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Spillway Debris Physical Model Study

Ogee Crest Spillway with Two Radial Gates

Dam Safety Technology Development Program

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Dam Safety Technology Development Program

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Cover Photo: Debris clogging in the ogee crest spillway with two radial gates in a physical hydraulic model at the Bureau of Reclamation's Hydraulics Laboratory in Denver, Colorado.

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Physical hydraulic model tests have been performed on an ogee crest spillway with two radial gates to determine the impacts of reservoir woody debris on the water surface elevation (WSE) behind a dam and the discharge capacity of the spillway structure. It was discovered that both impacts are strongly correlated with a dimensionless parameter defined as the gate index which is defined as vertical gate opening height divided by the reservoir head over the crest. Debris jams were formed by steadily introducing woody debris into a reservoir and allowing the jam to form with natural physical processes as the flow approached and passed the spillway structure. At small gate index values (i.e. small gate opening relative to reservoir head) woody debris impacts were minimal and at times produced a more efficient spillway structure. At high gate index values (i.e. large gate opening relative to reservoir head), the maximum impacts from a natural jam were a prototype WSE rise of 4.5 feet and a discharge reduction of 50 percent. In addition to the natural jam, debris was manually compacted to form an artificially dense jam as a conservative upper limit to the impacts of spillway woody debris jams. The maximum reservoir WSE impact from the artificially dense jam was a rise of 8.8 feet and an 82 percent reduction in discharge.

Background

Woody debris entering the Bureau of Reclamation's (Reclamation) reservoirs can clog spillways which reduces spillway discharge capacity and creates higher water surface elevation in the reservoir. During risk assessments for Reclamation facilities, uncertainty has existed around the issue of reservoir debris clogging and how significantly it will affect the reservoir elevation and discharge capacity during a flood event. For a risk analysis, a team of risk experts with relevant experience in the potential failure mode being evaluated, dam safety, and dam operations must estimate the probability of an event in a failure mode progression using professional experience and research from academia and laboratories. For potential failure modes that involve reservoir debris and spillway structures, there was limited published research to inform decisions. Notably absent in the literature was any information when gates are used with partial openings to regulate discharge.

Literature Review

The majority of literature discovered was based on physical hydraulic models of a site-specific structure with gates that were either 0 percent or 100 percent open. Johansson (1995) was the first to document probabilities of debris passing a spillway gate structure with multiple gates and discovered that multiple gates with uniform openings results in a greater probability of a jam formation. This study found that the uniform openings maintained the orientation of the woody debris as it approached the spillway and was more likely to cause a jam than when a single gate was opened which allowed woody debris to turn in the flow direction as the streamlines contracted towards the gate and have a greater likelihood of passing. If multiple pieces of woody debris are entangled, the turning of one piece may cause the second piece to turn across the flow and create a jam. Hartlieb (2012) also used gates that were either 0 or 100 percent open, and tested the differences between various open gate combinations in a structure with three gates. This study found that with multiple gates, operating gates 1 and 3 resulted in the lowest probability of jam formation, and added that the division of the approach flow tends to separate the groups of five logs into single logs. Figure 1 shows a schematic of how the approach flow contracts symmetrically when alternate gates are open with a center gate closed. The right side of the image shows how approach flow streamlines are perpendicular to the spillway when all gates are open uniformly. Debris is more likely to form a jam when approach flow streamlines are perpendicular to the spillway structure.

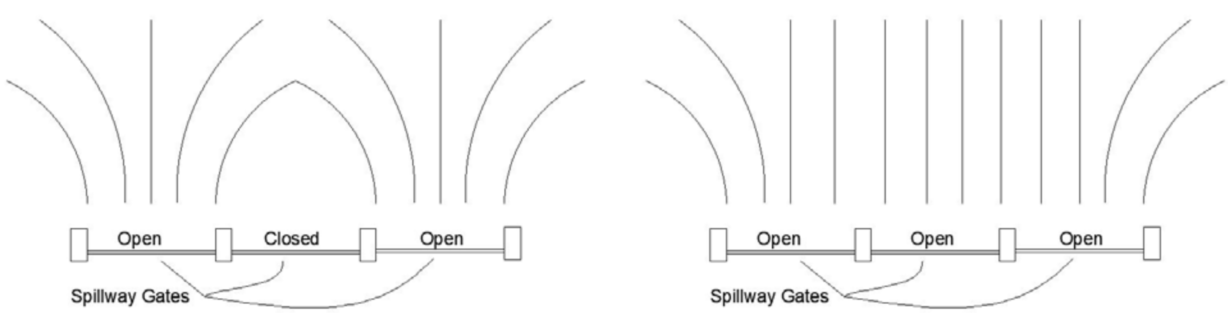

Figure 1 Schematic of how approach flow streamlines vary with alternate gates open (left), and with all gates open (right, Hartlieb 2012).

In addition to studies on gate operations, a few studies dealt with impacts to reservoir elevation or outflow. Johansson (1995) compared three different ratios of head to bridge approach width, and reported both the reduction in discharge as well as the rise in the WSE upstream of the structure. The study reported a larger percent deviation from clear water results for the smallest ratio of head to bridge approach width, with a 12.4 percent reduction in flow and a 10.5 percent increase in head. Hartlieb (2012) also studied impacts to reservoir WSE and outflow capacity by altering the density of the debris pieces being tested. At low specific gravities (lowest tested was 0.8) the debris would form a loose single layer carpet along the surface and would result in a 6 percent relative change to head and an 8 percent decrease in outflow. The highest specific gravity tested was 0.975 which created a jam that extended vertically below the water surface and resulted in a relative change to head of 46 percent and a decrease in outflow capacity of 43 percent. The study tested two intermediate specific gravities and found a non-linear relationship where the greater density produced a considerably higher impact to the results. Hartlieb also tested the change in reservoir head by increasing the flow through the gates creating higher velocity and higher Froude numbers. For slower velocity flows ($v \leq 1.48$ ft/s and $Fr \leq 0.15$) the jam would form a loose single layer carpet along the surface and had impacts to head of 6 percent or less. As the approach flow increased ($v > 1.64$ ft/s and $Fr > 0.3$), compact multi-layer debris jams were formed as the approach flow had sufficient energy to create a dense jam with surface debris pulled underwater to form a vertical barrier to flow in addition to a jam along the surface. These jams had a minimum impact to the head of 12 percent, and Hartlieb notes there is a strong random influence of the shape of the jams and the resultant impact to the head.

Crookston (2014) used a labyrinth weir to compare a relative ratio of head over crest with debris (H_{debris}) to head without debris (H) and used a mix of sagebrush and dowel rods. These tests were used to estimate how the coefficient of discharge for the labyrinth weir (C_d) changed for the condition with debris ($C_{d\text{-}debris}$). When the ratio of H_{debris}/H was 1.1, the resultant ratio of $C_{d\text{-}debris}/C_d$ was found to be 0.87. As the head with debris ratio was increased to the maximum value of 1.7, the $C_{d\text{-}debris}/C_d$ was found to be 0.45. The most common value of the head with debris ratio during the testing was 1.2 which resulted in a $C_{d\text{-}debris}/C_d$ of 0.76. The debris jam formed a single layer surface carpet of debris, but the report did not determine if this formation was a result of low approach velocities, or due to the nature of flow over the labyrinth weir.

Moulin and Piegay (2003) performed a study of debris that had accumulated in a reservoir on the Rhone River and found large pieces with intact roots are infrequent (10 percent) and most are smooth without branches and bark and were typically cylindrical. In this river, 90 percent of the wood was less than 3m (9.8 ft) in length and for pieces with diameters greater than 13 cm (5.1 in), the chance of branches, leaves and roots was rare.

There are many other studies published that deal with debris, but the remainder focus primarily on ratio of length of debris to width of gate, ratio of head over crest to bridge approach width, single logs versus multiple log clusters, bridge pier, abutment or chord height, diameter of root ball vs. bridge height, Froude number, ratio of head to drop height downstream of a structure, ratio of head to weir height, ratio of head to tailwater elevation, ratio of flow depth to log diameter, ratio of head to log diameter, volume of each debris piece, log density or flexibility, or debris jam properties.
To provide information to support the risk analyses that Reclamation performs, it was decided that a physical hydraulic model study was justified to look at the impacts of reservoir debris with various types of spillway structures. This paper focuses on an ogee crest spillway with two radial gates.

Physical Model

After reviewing an inventory of Reclamation's spillway structures, the most common structure type was found to be a gated ogee crest structure. While the design and configuration of these structures varied throughout the inventory, there were a few dams that were constructed with a potentially restrictive spillway design in locations with potential for a significant amount of debris to enter the reservoir. Cascade Dam north of Boise, Idaho and Granby Dam in North-Central Colorado are examples where large stands of dead or weakened lodgepole pine trees from recent pine beetle epidemic and/or fires could result in significant debris entering a reservoir during a rainfall event. The potential risk of debris blockage at these locations is thought to be the highest in Reclamation's inventory due to the quantity of debris, as well as the relatively small size of the gates in relation to the typical length of a mature lodgepole pine tree (between 50 to 70 feet in length).

Impacts to reservoir WSE and spillway discharge capacity were investigated using a 1:18 Froude-scale physical model tests at Reclamation's Hydraulics Laboratory in Denver, Colorado. Comparable results between the model and prototype data is achieved when the ratios of the major forces controlling the hydraulic processes are kept equal in the model and the prototype. Since gravitational and inertial forces dominate open channel flow, Froude-scale similitude was used to establish relationships between the model and prototype parameters. The 1:18 scale hydraulic model provided an accurate representation of prototype water surface elevation, flow rates, head loss, velocities and turbulence. One scaling limitation in the study is the flexibility of some of the natural debris pieces used would not match prototype debris. This was apparent with the sapling trees and the smallest of the branch pieces which were soft and bendable. The smallest dowel rod used (1/2-inch model, 9 inch prototype) had very limited flexibility and is thought to be more similar to a prototype tree.

The Froude number is defined as:

$$Fr = \frac{v}{\sqrt{gd}}$$

Where; v = velocity,
g = gravitational acceleration
d = flow depth.

When Froude-scale modeling is used, the following relationships exist between the model and prototype for the 1:18 geometric scale chosen:

Length ratio: $L_p = L_m * 18$

Velocity ratio: $V_p = V_m * 18^{1/2}$

Time ratio: $T_p = T_m * 18^{1/2}$

Discharge ratio: $Q_p = Q_m * 18^{5/2}$

The 1:18 Froude-scale model was designed in a 20-ft-wide by 20-ft-long model box and includes a rock baffle to smooth the incoming flow from the laboratory pump system. This simulated a reservoir with prototype dimensions of 360 feet wide by 300 feet long upstream of a generic earthen dam with the spillway structure located near the center of one wall of the model. All details of the spillway control structure are based on Cascade and Granby dams which have nearly identical designs. The radial gates are almost square with a 21-foot width and a 20-foot height and use a 25 foot radius of curvature. The approach channel extends 60 feet upstream from the ogee crest into the reservoir and includes circular guide walls on each side with a 15 foot radius. The floor of the approach channel is horizontal and is set at an elevation of 4 feet below the ogee crest based on the Granby design (Cascade has an ogee crest height of 3 feet above the approach floor). A single pier separates the two gates and has a bullnose shape that extends 5.5 feet upstream of the ogee crest. The upstream slope of the dam is 2.5:1 (H:V) and is covered with a coarse sand material to mimic the roughness of the earthen embankment. A bench was constructed along one wall of the model to accommodate a planned morning glory spillway structure for future testing. Figure 2 shows a profile of the gate and ogee crest shape with prototype dimensions. Figure 3 is a photograph of the upstream face of the dam.

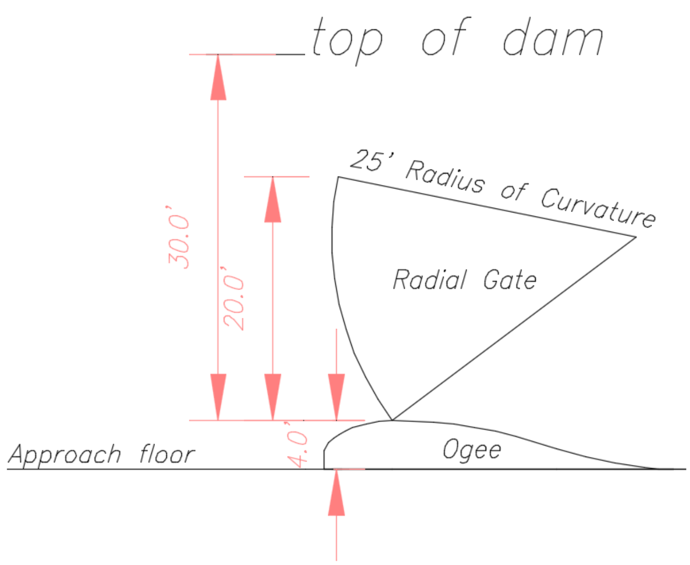

Figure 2 Profile of radial gate and ogee crest in prototype dimensions.

Figure 3 Photograph of the physical model upstream dam face and spillway structure.

Debris

Debris placed in the physical model was a mix of dowel rods, simulated trees created by adding root balls to dowel rods, natural sticks of various diameters and lengths, conifer sapling trees, and trimmed conifer branches with needles attached. Since much of the interaction between woody debris pieces is a result of branches, bends or splits in the wood, and other surface irregularities, the study used approximately 75 percent natural pieces and 25 percent of dowel rods. Debris length ranged from approximately 5 feet to a maximum length of 52.5 feet prototype which corresponds to a debris length to gate width ratio up to 2.5:1. Debris diameter ranged from 5 inches to 3 feet prototype. Figure 4 shows a random selection of debris material and sizes.

Figure 4 Photograph of assorted debris pieces.

Natural debris was collected locally and included both deciduous and coniferous species. Prior to testing, selected pieces of debris were measured to determine an initial density and resulted in specific gravities ranging from 0.41 to 1.01, with an average of 0.74. During construction of the physical model, approximately 50 percent of the collected debris pieces were soaked in water to increase their specific gravity. Between model tests, debris was stored in water to maintain a higher specific gravity of all the pieces. In total, there were over 200 individual pieces of debris that were used during the modeling.

Simulated trees created from dowel rods were designed to have a root ball diameter equal to 1/6th of the tree length following the typical sizing stated by Godtland (1994). Two sizes were created to correspond to debris to gate width ratios of 2.5:1 and 1.5:1. The larger size has prototype dimensions of 50 feet long, 1.5 foot diameter trunk with an 8.6 foot root ball diameter and the smaller size was 31.5 feet long, 1.13 foot (13.5 inch) diameter trunk with a 5.25 foot root ball. To create the root ball, an "X" shape of wood was attached to the dowel rod and was located at prototype 3 feet from the end for the larger size, or 1.5 feet for the smaller size. To account for roots that extend deeper into the ground and have a more complex shape that can bind onto other debris, a second, smaller "X" sized to ½ of the maximum root ball diameter was placed at the end of the dowel rod. Figure 5 is a photograph of the simulated trees created from dowel rods with root balls.

Figure 5 Photograph of simulated trees constructed with dowel rods.

Methods

Debris tests were conducted to determine properties of debris passage and were divided into three parts; single log tests (dowel rod both with and without root balls), clusters of 5 logs, and large complex debris mats. Two flow rates were used for the debris tests to correspond to approximately 50 percent (6,900 cfs prototype) and 80 percent (10,300 cfs prototype) of the dam maximum discharge capacity of 12,300 cfs. Gate openings were adjusted within each set of tests to capture the range between small openings and free flow conditions where the gates were out of the water. Tests for the single logs and the cluster of 5 logs were conducted to focus on the probability of passage whereas the large debris mat tests were conducted to determine impacts to WSE and discharge capacity. While reservoir impacts were recorded for the single and log cluster tests, a fully formed jam did not occur. The debris mats were used to test a fully formed debris jam and few, if any, logs were observed passing through the spillway.

All woody debris were dropped from a walkway at the upstream end of the reservoir (approximately 300 feet prototype upstream from the spillway structure) which allowed a random orientation of the debris in a location where the reservoir surface velocities were very small. As the debris approached the spillway structures, the velocities would increase which carried the debris towards the structure as it would during a flood event. Hydraulic data collection was automated and performed on a 5 second interval and included gate index (defined below), gate position and a stabilized WSE using a stilling well to dampen any wave action in the reservoir.

Early model tests identified a clear connection with the ability to pass debris beneath the spillway gates as a function of a ratio of the vertical orifice opening below the gate to the reservoir head above the crest. The term gate index (GI) defined in Equation 1 is used to express this relationship by creating a dimensionless term that can be calculated with commonly collected data for any reservoir during or following a flood event, a risk assessment, or hydrologic modeling of anticipated flood events. Higher GI values indicate the bottom lip of the gate will be closer to the debris and therefore will allow debris to pass but is also more likely to create a jam. Low GI values indicate that debris will be unlikely to pass, but also is unlikely to block a high percentage of the flow through the gate. Figure 6 shows how GI changes with gate positions and WSE (marked with a blue line).

$$Gate\ Index\ (GI) = \frac{Vertical\ Opening\ (ft)}{Reservoir\ Head\ over\ Crest\ (ft)}$$ Equation 1

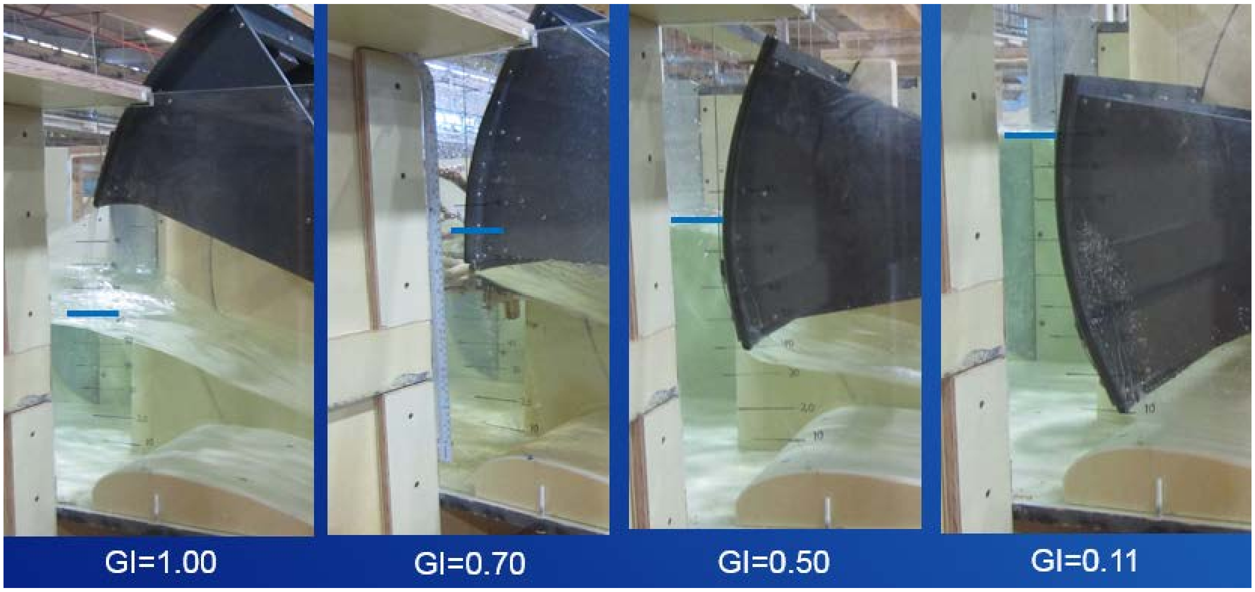

Figure 6 Photograph of four different gate index (GI) values and the gate position and water surface level.

Due to WSE drawdown when the gate is out of the water (discharge in free flow conditions), a GI value greater than 0.8 typically indicates the gates are out of the water. For the purpose of this study, any GI > 0.8 was assigned a value of 1.0 and data from this condition was not included with any trendline equations for gates regulating discharge due to a significant shift in debris jam and hydraulic characteristics.

Single log tests were conducted for three dowel rod diameters that correspond to prototype trunk diameters of 13.5, 18 and 22.5 inch, and a prototype length of 30 feet (ratio of debris length to gate width of 1.5:1). Single log tests with root balls were only conducted for the two logs sizes as described earlier and were not created for the trunk size of 22.5 inch, as this is typically larger than a mature lodgepole pine tree. Model tests were conducted for two flow rates and four gate positions. A single log was placed into the reservoir and allowed to approach the spillway structure with the flow. If the log passed either initially or within two minutes, it was counted as a pass. If the log remained racked in front of the gates or pier longer than two minutes, it was removed and counted as not passing. Tests were repeated 20 times to develop a data set for statistical analysis.

During initial model tests, it was observed that nearly all single logs were able to pass when the gates were fully out of the water, therefore tests focused on gate positions that were used to regulate flow and did not test free flow conditions. Table 1 summarizes the tests performed for an ogee crest spillway configuration with two radial gates.

Table 1. Spillway debris test matrix for an ogee crest spillway configuration with two radial gates.

	Flow Rates (cfs)	Gate Index (GI)	Log Diameter (in)	Log Configurations	Iterations
Single Log Tests	6,900 and 10,300	0.3, 0.4, 0.5, 0.6	13.5, 18, 22.5	with and without Root balls	20
Cluster of 5 logs	6,900 and 10,300	0.3, 0.4, 0.5, 0.6, 1	Range	Range	20
Large mats	6,900 and 10,300	0.35, 0.45, 0.55, 0.62, 0.7, 0.8, 1	Range	Range	4-10

Log cluster tests used the same five pieces of debris for all the test iterations. Pieces included one each of the large and small simulated trees, a sapling conifer with root ball and trimmed branches, and two sticks without root balls as shown in Figure 7. The cluster was placed into the reservoir with all five pieces touching, but not densely interlocked. Once the cluster reached the spillway structure, a count of the debris pieces that passed through the spillway was taken. Similar with the single log tests, remaining pieces would be allowed two minutes before being counted as either a pass or no pass. While this criterion is restrictive, model tests confirmed that captured debris would generally remain captured unless there was a large shift in the reservoir WSE which was not observed with the five-piece debris clusters. The model tests for the 5 log debris clusters were conducted for two flow rates and five gate positions and included 20 iterations of each test.

Figure 7 Photo of cluster of 5 debris pieces used for 5 log debris cluster tests.

The debris mat tests to determine reservoir impacts from jam formation included two flow rates and four gate positions. Due to the random nature of debris jam formation as noted by Hartlieb (2012), 10 iterations of each combination of flow and gate setting were performed to allow statistical analysis. Iterations from prior tests were reduced from 20 to 10 for time purposes (single log test iterations were typically five minutes each, whereas the debris mat iterations were up to 4 hours each). Individual pieces of debris were added (approximately one piece every 30 seconds) and spread laterally across the upstream reservoir surface until a jam was formed. Woody debris addition continued until the model reached an equilibrium where additional debris added did not create additional increase in the WSE. Table 2 lists the large mat tests and includes the initial head over the spillway crest as well as the gate opening amounts. During free-flow (GI= 1) conditions, a mat of interconnected debris and branches was added as an initial jam (Figure 8). The purpose of this jam was to recruit additional debris to clog in front of the ogee spillway.

Figure 8 Photograph of a representative jam for a large mat test in free-flow.

Table 2. Reservoir details for large mat tests.

Flow Rate (cfs)	Gate Index	Reservoir head above crest (feet)	Gate Opening (feet)
6,900	0.35	20.3	7.1
6,900	0.45	17.7	7.8
6,900	0.54	16.3	8.8
6,900	0.62	15.2	9.4
6,900	0.74	14.4	10.4
6,900	0.80	13.8	11.0
6,900	1.0	13.9	20
10,300	0.36	26.5	9.5
10,300	0.45	23.1	10.4
10,300	0.58	20.7	12
10,300	0.62	20.0	12.6
10,300	0.7	19.3	13.4
10,300	0.8	18.1	14.4
10,300	1.0	18.0	20

In addition to the jam that formed due to the physical process of flow velocity and acceleration as the debris approached the gate structures, each test was concluded by manual compaction of the natural woody debris jam to create an artificial debris jam. These results may be used as a conservative upper limit to the impacts that debris jams can make to the reservoir WSE and gate discharge. Once the natural jam WSE had stabilized for a period of no less than 10 minutes following addition of debris pieces, the debris was compacted by forcing surface pieces down into the water column. This allowed the pieces to obstruct the open orifice area, as well as becoming closer to the spillway structure and created a very dense compact jam unlikely to be reproduced by natural physical processes. The creation of the manually compacted jam provides an upper limit to the impacts of a debris jam that cannot be properly simulated with physical hydraulic model testing and represents densification created by changing reservoir WSE, wind, waves, and other environmental factors. The new, artificial WSE was allowed to stabilize for 10 minutes prior to concluding the test. On some tests, a few pieces of debris passed beneath the gates during the compaction process. Generally, this was only 1 to 5 pieces of the approximately 150-200 pieces in the model and is not thought to significantly decrease the artificial WSE.

Simulated hydrographs were also tested in the model to compare the differences between the equilibrium debris impacts and what would be expected at a reservoir during a flood event. The first event simulated a 0.001 probability (1/1000) flood event routing. The outflow hydrograph and the projected WSE from Granby Dam was obtained from the 2004 Reclamation flood routing in the Granby Dam Hydrologic Hazard report (Reclamation, 2004). Due to model temporal scaling, and the nature of changing model inflows, the prototype routing was modified to produce a test sequence that was achievable in 8 hours (the prototype hydrograph at model scale would be 82 hours). Figure 9 and Figure 10 contain the original and the truncated hydrographs respectively. Debris addition was based on a theoretical distribution of debris flux included in Figure 10 and used roughly 200 pieces of debris. This resulted in 50 percent of debris pieces being added to the model during the peak flows and a cumulative 1 percent following the peak flow in order to capture a worst-case scenario where the maximum debris would be available to impact gate operations at peak flow. To match the reservoir operations during this simulated flood event, the model inflow was set to match the projected outflow from the dam during the flood event.

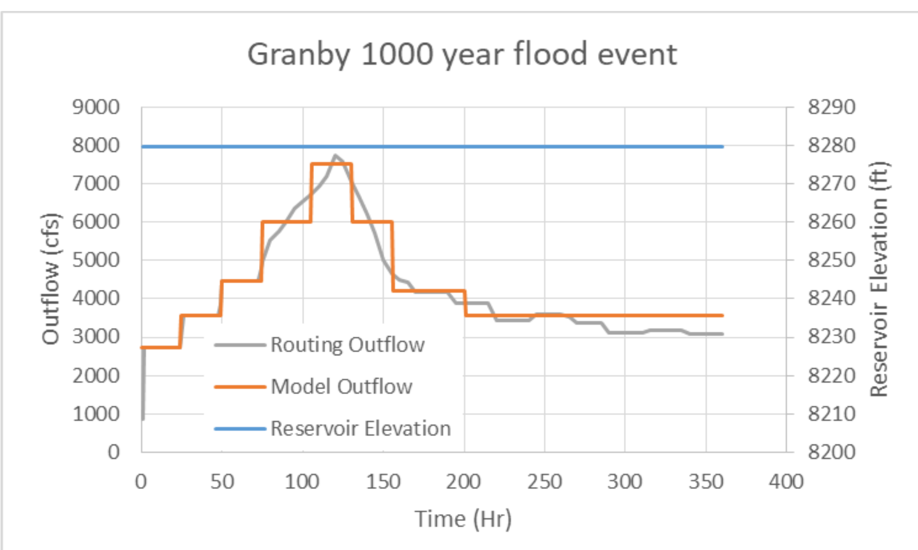

Figure 9. Prototype scale flood routing for 1/1000 event

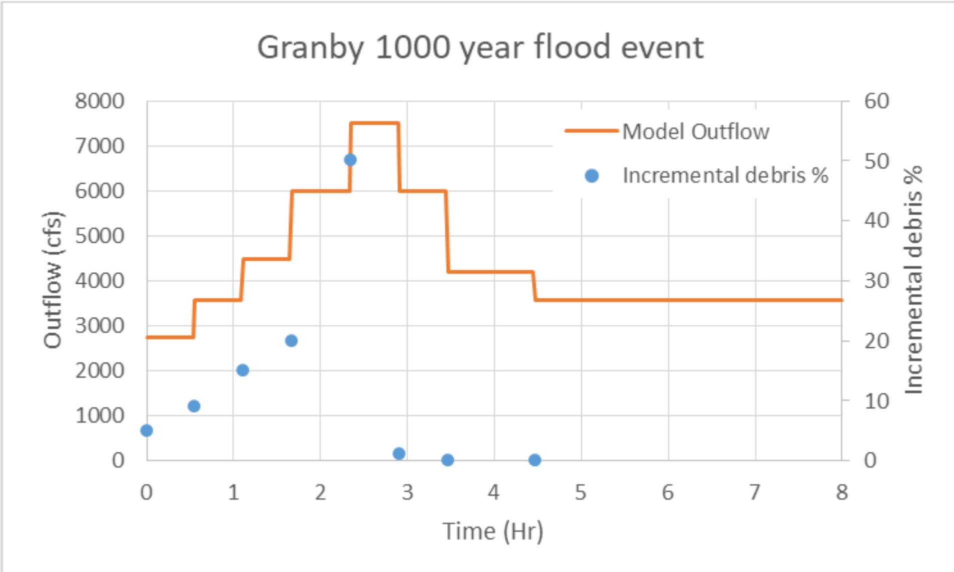

Figure 10. Truncated outflow hydrograph for 1/1000 simulated flood routing & debris addition.

A second simulated hydrograph was performed to test a 0.0001 probability (1/10,000) flood event. This event was selected since the 1/1000 event did not produce a significantly different operation of the spillway gates than the clearwater routing. Like the 1/1000 event, the 1/10,000 event was predicted to maintain a steady reservoir elevation at 8279.5 feet in the flood routings. However, while the 1/1000 event was estimated to have a gate opening of 42 percent and peak outflow of 7,730 cfs, the 1/10,000 event was estimated to have a gate opening of 71 percent and a peak outflow of 11,555 cfs. The debris distribution was also shifted to have more debris approach the spillway structure following the peak reservoir inflow.

Results

Model Validation

To validate the model construction, clear water (without debris) tests were performed to document the flow velocities in the reservoir and approach channel to ensure symmetrical velocities to the spillway structure. Figure 11 shows the surface velocity contours for the physical model at the highest flow rate tested (10,300 cfs prototype). While there was some asymmetry on the right side approach to the spillway structure, and further back in the reservoir, this was mostly due to interpolation between data points (black dots), and symmetrical flow was observed by surface tracers.

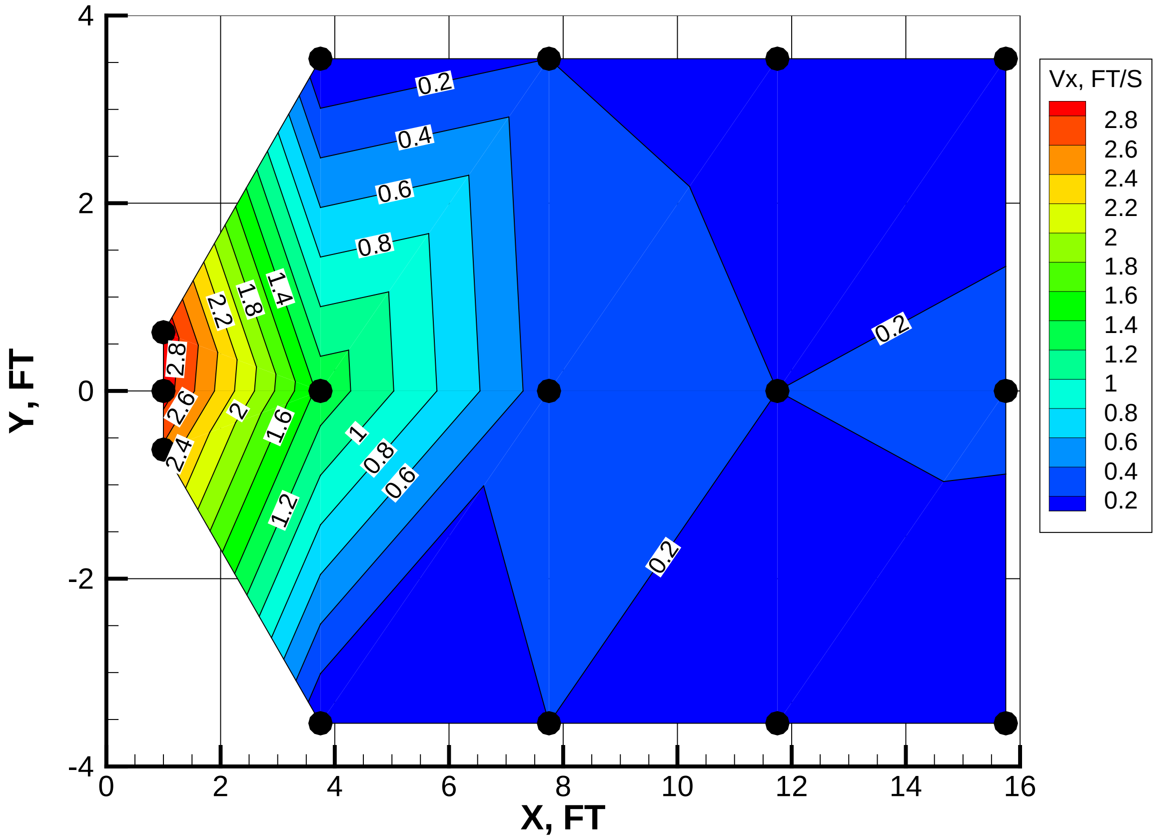

Figure 11. Plan view of surface velocity contours for prototype flow of 10,300 cfs. Axis of dam is located at X=0 feet, and centerline of spillway structure is located at Y=0 feet.

Single Log Tests without Root Balls

The probability of passage for the single log tests was found to be highly dependent on the gate index ratio and the diameter of the log. Log lengths for all tests without root balls are a ratio of 1.5:1 of debris length to gate width. For either flow rate tested, very little passage was observed until the lower lip of the gate was closer to the water surface elevation. Once the gate was no longer regulating flow (free flow conditions through the spillway), log passage was essentially 100 percent. Figure 12 shows the trends of how the probability of debris passage changes with log sizes tested and the gate index. The WSE in the model did not rise during these tests.

While all logs were soaked in water to increase their specific gravity, the larger sized logs were able to pass better due to their larger mass and position deeper in the water column than the smaller logs. As a result, the larger, heavier logs had a higher chance of being swept under the gate. If a log racked against the central pier, it would bob in the turbulent flow. Occasionally, the turbulence would bring one end of the log low enough to be swept under the gate with the approach flow.

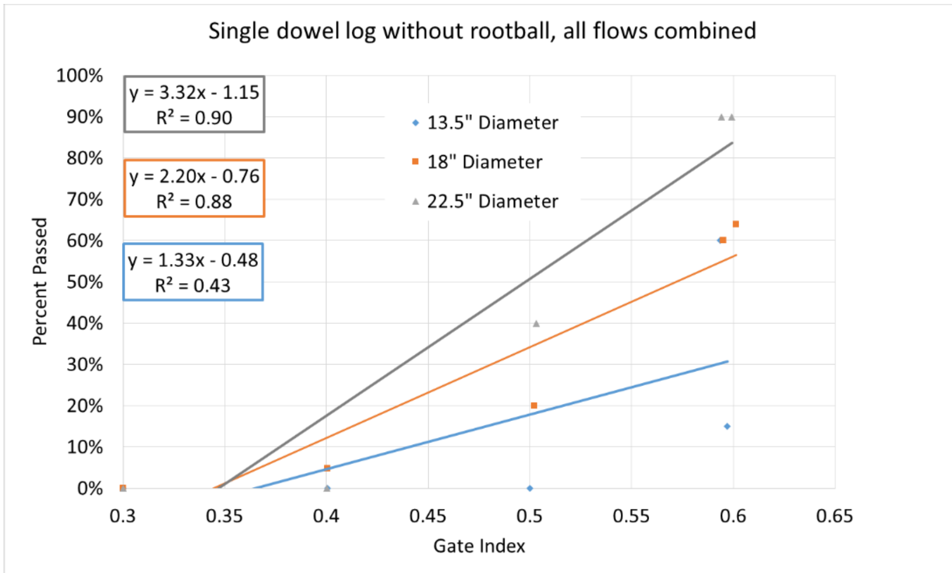

Figure 12. Single log probability of passage for three log diameters without root balls.

Single Log Tests with Root Balls

Similar to the single log tests without root balls, the probability of passage for the single log with root ball tests was found to be highly dependent on the gate index ratio and the diameter of the log. However, while the larger diameter logs passed more readily without root balls, the smaller logs with root balls had a much higher percent passage than the larger woody debris with root ball. This is likely due to the smaller overall size of the logs (length, diameter and root ball were all smaller which is less likely to form a jam), but could also be impacted by the added weight of the root ball on the smaller logs which allowed the logs to sink deeper in the water column. The maximum WSE rise for a single test was 0.70 feet prototype and the second highest was 0.25 feet prototype.

For either flow rate tested, very little log passage was observed until the lower lip of the gate was closer to the water surface elevation. Once the gate was no longer regulating flow (free flow conditions through the spillway), log passage was essentially 100 percent. Figure 13 shows the probability of log passage for logs with root balls.

As a single debris piece approached the spillway structure, it would orient itself so a line drawn through its length would be perpendicular to the gate face. For single logs with root balls, this process would occur for whichever end (either tip or root ball) was closer to the spillway structure and encountered the contracting approach streamlines first. Therefore, the process was random based on how the debris entered the reservoir and approached the spillway structure. It was observed that single logs with root balls that approached the spillway structure with the root ball end leading had a higher likelihood of passing.

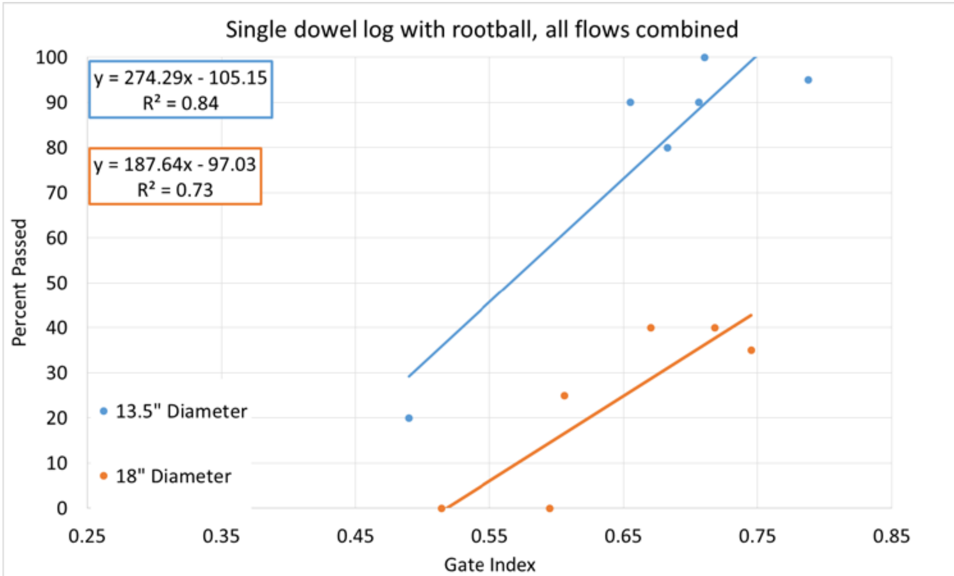

Figure 13. Single log probability of passage for two log diameters with root balls.

Log Cluster Tests

Similar trends in the ability to pass debris were observed during the log cluster tests. At small gate index values, very few pieces were able to pass; whereas, a considerably higher amount was able to pass at large gate openings. The percent of debris passing the spillway structure was analyzed to compare the two flow rates since the debris pieces were identical. Figure 14 compares the percent of clusters that had one or more pieces of debris that passed the spillway structure. Also plotted on this figure is the percent of clusters that all five pieces were passed downstream which only occurred on one iteration of the 10,300 cfs flow test. Figure 15 tallies the total logs of all iterations that passed for each test setup and compares trends between the two flow rates. The tests at GI=1 were not included in the trendline equations, but are plotted to show the difference between woody debris passage when the gates are regulating flow, compared to free-flow.

As the debris cluster approached the spillway structure, the debris would tend to orient itself similar to the single log tests where the long axis of the cluster would attempt to become perpendicular to the gate face. However, since there were now five pieces of connected debris the shape would never truly become perpendicular. If the debris cluster was approximated as an ellipse, the major axis would orient similar to the single log orientation. Depending on how tightly connected the five pieces were would determine how much the minor axis would be reduced. If the pieces were caught and unable to slide along one another, the minor axis would remain unchanged. If the pieces could slide along one another, debris pieces that were oriented along the minor axis would shift towards the major axis which reduced the total length of the minor axis. It was also observed that very loosely connected debris pieces would separate from the cluster and would approach the spillway structure as single logs due to flow acceleration near the spillway structure. The acceleration was large enough to allow the individual piece to pass a considerable time ahead of the remaining cluster.

The trends in the ability for a single piece or more to pass from a debris cluster have a similar slope and a slightly higher magnitude for the smaller flow rate. This is likely because the approach velocity is lower which allows the debris to have a longer time to orient into the flow as they approach the spillway structure, and a lower velocity that would allow some shifting once the debris contacted the approach side walls, the pier, or the gate face.

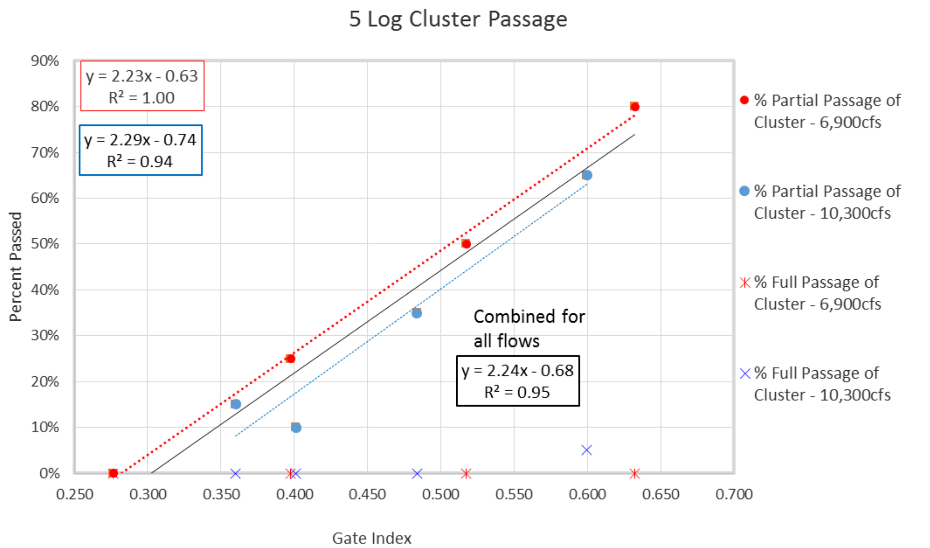

Figure 14. Five log cluster percent passing. Partial passage of cluster means that at least one log passed, and full passage of cluster means that all five logs passed.

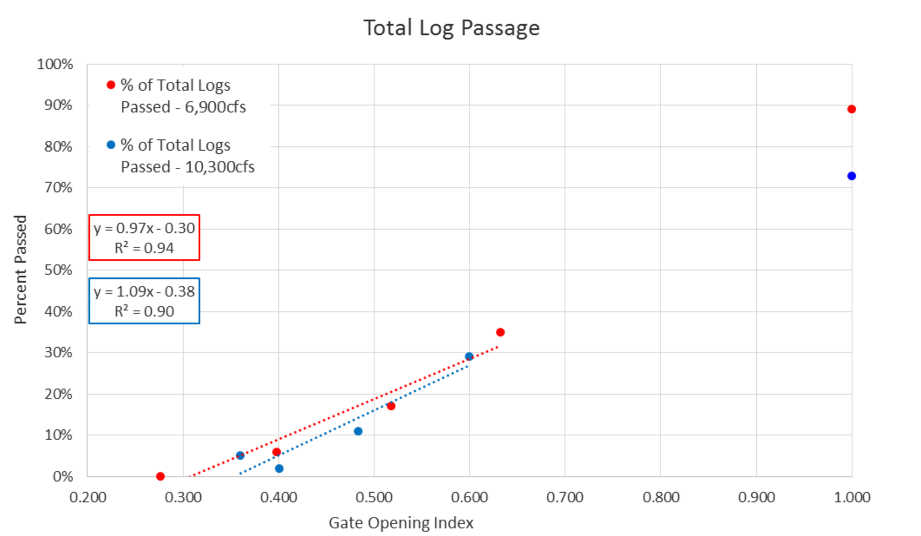

Figure 15. Five log cluster percent of total logs passing

Large Debris Mat Tests

Approximately 200 individual pieces of debris were introduced into the model one at a time. Occasionally, one to five pieces of debris would orient with the streamlines and pass through the spillway. In addition, the debris jam would shift during a test as the WSE increased which would allow one or more pieces of woody debris to pass.

As previous researchers have noted, the jam formation typically starts with debris forming a dense compact jam immediately upstream from the spillway structure. The initial piece(s) that formed the jam would become lodged due to contact with either the gates, pier or the side walls of the approach channel. Once a jam was started, additional pieces would become recruited due to obstructed area, by irregularities in shape, branches and/or roots. Close to the spillway gates, a multilayer jam (vertical stacking of debris pieces) would form where the velocities were the highest. As the jam spread out into the reservoir, the approach velocities are decreased (partially due to surface flow blockage by the existing jam, and partially due to the increased flow area once outside the approach channel confines), and the jam would become less compact with fewer if any pieces being pulled beneath the water surface. Eventually, any additional debris will form a loose single layer carpet along the reservoir surface. Once this equilibrium WSE was achieved, the elevation was recorded. Due to space limitation, the physical model only modeled a portion of a hypothetical reservoir's total volume, and the stable WSE applied to the entire reservoir. At prototype scale, the reservoir could extend upstream many miles, and would not be expected to have a stable WSE throughout.

There were slight differences in the initial jam formation depending on whether the spillway gates were being used to control flow or not. With low GI values, heavily saturated logs, or those with large root balls (weight as well as surface area) would be able to submerge to the orifice area of the gates and have the potential to block the opening. As the GI value increased, more logs were able to obstruct the orifice area until the two highest GI values of controlled flow were tested (GI=0.74 and 0.81). Tests at these GIs were able to pull any piece of surface debris into the orifice area since the lower lip of the gate was very near the top of the water column, creating an opening that was larger than some of the large root ball debris. In some instances, the initial debris jam was denser at these tests than with the uncontrolled (GI=1.0) test. This was due to downward velocity as the flow contracted to go through the open orifice area. With the uncontrolled flow tests, the debris velocity was entirely perpendicular to the spillway gates and did not have any additional downward component to aid in pulling debris down in the water column which had the potential to form a denser natural jam.

Once the final stable WSE was recorded, the manual compaction to create the artificial jam was started and the WSE was allowed to stabilize. Due to the density of the resulting jam, the WSE would rise rapidly and in a few tests overtopped the model dam crest. Figure 16 contains photographs of the initial jam (top) and the final jam showing the loose single layer carpet of surface debris at the end of the test (middle) and the artificial jam after manual compaction (bottom). Figure 17 shows the same test images from below the water surface. Photographs from this test correspond to a 2.5 foot increase in the reservoir WSE and a 14.8 percent reduction in dishcarge capacity for the natural jam and a 5.3 foot increase in the reservoir WSE and a 31.4 percent decrease in discharge capacity for the artifical jam. All deviation in the reservoir WSE is calculated from clear water (no debris) values for each test prior to adding debris.

Figure 16 Photographs of initial (top), final natural jam (middle) and manually compacted jam (bottom), 6,900 cfs, GI=0.71. Final natural jam produced a 2.5-foot higher WSE and 14.8 percent decrease in discharge. The artificial jam produced a 5.3-foot higher WSE.

Figure 17 Underwater photographs of initial jam (top), final natural jam (middle) and artificial jam (bottom), showing same test as in Figure 16 (6,900 cfs, GI=0.71).

Water Surface Elevation Impacts

To evaluate the debris impacts to the reservoir WSE, statistics were compiled for all iterations of each large mat test configuration. Separate analyses were performed for both the natural debris jam, as well as the artificial debris jam. Plots for WSE changes can be found below in Figure 18 and Figure 19. The standard deviation of each mean value is shown with the vertical error bars, and the trendline equation was created using only the GI values that control flow (i.e. free flow condition was not included in the data used to calculate the trendline). For natural debris jams, there is a clear trend towards a greater impact to the WSE as the GI rises for either flow rate tested. However, this trend was not observed for the artificially compacted debris jams that resulted in similar WSE impacts at 6,900 cfs and an increasing trend with the 10,300 cfs flow rate. When data for all tests are combined as in Figure 20, the amount of individual test variability can been seen, and it appears that the GI is not the only controlling parameter as the high flow rate (darker color) results in a larger WSE impact than the low flow rate. This is likely due to the higher approach velocities which result in higher head loss values through a similar debris obstruction.

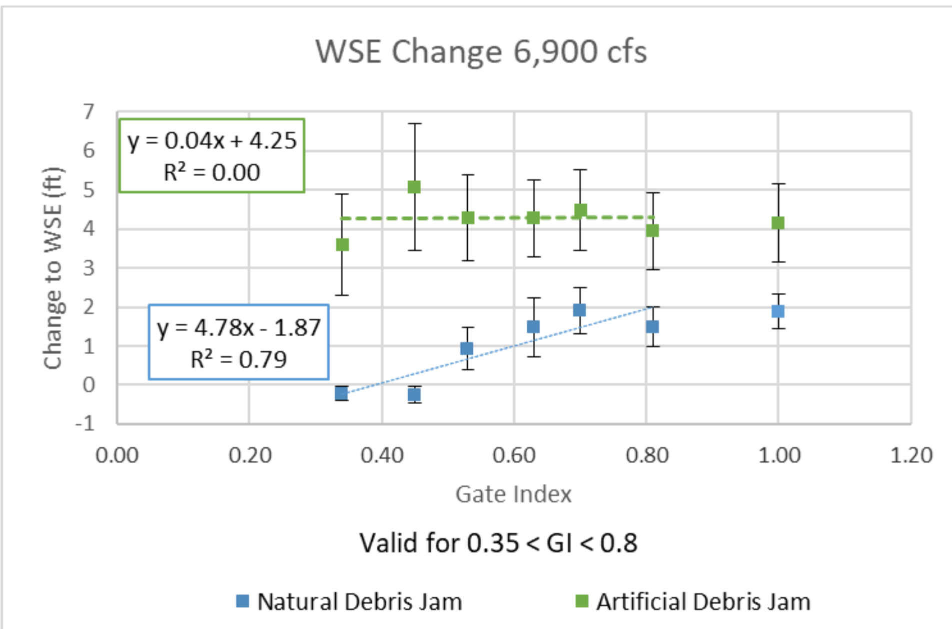

Figure 18. WSE changes for natural and artificial debris jams for 6,900 cfs

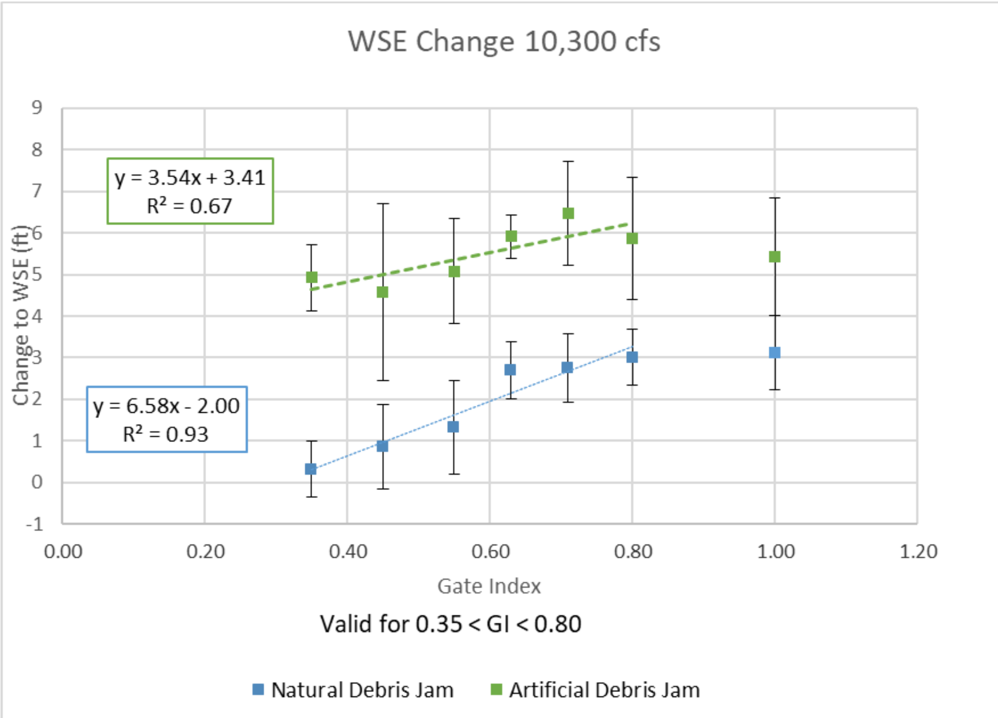

Figure 19 WSE Changes for natural and artificial debris jams, 10,300 cfs.

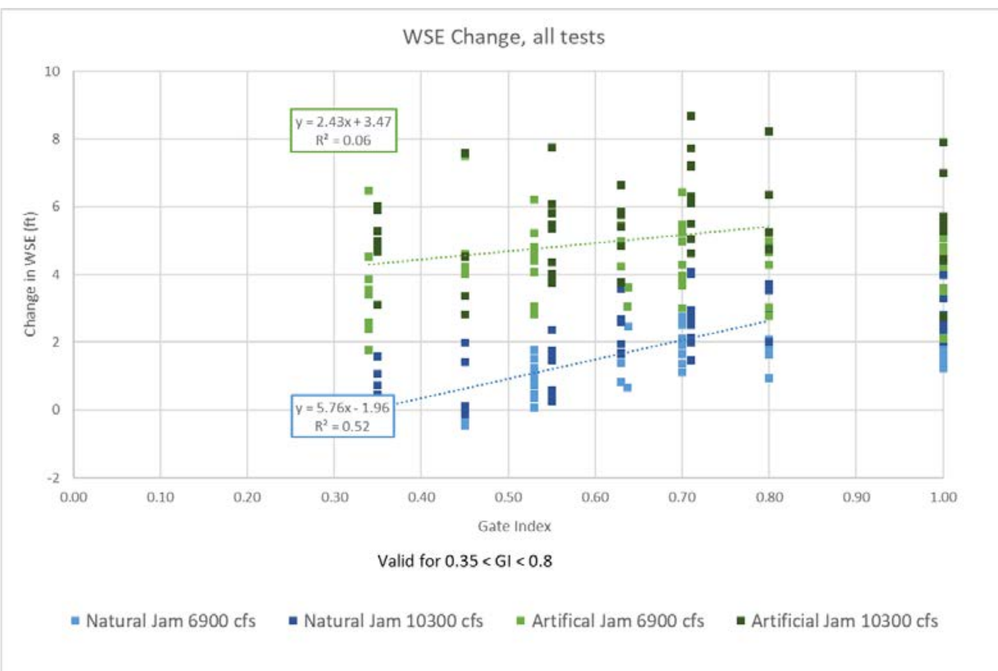

Figure 20. WSE changes for natural and artificial debris jams, all flow rates

For both debris tests at the lowest GI values (GI=0.35 at 6,900 cfs and GI=0.36 at 10,300 cfs), it was observed that almost all tests resulted in a decreased reservoir WSE at some point. At the low GI values where there is a high WSE in front of the gate, vortices were observed with clear water prior to the addition of debris. These vortices were due to the approach flow channel geometry and separation caused by the central pier and allowed symmetrical vortices to develop on the opposite gate side of the pier as shown in Figure 21. Once debris was added, the surface velocity patterns observed with clear water were disrupted which altered the circulation in the approach flow and stopped vortex formation. As shown in Figure 22, when debris was floating on the surface in front of the gate and not blocking any of the orifice area, the debris created ineffective flow area which forced the approach flow streamline to contract at less severe angles, reducing losses and leading to a higher gate coefficient of discharge and therefore allowing the reservoir elevation to decrease.

Figure 21. Vortex pattern in front of gates with clear water at GI=0.35. The trace shows how the approach flow would separate at the pier and create a vortex in front of each gate.

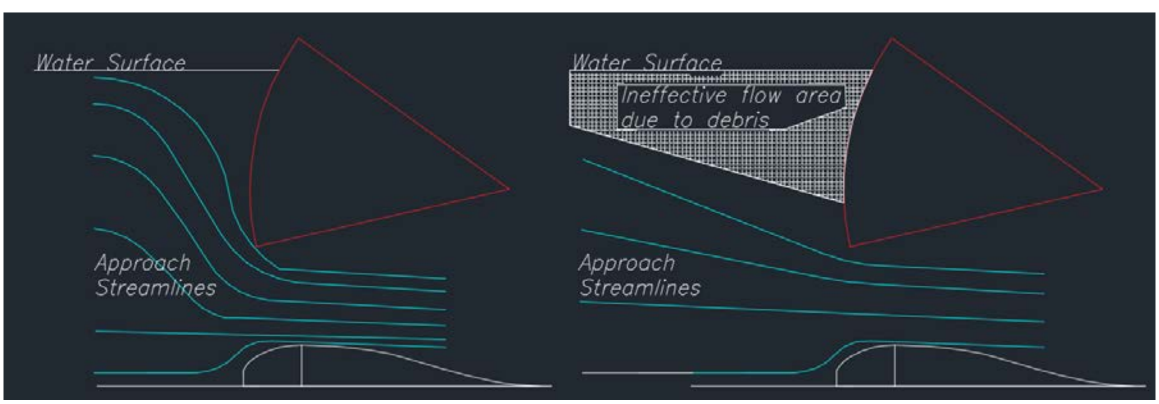

Figure 22 Schematic of approach flow streamlines with GI=0.35 showing how the obstructed surface area in front of the gate due to debris allowed the streamlines to approach the gate orifice with less contraction, and therefore allow a more efficient gate.

Discharge Capacity Impacts

Since the model inflows were held constant during testing, the resulting increased WSE post-jam can be used to interpolate what the clear water (without debris) discharge would be at the post-jam WSE from the spillway rating curve as a theoretical clearwater discharge. Then the reduction in discharge can be estimated by dividing the actual model inflow by the calculated clear water flow rate and subtracting 1.0. The calculated change in flow rate then yielded percent reduction in discharge capacity. This method was utilized for both individual tests and the average final WSE at each flow rate. Additional theoretical orifice calculations can be found in Appendix B.

To calculate the reduction in discharge:

$$Percent\ Q_{reduction} = \frac{Q_{Debris} - Q_{Clearwater}}{Q_{Clearwater}} * 100\% \quad \text{(Eqn. 2)}$$

To calculate the change to water surface elevation:

$$\Delta_{WSE} = WSE_{Debris} - WSE_{Clearwater} \quad \text{(Eqn. 3)}$$

Figure 23 (low flow) and Figure 24 (high flow) illustrate the percent change to the discharge capacity for both the natural and the artificial debris jams while Figure 25 combines all test data. Note that in the figures, the trendlines are calculated for controlled flow and do not represent model results for GI = 1.0 freeflow conditions. Results indicate that the increasing trend in discharge reduction as GI increases has a comparable slope between natural and artificial debris jams, and an offset of about 17 percent. When looking at the higher flow rate, the trend is less apparent, as the natural debris jams show a greater impact as GI increases whereas the artificial debris jam has a flatter slope. The trendline equations in Figure 25 utilizes both flow rates, and again show a consistent slope to the increasing discharge reduction impact as GI increases with an 18 percent offset.

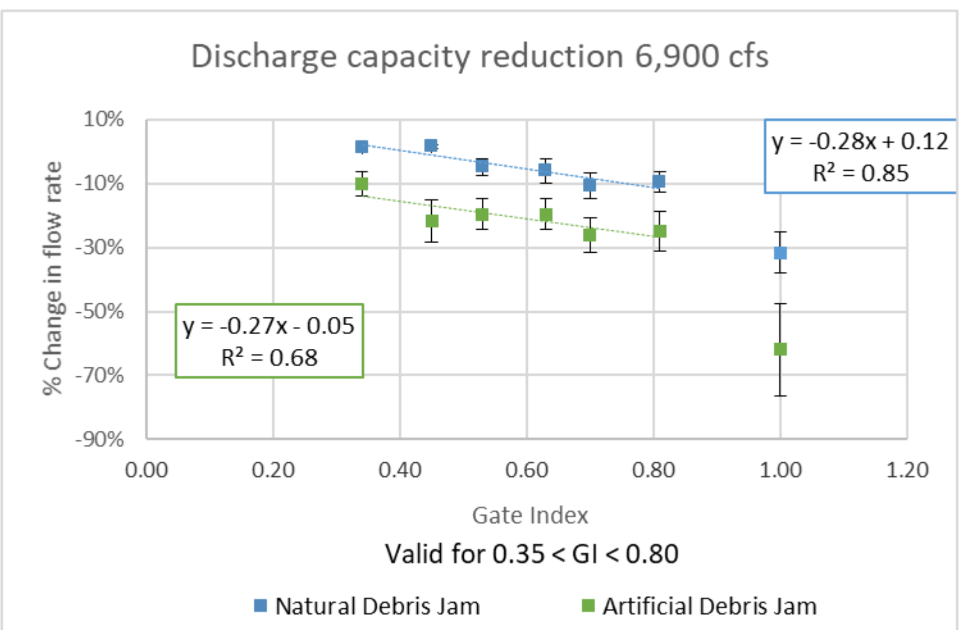

Figure 23. Discharge capacity reduction at 6,900 cfs flow rate

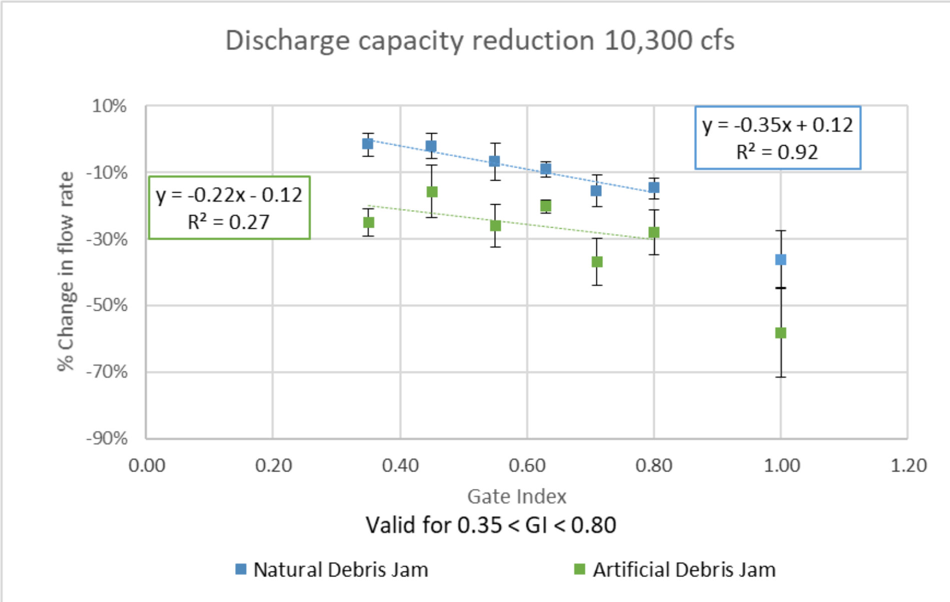

Figure 24. Discharge capacity reduction at 10,300 cfs flow rate

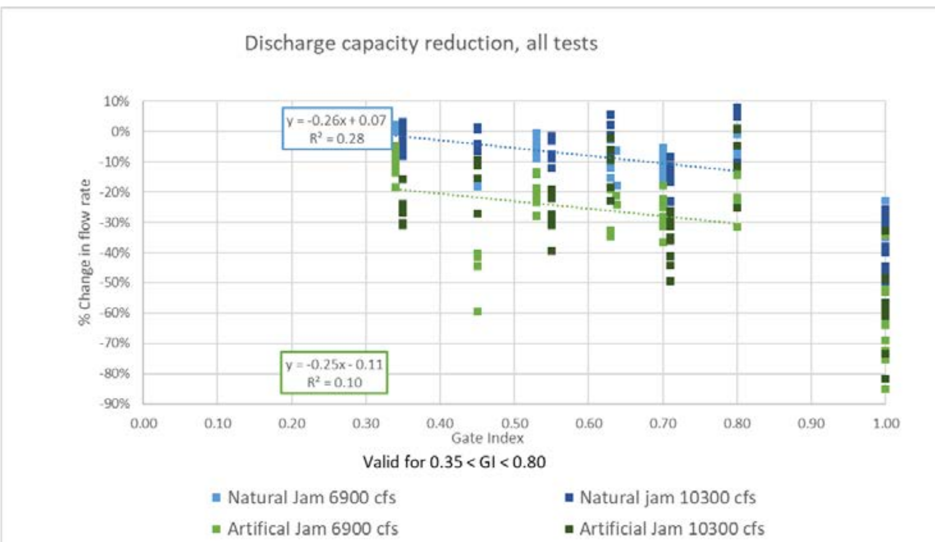

Figure 25. Discharge capacity reduction for all flow rates (darker points are 10,300 cfs)

Timing of Debris Impacts

While every debris jam is unique and will likely shift at some point during a flood event as the WSE rises, or as the gates are opened to maintain a desired pool elevation, a brief analysis was performed to determine the total amount of time necessary to create a stable equilibrium WSE. In the physical model debris for the large mat tests was typically introduced over a period of 1 to 1.5 hours until a stable condition was reached. This model duration corresponds to a prototype flood event that produces a large quantity of debris over a 4 to 7 hour period. Generally, this debris would create a stable water surface elevation within 1 hour (prototype) of the final debris piece being added. However, there were numerous tests that produced unstable debris jams that shifted during the test and needed additional time to stabilize. Occasionally, the altered jam would reduce the impact to the WSE, however, the majority of jam shifts created a more stable, dense and compact jam that produced greater impacts to the WSE.

While the ten tests at 10,300 cfs and a gate index of 1.0 were not the longest tests recorded, there were many tests that routinely would shift to create a more dense jam and produced episodic shifts in the WSE as shown in Figure 26. The longest tests correspond to a prototype duration of 15 hours of reservoir response, with elevations still shifting up to 6 hours after the last debris was added. For a small watershed that tends to be flashy, this duration can produce uncertain results for any flood routing or predicted reservoir responses during a flood event since debris will still be traveling to the spillway structure, and may or may not have developed a stable WSE behind the debris jam. For much larger watersheds where the duration of a flood hydrograph is 72 hours or longer, the delay between debris and reservoir change may still produce increases in the WSE during the falling limb of the hydrograph. Generally, the larger watershed would be expected to dampen the response of a flashy hydrograph and therefore lead to lower impacts.

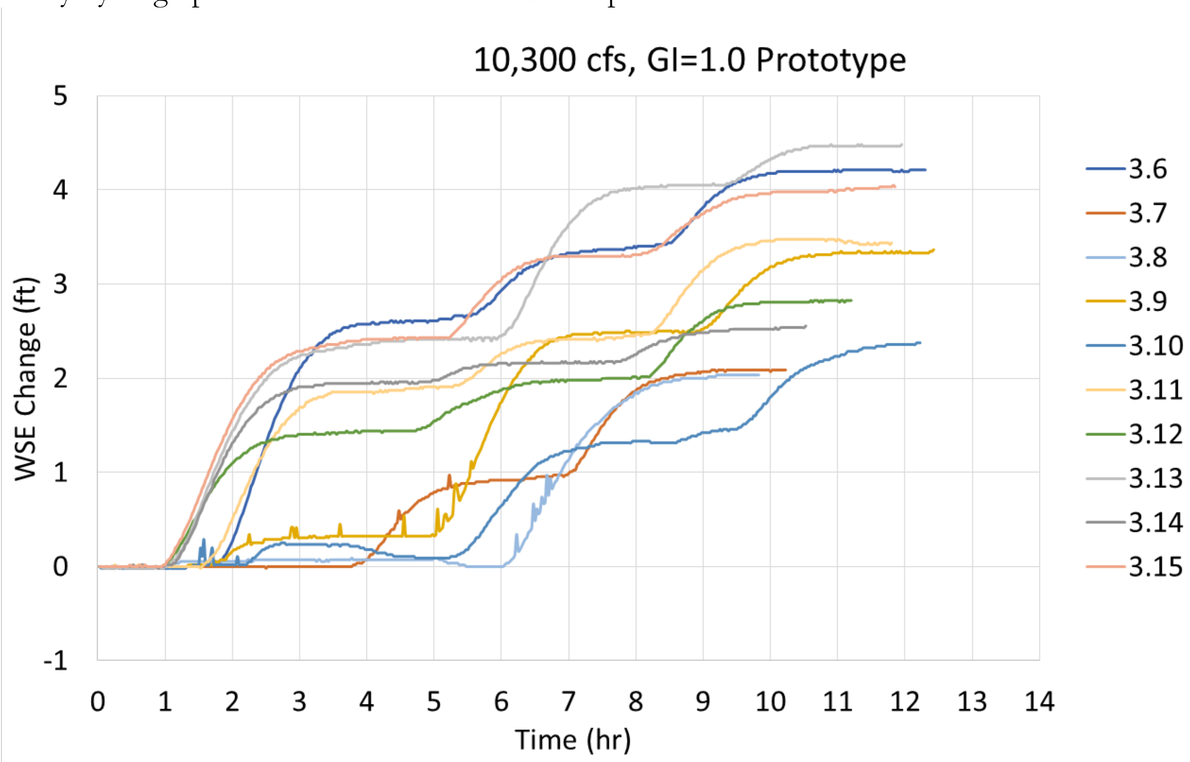

Figure 26. Prototype scale change in WSE for ten test iterations (iteration number 3.6 through 3.15) at a flow of 10,300 cfs and GI=1. The y-axis is change in head from clear water conditions due to debris.

A large determining factor in the timing of debris and reservoir impacts is the shape of the reservoir and the location of the primary tributaries. With a long narrow reservoir, the debris will have a much longer residence time in the reservoir due to long distances between the headwaters where the debris is captured by the flow and the spillway structure. In this case, the debris may arrive at the spillway after the peak flow and potentially even after the majority of the flood has been passed. This would result in minimal impacts during the flood event, but a large potential for future impacts should a second storm come prior to debris removal from the reservoir. The opposite would be true with

small nearly round reservoirs where the primary tributary directs the debris towards the spillway. In addition, the reservoir shape will also have an impact to how quickly, and how much the WSE changes across the entire reservoir due to a debris jam at the spillway structure.
Another consideration would be the density of the incoming floodwater that could result in nearly all the debris being caught in a recirculation zone where the denser inflow plunged below the less dense reservoir surface water. This could be caused by cooler runoff from high elevation snowpack or rain on snow event as well as by high sediment loads.

A final consideration on timing of large woody debris impacts would be how the reservoir is aligned with prevailing wind directions during large rainfall events. If the prevailing wind typically would go from the dam to the headwaters, this will reduce the amount of debris that will approach the spillway during the flood event depending on the surface velocities in the reservoir. In this case, a long narrow reservoir would be expected to have higher surface velocities along its length than a nearly round reservoir.

Simulated Flood Routing

Initially, the model flood routing was performed to match the clear water gate positions to determine the change in WSE during the test. However, project operations during a flood event would not allow the WSE to exceed maximum pool elevation when there is available gate outflow capacity. Therefore, the strategy during the test was altered to operate the spillway gates to maintain a stable pool elevation at approximately 1.5 hours into the test. Once the operational change was made, the target WSE was achieved for the remainder of the test with only small fluctuations to the reservoir WSE as shown in Figure 29.

Prior to the flood routing, the clear water Gate Index values were calculated for each of the gate changes during the routing. The initial GI value for the test was 0.15 with stepped increases up to the highest GI value of 0.37. This GI was comparable to the lowest value tested for the large debris mats, and resulted in minimal changes to both the WSE and the discharge capacity as shown in Figure 29 and Figure 23. A hypothesis was made prior to the routing that there would be minimal if any impacts to the WSE, and it was decided to match the dam operation to the clear water gate positions. During the test, waves from debris addition, varying approach velocity due to debris obstruction, WSE changes and gate changes shifted debris pieces and created a more compact debris jam than would be predicted for a stable GI of 0.37. The greater density of the debris jam required the gate opening to be increased from 37 percent with clear water to 40 percent with the jam. Figure 28 is an underwater photograph of the debris jam at the peak outflow (maximum gate opening) during the flood routing and shows that a majority of the gate open area is not obstructed by debris resulting in only minimal impacts to the WSE with this hydrograph test.

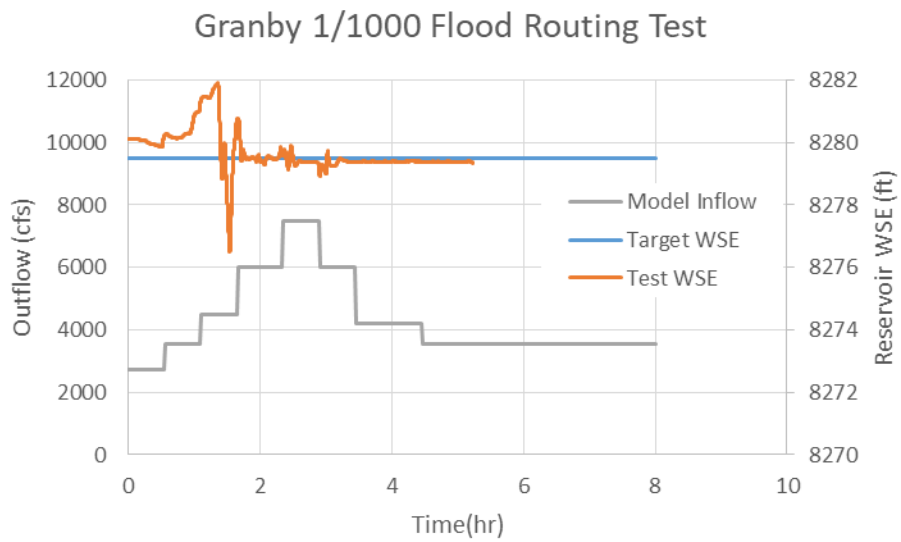

Figure 27. Simulated flood 1/1000 routing on Granby Dam.

Figure 28. Underwater photograph looking downstream for the 1/1000 flood routing test at the peak outflow.

The 1/10,000 event had a much larger impact to the reservoir and operations than the 1/1000 event. Prior to the peak inflow, there were two occurrences of minor debris jams (one at 0.5 hours, and one at 1.3 hours) that formed and eventually passed resulting in nearly clear approach conditions. Once a stable jam formed, debris blockage resulted in an increase in the maximum reservoir elevation of 3.8 feet prototype during the peak inflow, even with the gates 100 percent open. Since the hydrograph used in the model testing was truncated significantly from the flood routing, the reservoir response would have been considerably higher and may have overtopped the dam (the model tested roughly 2.3 of the 21 hours of peak prototype inflows). Figure 31 shows the WSE during the 1/10,000 event test.

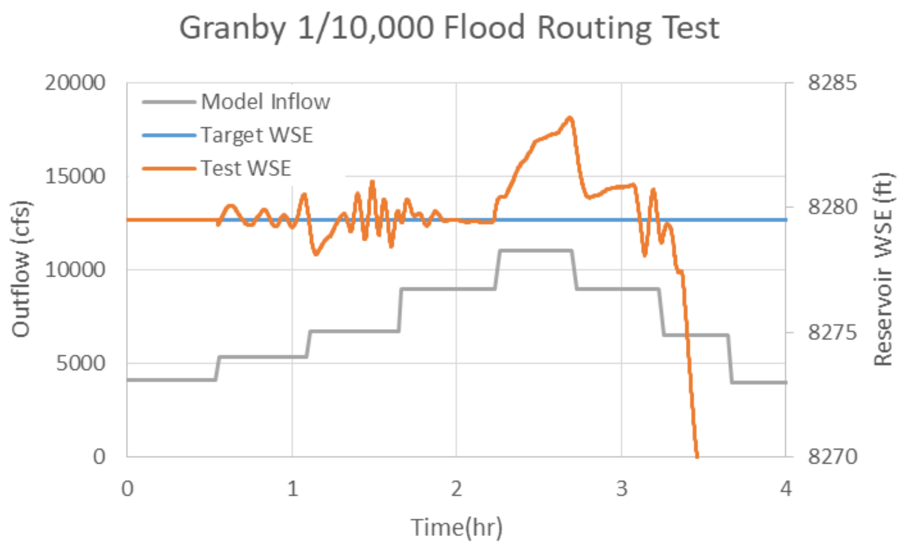

Figure 29. Simulated 1/10,000 flood routing on Granby Dam

Figure 32 compares the predicted Gate Index values and the actual recorded gate index during the simulated hydrograph test. This shows that up to the peak inflows, the reservoir elevation could be held at a constant value, and roughly approximating the predicted gate index until the peak inflow where the debris jam caused the WSE to rise sharply and could not be lowered since the gates were 100 percent open.

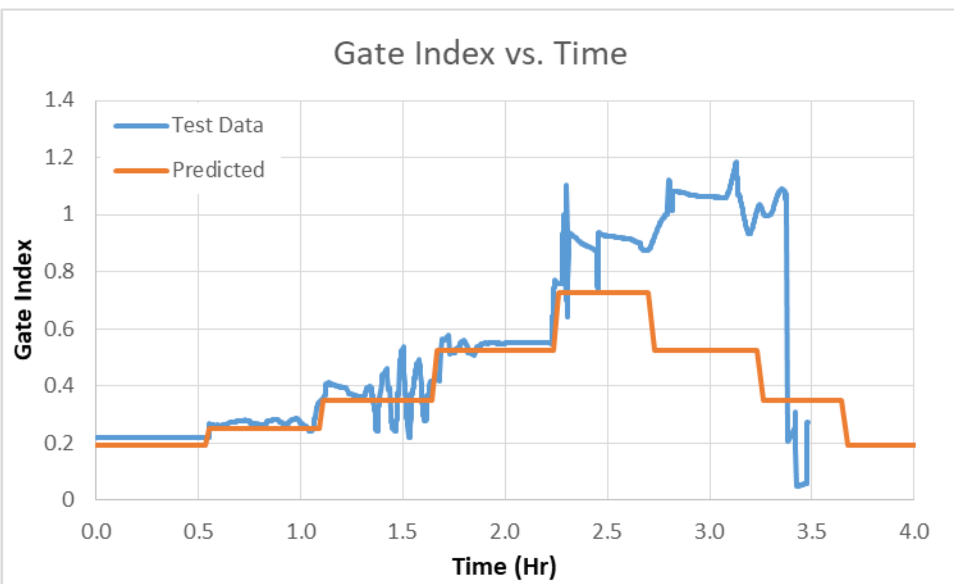

Figure 30. Comparison of Gate Index values for the 1/10,000 event

In addition, as approach velocities increased when the gates were fully opened, the debris jam shifted closer to the control structure and resulted in a loss of ability to close one of the two gates following the peak flows. Even when the left gate was fully closed, the reservoir rapidly lowered and lost storage down to the invert of the ogee crest (19.5 feet of reservoir storage for Granby Dam). Figure 32 shows the debris jam in front of the spillway gates, and the piece of debris that prevented the right gate from closing can be seen under the right side of the gate lip.

Figure 31. Photograph of the 1/10,000 event debris jam and resultant loss of function of the right gate due to debris obstruction.

Conclusions

Physical hydraulic model experiments were conducted to determine the impacts that floating woody debris can create on reservoir WSE and outflow capacity for a gated ogee crest spillway with two radial gates. A test matrix was established to test two different flow rates, four different gate positions, and three debris influx conditions. For the single log and cluster tests, each configuration was repeated 20 times whereas the large mat tests were repeated 4-10 times for statistical analysis. Since debris entraining in the reservoir inflow will be varied, a mix of natural and simulated debris of varying density and specific gravities was used. A dimensionless index (termed gate index) created by dividing the vertical gate orifice opening by the reservoir head above the ogee crest was used to compare the data.

For single logs and small clusters, very little impacts were observed to the WSE or the discharge capacity most likely due to the short duration and inability of any potential jam to recruit additional debris. For these tests, the focus was on the probability of passage. With the single log without root ball, larger logs that float lower in the water column were more likely to pass. When tested with root balls, the smaller logs were much more likely to pass. This illustrates how the type of debris and debris density matter with jam formation. Both conditions plotted results along a trendline with decent agreement when using gate index as the independent variable.

Test results from the cluster of five debris pieces resulted in a similar trend where the higher gate index value allowed a larger percentage of debris pieces to pass the spillway structure. There did not seem to be a significant difference in the total percent of pieces passed when flow rates were analyzed. With debris clusters, only 1 out of 180 iterations allowed all five debris pieces to pass the structure when the gates were regulating flow. During a flood event, debris could continue to accumulate and create the impacts to the WSE and discharge capacity that was tested with the large mat condition.

For large debris mat testing, natural jams were created by continually adding pieces of debris and allowing a steady WSE to be established. At this point, additional debris did not produce greater impacts to the reservoir WSE since the approach velocity where debris contacted the existing jam was low enough that debris created a loose single layer carpet along the surface. Higher flow rates lead to higher initial debris approach velocities and slightly greater impacts to the WSE and discharge due to greater debris jam density. Test results from the 4-10 iterations found the maximum impact to WSE to be about 4.5 feet for a natural jam and a corresponding discharge reduction of 50 percent. Discharge impacts increased as GI values increased, even when the flow transitioned to free-flow conditions under the gates. WSE impacts were found to generally increase as GI values increased, with the exception that the natural jam was observed to have a relatively constant WSE impact for the lower flow rate.

To estimate an upper limit to the impact that debris jams can create at a reservoir, an artificial debris jam was created by manually compacting the natural jam to obtain a worst-case scenario. The compaction attempted to account for any surface disturbances to the reservoir that could create a denser debris jam, such as wind, waves, or WSE fluctuations. For these tests, the maximum impact to the WSE was 8.8 feet and the maximum discharge reduction was 82 percent. For more information on the maximum discharge reductions compared to the average reduction, please see Appendix A.

A flood routing was performed to determine the impacts of changing the debris loading rate with the inflows. For Granby Dam, the 1/1,000 flood event is not predicted to deviate from the conservation pool elevation, and no overtopping was expected. However, due to the changing WSE, surface disturbances and inflow rates, the debris jam formed was more compact than the single flow and gate position test configurations. While the impact is slight, it required increasing the gate opening from 37 percent to 40 percent and indicates that prototype impacts from debris loading are likely between the natural and the artificial jam impacts. However, due to the variability in jam formation, it is uncertain if tests repeated with surface disturbances would produce significantly different results.

The 1/10,000 event flood routing showed that debris can cause both a rise to the WSE from obstruction of the gate open area, as well as the loss of reservoir storage if the debris jam obstructs one of the gates from closing. Both of these are significant impacts either from a risk of overtopping and dam failure, or from the loss of project benefits by loss of storage. Since only one iteration of each of the flood simulations was performed, it is unknown how much variability would be observed if multiple iterations were performed. Information from this study can be used to adjust spillway rating curves during a risk analysis or flood routing to gain a better understanding for an overtopping potential failure mode. Engineering judgement will then be required to categorize the watershed to determine availability of debris in the upstream watershed, a relationship between flow magnitude and ability to transport debris to the reservoir, and its residence time prior to approaching the spillway structure.

Recommendations

In risk analyses prior to the results of this research, the discharge capacity has been reduced with a constant percentile for the full duration of the flood event. From the results herein, that appears to have been an overly conservative approach that has resulted in an overestimation of maximum reservoir WSE, and a potentially increased risk estimate. Dams that have debris plugging concerns and elevated risk due to the previously used method should be re-considered to determine if updated flood routings are needed.

For projects where debris loading is thought to drive the risk decision, an inventory of the woody species in the watershed would be important. Also included in this would be estimates of typical specific gravity, and how quickly the specific gravity changes when the debris is saturated in the reservoir to determine how likely older debris already staged in or along the reservoir shore is to transport to and obstruct spillway gates.

A thorough investigation of debris impacts during the Colorado Front Range flooding of 2013 would be useful to see if the information contained in this report is supported by regional data collected during a period of intense rainfall that produced long duration rainfall totals that exceeded a 1/1000 frequency of occurrence. This data may also be used to determine the relationship of reservoir size and timing of debris impacts.

The original test matrix included two different flow rates designed to represent approximately 50 percent and 80 percent respectively of Granby Dam outflow capacity. There would be value to testing a third flow rate while maintaining the gate index values tested herein to gain further information on how sensitive the debris impacts are to varied flow rates / approach velocities. This study discovered that surface disturbances and gate changes during testing produced a slightly denser debris jam than the previously recorded natural jam tests where a steady flow rate and gate position were used. While a compacted debris jam will produce greater impacts to the WSE and discharge capacity, it is uncertain if there would be statistically significant changes to the results presented for the natural debris jam due to the random nature of jam formation.

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Appendix A: Test Data

Table A- 1 Dowel log without root ball tests. Where H_R is reservoir head, H_G is head at the gate, and G_0 is the calculated gate opening.

Q (cfs)	Dowel Diameter (in)	Gate Avg % Open	H_R (in)	H_G (in)	G_O (in)	H_G -G_O (in)	H_G -G_O (ft)	Drawdown (in)	Height Open (in)	G_O/H_R	# Passed	# Blocked	% Passed
										0.3			0%
4.99	0.75	46.1	10.3	9.0	6.1	2.9	0.2	0.9	6.1	0.59	12	8	60%
7.49	0.75	49.0	16.3	15.5	6.5	9.0	0.7	1.0	6.5	0.40	0	20	0%
7.52	0.75	55.0	14.6	13.8	7.3	6.4	0.5	0.9	7.3	0.50	0	20	0%
7.50	0.75	61.0	13.6	12.2	8.1	4.1	0.3	0.9	8.1	0.60	3	17	15%
5.00	1									0.30	12	8	0%
5.00	1	46.1	10.3	9.0	6.1	2.9	0.2	0.9	6.1	0.60	12	8	60%
7.50	1	49.0	16.3	15.5	6.5	9.0	0.7	1.0	6.5	0.40	1	20	5%
7.51	1	55.1	14.6	13.8	7.4	6.4	0.5	0.9	7.4	0.50	4	16	20%
7.51	1	61.5	13.6	12.2	8.2	4.0	0.3	0.9	8.2	0.60	16	9	64%
4.99	1.25									0.30	18	2	0%
4.99	1.25	46.1	10.3	9.0	6.1	2.9	0.2	0.9	6.1	0.59	18	2	90%
7.49	1.25	49.0	16.3	15.5	6.5	9.0	0.7	1.0	6.5	0.40	0	20	0%
7.51	1.25	55.1	14.6	13.8	7.3	6.4	0.5	0.9	7.3	0.50	8	12	40%
7.50	1.25	61.2	13.6	12.2	8.2	4.0	0.3	0.9	8.2	0.60	18	2	90%

Table A- 2 Dowel log with root ball tests. Where H_R is reservoir head, H_G is head at the gate, and G_0 is the calculated gate opening.

Flow Rate (cfs)	Dowel Diameter	Gate Avg % Open	H_R (in)	G_O (in)	Gate opening index	# Passed	# Blocked	Δ WSE	% Passed
2.50	1" Dowel	28.23	6.32	3.76	0.60	0	20	0.039	0
2.50	1" Dowel	33.13	5.93	4.42	0.75	7	13	0.014	35
5.02	1" Dowel	41.96	10.88	5.59	0.51	0	20	-	0
5.00	1" Dowel	49.61	9.86	6.61	0.67	8	12	-	40
7.50	1" Dowel	61.08	13.44	8.14	0.61	5	15	-	25
7.50	1" Dowel	67.86	12.60	9.05	0.72	8	12	-	40
2.50	3/4" Dowel	24.95	6.79	3.33	0.49	4	16	0.006	20
2.50	3/4" Dowel	31.65	5.98	4.22	0.71	18	2	-	90
5.01	3/4" Dowel	48.87	9.95	6.52	0.65	18	2	-	90
4.97	3/4" Dowel	51.35	9.64	6.85	0.71	20	0	-	100
7.50	3/4" Dowel	65.77	12.84	8.77	0.68	16	4	-	80
7.50	3/4" Dowel	71.80	12.16	9.57	0.79	19	1	-	95

Table A- 3 Cluster of five debris pieces tests. Where H_R is reservoir head and G_0 is the calculated gate opening. The fraction represents the number of logs passed in a given cluster.

Q (cfs)	Avg % Open	H_R (in)	G_O (in)	G_O/H_R	0/5	1/5	2/5	3/5	4/5	5/5	% Passed of total logs	% of the Avg per 5 that pass	Avg # logs passed	% Clusters full pass	% Clusters partial pass	Model Δ WSE (ft)
4.99	**30%**	14.64	4.05	0.28	20	0	0	0	0	0	0%	0.0%	0.00	0%	0%	
5.01	**48%**	10.08	6.37	0.63	4	4	7	3	2	0	35%	7.0%	1.75	0%	80%	
5.00	**36%**	12.20	4.85	0.40	15	4	1	0	0	0	6%	1.2%	0.30	0%	25%	0.02
5.02	**42%**	10.92	5.65	0.52	10	5	3	2	0	0	17%	3.4%	0.85	0%	50%	0.01
5.00	**100%**	9.41	13.33	1.00	0	1	0	1	5	13	89%	17.8%	4.45	65%	100%	0.007
7.50	**61%**	13.56	8.13	0.60	7	6	3	0	3	1	29%	5.8%	1.45	5%	65%	0.03
7.50	**54%**	14.88	7.20	0.48	13	4	2	1	0	0	11%	2.2%	0.55	0%	35%	0.03
7.49	**47%**	17.26	6.21	0.36	17	2	0	1	0	0	5%	1.0%	0.25	0%	15%	
7.50	**49%**	16.28	6.53	0.40	18	2	0	0	0	0	2%	0.4%	0.10	0%	10%	0.01
7.50	**100%**	12.06	13.33	1.00	2	2	2	0	3	11	73%	14.6%	3.65	55%	90%	

Table A- 4 Large debris mat tests at 6,900 cfs.

Gate Opening (%)	Initial mean Head above crest Prototype, (ft)	Final mean Head above crest Prototype (with debris), (ft)	Mean Prototype change in WSE (ft)	Max Prototype change in WSE (ft)	Artificial mean Prototype Head above Crest (ft)	Artificial Mean Prototype WSE Change (ft)	Artificial Jam Mean WSE change, ft (Prototype)	Artificial Jam Min WSE change, ft (Prototype)	Artificial Jam Max WSE change, ft (Prototype)
0.35	20.3	20.0	-0.2	0.2	23.9	3.6	3.6	1.8	6.5
0.39	17.5	17.2	-0.3	0.0	22.6	5.1	5.1	4.0	7.5
0.44	16.3	17.2	0.9	1.8	20.6	4.3	4.3	2.8	6.2
0.47	15.0	16.4	1.5	2.5	19.2	4.3	4.3	3.1	5.5
0.51	14.4	16.3	1.9	2.8	18.8	4.5	4.5	3.0	6.4
0.55	13.8	15.3	1.5	2.1	17.8	3.9	3.9	2.8	5.0
1.00	13.9	15.8	1.9	2.8	18.1	4.1	4.1	2.1	5.6

Table A- 5 Table A- 4 Large debris mat tests at 10,300 cfs.

Gate Opening (%)	Initial mean Head above crest Prototype, (ft)	Final mean Head above crest Prototype (with debris), (ft)	Mean Prototype change in WSE (ft)	Max Prototype change in WSE (ft)	Artificial mean Prototype Head above Crest (ft)	Artificial Mean Prototype WSE Change (ft)	Artificial Jam Mean WSE change, ft (Prototype)	Artificial Jam Min WSE change, ft (Prototype)	Artificial Jam Max WSE change, ft (Prototype)	Artificial Jam WSE change StDev, ft (Prototype)
0.47	26.5	26.8	0.3	1.6	31.4	4.9	4.9	3.1	6.0	0.8
0.53	22.9	23.8	0.9	2.0	27.5	4.6	4.6	2.8	7.6	2.1
0.57	20.7	22.1	1.3	3.9	25.8	5.1	5.1	3.7	7.8	1.3
0.63	19.9	22.6	2.7	3.6	25.8	5.9	5.9	5.4	6.6	0.5
0.68	19.3	22.0	2.7	4.1	25.7	6.5	6.5	4.6	8.7	1.3
0.73	18.2	21.2	3.0	3.7	24.0	5.9	5.9	4.7	8.2	1.5
1.00	18.0	21.1	3.1	4.5	23.4	5.4	5.4	2.8	7.9	1.4

Appendix B: Error Analysis for Theoretical Orifice Flow in Large Debris Mat Testing

In order to accurately analyze the discharge reduction from debris jams, an error analysis was performed. This error analysis compared the expected flow entering the model from the laboratory system to the outflow through the ogee spillway radial gates using the orifice discharge calculation. The theoretical orifice discharge was calculated for each combination of gate opening and water surface elevation used for testing. The orifice equation for discharge (cfs) is as follows:

$$Q = C_d * A * \sqrt{2 * g * h}$$

Where; C_d = coefficient of discharge,
A= area of gate opening,
g = gravitational acceleration,
h = head to center of gate opening.

The coefficient of discharge was selected as a function of the angle formed tangent to the gate lip and tangent to the crest curve at the nearest point. This method is detailed in Design of Small Dams, Chapter 9: Spillways for discharge over gate-controlled ogees (Reclamation 1987). While coefficients of discharge did not vary greatly, there was an overall increase in the coefficient of discharge as the gate opening is increased.

Once the flow regime entered free-flow, GI=1, the weir equation for vertical-faced ogee crests was used. The coefficient of discharge for weir flow varied as a function of the head over the crest, detailed in Design of Small Dams, Chapter 9: Spillways for discharge coefficients for uncontrolled ogee crests. Similar to the orifice flow coefficient, the coefficient of discharge did not vary greatly for free-flow scenarios.

$$Q = C_O L H_O^{\frac{3}{2}}$$

Where; C_O = coefficient of discharge,
L = crest width,
H_O = head to center of gate opening.

After these theoretical flows were calculated for clearwater (no debris) conditions, the expected laboratory values were compared for a percent difference, or variance (Figure B- 1). Negative values mean the orifice equation underestimated the flow coming into the model; positive values mean the orifice equation overestimated flow into the model. For this calculation, there is a strong trend of increasing variance between the expected flow rate and the theoretically calculated flow as GI increases. Furthermore, the higher tested flow rate (10,300 cfs) has a larger variance than the lower flow rate at all orifice flow conditions. All deviations are between -4 and 10 percent, this could be caused by error when setting the gate openings.

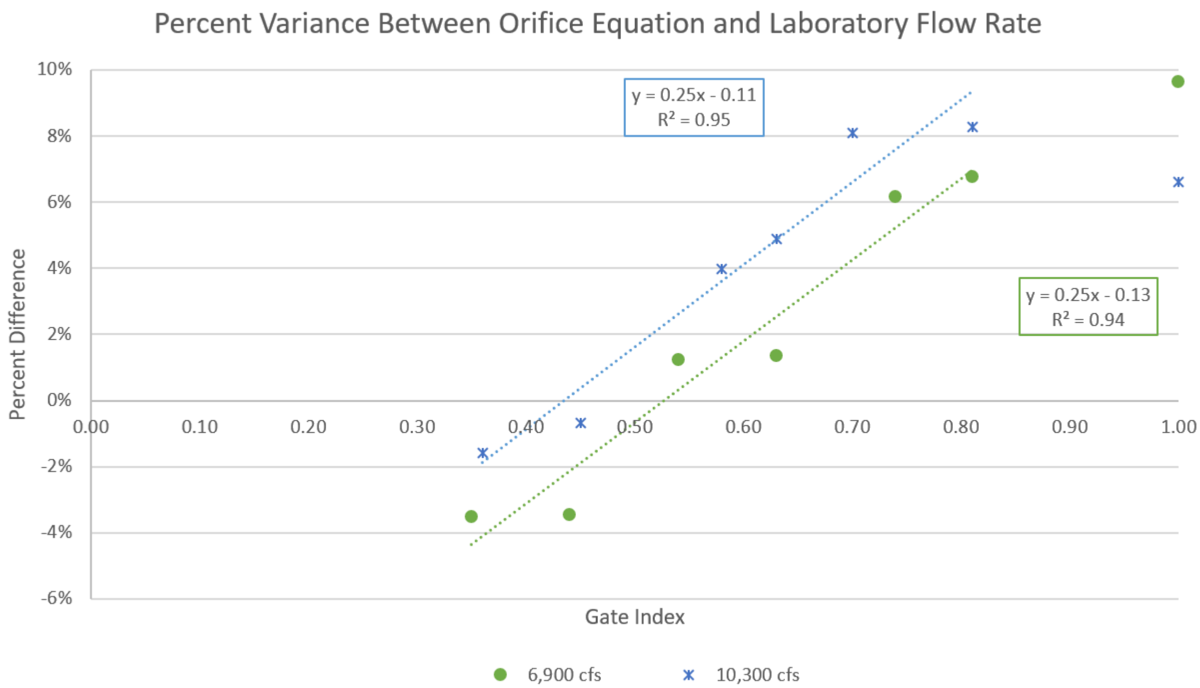

Figure B- 1 Comparison of the expected laboratory flow rate to the calculated discharge through the ogee gates via the orifice equation.

This method was also used to calculate the theoretical orifice discharge when estimating the percent reduction in outflow caused by the debris jams. These were compared to a calculation that utilized an interpolated clear water discharge to estimate the discharge reduction caused by the debris jams. When applied to the mean WSE for each GI with natural and artificial debris jams, the trend between theoretical orifice and theoretical clear water outflow is consistent in that increase to GI has a corresponding increase in discharge reduction (Figure B- 2). Between the two calculation methods, the theoretical orifice had less consistent results and it also tended to overestimate the WSE, resulting in less discharge impacts. For this analysis, the theoretical clear water discharge reduction method was selected to simulate the worst-case scenario and provide a conservative upper limit to discharge impacts.

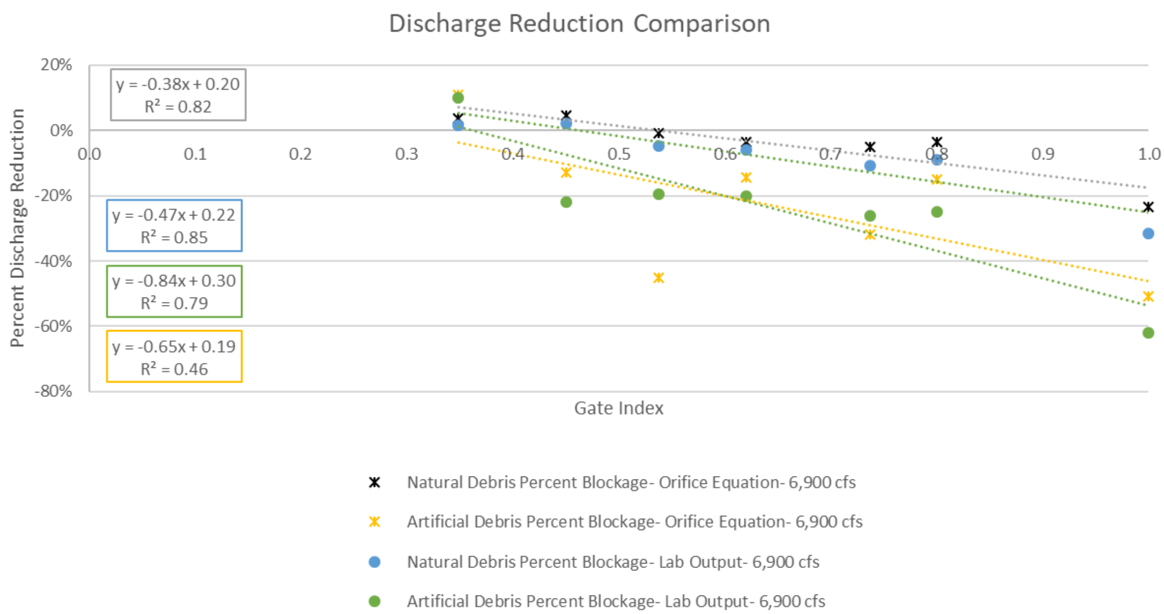

Figure B- 2 Comparison of the discharge reduction between the orifice equation and the laboratory output.