Monte-Carlo Simulation and Analysis (MCSA) for 1D HECRAS Sediment Transport Modeling: A Case Study in the Navajo and Blanco Rivers of the San Juan Mountains, CO

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Abstract

The Monte Carlo Simulation Analysis (MCSA) software allows the modeler to investigate the sensitivities of a robust unsteady or sediment transport 1D HEC-RAS model to a number of inputs. Uncertainties are represented using a number of probability distribution functions. The MCSA is used to visualize model sensitivities to identify system thresholds and characteristics.

The San Juan-Chama Project includes trans-boundary tunnels and diversion dams in the Blanco and Navajo Rivers of southern Colorado. These facilities experience a not insignificant amount of sediment load and debris. Due to issues associated with sluicing in the early years of Project operation, the decision was made to cease the use of dam sluiceways. This project set out to investigate the impact of this operation and what opportunities there are to use the sluiceway in an effective and appropriate way.

It was determined that not using Project sluiceways during floodflows has several impacts: diversion capacity is lost, sediment transport and debris often requires emergency operations to maintain diversions, sediment accumulation requires regular dredging operations, tunnel maintenance due to erosion is accelerated, loss of desired downstream aquatic habitats.

The following conclusions were derived from this investigation: channel forming flow is approximately 200 cfs and 300 cfs in the Blanco and Navajo Rivers, respectively, Blanco River is unlikely to experience negative consequences if sluicing is done with an effective and appropriate strategy, Navajo River is more depositional environment and more water for a longer duration is required to minimize potential negative outcomes.

The recommendations include: develop a comprehensive sediment transport data collection program, analyze flow data to gain understanding of diversion:bypass ratios during flood flows, develop a testing plan for intermittent sluicing operations, and investigate large-scale solutions to improve facility operations and maintenance.

Introduction

Hydraulic and sediment transport modeling of open channels is used in a variety of ways to inform waterway and irrigation system management. This information is used to design and operate infrastructure, protect communities from flooding, and better understand aquatic and riparian ecological relationships and river geomorphology. Most of the modeling done, in this context, are done deterministically, suggesting that the model inputs are known and any changes within the model domain can only come from those processes represented in the model. In the case of engineered systems, these assumptions are largely true. However, in natural open-channel systems, this kind of surety is unlikely.

The first step in sediment transport modeling is to construct a robust hydraulic model. The model should be calibrated and validated to produce reasonable results under the variety of discharge conditions that occur in the modeled system. Modeling protocols also suggest that some sensitivity analyses, such as roughness parameterization and different model representations, be implemented. This practice gives the modeler insight into the behavior of the model including identifying locations where higher resolution or other information may be required. Sediment transport modeling introduces several uncertainties associated with sediment load inputs, bed material distributions, transport function, fall velocity method, and sorting method.

MCSA Background

This project set out to build a software tool to facilitate these sensitivity analyses and provide probabilistic results based on known input distributions. The MCSA software developed a wrapper around HEC-RAS 5.0.7 (USACE, 2016). The core components and functions of MCSA are demonstrated by Figure 1. The main modules of the MCSA Tool include Monte-Carlo sample generation and ingestion, implementation of samples through modifying HEC-RAS input files, post-processing, statistical analysis and visualization. The whole process starts with a precursor baseline simulation that is set up by the user in HEC-RAS, which represents the best estimate of parameters, boundary conditions and models. Then MCSA starts by guiding the user to specify parameters, boundary conditions and models to be perturbed and varied. With the individual uncertainties established, MCSA continues to generate samples with the user-defined sample size for the Monte-Carlo loop. Inside the Monte-Carlo loop, the software implements the samples into HEC-RAS input files and conducts individual simulations. Once a simulation is finished, the corresponding HEC-RAS output file is archived with some results extracted via graphical user interface. Once the Monte-Carlo loop is finished, the extracted results are exported in addition to the archive of HEC-RAS output files. The user can also perform visualization and initial statistical analysis for the extracted results.

The types of HEC-RAS simulation included in MCSA are 1D Unsteady Flow and 1D quasi-unsteady Sediment Transport simulation for a single reach. The MCSA is developed using Python 3.8.8, the HEC-RAS API, and HECRASController to automate Monte-Carlo simulation. The software is distributed in the form of a Windows executable file and Python installation is not required for execution. The sources of uncertainties included in the MCSA are summarized in Table 1 along with their corresponding HEC-RAS input files.

Internal Monte-Carlo sample generator parameterization: The general design strategy of sample generation is that for a specific parameter or boundary condition the user provides a best estimate, probabilistic distribution function (pdf) and the associated parameters. The best estimate is what the user specified in the benchmark HEC-RAS setup for the application. It could be the mean or the median of a distribution. The general methodology to generate samples in MCSA is to add a perturbation, ε, to the best estimates (Eqn. 1).

$$\text{Monte-Carlo sample} = \text{Best estimate} + \boldsymbol{\varepsilon} \qquad \text{(Eqn. 1)}$$

Built-in User Defined, Uniform, Normal, Lognormal, Exponential, Gamma, Weibull, and Logistic pdfs and their associated internal index are provided for perturbation ε. The user specifies the pdf and provides the corresponding parameters to quantify the variance of $\boldsymbol{\varepsilon}$.

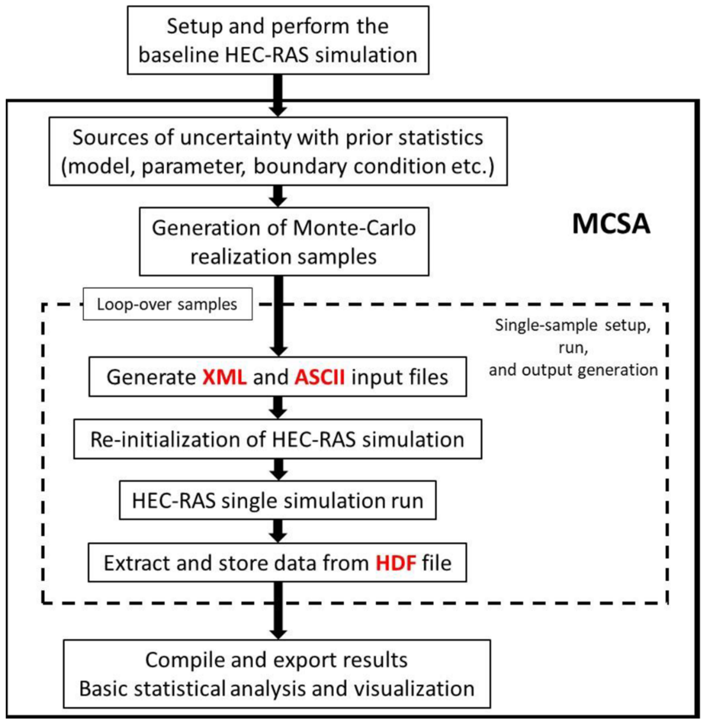

Figure 1. Flowchart of MCSA processes from baseline model to statistical results visualization.

For Manning's roughness coefficient, the MCSA only allows specification of exactly three values in the benchmark HEC-RAS setup, i.e., Left Over Bank (LOB), Channel, and Right Over Bank (ROB). A single value of perturbation is added to the best estimates of the three Manning's values. Therefore, for a certain Manning's roughness sample, the perturbation to the three Manning's values is the same. The same strategy also applies to the cross-sectional profile perturbations. Figure 2 shows two samples of perturbed cross-sectional profile around the best estimate, which are characterized by the vertical translation of bed elevation by ε1 and ε2.

The generation of perturbation to time series, such as an unsteady flow hydrograph or sediment load sedigraph, is similar to that of the cross-sectional profile. The difference is that the perturbation $\boldsymbol{\varepsilon}$ is not constant for the individual values of the time series, but is scaled to the peak of the time series. The calculation steps are: 1. A reference perturbation, $\boldsymbol{\varepsilon_{max}}$, is generated based on the selected distribution and parameters, which is by default applied to the peak value of the time series, $\boldsymbol{q_{max}}$; 2. For the rest of the values in the time series, $\boldsymbol{q_i}$, the corresponding perturbation, $\boldsymbol{\varepsilon_i}$, is scaled with respect to the peak value as shown in Eqn. 2. The purpose of this setup is to simulate the dependence of uncertainty on the time series magnitude. For example, the uncertainty of flow measurement at the peak flow is usually larger compared with the uncertainty of base flow.

$$\boldsymbol{\varepsilon_i} = (\boldsymbol{q_i}/\boldsymbol{q_{max}}) * \boldsymbol{\varepsilon_{max}} \qquad \text{(Eqn. 2)}$$

Table 1. Sources of uncertainties included in the MCSA (“xx” in the file extensions represents the integer index of the HEC-RAS input files).

1D Unsteady Flow Simulation	
HEC-RAS Input File	Uncertainty
Geometry Data File (.gxx)	Manning Roughness
	Cross-Section Profile
Unsteady Flow File (.uxx)	Flow Hydrograph
	Uniform Lateral Inflow
	Lateral Inflow Hydrograph
1D Quasi-Unsteady Sediment Transport Simulation	
HEC-RAS Input File	Uncertainty
Geometry Data File (.gxx)	Manning Roughness
Quasi-Unsteady Flow File (.uxx)	Flow Series
	Uniform Lateral Inflow
	Lateral Flow Series
Sediment Data File (.sxx)	Transport Function Sorting Method Fall Velocity
	Bed Gradation
	Sediment Time Series

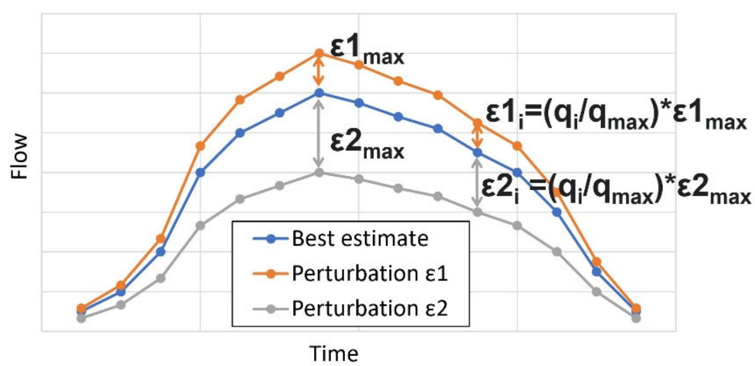

Figure 2. Demonstration of flow hydrograph perturbation based on magnitude.

Case Study: Blanco and Navajo Rivers of the San Juan-Chama Project

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 Azotea Tunnel and into Willow Creek, where it is eventually stored in Heron Reservoir. During the first season of diversions, downstream users complained of increases in turbidity and the settling of fine sediments in the gravel beds and pools that comprise the trout habitat and in the irrigation diversions. In 1972 and 1973, the same issues occurred. According to the available documentation, downstream diverters claimed they were not given notice about the intended sluicing operations that caused impairment of their water use. By 1974, civil action was taken on behalf of the downstream users against the Bureau of Reclamation. The case was named Schutz (a large landowner) and CO Southwest Water Conservation District v. Stamm (Commissioner of the Bureau of Reclamation).

Since these events, Reclamation ceased sluicing activities at Project diversions. This investigation is an attempt to characterize potential downstream impacts and use of the sluicegates, and what conditions should be considered in order to safely and appropriately sluice sediment and debris downstream.

Diversion Dam Operations and Sediment

The Designer's Operating Criteria (Bureau of Reclamation, 1972) calls for use of the sluicegate, *"during periods of floodflow."* The sluicegates are adjacent to spillway weirs just downstream of the diversion headworks. The diversion headworks sit on a concrete sill 5-feet above the dam apron. This design is intended to direct bedload toward the sluicegate, at the elevation of the dam apron, and minimize sediment entrainment to the tunnels. The designers of the Project anticipated that, "*Because the bypass requirements at the Diversion dams will provide significant amounts of sluicing water, it was considered that no bedload would be diverted from the Rio Blanco and the Little Navajo and Navajo Rivers.*" (Reclamation, 1964).

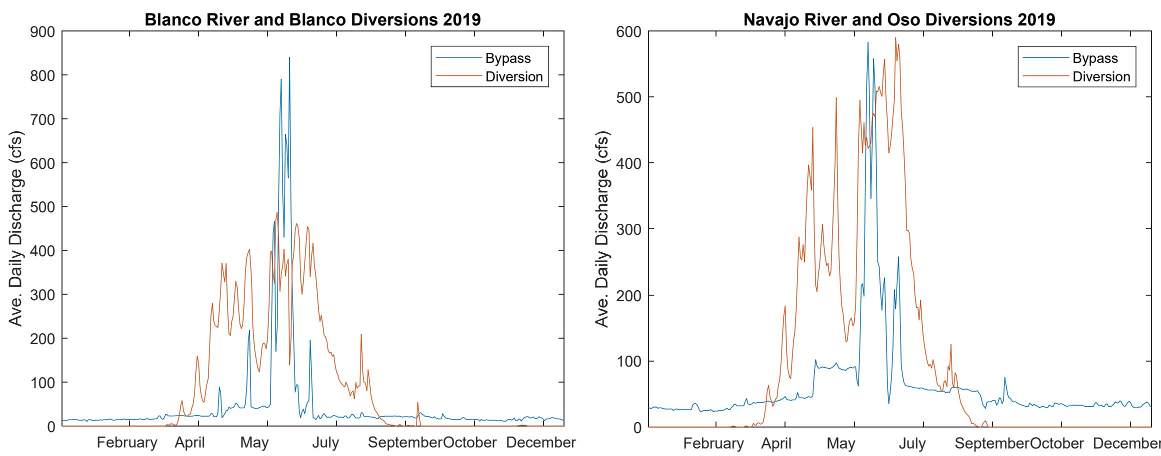

Figure 3. Diversion and Bypass hydrographs for 2019 at Blanco (left) and Oso/Navajo (right) Rivers.

When the sluicegate is closed during floodflows, the bedload quickly aggrades to the level of the headworks sill, facilitating bedload transport into the tunnels. Having the new channel bed at the height of the headworks sill has two significant impacts, 1) bedload is very erosive and 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 Figures 3. This figure shows that in 2019, a relatively wet year, during the spring peak flows, diversions decrease while bypass flows increase. This same phenomenon can be seen in most wet years or during large monsoon events.

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 top of the deposited material. The sluicegates being open for a short duration under these conditions, followed by the minimum bypass flow, is what led to much of the consternation by downstream water users. Sediment is removed regularly by Reclamation to staff in order to reset the channel, provide as much space as possible for the incoming material, and maintain diversion efficiencies as long as possible when floodflows occur again.

Blanco Diversion Dam: This dam sits at the downstream portion of a 90-degree bend. The 5'X17' radial gate in the sluiceway sits next to a 50' ogee weir. 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 Reclamation, 2019.

The Blanco Diversion Dam can experience large hydrologic events that carry significant sediment loads. The sediment yield study (Reclamation, 2019) found that on average the volume available below the headworks sill is likely to fill more than three times. The degree of sedimentation is not well documented.

The 2007 Review of Operations and Maintenance Report claims that 6000 cu. yds 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, indicating that sediment accumulation was at a higher elevation than the dam crest.

Oso Diversion Dam: This dam transects the Navajo River. Oso Diversion can be distinguished from Blanco in several significant ways, 1) the dam is 4.5 feet taller, 2) the slope of channel is less than Blanco with a much larger operating pool, and 3) the sluicegate is a 6'X6' vertical slide gate.

An impact of the lower slope and wider operating pool is the degree to which fine materials can deposit over a large area in the immediate vicinity of the dam. Fine material and sands deposit near the dam and inside the forebay and the low flow diversion gate is often buried in sediment. Regular dredging to maintain a channel to the diversion headworks is required, including excavation within the forebay where a small skid steer is used.

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 operations to maintain diversion capacity
- Diversion of bedload results in accelerated tunnel erosion
- Willow Creek and Heron Reservoir design based on assumption that no bedload is diverted
- Downstream 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 to the downstream reaches.
2. There is a minimum duration of this threshold discharge that will transport sands and gravels through the reach of interest.
3. The dam sluiceways are sufficient to pass sands and gravels through the Blanco and Oso diversion dams.

Data Availability

Elevation Data: This investigation benefitted greatly from the recent acquisition by the US Geological Service in 2018 and 2019 (Quantum Spatial, 2020). This project collected data across a large portion of southwest Colorado at a 1m horizontal resolution. In the vertical, their QA/QC report found the RMSEz ≤ 10cm. Acquisition of this data is directly through the Colorado GIS Coordination and Development Program.

The data was collected over two time periods, 10/05/2018-11/10/2018 and 07/27/2019-09/24/2019. 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 area resulted in the following model domains:

- Blanco: Upstream 4.5 miles, Downstream 67.7 miles; Total = 72.2
- Navajo: Upstream 11.1 miles, Downstream 47.1 miles; Total = 58.2

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.

Hydrologic Data: The Colorado Department of Water Resources operates and maintains the stream gages downstream of the Project diversions. With a 30-yr record, between 1971 and 2021, the mean value at the Blanco River barely makes it to 100 cfs and the max is over 1200 cfs. In addition, the data show the extreme variability associated with the summer monsoons, where max values are over 800 cfs and the mean representing the required minimum bypass flows.

Both the daily average and the instantaneous annual peaks were used to derive flood frequencies. These analyses indicate that in any given year there is a 50% chance (2-yr flood) of a daily average of 256 cfs. The instantaneous 2-yr peaks are much smaller at the Oso Diversion dam bypass, resulting in a 2-yr instantaneous peak of only 429 cfs, to Blanco's 679 cfs. However, the annual volumes are greater in the Navajo River.

Bed Material Data: Bed material samples were collected and analyzed for the sediment yield study (Reclamation, 2019) and were also used herein. A Reclamation gravel augmentation study was also used. These samples represent the incoming bed material and a portion of the upstream bed material.

Model Development

In order to properly represent the systems of interest in a numerical computational model, the model must be properly constructed, some of the system elements include:

- Flow inputs from 50cfs to 1000cfs
- Durations from 1 to 3 days
- A 5-day warm-up period of minimum bypass flows
- Equilibrium sediment load boundary conditions
- Bed material size distribution up- and downstream of the dams
- Channel and floodplain elevations
- Structures 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. 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 RAS Mapper in HEC-RAS version 5.0.9. was used to develop cross section geometry, including distance between cross sections. Within each of the models there are two structures that span the channel. The diversion dams were modeled as lateral weirs with adjustable gates. Dam design drawings were used to input the dam apron, crest, and sluicebox elevations.

Sediment Transport Function Sensitivity

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 Definite Plan Report (DPR) suspended sediment investigations. Figure 4 suggests that at high flows the measured 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 ~500 cfs the sediment load is likely much greater than what was measured. Figure 4 also shows the averaged transport potential for the subreaches from the model boundary to the dam and from the dam to Hwy 84. The functions are most consistent in finding that the greatest transport potential is in the upstream subreach, followed by the downstream subreach.

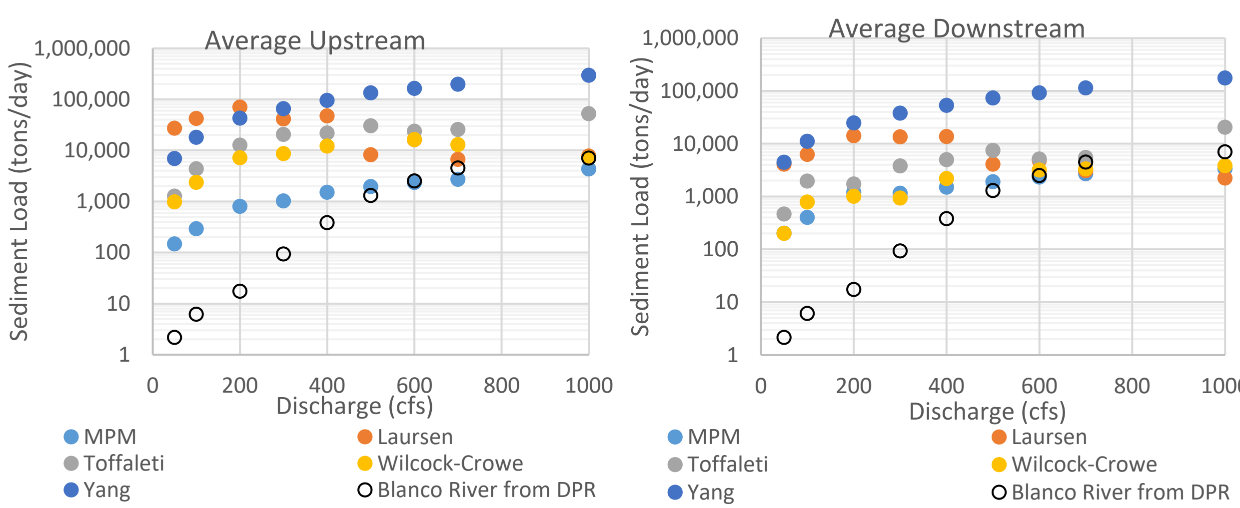

Figure 4. Sediment transport capacity rating curves for Blanco River, up and downstream of Blanco Diversion Dam.

The longitudinal change in transport potential at 1000cfs for three of the functions is seen in Figure 5. 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.

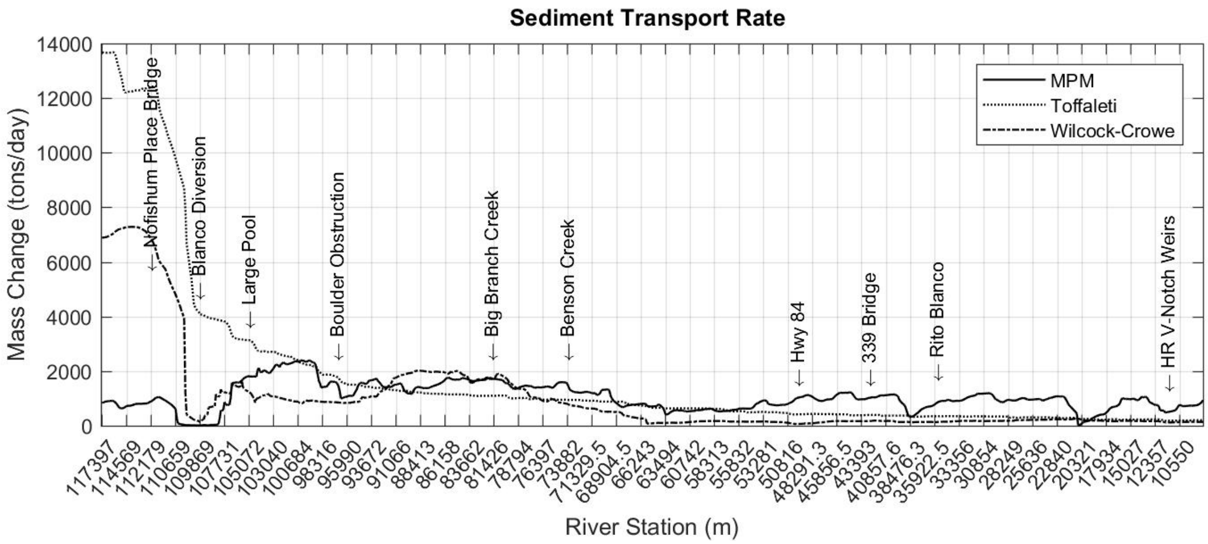

Figure 5. Cross section transport rate at Blanco River model sensitivity to three transport functions at 200 cfs.

Discharge Sensitivity

The sensitivity of the models to changes in discharge was implemented for a 3-day duration, after a 5-day 20 cfs warm-up period, with discharge rates ranging from 50 cfs to 1000 cfs. 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. These figures combined reveal several things about the communalities and differences between the two river systems.

D50: These 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 Figure 6 indicates the riffle/pool sequences associated with the meandering streams of the San Juan Mountains. Figure 6 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 cfs and 100 cfs, with a jump in coarsening beginning at 200 cfs. There is no fining that occurs in the Blanco Model. This suggests that there is a very high transport capacity, and that any sediment will be transported through the modeled reach.

In the Navajo River model, a very distinct signal can be seen. Figure 6 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 cfs and 200 cfs. At 300 cfs 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 cfs and greater. The pool locations are represented by the finer material and the model predicts that little change will occur there.

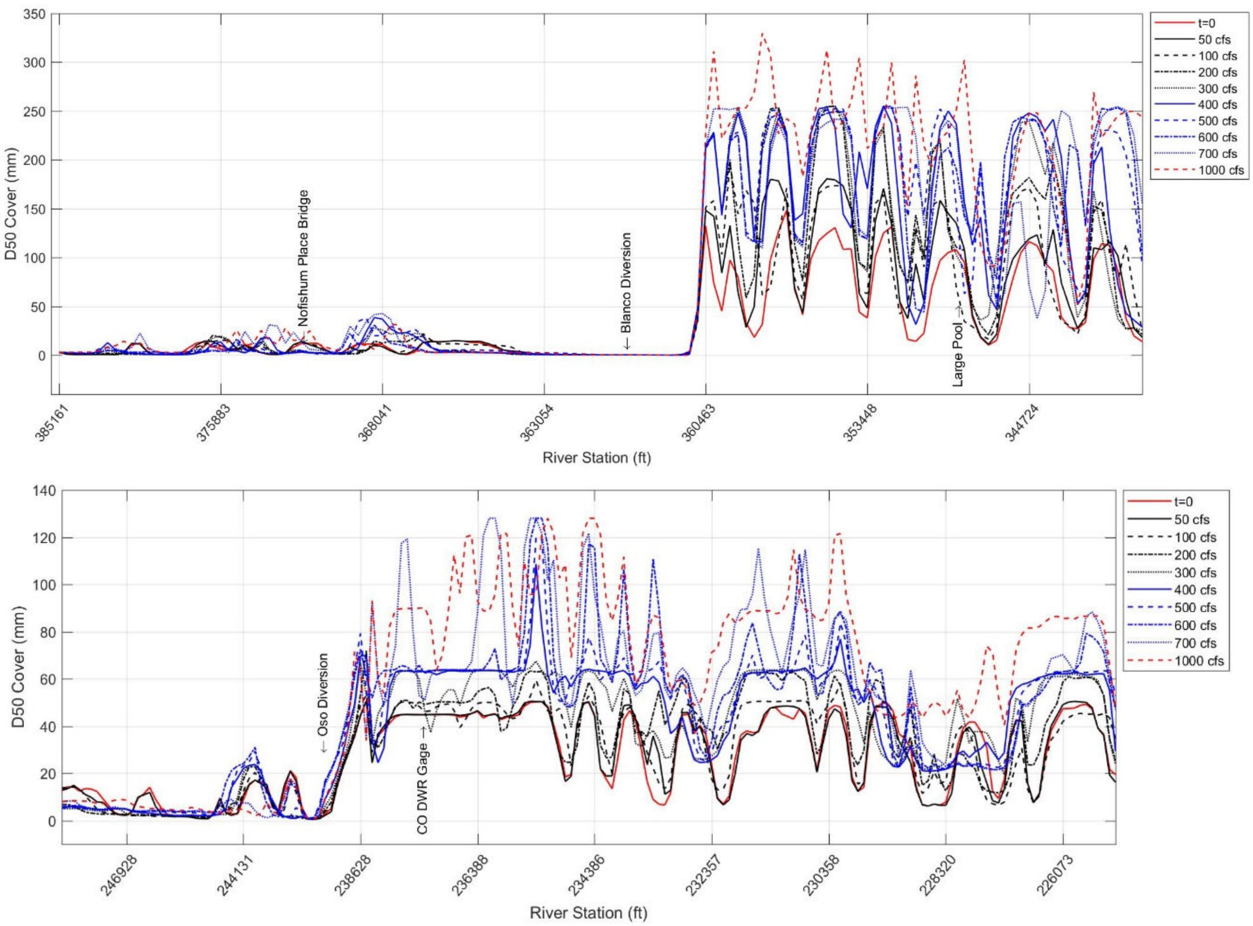

Figure 6. D50 change discharge sensitivity for the Blanco (top) and Navajo (bottom) River models.

Longitudinal Cumulative Mass Change: The Longitudinal Cumulative Mass Change plot represents the total change in bed mass, cumulative 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 in response to different discharge conditions. 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 7 highlights the very different dynamics of the Blanco and Navajo Rivers within this model domain.

The Blanco River model results indicate that much of the mass evacuated upstream is deposited behind the Blanco Diversion Dam. At flows of 200cfs and greater and downstream of the Blanco Dam until the large boulder obstruction, material continues to be evacuated from the bed. At lower flows the bed is very stable. From this point, the river begins to deposit material until Hwy 84. Downstream of Hwy 84, at higher flows, some bed material is lost in association with distinct geomorphic features such as tributaries, sharp river bends, and constructed weirs. Blanco model results also suggest that downstream of Hwy 84 some locations switch from degradational to aggradational when flow increase from 700 cfs to 1000 cfs.

The Navajo River model results suggest that the subreach upstream of the dam is degradational and the subreach downstream of the dam is aggradational. The results also suggest that at 50 cfs and 100 cfs little change occurs.

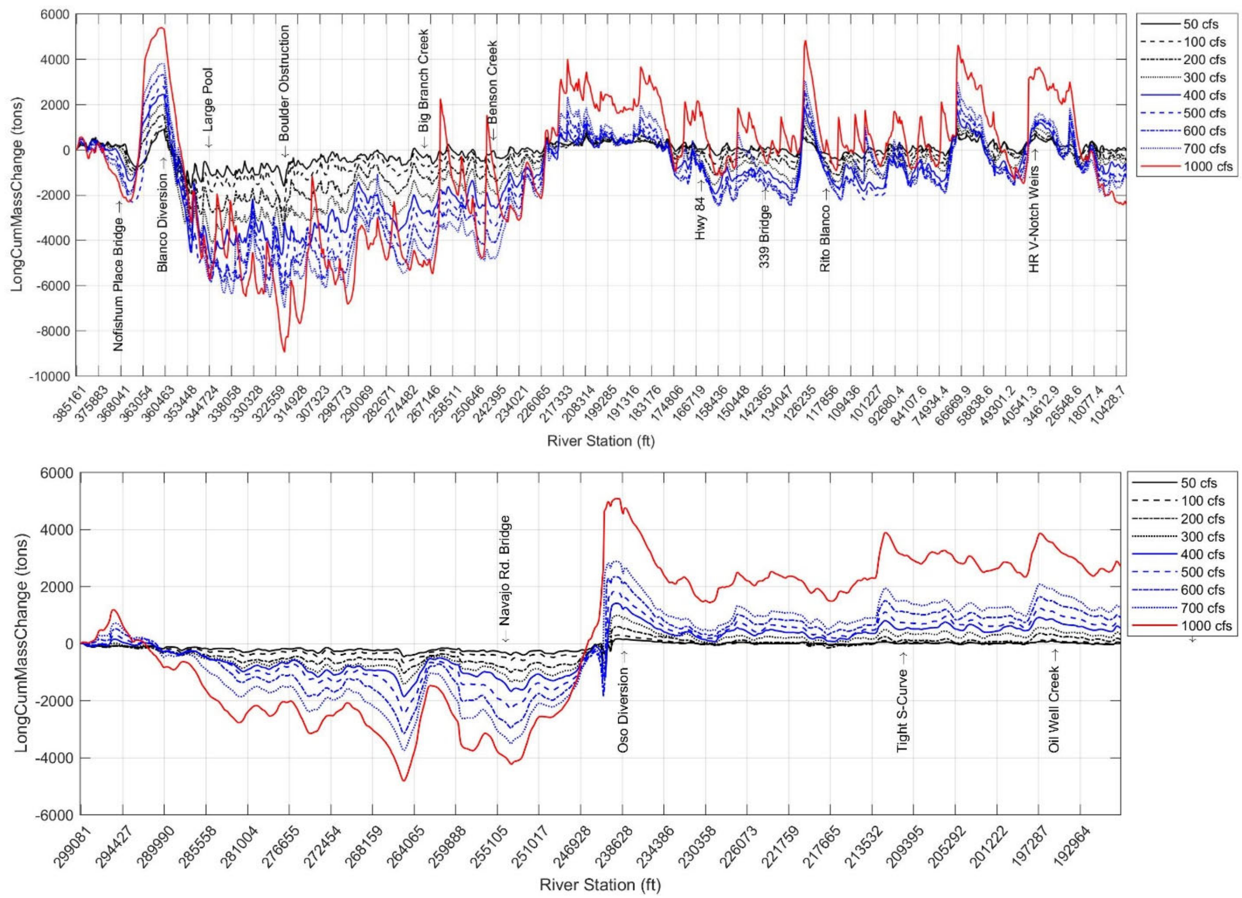

Figure 7. Longitudinal cumulative mass change discharge sensitivity for the Blanco (top) and Navajo (bottom) River models.

Sediment Supply Increase Sensitivity

It is well established than that land cover disturbance such as wildfire will greatly increase the sediment yield from a watershed. The RMRS studied the impact of wildfire on stream sediment supply in northwestern Wyoming and found that 8 years post-burn the suspended sediment yield was still double the pre-burn condition (USFS, 2014). Rathburn et. al. (2018) found that recovery of streams to pre-burn conditions can vary from 3 years to centuries depending on a metric they developed the index of resilience as *sediment recovery/disturbance recurrence*. Finally, Woody and Martin (2009) investigated post-fire sediment yields under varying rainfall conditions. One their more interesting findings was the fact that sediment yield was poorly correlated to slope or soil erodibility, and that ~75% of the sediment was derived from channels and ~25% from hillslopes. This information could be applied to prioritizing watershed resiliency projects.

In order to test the model sensitivity to increases in sediment yield from the watershed, the boundary condition sediment transport rate was varied. In order to best accomplish this analysis, the newly developed software by the Hydrologic Research Center (2022), in cooperation with the Bureau of Reclamation, was used.

This software allows the user to define a Probability Distribution Function and its parameters that are added to the best estimate developed in the base model. For this testing a flow of 300 cfs was used in the Blanco River, which translates to a sediment load of 116 tons/day and a discharge of 252 cfs in the Navajo River that corresponds to a sediment load of 427 tons/day.

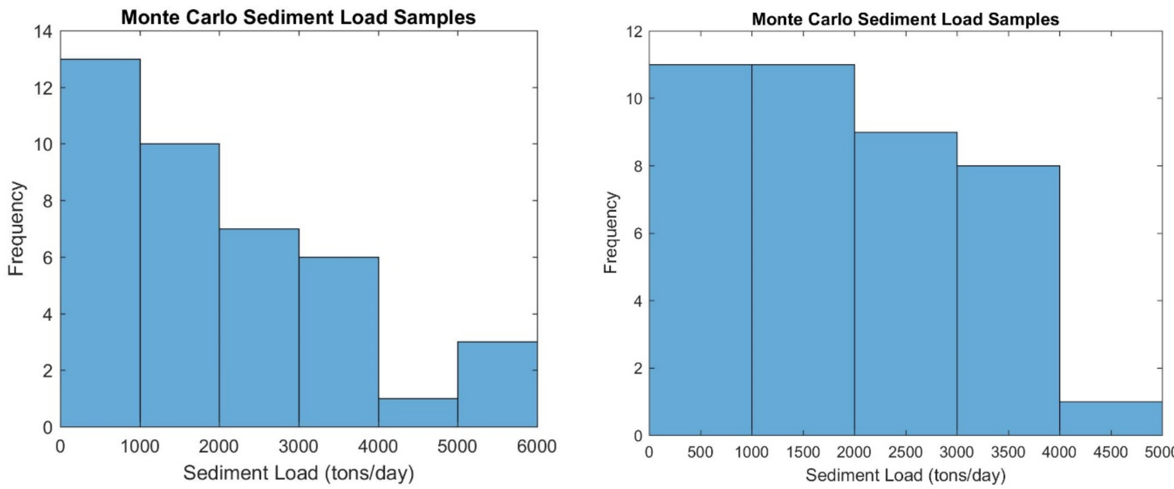

Figure 8. Histogram of sediment load boundary conditions for the Blanco (left) and Navajo (right) River models.

Figure 8 shows the range of inputs for the Blanco and Navajo River models represents an increase in sediment load of nearly 50X and a 10X increase in the Navajo River model. The results of these increases can be seen in Figure 9. These results are consistent with other findings wherein the large transport capacity of the Blanco River means that even with this large increase in input sediment load, still little net change occurs. Meanwhile, in the Navajo River model an increase in the sediment load input can have very dramatic impacts to the downstream sediment accumulation. The Navajo River model results, suggest increases in sediment load could turn the upstream degradational reach into a depositional one. These findings suggest that the Navajo River will take a much longer time to return to pre-disturbance conditions and that the Blanco River will likely return to pre-disturbance conditions quite quickly.

Conclusions

This case study highlights the power and utility of the MCSA to facilitate sensitivity analyses. The flexibility of the software allows the user to define samples of simulation inputs from probability density functions or user defined inputs. MCSA visualization tools can be used for locations and variables of interest. The preservation of HDF5 HEC-RAS outputs from each model realization allows for the development of custom post-processing tools. These sensitivity analyses result in an improved understanding of the model, and prototype, behavior.

Both the 1972 DOC and the 2009 SOP make clear that sluicing should be carried out during "floodflows." This investigation documented the challenges associated with those sluicing operations beginning with the first year of operations, through a lawsuit, to the current state where tunnel and dam maintenance, optimizing diversion during flood flows, and aquatic habitat is a primary concern.

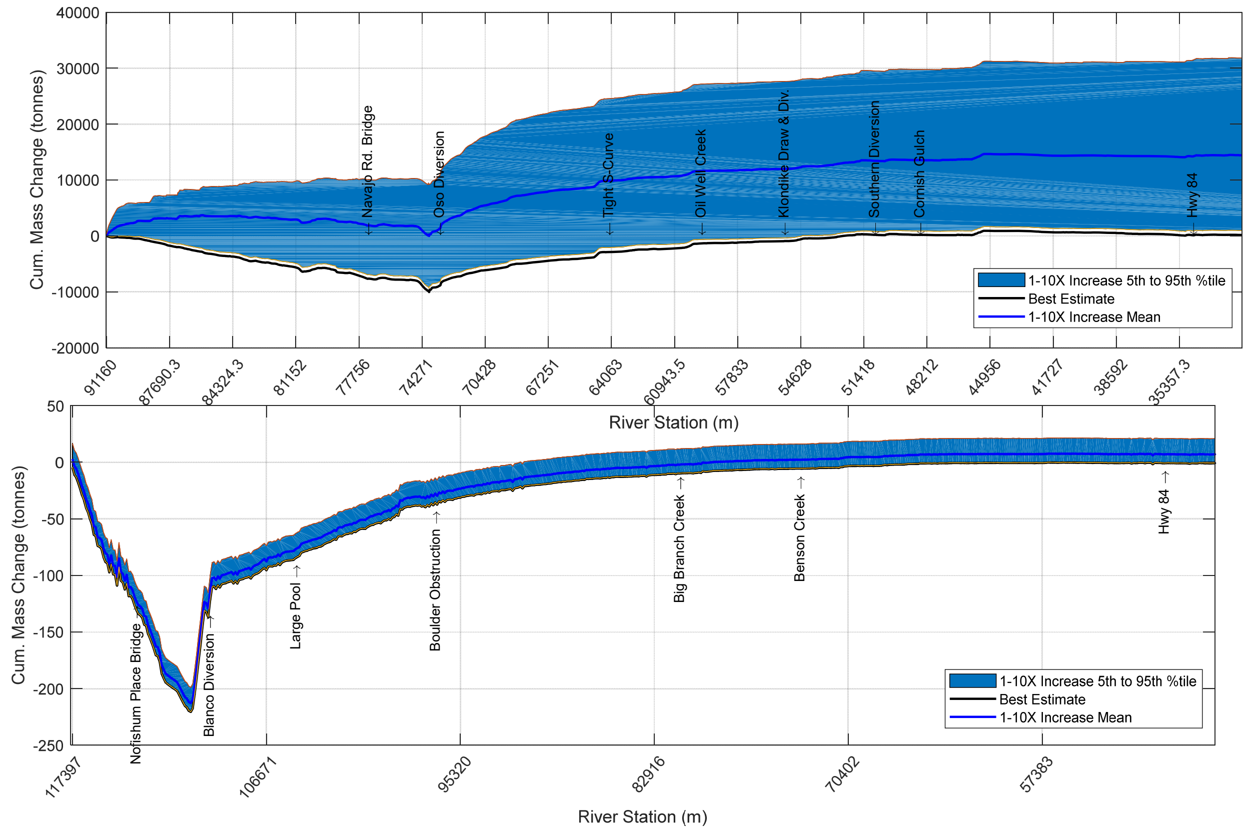

Figure 9. Longitudinal Cumulative Mass Change plots for range of sediment load boundary conditions for Blanco (top) and Navajo (bottom) Rivers.

This investigation highlighted a number of things. Firstly, there is a serious dearth of sediment transport data associated with the Project streams and diversions. The sediment rating curves developed for the Project design included only suspended sediment, as they assumed all bedload would be bypassed through the sluiceway.

Recommendation 1: Develop comprehensive sediment transport data collection campaign

Having robust and reliable sediment rating curves will help Project planning and decision-making.

This investigation also compiled and analyzed the available stream gage data. An analysis of the combined gages can be found in Reclamation (2019). However, this report does include 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 decease and bypass flows increase. This should not be a surprise, given the descriptions with trash and sediment described herein. However, this relationship is not well known and no effort was done to quantify or better understand this dynamic and whether or not any predictable relationships exist.

Recommendation 2: Analyze diversion and bypass data to identify diversion losses associated with flood conditions.

Understanding how Project facilities are able to deal with flood flows, in terms of diversion and bypass, will help Project planning and decision-making.

The hydraulic insights provided by modeling the gate openings, the operating pool aggradation trends, and reading the reports and communications about the sluicing (particularly at Blanco) suggests a few things. Firstly, that a sluicing operation is a finite amount of time, or that sluiceway gate does not necessarily remain in the open position for any extended period of time and should be flow or WSE, dependent. Second, this investigation found that a sluicing operation is done optimally with the diversion gate closed. This finding comes from both the description of the sluicing operation directed by ERC staff when operating the new dam, but also this finding is intuitively correct. If a large portion of flow is being directed into the dam tunnel, this flow will impinge trash against the trashrack and prevent it from going downstream. In addition, much of the sediment intended to be sluiced will be entrained into the tunnel.

Recommendation 3: Develop a testing plan for intermittent sluicing operations

In conjunction with downstream users and aquatic resource partners, develop conditions and protocols for when intermittent sluicing should occur. This could include a flow threshold, a condition of pool threshold, required data collection, duration of sluicing operation, etc. The findings in this report suggest that at a minimum 200cfs at Blanco and 300 cfs at Oso be available for a sluicing operation and to bypass. Drawdown of flow should be considered to transport material evenly downstream.

Ideally, such a testing plan would result in guidance that would allow dam automation to include intermittent sluicing operations under specified conditions.

Lastly, the issue of sediment and trash is not going away. This investigation found that the Project facilities are in areas with a high potential for sediment yield from the upstream watershed. The dam designers at the ERC acknowledged as such in their communications with local operators and users. The dam designs are not appropriate for the conditions in which they are built. The 3" vortex tube with 6 inches between the trashrack bars, and the clogged bypass channel, are examples of this. The ERC proposed one solution to be replacement of the ogee weir section of the dam with radial gates. Chama personnel recommended a guide wall. Upstream private landowners have had success with cross stream vortex tubes. This investigation found that the Blanco Dam is higher in the watershed, resulting in greater transport capacity and coarser bed material. In addition, there are no private homes or agricultural lands downstream of Blanco until downstream of Hwy 84. In contrast, Oso, is lower in the watershed, resulting in more total flow, but a high proportion of sands and lower transport capacity. In addition, there are many homes and agricultural diversions immediately downstream of Oso Dam on the Navajo River.

Recommendation 4: Investigate large-scale solutions to improve facility operation and maintenance

The costs and impacts associated with current operations should be assessed in comparison to possible facility improvements. These analyses may include gate optimization, updates to trash and sediment management, downstream aquatic habitats, fish passage, etc.. 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. They literally risked their lives on the edge of that trash rack to keep the water flowing into the tunnels. I have no doubt that even today, with automated dragbars and long-reach excavators, there are times under flood conditions with great risk. 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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