third of the full tunnel or the tunnel is full to capacity. During high flow years, when significant amounts of daily sediment and debris clearing is required, preliminary estimates indicate that the tunnel capacity begins to be reduced shortly after clearing operations with a significant diversion capacity loss associated with the snow melt pulse sometime in the late afternoon.

Due to the nature of the system, sluicing operations should not take place during the regular morning operations, as flows are receding during this time of day, maximizing the likelihood of deposition downstream, even though overnight flows are likely to remobilize this material. Rather, sluicing operations should occur during the rising limb of the hydrograph, preferably as late in the day as possible. A sluicing operation functions to evacuate the material directly in front of the tunnel, thus providing available volume for the new material arriving overnight.

It is also highly likely that a significant portion of the debris that is impinged on the trashrack is the result of a "first flush," or arrives with the first portion of the rising limb of daily snowmelt runoff. Therefore, removing this debris later in the day, may reduce the impact of debris on loss of tunnel capacity in the overnight and early morning hours. This finding, along with a flow threshold for sluicing, represents important guidance for development of comprehensive operating procedures for sluicing. Having defined floodflows needed to implement a sluicing operation, the next step is to optimize the operations of the sluiceway and tunnel headworks gates.

7.1 Recommendation 1: Develop a Testing Plan to Optimize Sluicing Operations

A testing regime, including data collection on efficacy and impact, should be planned, and implemented. The results of this sluiceway testing should inform future decisions about standard operating procedures or opportunities for automation. The conditions in which this testing can occur may not exist for several years, given the restriction to those flood conditions outlined above. A mobile-bed physical model of the dam could be used to optimize gate operations for sluicing efficacy. A model allows testing under a wide range of conditions, improving confidence in operational optimization. A model also allows the testing of changes to diversion dam properties to identify other potential solutions.

Sluicing operational testing should occur in conjunction with downstream users and aquatic resource partners, including development of monitoring sites and protocols. In addition to flow thresholds outlined herein, conditions regarding operating pool conditions, required data collection in real-time and post-operation, duration of sluicing operation, etc. should be considered. Ideally, such a testing plan would result in guidance that would eventually allow dam automation to include sluicing operations under specified conditions.

This investigation also compiled and analyzed all available stream gage data. Appendices A and B are plots of the combined bypass and diversion annual hydrographs. These plots allow a visual inspection of flood flows and how the diversion and bypass flows are divided. This visual inspection highlights that when flooding occurs, there are many cases when diversions decrease due to tunnel blockage, and bypass flows increase as flows are forced over the diversion dam spillways.

The relationship between the magnitude of high flows and the magnitude of diversion losses due to sediment and debris is not well known. This relationship was not in the scope of this analysis and no effort was done to quantify this dynamic, nor characterize of the extent of lost capacity or lost volume due to floodflows through the life of the Project. In a 2006 Reclamation water quality monitoring report for Rio Blanco annual dredging operations, they report that two in the previous ten years required any dredging activities. Characterizing the degree to which diversions are being lost during high flows is critical to assessing the cost/ benefit of any proposed solutions.

7.2 Recommendation 2: Analyze Historical Record of Diversion and Bypass Data to Characterize Extent of Diversion Losses Associated with Flood Conditions

The data compilation and analysis carried out highlighted several things. Firstly, there is a serious dearth of sediment transport data associated with the Project streams and diversions. Ernest Pemberton, in 1975 wrote:

> "The suspended sediment data collected during 1972 to 1974 represents a random sampling program heavily influenced by radical changes in both discharges in the stream channel, both occurring naturally and influenced by a diversion dam. A more detailed sampling program should have been undertaken. This may not have actually been more expensive, but it would have concentrated on a particular flow period or cycle. This type of sampling program would have given better insight on what was physically taking place."

This finding remains the most recent undertaking to measure the sediment transport associated with Project facilities. The sediment rating curves developed for the DPR were derived from a data collected in 1962 and used to calculate the change in storage in Heron Reservoir. However, they included only suspended sediment, as they assumed all bedload would be bypassed through the sluiceway.

7.3 Recommendation 3: Develop Debris and Sediment Transport Data Collection Plan

Given the extent of debris collected from the trash racks during floodflows in the past, it clearly plays an important role in blockage of the tunnel. Appendices B and C are a sample of inspection photos at Blanco and Oso Diversion Dams, respectively. While these photos show significant sediment deposition in front of and behind the trash racks, the dynamics between debris and sediment deposition is unknown. A carefully designed data collection plan will help show the relationship between discharge hydrograph, and the debris impinging on the trashrack, sediment depositing in front of the tunnel, and diversion capacity changes. It is possible that a small change in operation of debris management will ameliorate much of the tunnel blockage.

No effort was ever done to characterize the bedload component of sediment transport. Having robust and reliable sediment rating curves will provide valuable information for any future modeling efforts and help characterize the extent of sedimentation arriving at the diversion dams under a variety of conditions.

This investigation found that the Project facilities are in areas with a high potential for debris and sediment yield from the upstream watershed. The Blanco Dam is higher in the watershed and closer to sediment and debris sources, resulting in greater transport capacity and a higher proportion of gravel. In addition, there are no private homes or agricultural lands downstream of Blanco until downstream of Highway 84. In contrast, Oso, is lower in the watershed, resulting in more total flow, but a high proportion of sands and lower transport capacity, with many homes and agricultural diversions immediately downstream on the Navajo River, making it a poorer candidate for sluicing operations.

7.4 Recommendation 4: Investigate Structural Solutions to Improve Facility Sediment and Debris Management

This investigation did not investigate solutions to sediment and debris management at the diversion dams. This investigation set out only to define the discharge required for effective sluicing that would be least likely to result in negative impacts downstream. Improvements to debris management have occurred over the years including drag bar mechanization. Various proposals were made during the early efforts at sediment management including skimmer walls, training walls, and changes to sluice gate sizing. If it is determined that the diversion volume lost is significant, an alternative evaluation for facility improvement to the diversion dams should be considered. The costs and benefits associated with current operations should be assessed in comparison to possible facility improvements. Numerical and physical models should be used to assess alternatives. Physical models can also be used to optimize gate and trashrack raking operations for sediment and debris management. Numerical models are very limited in their ability to represent sediment transport around complex hydraulic structures like the diversion dam. Reclamation uses planning structures such as the Value Planning Study to implement these kinds of high-level analyses.

The Blanco and Oso diversions in the San Juan Mountains, and the tunnels that carry that water through the continental divide, is one of the most ambitious undertakings in the history of western water. The early operators and maintenance staff that had to learn how to use this dam on the fly should get all the praise and admiration the users of that water have. Optimizing the operations and maintenance of these facilities is an on-going effort. The analysis presented herein is another step toward that effort.

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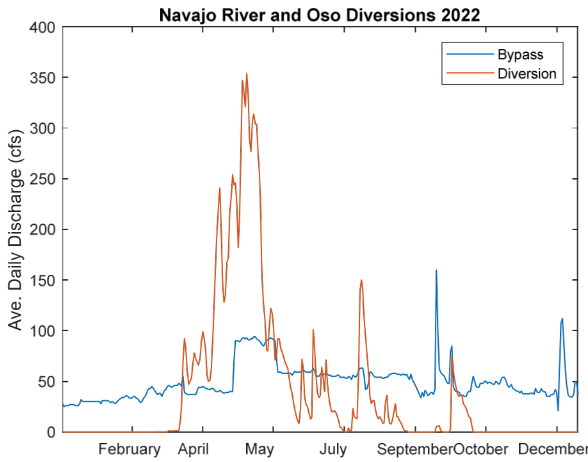
Appendix A

Oso Diversion and Navajo River Bypass Hydrographs


Navajo River and Oso Diversions 2022
Ave. Daily Discharge (cfs)
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Bypass
Diversion
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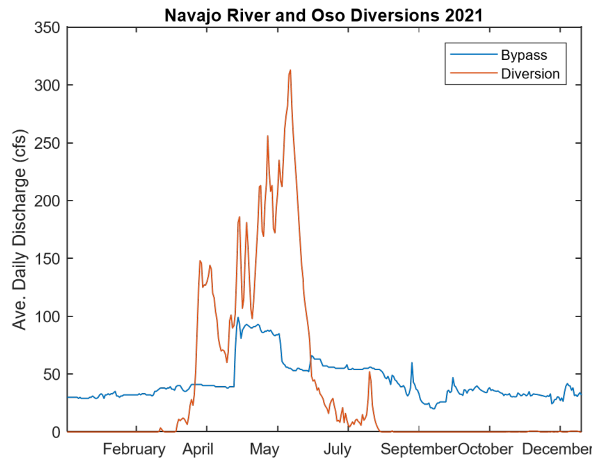
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Ave. Daily Discharge (cfs)
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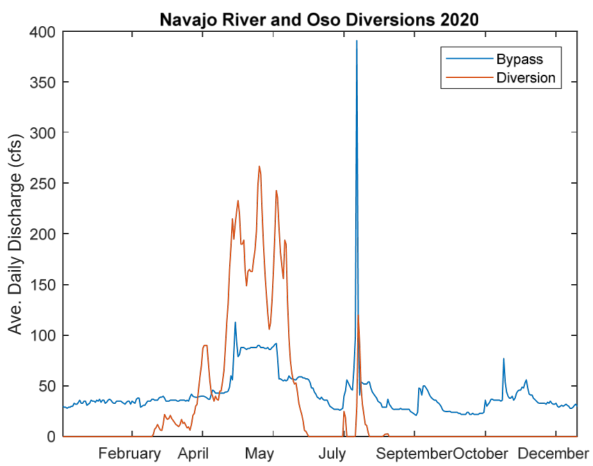
Navajo River and Oso Diversions 2020
Ave. Daily Discharge (cfs)
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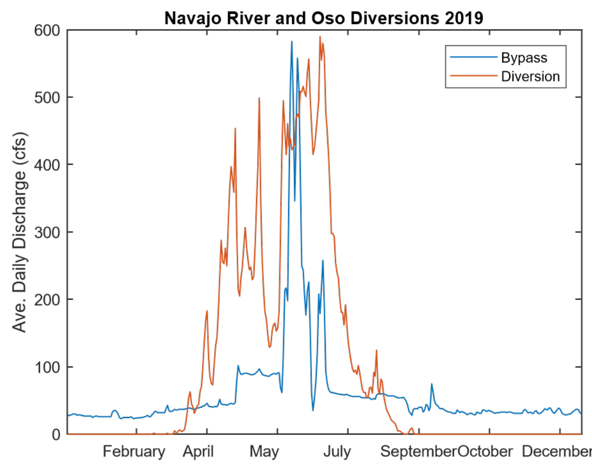
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Ave. Daily Discharge (cfs)
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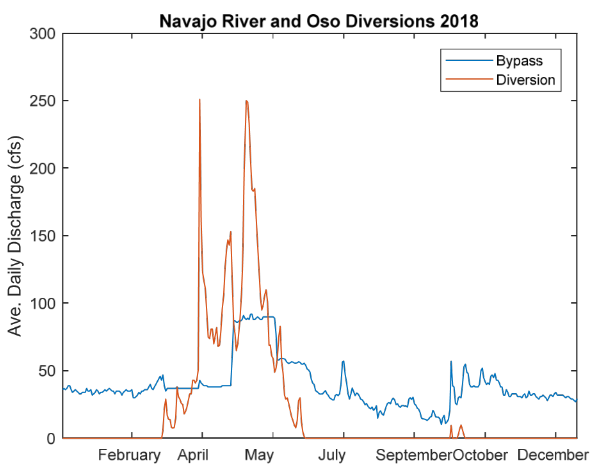
Navajo River and Oso Diversions 2018
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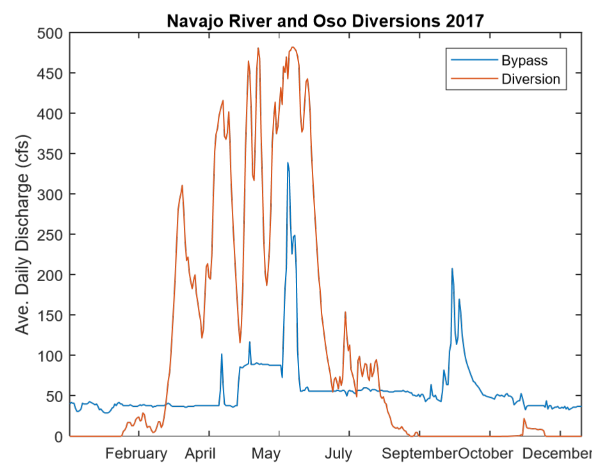
Navajo River and Oso Diversions 2017
Ave. Daily Discharge (cfs)
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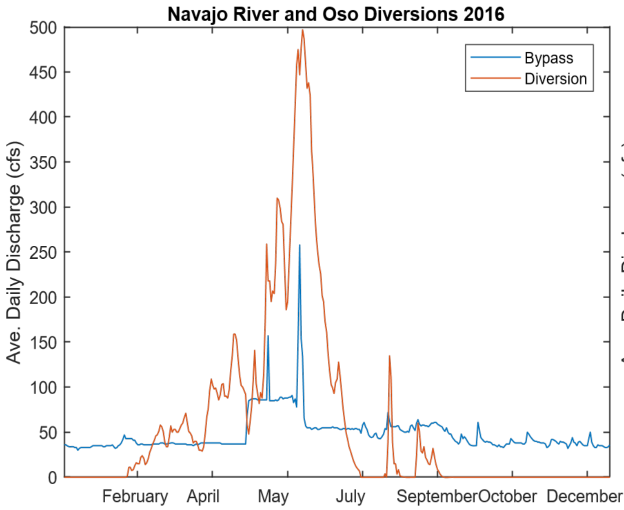
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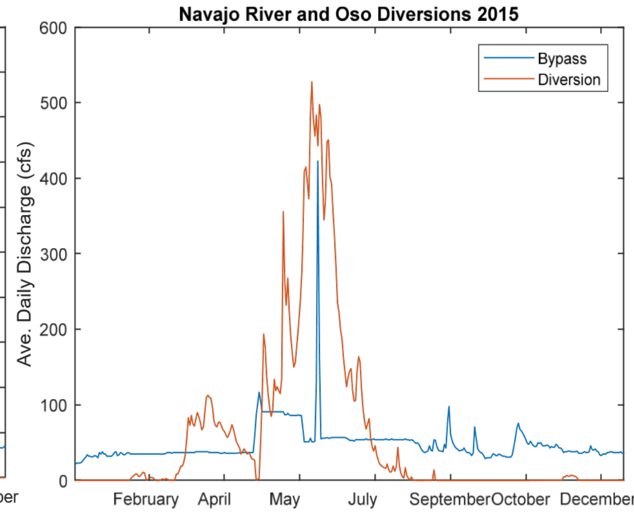
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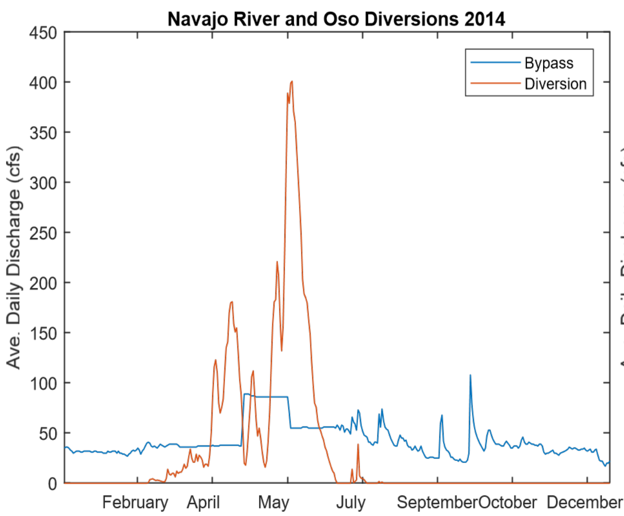
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Ave. Daily Discharge (cfs)
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Diversion
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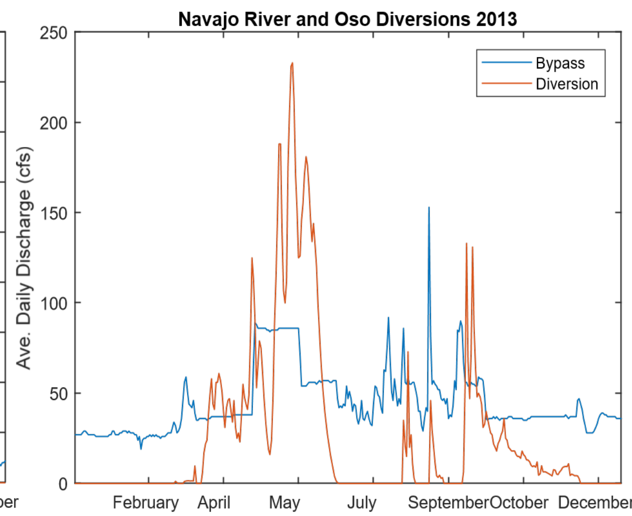
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Diversion
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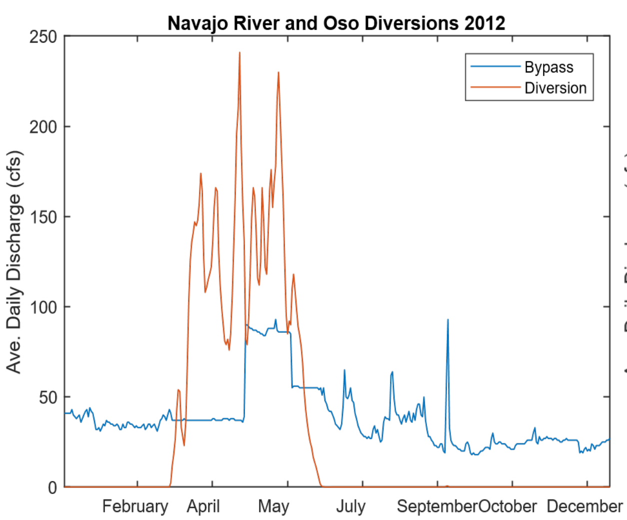
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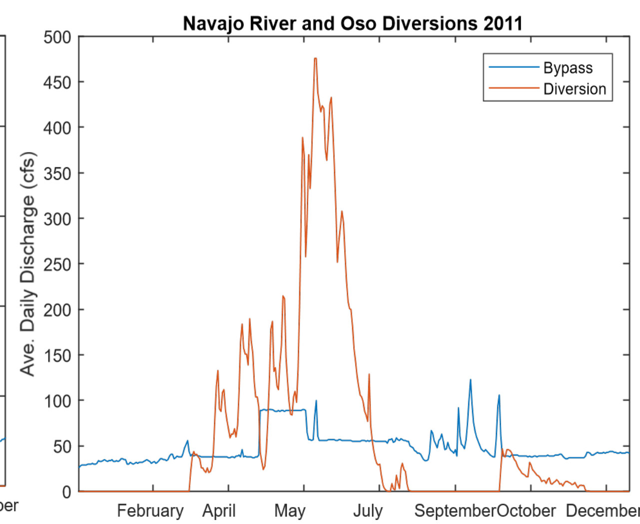
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Diversion
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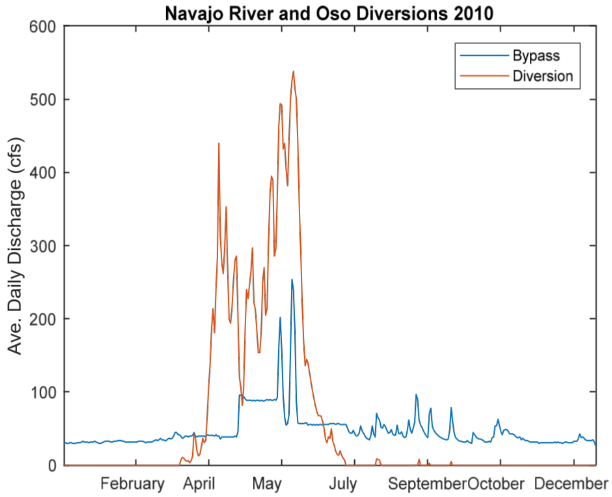
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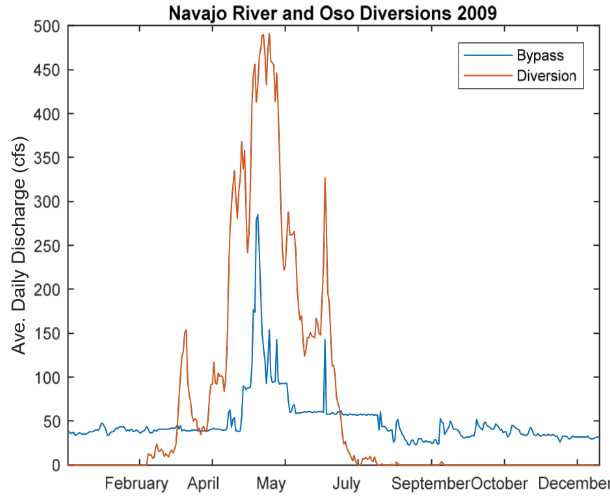
Navajo River and Oso Diversions 2009
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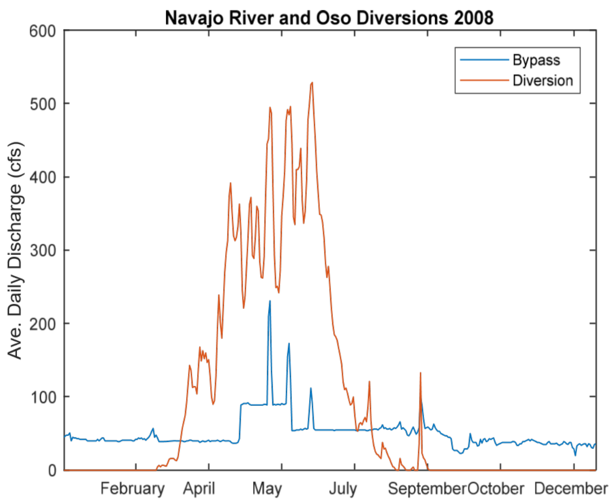
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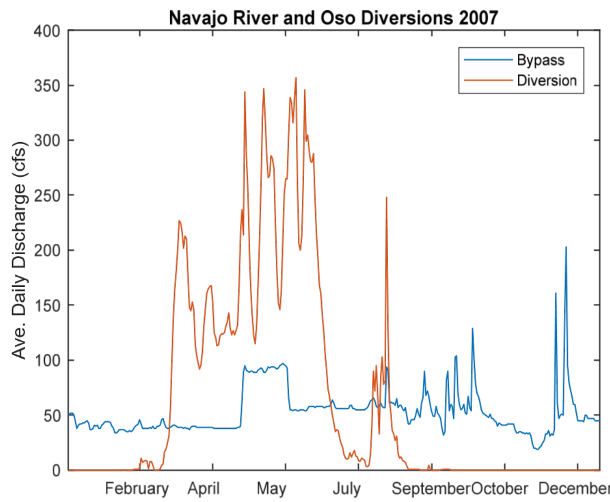
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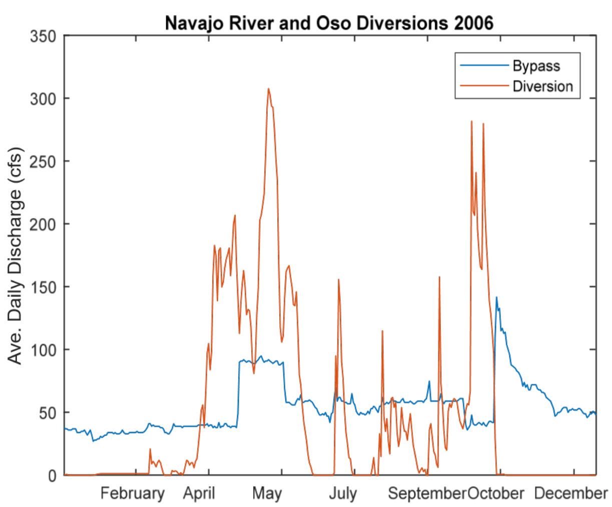
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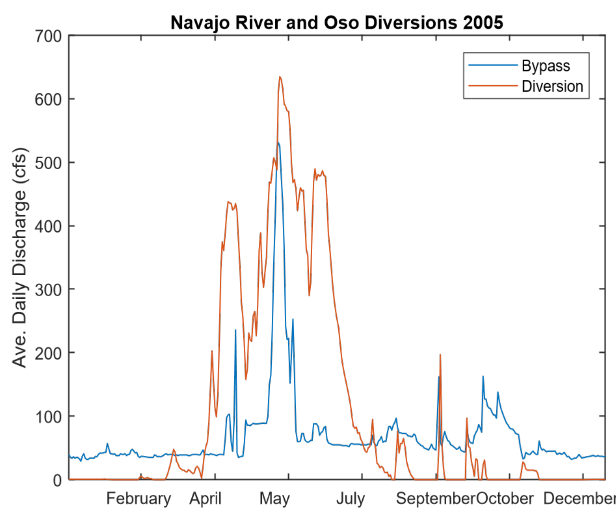
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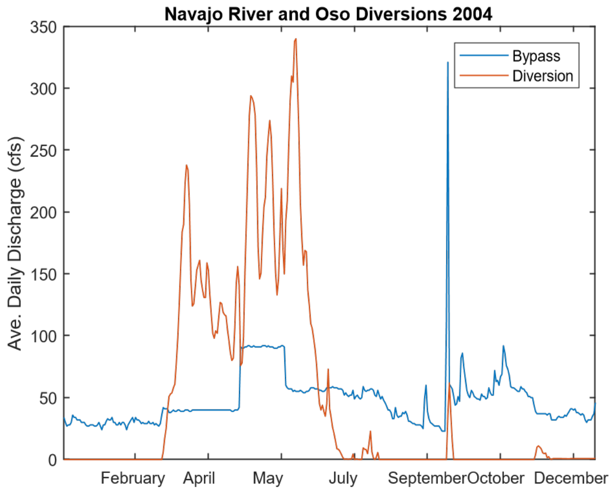
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Diversion
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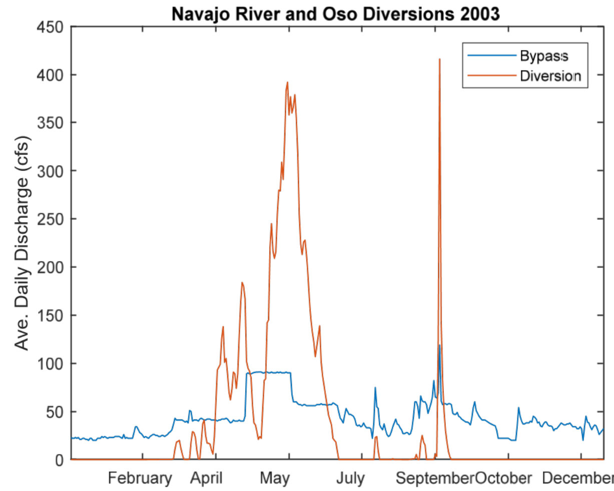
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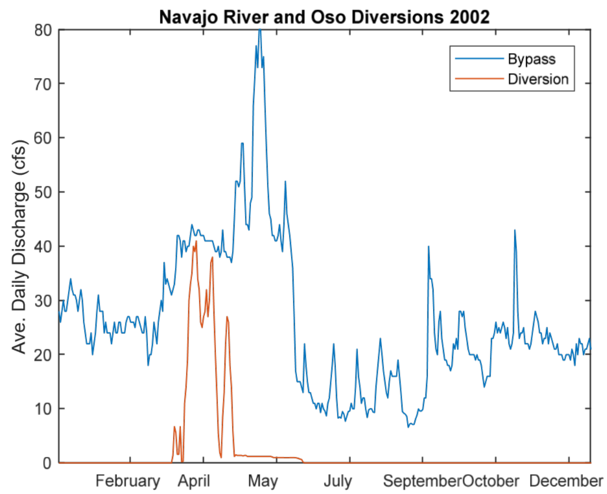
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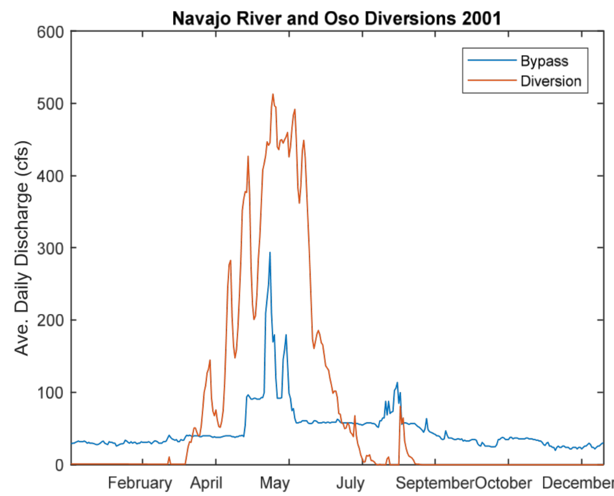
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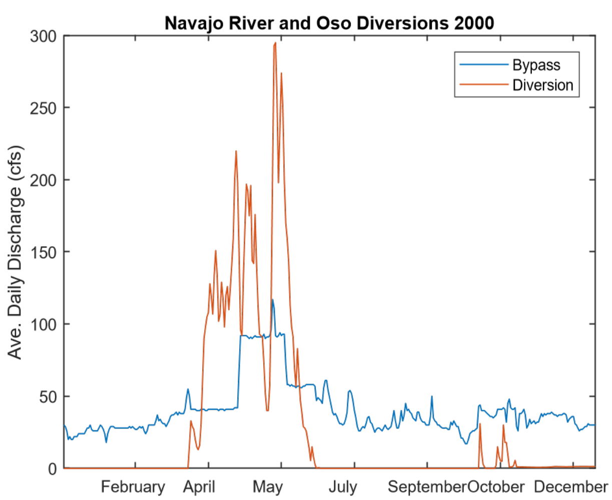
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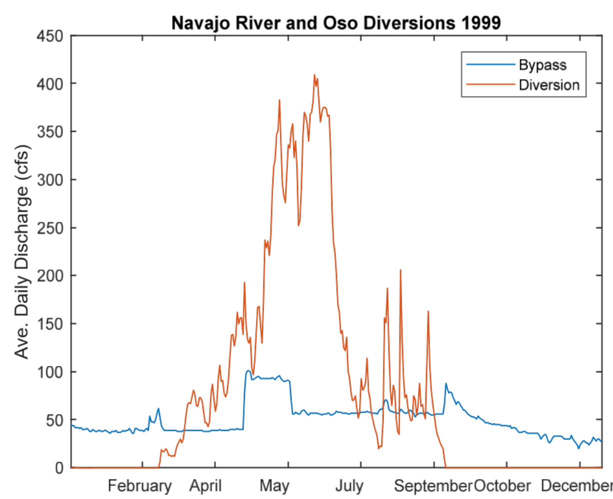
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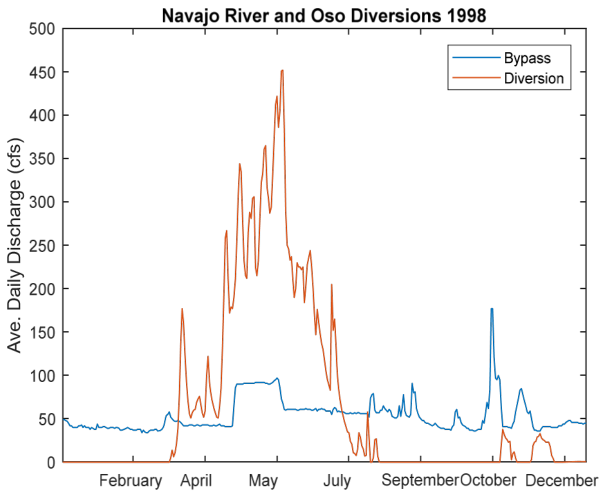
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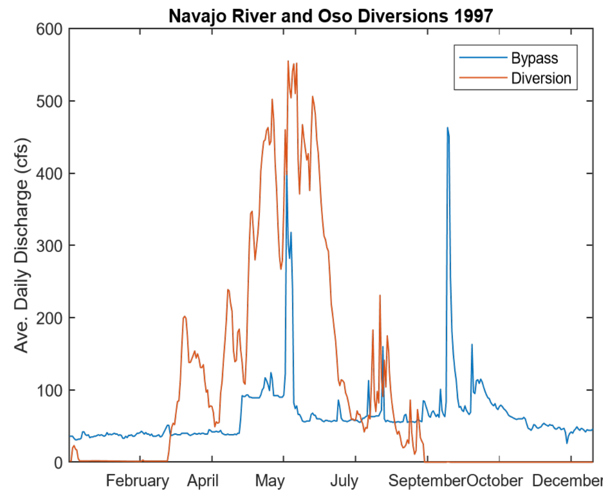
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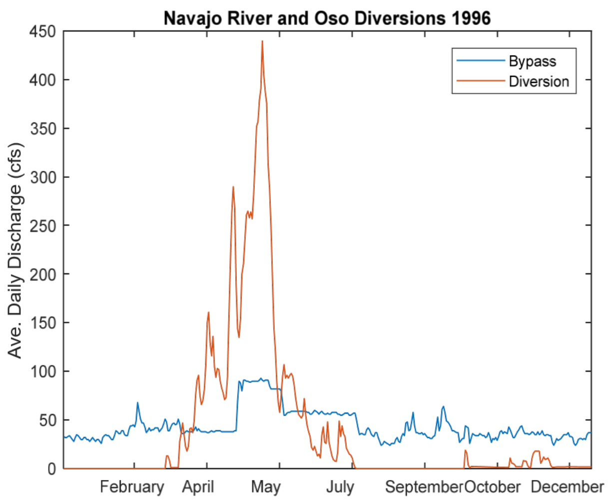
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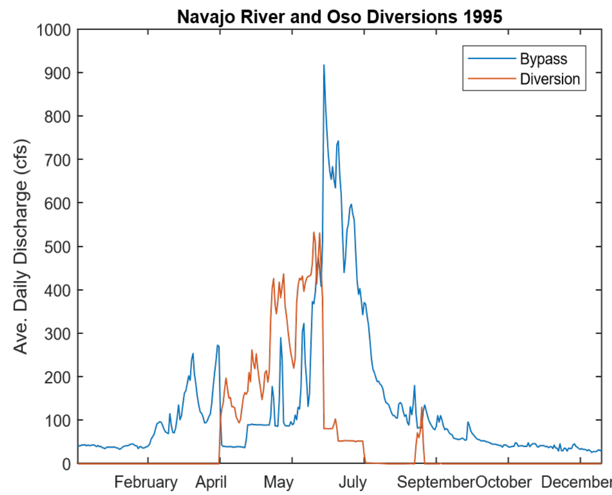
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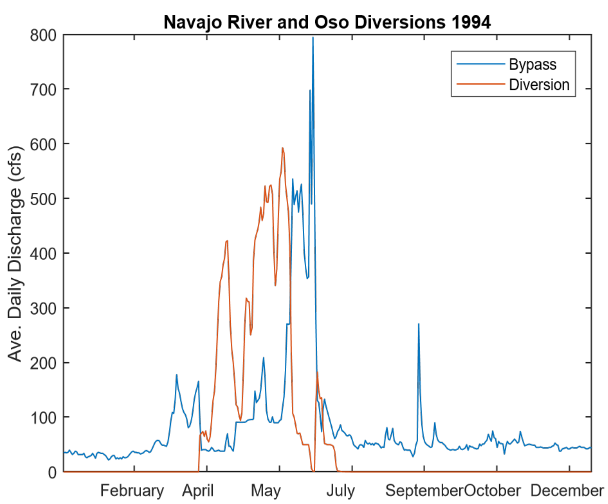
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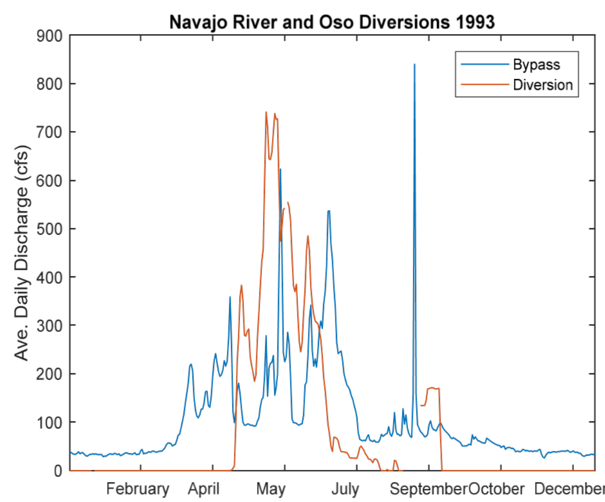
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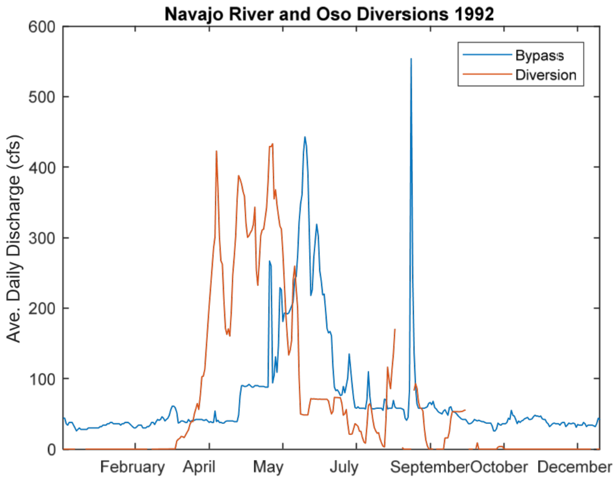
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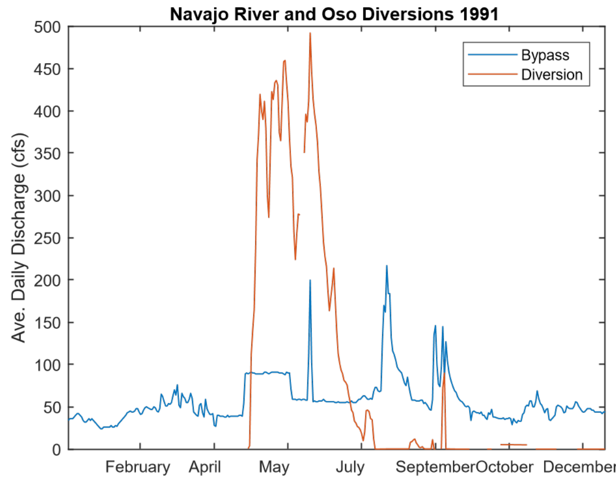
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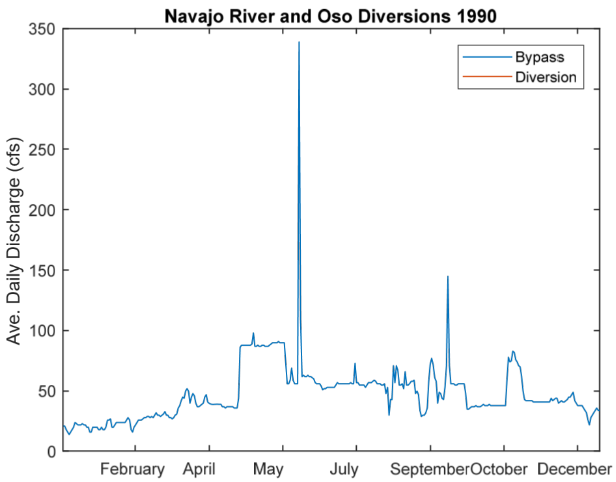
Bypass
Diversion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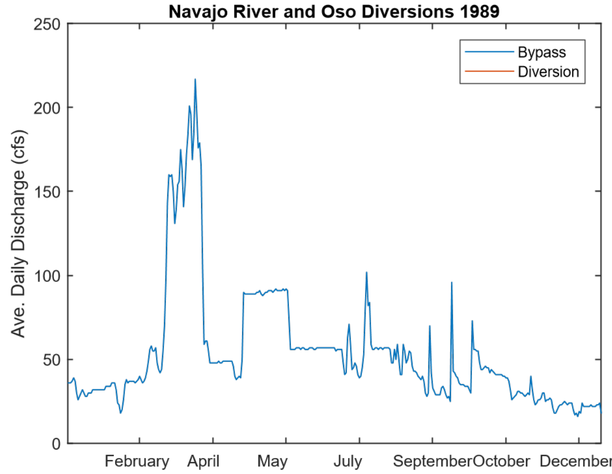
Diversion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Bypass
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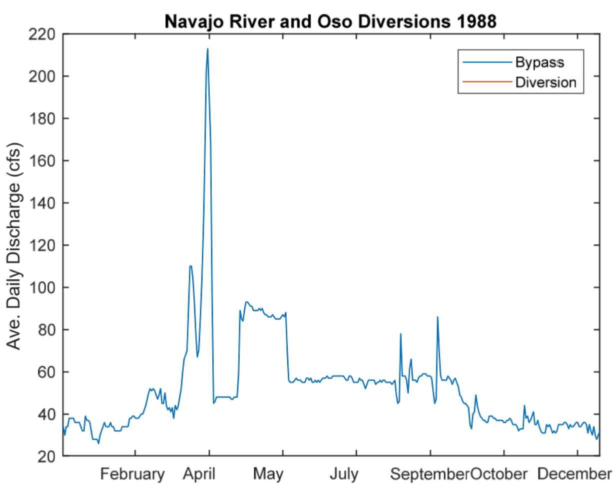
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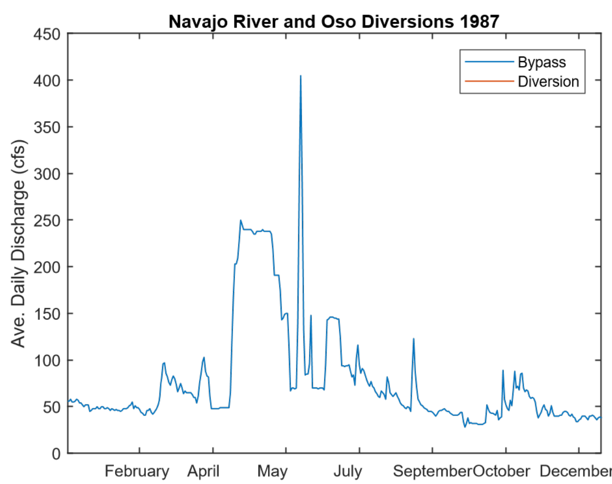
Bypass
Diversion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Ave. Daily Discharge (cfs)
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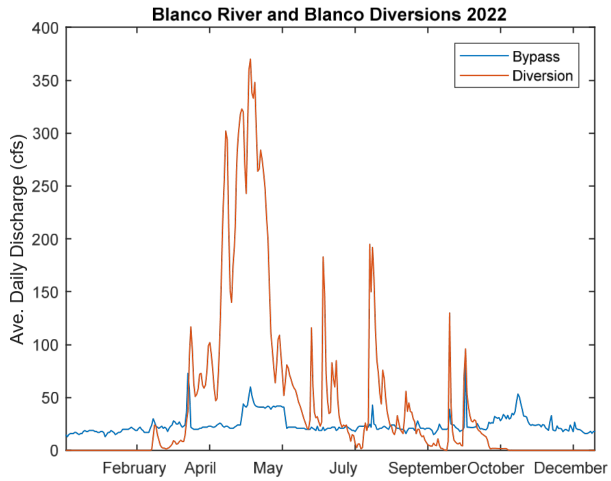
December
Bypass
Diversion

Appendix B

Blanco Diversion and Blanco River Bypass Hydrographs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Bypass
Diversion
Ave. Daily Discharge (cfs)
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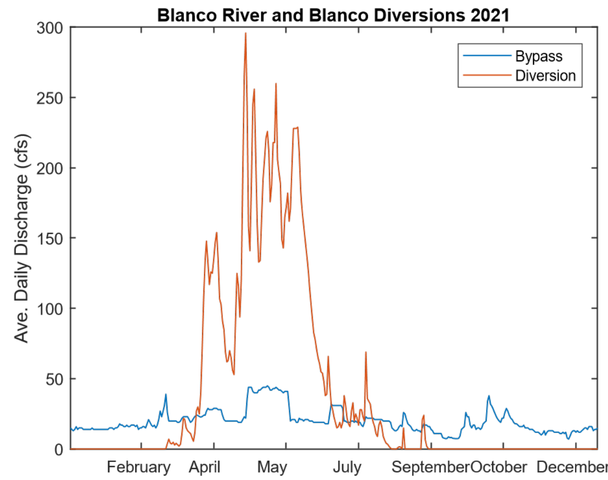
Blanco River and Blanco Diversions 2021
Bypass
Diversion
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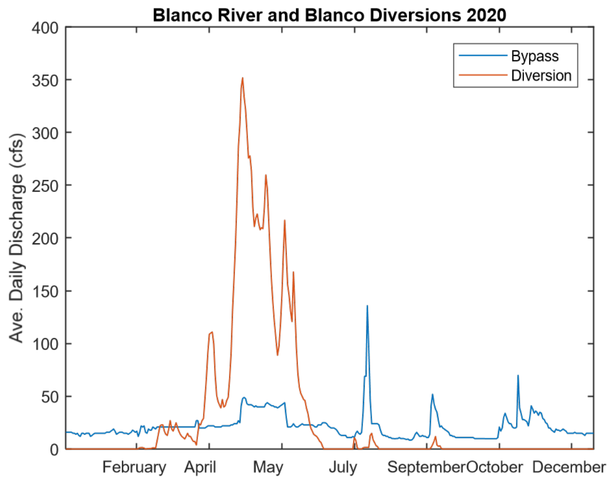
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Bypass
Diversion
Ave. Daily Discharge (cfs)
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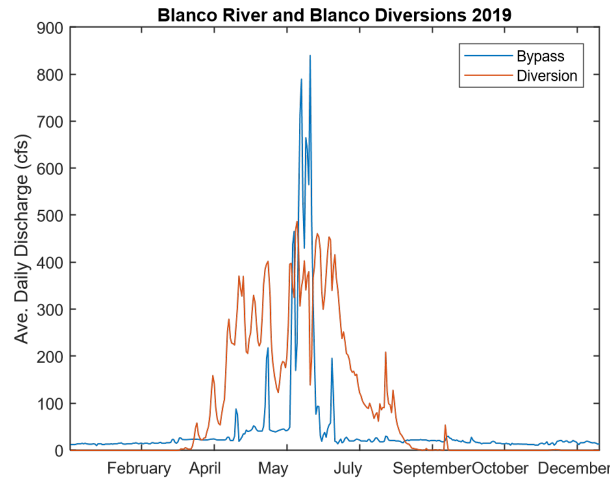
Blanco River and Blanco Diversions 2019
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Diversion
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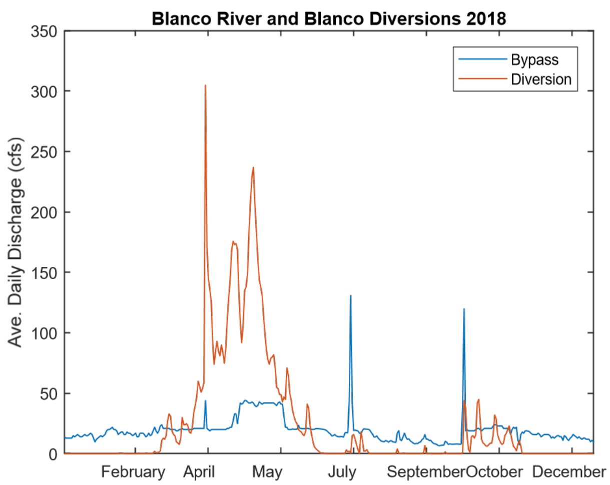
Blanco River and Blanco Diversions 2018
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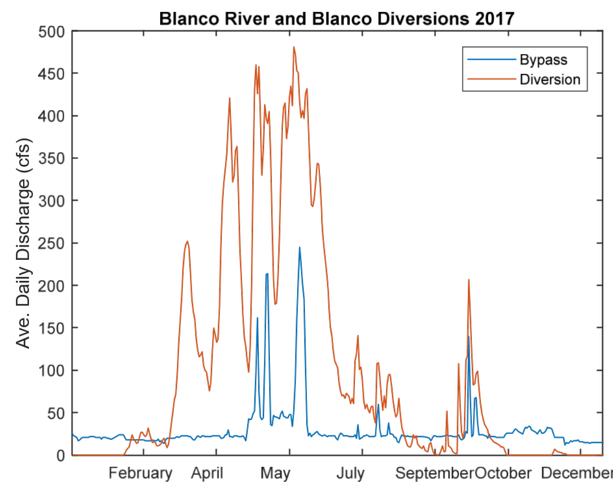
Blanco River and Blanco Diversions 2017
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Diversion
Ave. Daily Discharge (cfs)
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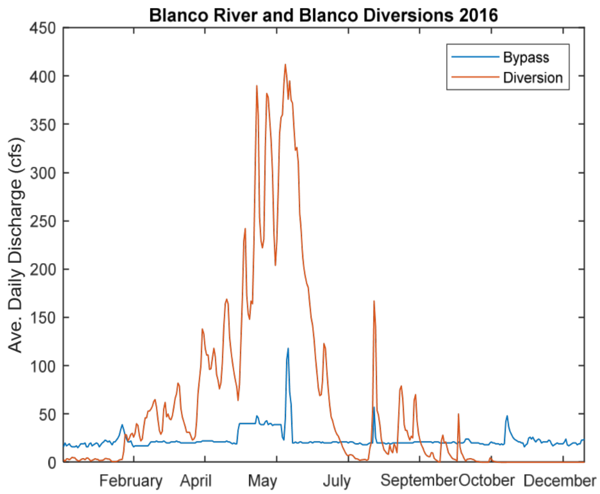
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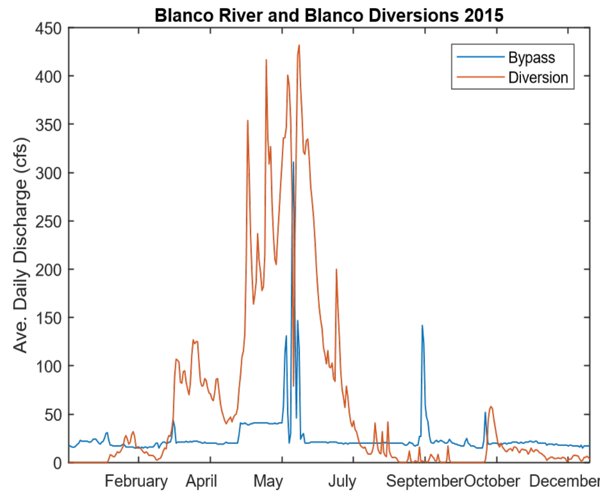
Bypass
Diversion
Ave. Daily Discharge (cfs)
February April May July September October December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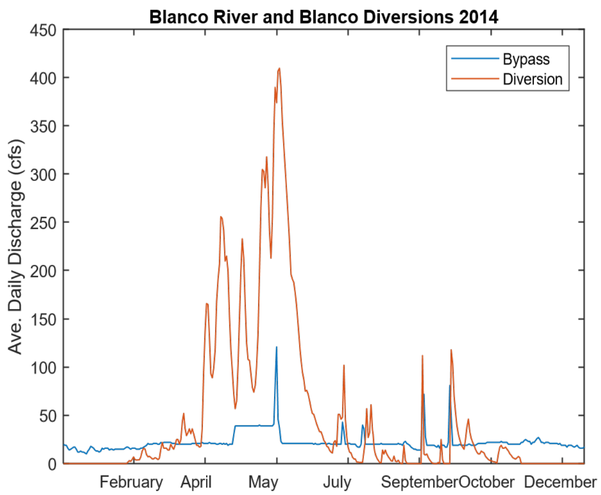
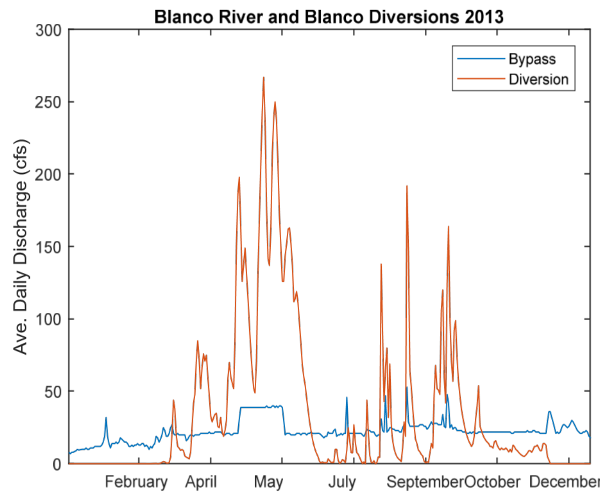
Bypass
Diversion
Ave. Daily Discharge (cfs)
February April May July September October December


Blanco River and Blanco Diversions 2014
Bypass
Diversion
Ave. Daily Discharge (cfs)
February April May July September October December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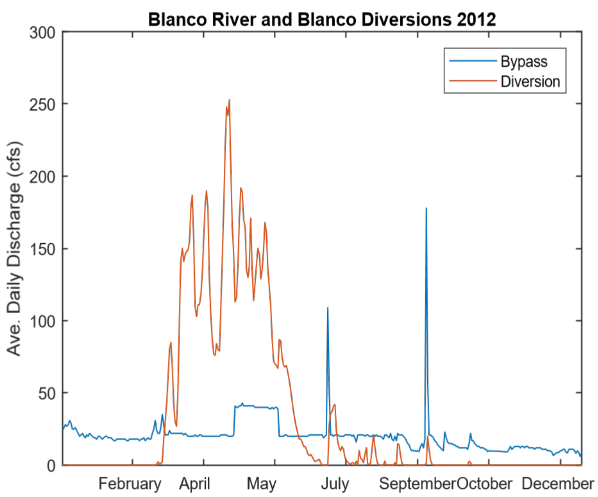
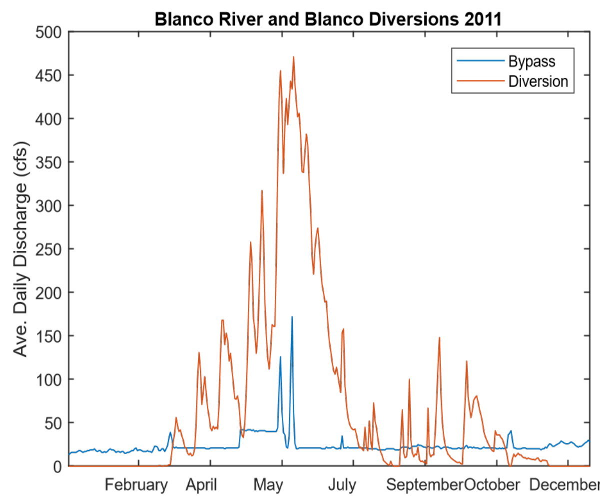
Bypass
Diversion
Ave. Daily Discharge (cfs)
February April May July September October December


Blanco River and Blanco Diversions 2012
Bypass
Diversion
Ave. Daily Discharge (cfs)
February April May July September October December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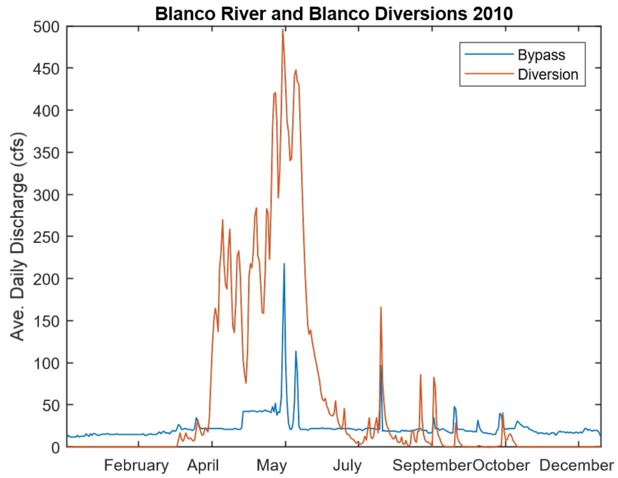
Bypass
Diversion
Ave. Daily Discharge (cfs)
February April May July September October December


Blanco River and Blanco Diversions 2010
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Diversion
Ave. Daily Discharge (cfs)
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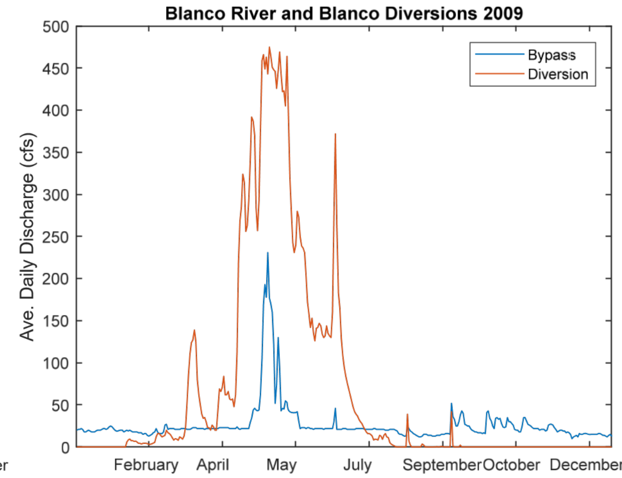
Blanco River and Blanco Diversions 2009
Bypass
Diversion
Ave. Daily Discharge (cfs)
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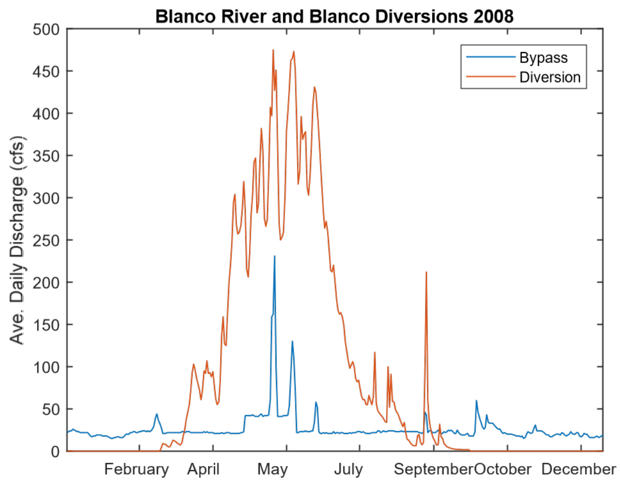
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Bypass
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Ave. Daily Discharge (cfs)
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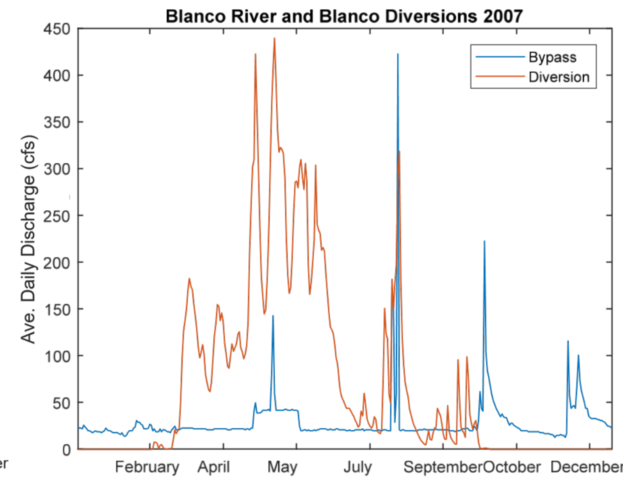
Blanco River and Blanco Diversions 2007
Bypass
Diversion
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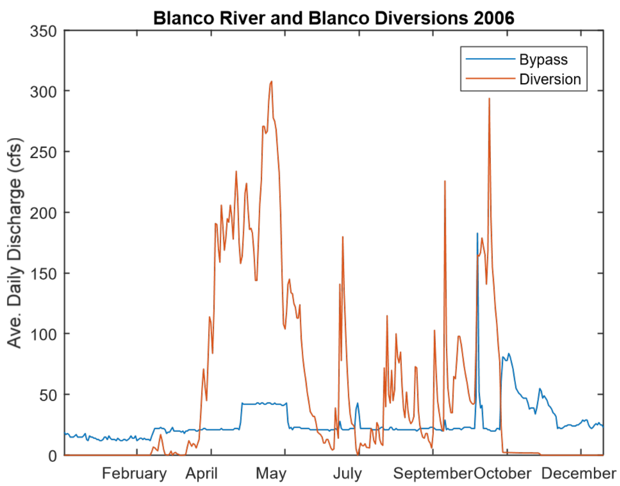
Blanco River and Blanco Diversions 2006
Bypass
Diversion
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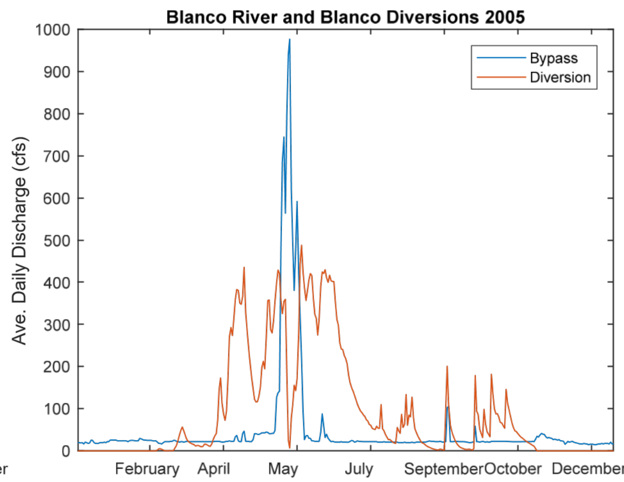
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Bypass
Diversion
Ave. Daily Discharge (cfs)
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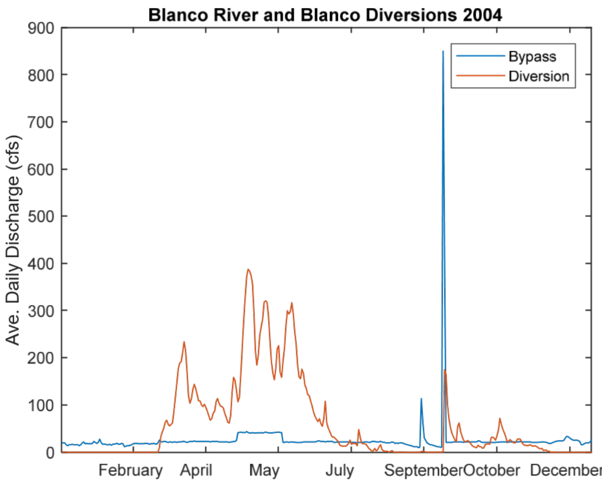
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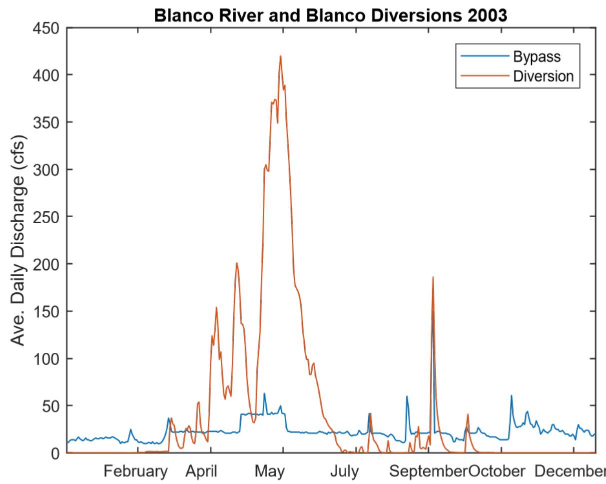
Blanco River and Blanco Diversions 2003
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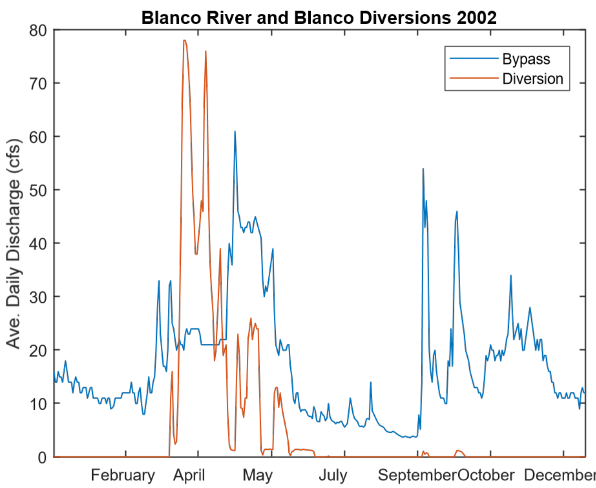
Blanco River and Blanco Diversions 2002
Ave. Daily Discharge (cfs)
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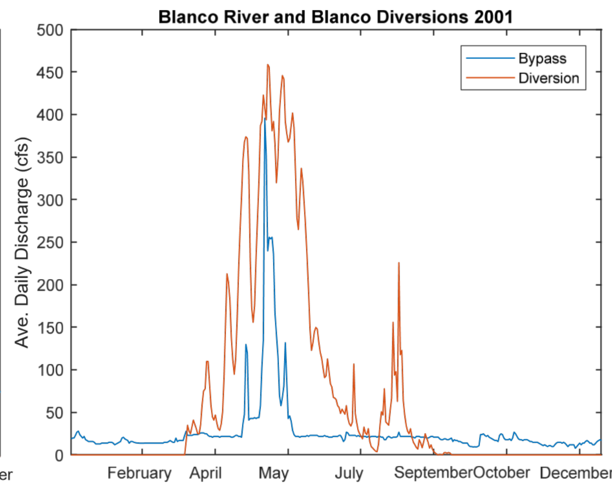
Blanco River and Blanco Diversions 2001
Ave. Daily Discharge (cfs)
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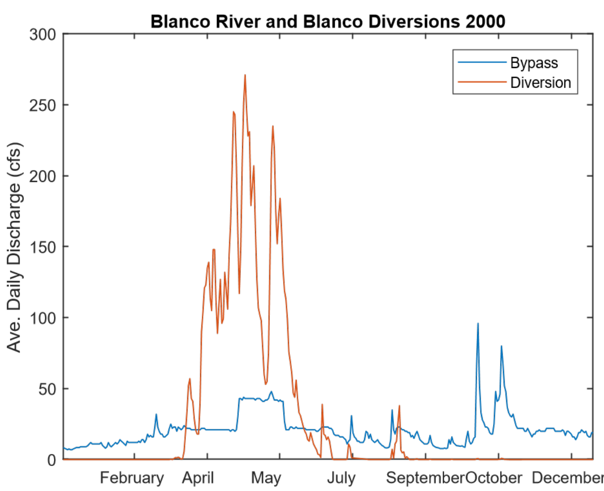
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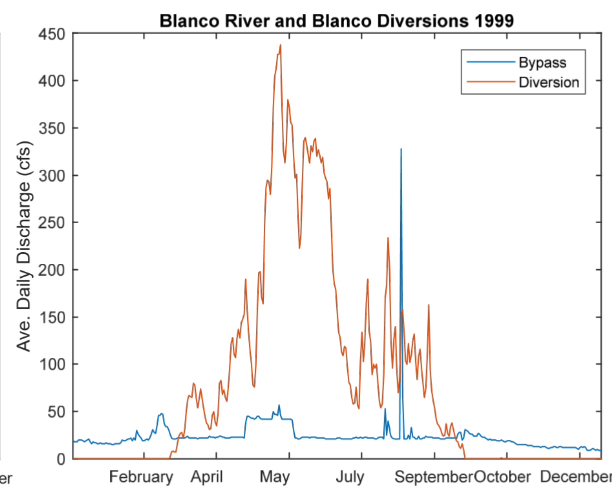
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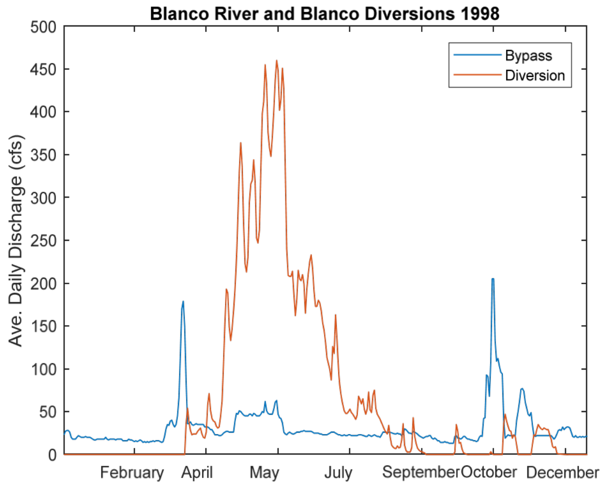
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Ave. Daily Discharge (cfs)
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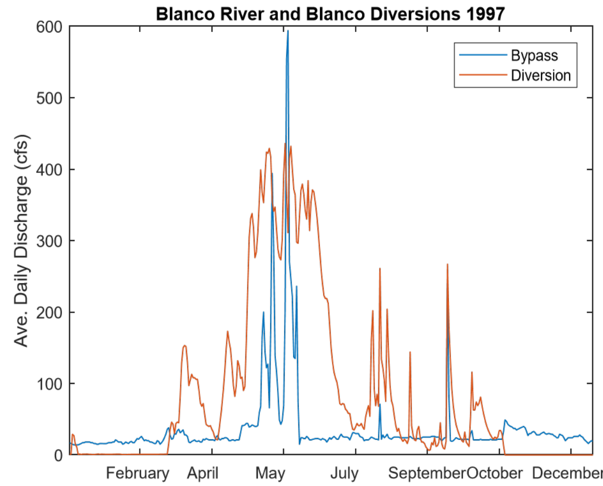
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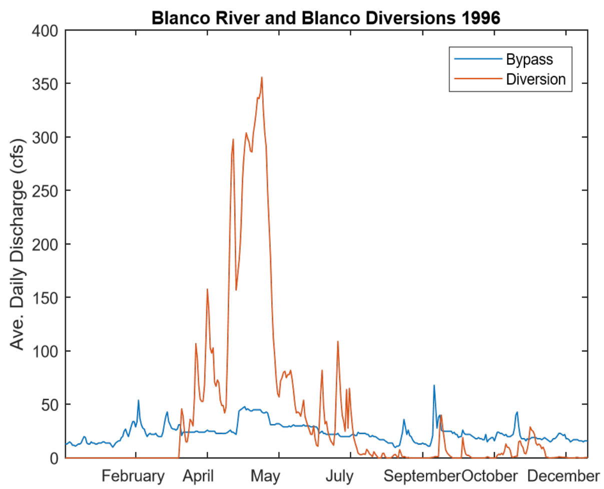
Blanco River and Blanco Diversions 1996
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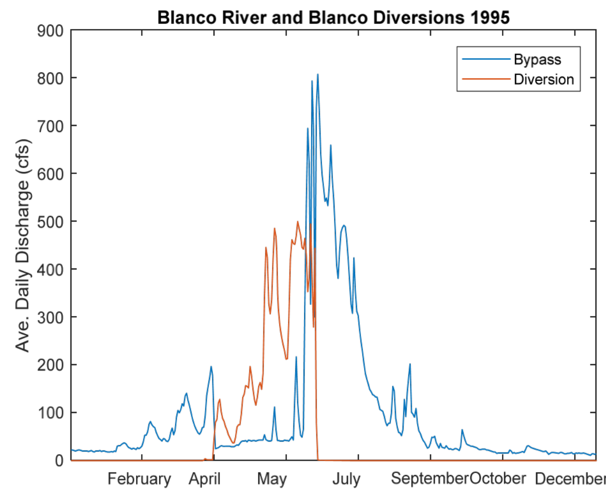
Blanco River and Blanco Diversions 1995
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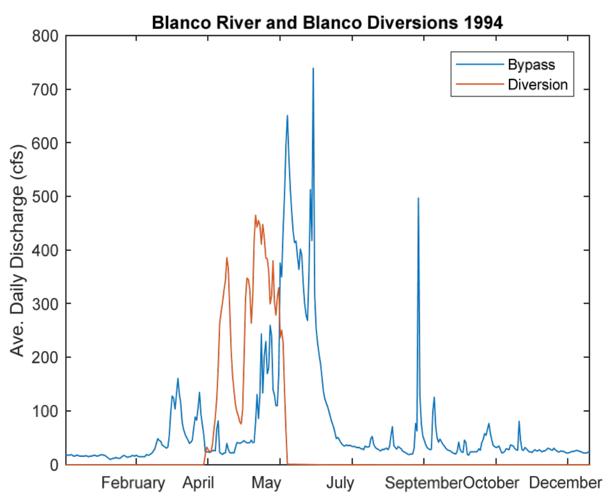
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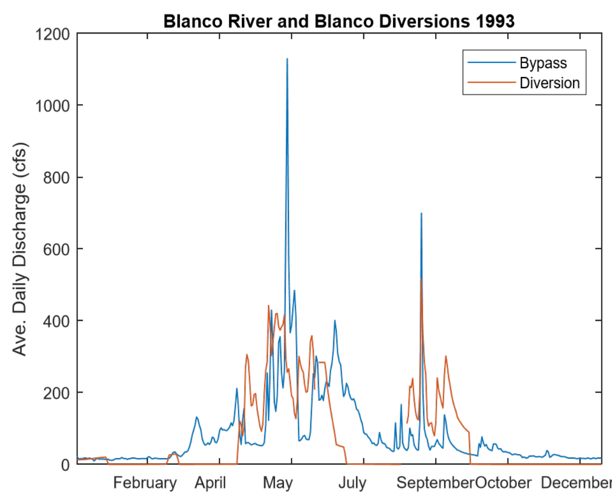
Blanco River and Blanco Diversions 1993
Ave. Daily Discharge (cfs)
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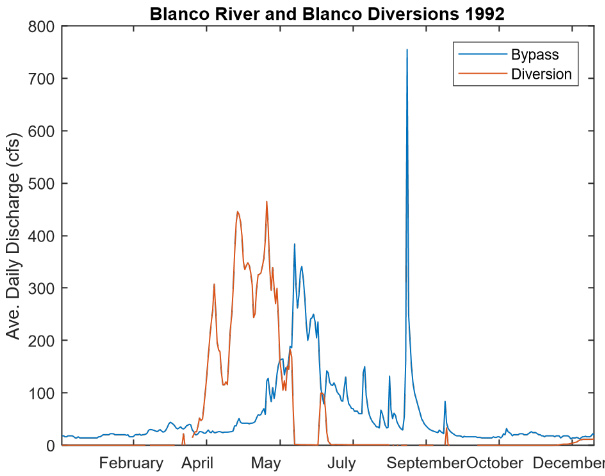
Blanco River and Blanco Diversions 1992
Ave. Daily Discharge (cfs)
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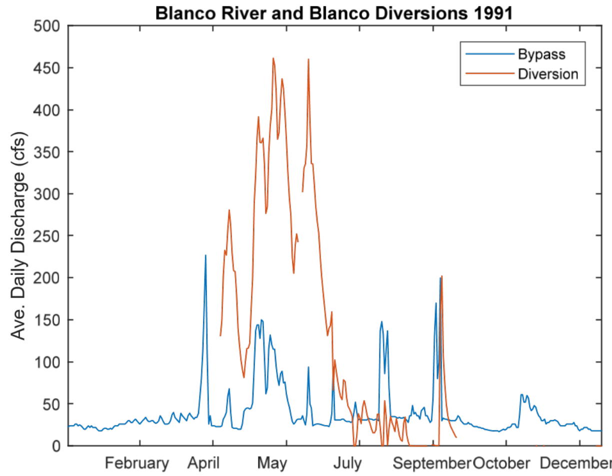
Blanco River and Blanco Diversions 1991
Ave. Daily Discharge (cfs)
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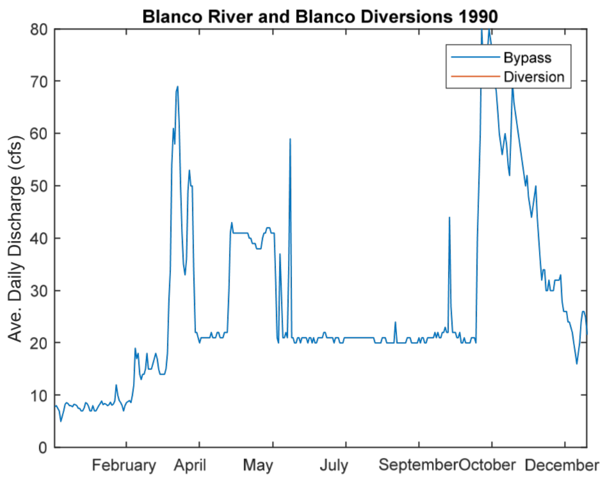
Blanco River and Blanco Diversions 1990
Ave. Daily Discharge (cfs)
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Diversion
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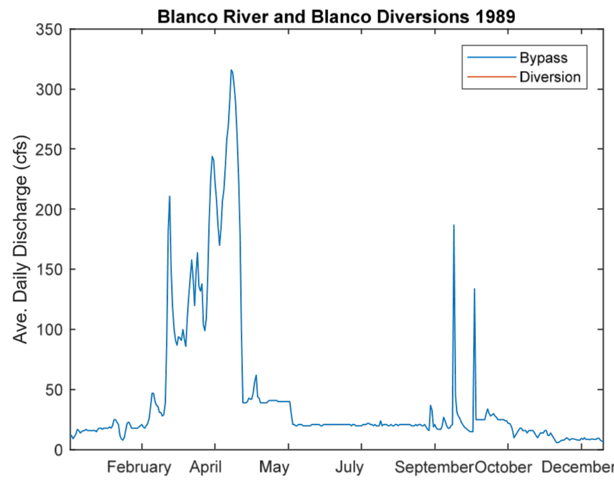
Blanco River and Blanco Diversions 1989
Ave. Daily Discharge (cfs)
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Bypass
Diversion
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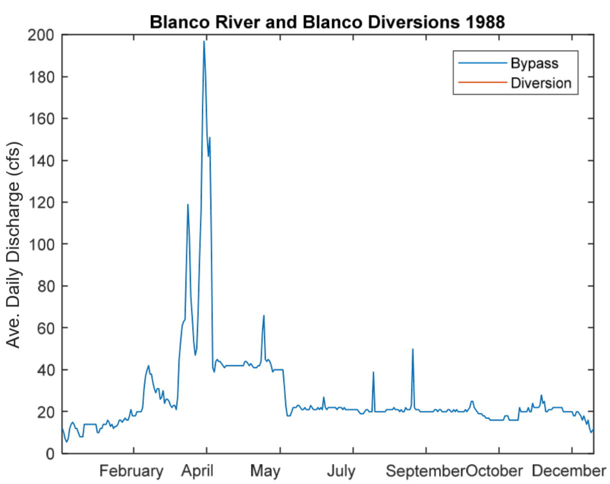
Blanco River and Blanco Diversions 1988
Ave. Daily Discharge (cfs)
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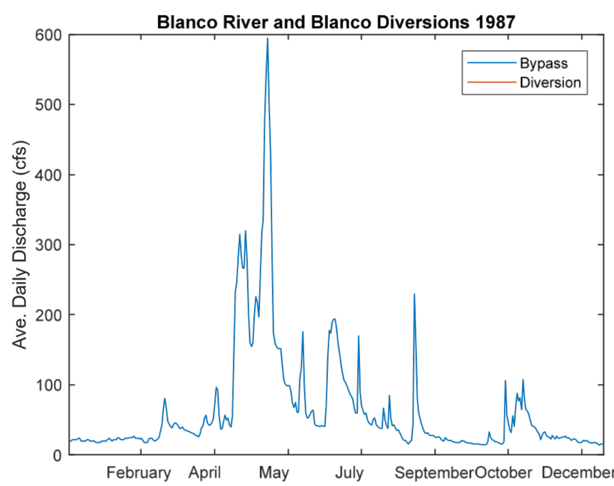
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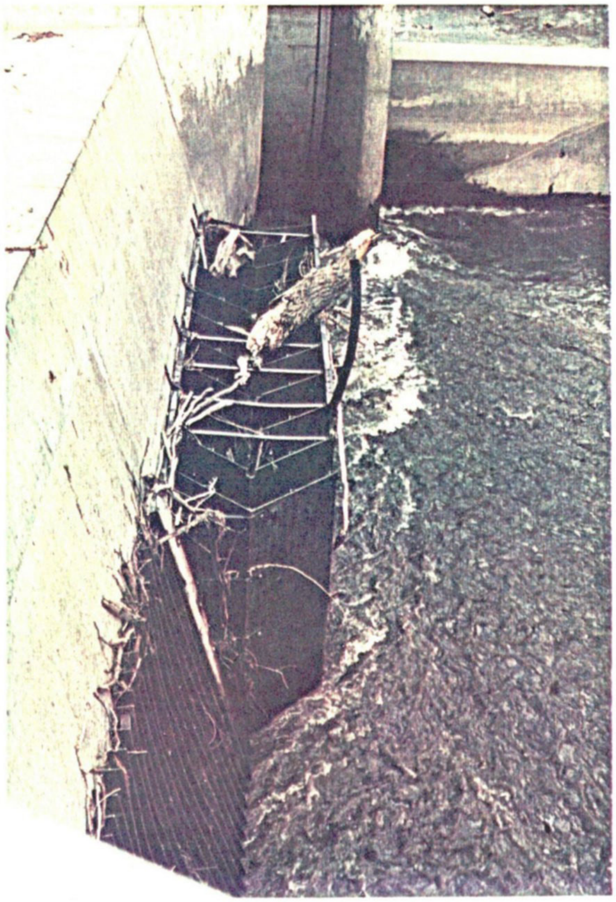
Appendix C

Blanco Diversion Dam Inspection Photos



Photograph No. 3 - San Juan-Chama Project - Blanco Diversion Dam - View of field office constructed chevron trashracks on diversion inlet. Wasteway radial gate in background. Photo by R. Ochs August 26, 1980

Photograph No. 5 - San Juan-Chama Project - Blanco Diversion Dam - View from inside structure of original trashrack and accumulated rock. Note rock along right is nearly to top of trashrack.
Photo by R. Ochs August 26, 1980

CN465-518-448
Station 463+00. Photo shows transition section with exposed reinforcement at the outlet portal of Blanco Tunnel. Figure 18.

Photograph No. 1
San Juan-Chama
Project
Colorado-New Mexico

Blanco Diversion
Dam. Note
sediment accu-
mulation at
overflow weir.

October 16, 1984

Photograph No. 35 - San Juan-Chama Project -- Blanco Tunnel - Photograph of Charles Fisher measuring the tunnel invert erosion using template and measuring device.

Photo by Jerry Moore 10-20-87

CN465-518-442
Photo shows gravel and sediment at the inlet immediately downstream of the Chevron trash rack at Blanco Diversion Dam.
Figure 12.

Photo 2
San Juan-Chama Diversion and Collection System

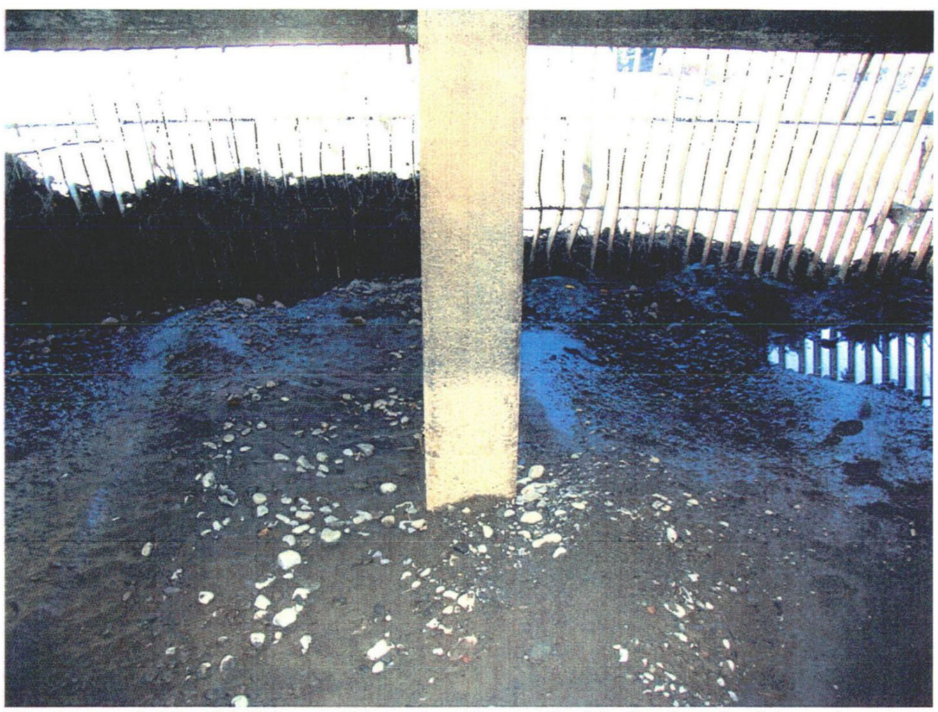
Looking downstream at the headworks (left) and over-flow spillway (right) at Blanco Diversion Dam. Sediment deposits (lower left) are removed annually with heavy equipment.

10/4/94

Photo 3
San Juan-Chama
Diversion and
Collection System

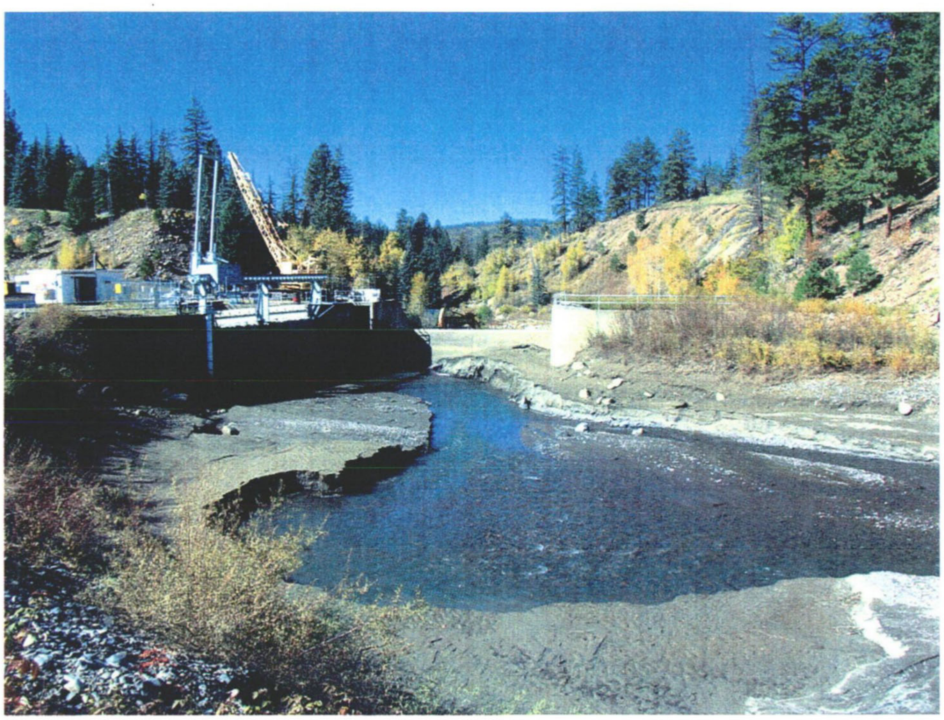
Blanco Diversion
Dam headworks
looking upstream
toward trashracks.
Sediment deposited
to nearly top of
headworks opening.
Sediment removed
annually with a
bobcat.

10/4/94

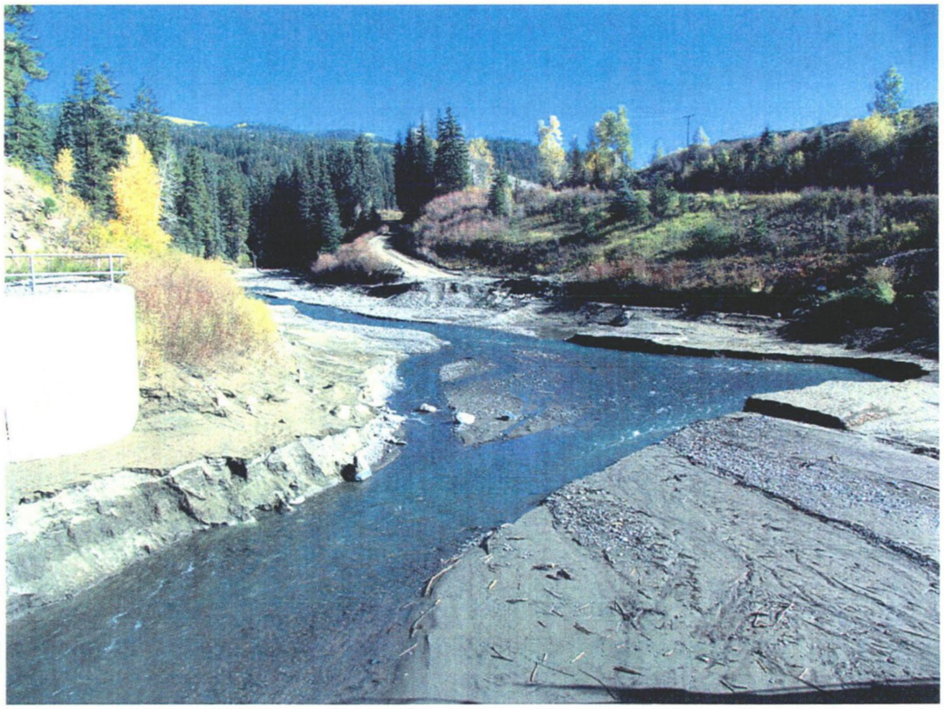


Photograph No. 13. Blanco Diversion Dam – Inside forebay looking u/s.
Photograph Date 10/03/07 by: A. Vigil

Photograph No. 14. Blanco Diversion Dam – Inside forebay. Note sedimentation buildup. Photograph Date 10/03/07 by: A. Vigil



Photograph No. 1. Blanco Diversion Dam - Upstream view of Blanco River Channel after sedimentation removal. Photograph Date 10/03/07 by: A. Vigil



Photograph No. 2. Blanco Diversion Dam – Upstream view of Diversion Dam.
Photograph Date 10/03/07 by: A. Vigil

Appendix D

Oso Diversion Dam Inspection Photos

Photograph No. 20
San Juan-Chama
Project
Colorado-New Mexico

Low-flow diversion
slide gate -
Oso Diversion Dam.

October 18, 1984

P465-528-1905NA Oso Diversion Dam--San Juan-Chama Project--Colorado-New Mexico Setting formwork for part of the right weir wall and compacting the sub-grade for the weir approach slabs at the Oso Diversion Dam.
Specifications No. DC-6380 Boyles Bros. Drilling Company
3-20-68 Bureau of Reclamation Photo by D. Manning

Photograph No. 65 - San Juan-Chama Project -- Oso Diversion Dam - Photograph of the diversion dam looking downstream after the storage space had been evacuated.

Photo by Jerry Moore 10-22-87

P465-528-2498NA Oso Diversion Dam--San Juan-Chama Project--Colorado-New Mexico General view of completed features of the Oso Diversion Dam looking toward the northwest from the left abutment. Pieces of the 96-inch diameter precast concrete pipe remaining to be laid for the Oso Siphon are shown at the left in photo.
Specifications No. DC-6380 Boyles Bros. Drilling Company
2-20-70 Bureau of Reclamation Photo by D. Manning

Photograph No. 74 - San Juan-Chama Project -- Oso Diversion Dam - View of the 36- by 36-inch low flow vertical slide gate located in the headwork to Oso Feeder Conduit.

Photo by Jerry Moore 10-22-87

CN465-528-1855 Station 736+88. Photo shows exposed reinforcement in invert of Oso Siphon. Figure 18.

Photo by Jerry Moore 10-22-87

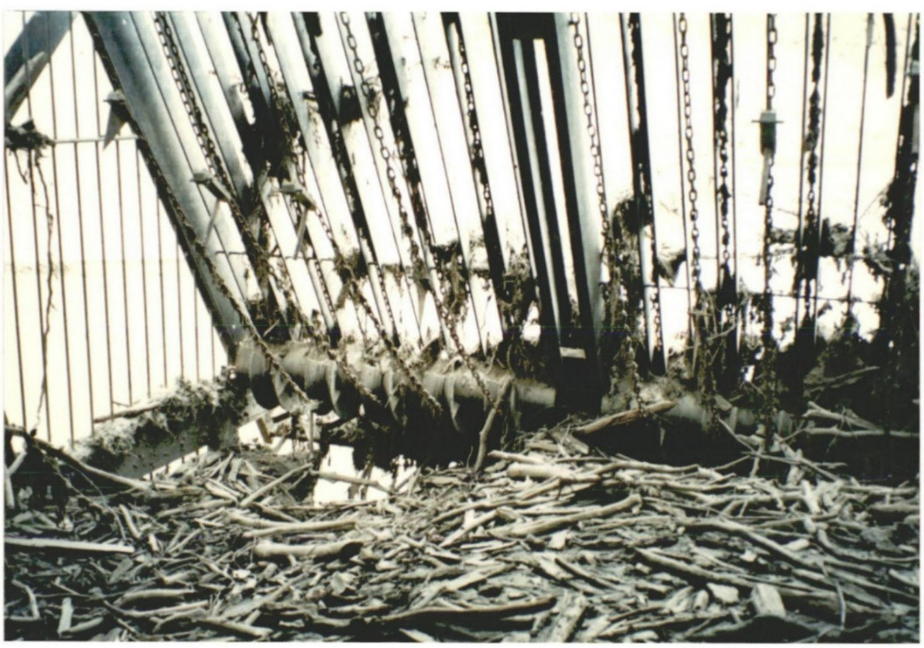


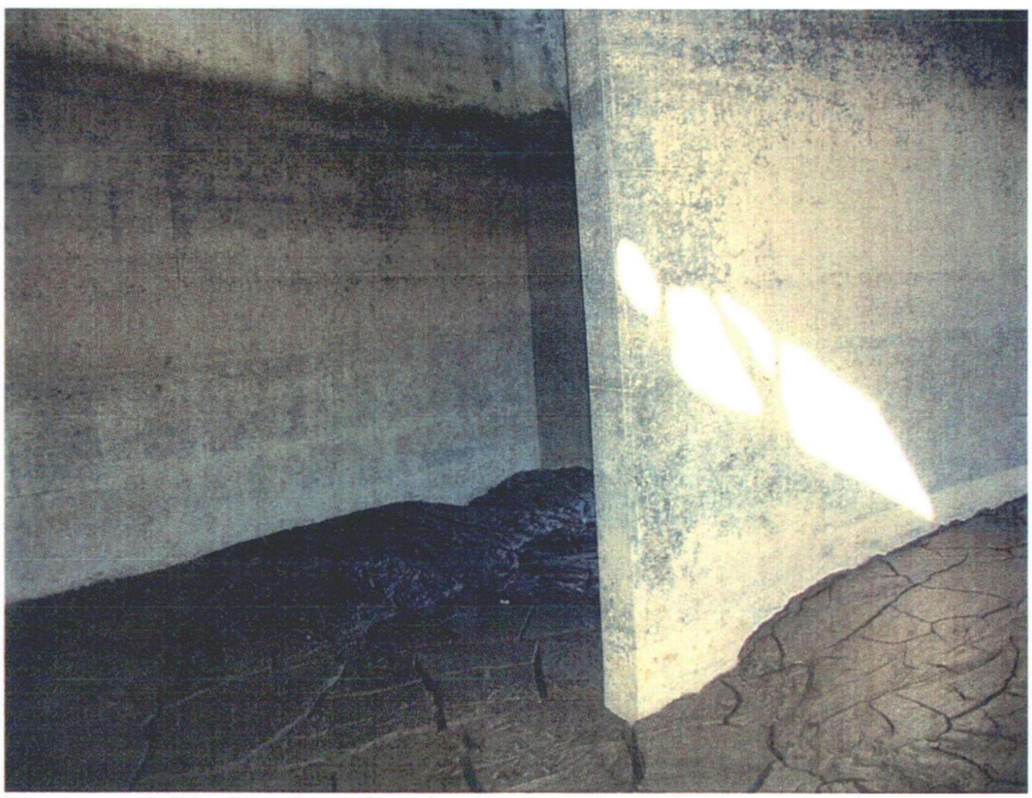
Photo 23
San Juan-Chama
Diversion and
Collection System

Trashrack and
inadequate
automatic trash
rake system at Oso
Diversion Dam.

10/4/94

Photograph No. 36. Oso Diversion Dam – Upstream View of excess sediment buildup. Photograph Date 01/03/07 by: A. Vigil

Photograph No. 38. Oso Diversion Dam – View of sediment buildup on Trash-Rack System. Photograph Date 10/03/07 by: A. Vigil



Photograph No. 37. Oso Diversion Dam – View of sediment inside forebay. Photograph Date 10/03/07 by: A. Vigil