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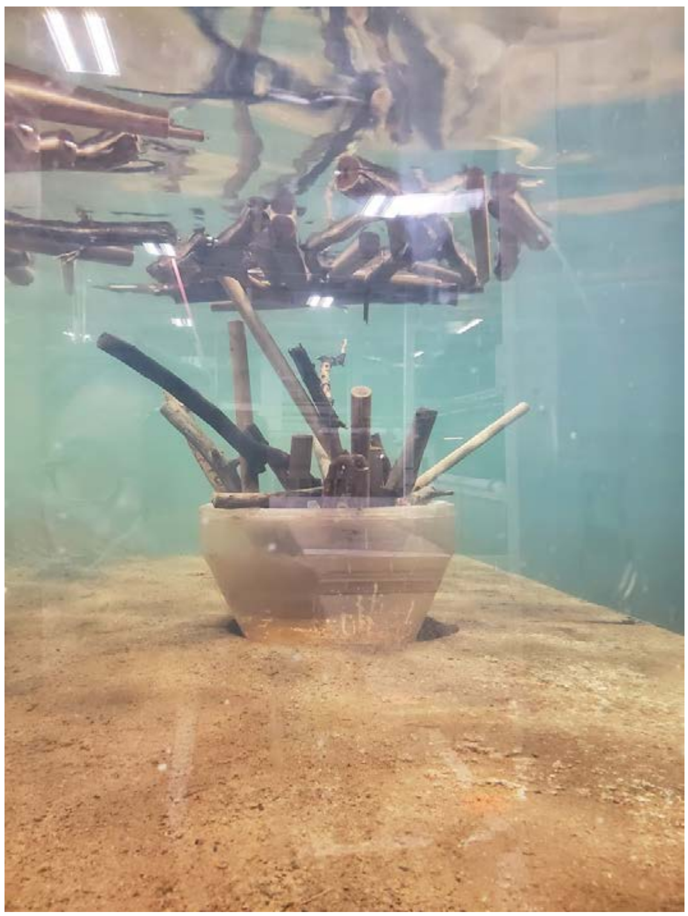
Hydraulic Laboratory Report HL-2020-08

Spillway Debris Physical Model Study

Morning Glory Spillway Structure

Dam Safety Technology Development Program



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14. ABSTRACT Physical hydraulic model tests have been performed on two different configurations of a morning glory spillway (with and without piers) 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. 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. Piers would prevent major blockages from occurring within the morning glory spillway for at least one iteration at every flow rate tested. Without piers, a vortex formed that was able to pass nearly all debris from the reservoir through the transition into the downstream conduit, even if the debris length exceeded the geometric length of the opening. Occasionally, this would cause major jams within the transition and cause the WSE to rise to a level that would exceed the model test capacity. For both configurations, weir flow presented the greatest impacts to discharge, specifically discharge capacity reduction. When in weir flow, debris could restrict the flow up to 60 percent. Once the flow regime progressed to orifice or pipe control, debris impacts were reduced because buoyancy kept the debris pieces at the surface of the reservoir. In addition to the natural jam, the debris was manually compacted to form an artificial cluster as a conservative upper limit to debris impacts. Often, debris clusters were broken apart by the piers or the vortex, depending on which was present. Debris presents a significant risk to morning glory spillways regardless of pier configuration once flows begin passing through the spillway.						
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November 2020

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Cover Photo: Debris clogging the morning glory spillway intake in a physical hydraulic model at the Bureau of Reclamation's Hydraulics Laboratory in Denver, Colorado.

November 2020

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Executive Summary

Physical hydraulic model tests have been performed on two different configurations of a morning glory spillway (with and without piers) 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. 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. Piers would prevent major blockages from occurring within the morning glory spillway for at least one iteration at every flow rate tested. Without piers, a vortex formed that was able to pass nearly all debris from the reservoir through the transition into the downstream conduit, even if the debris length exceeded the upper limit of the spillway geometry. Occasionally, this would cause severe jams within the transition and result in the WSE rising to a level that would exceed the model test capacity. For both configurations, debris impacts were greatest during weir flow, specifically discharge capacity reduction. In this flow control, debris could restrict the discharge by up to 52 percent. Once the flow regime progressed to orifice or pipe control, debris impacts were reduced because buoyancy kept the debris pieces at the surface of the reservoir. Often, debris clusters were broken apart by either the piers or the vortex, depending on which was present. Debris presents a significant risk to morning glory spillways regardless of pier configuration by significantly reducing the discharge capacity, especially when under weir control.

Background

Many recent risk assessments for the Bureau of Reclamation (Reclamation) encountered the issue of reservoir debris and how significantly it will affect the reservoir elevation and discharge capacity during a flood event. Risk analysis consists of developing potential failure modes that define a probable series of events that can be quantitatively estimated and multiplied together to estimate an annual exceedance probability for the defined event or events. The probability of an event occurring is estimated by a team of risk experts with relevant experience in the potential failure mode being evaluated, dam safety, and dam operations. In addition to relevant experience, research from academia and laboratories is sought to help inform the assessment. For potential failure modes that involve reservoir debris and spillway structures, there was limited published research. Notably absent in the literature was any information on the impact to reservoirs created by debris in morning glory spillway structures.

To provide information to support the risk analyses that Reclamation performs, it was decided that a physical model study was justified to look at the impacts of reservoir debris with various types of spillway structures. The results of this paper focus on morning glory spillways with and without piers.

Literature Review

A morning glory spillway is an inverted bell-shape that allows water to enter the spillway from the reservoir surface and exit through a conduit that passes downstream of the dam. After flow passes over the crest of the morning glory, it enters the bell-shaped mouth leading into a transition section that allows the flow to converge and is redirected into the conduit. Morning glory, or drop inlet, type spillways were first used around 1896 (Bradley, 1952). Morning glory spillways are typically used on sites with restricted space or where downstream flow from a reservoir needs to be restricted. Currently, morning glory spillways are less utilized than other forms of flow control due to concern around air demand, flow control, limited discharge capacity, and limited ability to be modified. Furthermore, once debris enters the throat of the control structure, it cannot be removed until the spillway is no longer operating.

Design of Small Dams (Reclamation, 1987) describes typical operation of a morning glory spillway and outlines the three flow regimes that these spillways can operate in. Weir flow occurs for small heads where the spillway is governed by the characteristics of crest discharge. Weir control is the most efficient flow regime of passing flow per unit of head on top of the crest. Orifice flow, or throat control, occurs when the spillway becomes submerged and control shifts from weir flow to pipe flow. During orifice flow, the pipe is not flowing full. In the testing of this model, orifice control tends to be brief, extending only over a 100-200 ft^3/s range. At higher heads, pipe flow occurs where the spillway is fully submerged, and the pipe flows full (Figure 1).

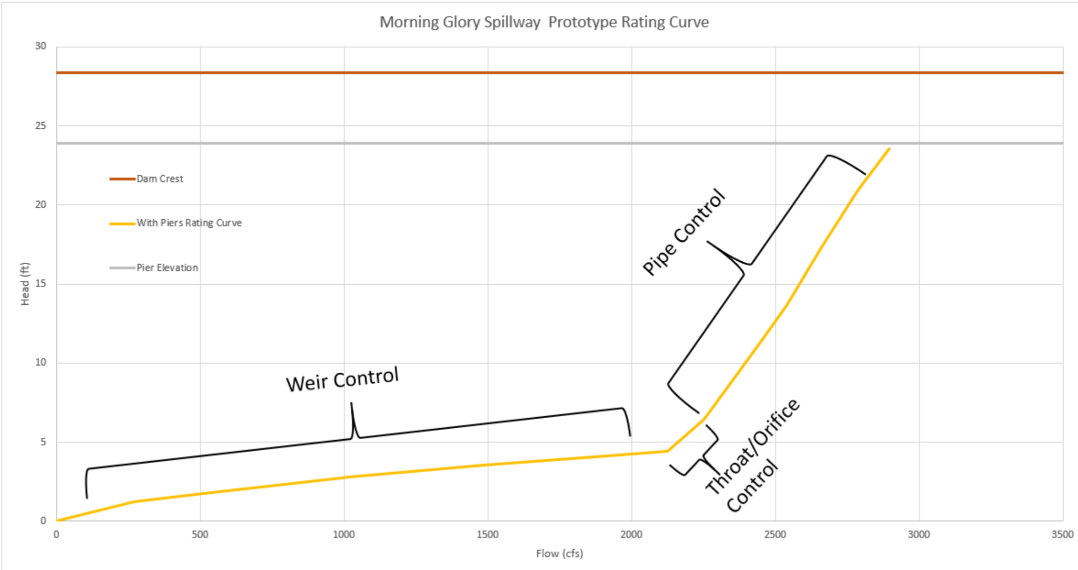

Figure 1 Flow regimes for a rating curve.

Piers can be utilized as vortex breakers in order to maximize the coefficient of discharge for morning glory spillways (Figure 2). To understand the best configuration for utilizing piers, Musavi-Jahromi, et al. tested 17 configurations by varying the number of vortex-breakers and the angle of the blade while in pipe control. The most efficient configuration was found to be six piers at an angle of 45°, increasing the discharge coefficient by approximately 545 percent. Furthermore, piers slightly increase the flow at which the transition from weir to orifice occurs, thereby shifting the transition to orifice flow to a later point along a rating curve. Generalized studies like Musavi-Jahromi can be used in ideal circumstances but in most cases bulk circulation of the approach flow can lead to vorticity and a physical model study is recommended to select the optimal pier configuration (Hydraulic Laboratory Techniques, 1980).

Figure 2 Profile view of morning glory spillway, with piers (left) and without piers (right).

Additional literature concerning the relationship between debris loading and water surface elevation (WSE) can be found in the report "Spillway Debris Physical Model Study – Ogee Crest Spillway with Two Radial Gates" that investigated debris clogging with various openings of a radial gated ogee crest spillway (Walker, 2018). To test clogging caused by woody debris, debris pieces of various sizes were introduced to the ogee crest spillway at varying flow rates. According to this study, the woody debris caused a maximum discharge reduction of 36 percent with a WSE increase of 4.5 feet prototype for jams that formed under natural processes. To provide an estimate of the upper range of debris jam impacts, debris pieces were manually compacted to create a very dense jam. Artificial debris jams were found to have up to a 9-foot change in WSE and a discharge reduction of 62 percent.

Physical Model

Reclamation has constructed twenty-five drop inlet or morning glory type spillways. The design and configuration of these structures varies, but some dams have more restrictive spillway designs and are in locations with potential for a significant amount of debris to enter the reservoir. These spillways had a similar geometry with a crest diameter of approximately 20-25 feet.

The physical hydraulic model was based on Reclamation's Foss Dam, located on the Washita River in Oklahoma. This dam was deemed as a suitable example of a morning glory spillway geometry with a partly wooded drainage area that is subject to a medium likelihood of clogging. Foss Dam has six piers on the morning glory spillway, similar to the recommended number of the vortex-breakers utilized in other studies. After testing was completed with spillway piers, the hydraulic model was reconfigured to remove the piers from the design.

Impacts to reservoir WSE and spillway discharge capacity were investigated using a 1:18 scale physical model at Reclamation's Hydraulics Laboratory in Denver, Colorado. Comparable results between model and prototype data is achieved when the ratios of the major forces controlling hydraulic processes are kept equal in the model and prototype (Hydraulic Laboratory Techniques, 1980). 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 limitation in model similitude was the flexibility of some of the natural debris pieces which would not match prototype debris. This was apparent with the slimmest 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 similar to a prototype tree.

The Froude number is defined as:

$$Fr = \frac{v}{\sqrt{gd}} \quad \text{(Eqn. 1)}$$

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 scale Froude model was designed as a 20-ft-wide by 20-ft-long model box with a rock baffle to distribute the incoming flow from the laboratory pump system. This created a reservoir with prototype dimensions of 360 feet wide by 300 feet long upstream of a morning glory spillway towards the left of the box with an overflow weir structure located near the center of one wall of the model further downstream (Figure 3). The reservoir was also designed with an "emergency spillway" that controlled model outflow should the reservoir exceed the dam crest elevation. If a test exceeded the crest elevation due to a severe debris jam, the WSE was recorded. However, these points were removed from average flow calculations since the morning glory was unable to pass all flow and therefore never achieved an equilibrium WSE. Furthermore, as the reservoir contained in the box structure does not encompass the entire reservoir at Foss, it is assumed that this box is representative of the area immediately surrounding the morning glory. More details on the model design and construction can be found in Walker, 2018.

After the completion of the ogee spillway tests, an air bubbler was installed in the model reservoir to create surface disturbances. This was installed for two reasons: the flat reservoir surface of the model was thought to be unrealistic for a prototype reservoir that is experiencing flooding significant enough to produce debris loads and the observation that surface disturbances lead to a more dense jam formation. The manually compacted artificial jams were tested to record impacts from jams with greater densities in the 2018 study.

The morning glory had a model crest diameter of 24.33 feet prototype, with six piers of 23.9 feet tall (Figure 2). The crest then transitioned from vertical to a nearly horizontal conduit with a 9.5 foot prototype diameter. Due to model scaling and the availability of custom inside diameter pipes, the discharge conduit was reduced to 9.0 feet prototype using standard PVC sizes at 54 feet downstream of the transition to horizontal standard PVC sizes. The reduced pipe diameter results in impacts to the rating curve once it has transitioned into pipe control.

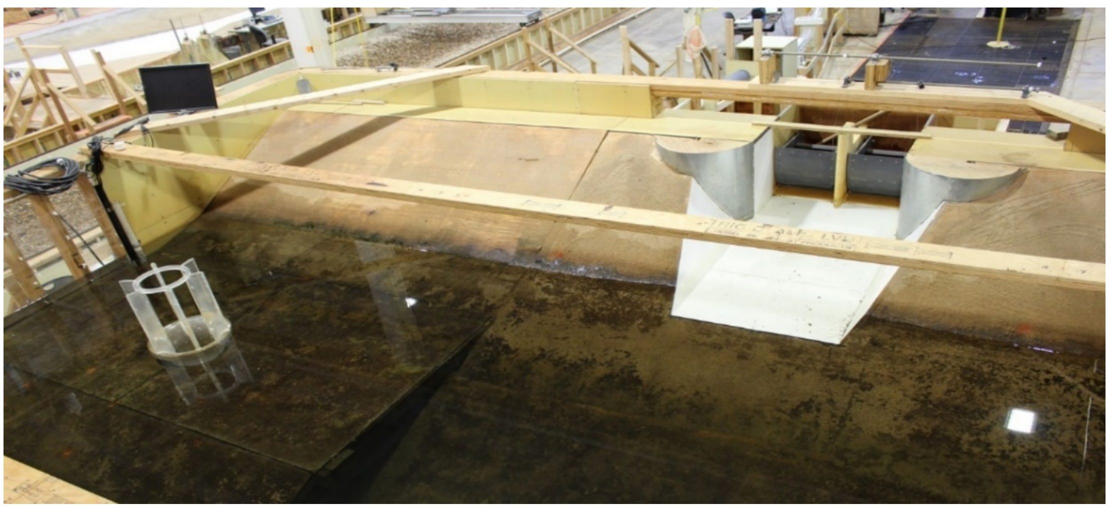

Figure 3 Photograph of the 1:18 Froude scale physical model morning glory spillway (left) with the radial gated ogee crest overflow weir structure (right) from the previous model study (Walker 2018).

Debris

Debris observed in reservoirs is variable and can include naturally occurring wood species as well as docks, boats, and debris from other anthropogenic structures. Variables for woody debris can include, but are not limited to: flux, density, species, length, diameter, and branch complexity. To represent the range of expected flood debris in the physical model, pieces used for modeling included sapling conifer trees, natural sticks, and dowel rods. Natural debris were collected locally to include both deciduous and coniferous species and was sized to best match what would be found in the reservoir surrounding Foss Dam.

The range in prototype lengths of debris was 10 to 35 feet while diameters ranged from 9 inches to 3 feet. For the purpose of this study, debris was simplified to not include root-balls or other branches and shorted to exclude pieces too long to pass through the morning glory transition portion of the spillway. This was to illustrate the recruitment potential of additional debris once a jam has formed.

This will result in jams that are less likely to form due to lower debris complexity, but jams that have greater density due to a more regular cylindrical shape of the pieces. This was also performed to determine how likely smaller pieces of debris are to pass if a jam has already formed. For example, debris that is too long to pass through the transition of the morning glory pipe would logically always form a clog in that location. Subsequently, root-balls and pieces with lots of branches would significantly increase the likelihood of cluster formation and not demonstrate the impact of individual pieces of debris studied in the Individual Log Testing. The impacts of clusters specifically were noted in the Cluster Testing.

Approximately 300 assorted debris samples were utilized per test. Figure 4 shows a random selection of debris material and sizes. During testing, debris was pre-soaked for some trials to decrease buoyancy. Upon comparing iterations, pre-soaking debris did not appear to impact the location of jams.

Figure 4 Photograph of assorted debris pieces with natural wood (left) and dowel rods (right).

While any length of debris has the potential to form a jam, a morning glory spillway has an upper limit that debris longer than the maximum length calculated by the transition geometry will not be able to pass. Any debris that exceeds this length will become jammed and recruit other pieces. During a risk assessment, an inventory of the watershed can determine if logs are long enough to jam with the geometry of the existing morning glory. Therefore, to ensure the creation of a jam for every iteration of the testing, a “primary log” was utilized. The primary log was selected to be a straight piece of dowel rod and was used to show how jams can recruit and build after a single featureless piece of debris obstructs the passage of water (Figure 5). All pieces of debris other than the primary log were smaller in length and would clear the morning glory spillway if introduced individually. The initial primary log was a dowel rod with dimensions of 33 feet long by 6 inches diameter prototype. This was used for testing with and without piers during individual log and simulated flood routing tests. However, during testing without piers, a vortex formed during pipe control flow. Discussed in greater detail later, this vortex was able to pull debris through the transition of the pipe that would exceed the critical dimension of the pipe, specifically bending and eventually snapping the primary log. To maintain test similarity for tests with and without piers, the primary log size was increased to 33 feet long by 9.5 inches diameter prototype. During the first test with this dowel, the vortex snapped the primary log. Testing continued to the extent possible with a new 9.5-inch-prototype diameter dowel and was replaced every time the vortex was able to remove it.

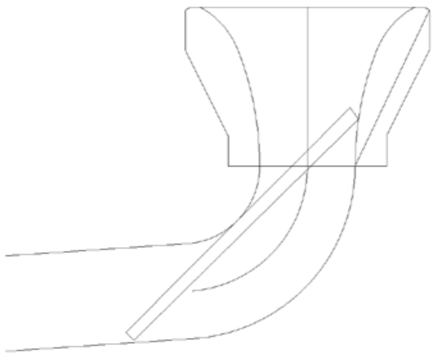

Figure 5 Schematic of primary log clogging the transition.

Methods

Three debris tests were conducted with the morning glory spillway both with and without piers to determine properties of debris passage: individual log testing, log clusters, and flood routing hydrographs (Table 1).

Individual log testing utilized a given flow rate and adhered to the following procedure: 1) wait for the clearwater to stabilize, 2) insert a primary log in the transition of the morning glory spillway, 3) subject the model to all single pieces of woody debris randomly dispersed, 4) record where the original jam formed, and 5) record WSE and other parameters after the WSE stabilized with the clog. After the introduction of debris into the model, clogs in the morning glory spillway were grouped into four primary categories: crest, mouth, transition, or a combination. Figure 6 exhibits how these jams can potentially obstruct flow, causing an increase in WSE. Tests at a given flow rate were repeated approximately ten times or until it became apparent that clogs were occurring at only one location in the morning glory (e.g. crest clogs for orifice flow conditions) for tests with piers; tests were repeated five times for the without piers configuration (Table 1).

Figure 6 Photographs of debris jamming in crest (left), mouth (center), and transition (right).

Cluster tests entailed utilizing pre-formed clusters at different flow rates to test if jams would behave the same as single logs at the same flow rate. Debris was introduced as pre-formed clusters of 4-5 logs representing a combination of natural pieces and dowels, without the use of the primary log. These pre-constructed jams are capable of creating a jam without the need for initiating a jam with a primary log. Two types of testing were conducting utilizing clusters. The first method involved a "rapid" set of testing which introduced clusters and removing them as soon as a jam formed before the WSE stabilized. This test was devised to establish the frequency with which the jams would occur at the piers (when applicable), crest, mouth, transition, or a combination of the three locations and was utilized for both with and without pier configurations. The second method was only conducted on the with piers configuration. Here, a pre-formed cluster was introduced into the model and allowed to stabilize to ascertain the final change in WSE. Due to nearly all cluster jams occurring in the same location of the morning glory spillway, this method was not continued for testing without piers.

Simulated flood routing followed the results of the 2005 Foss Dam Frequency Flood Routing Study (Technical Memorandum, 2005). However, instead of simulating a specific storm event (i.e. the 100-year storm hydrograph), a modified hydrograph was used to optimize the potential for a jam to form under weir conditions, then shift to higher WSEs under pipe control and return back to weir flow. This storm condition aimed to determine how the shift in flow control changes the debris jam. As was observed in the Individual Logs and Cluster Testing, debris does not have a large impact after the morning glory spillway is fully submerged in pipe flow. Therefore, the hydrograph was shortened to optimize impacts of debris.

During testing, the flow rate was raised and then lowered in increments of ten minutes model or approximately 45 minutes prototype. After the first interval, the primary 6-inch-prototype diameter dowel was introduced, following a similar procedure to the individual log testing. At each new interval, a percentage of debris was introduced to reflect the natural loading of debris in a typical storm with more debris being introduced as the flow rate increases. A limitation of simulated flood routing in the model is the inability to accurately represent a delayed reservoir response time that would be seen in prototype situations, as the model area is not scaled to include the whole reservoir of Foss Dam. For the table of flow rates and the time these increments were implemented, see Appendices I and II.

Table 1. Spillway debris test matrix. Tested flow rates were selected to represent all three flow regimes (Figure 1). For more information on hydrograph test matrix, please see Appendices I and II.

		Flow Rates (ft^3/s)	Iterations
Individual Log Tests	*With Piers*	500 to 2,500	10
	Without Piers	500 to 2,900	5
Cluster of 4-5 logs	*With Piers*	500 to 2,500	10
	Without Piers	500 to 2,900	5

Woody debris was dropped into the model reservoir from a walkway directly upstream of the morning glory spillway to ensure random orientation of the debris in a location where the reservoir surface velocities were low. Hydraulic data collection was automated and performed on a one second interval for WSE utilizing a Massa M-5000 ultrasonic water level sensor in a stilling well. Other hydraulic data was collected after the WSE stabilized both with and without debris and included the location of the jam (e.g. piers, crest, mouth, transition, combination), flow rate, and any other relevant observations.

Clearwater (debris-free water) testing was conducted to create a rating curve for the model both with and without piers. In Figure 7, these rating curves are compared to the theoretical curve initially derived for Foss Dam in 1959. The model rating curve with piers trended with the theoretically derived rating curve during weir flow. Pipe flow occurred sooner in the physical model due to the conduit scaling and behaved in accordance with a typical morning glory spillway with a brief transition from orifice control to pipe control (Figure 7). The piers were then removed and the rating curve was recorded again.

After the piers were removed, a comparison of rating curves was made between the model with the air vent closed and opened. The opening for the air vent for Foss Dam, along with many morning glory spillways that utilize piers, is at the same elevation as the top of the piers. The air vent supplies air near the top of the transition from vertical to horizontal, to allow atmospheric pressure to be maintained in the conduit. However, in Reclamation's inventory of morning glory spillways those without piers generally either do not have air vents or have air vents at a low elevation where they can become submerged. Therefore, to best reflect prototype situations, the air vent was closed. Upon comparison of the two curves, the rating curve with a closed air vent was found to remain in weir flow for a longer period of time than the open air vent. As weir flow presents the highest risk to debris clogging, this further supported the decision by the modeling team to close the air vent for debris tests without piers.

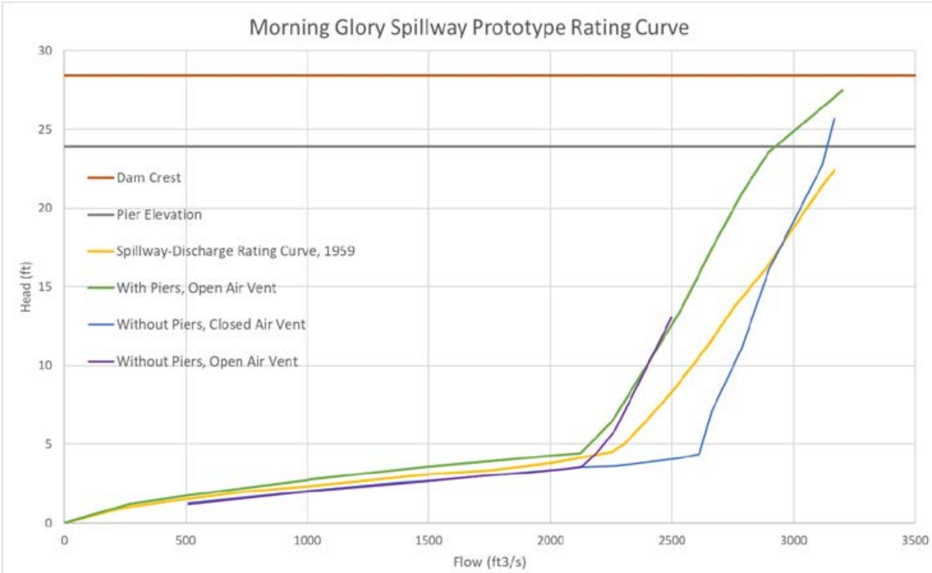

Figure 7 Clearwater morning glory spillway rating curves with and without piers compared to the theoretical rating curve originally calculated for Foss Dam.

Results

Individual Log Testing

With Piers

The impacts to discharge capacity from individual pieces of debris were related to the flow regime the morning glory spillway was operating in. The transition from weir flow to orifice flow begins at approximately 2100 ft^3/s, with the full transition to pipe flow completing at 2250 ft^3/s. During weir flow, discharge capacity was reduced by between 13 and 52 percent, with the greatest impacts observed upon initiation of flow through the spillway (Figure 8). While the debris did reduce the flow through the spillway, a majority of the impact is due to how the discharge reduction is calculated. Weir flow, especially at low head values, is very efficient and therefore a slight change in the reservoir WSE would result in a large discharge reduction. When operating in pipe flow, the debris' natural buoyancy tended to prevent it from entering the morning glory spillway. This created a near zero percent impact to the reservoir WSE and therefore discharge capacity (Figure 9).

Since the model inflows were held constant during the test, the resulting increased WSE post-jam can be used to interpolate what the clear water 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.

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:

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

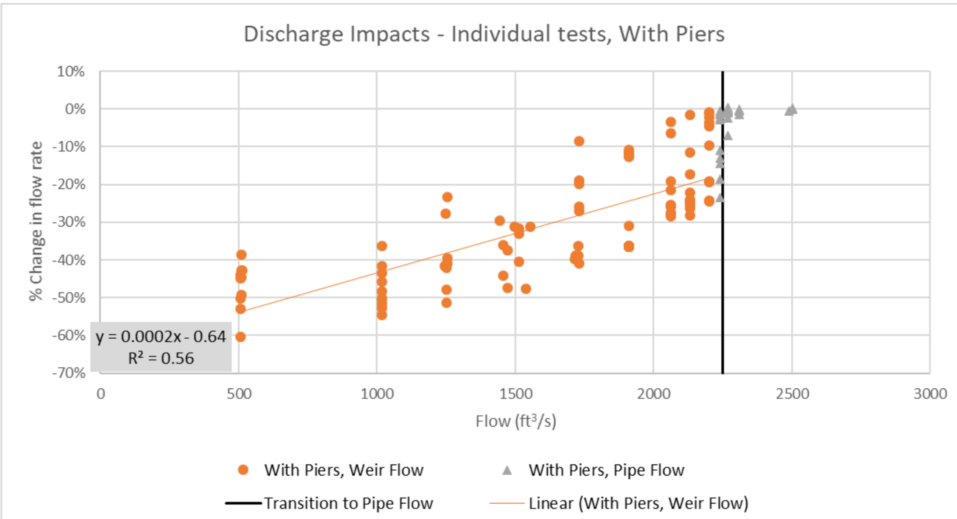

Figure 8 Percent change in flow rate for all test iterations with piers. Gray triangular points represent test flow rates in pipe flow.

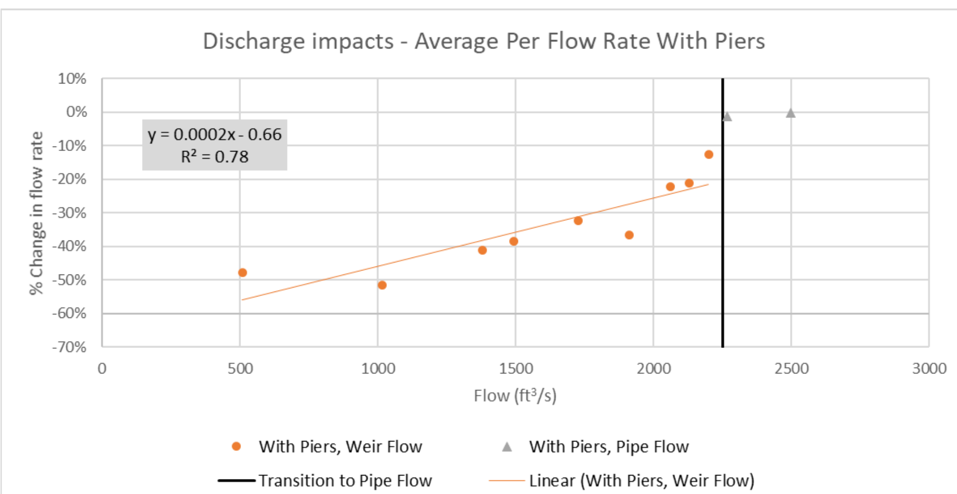

Figure 9 Average percent change in discharge over each flow rate with piers. Gray triangular points represent test flow rates in pipe flow.

Transitions from weir flow into orifice flow yielded the largest impact to WSE for the with piers testing (Figure 10). Since the transition period occurred over a small increase in discharge, flows near this level would oscillate between weir flow and orifice flow through the spillway. Therefore, while debris was observed to pass beyond the piers it was contained in the area above the entrance on the boil of water created by the submerged weir condtion. Debris bouyancy kept the pieces at the surface and prevented them from entering the spillway during this transitional period and throughout all tests that were completely in pipe flow.

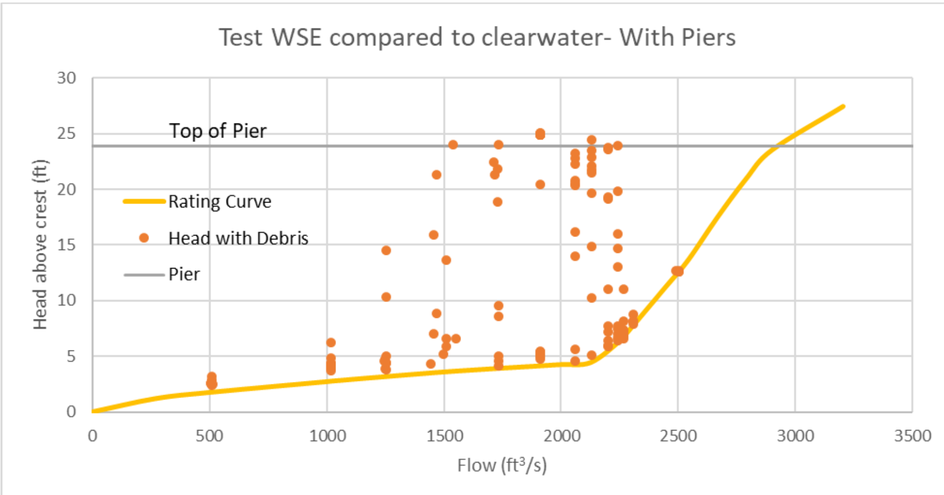

Figure 10 Water surface elevations (WSE) for individual tests with piers.

The timing of jams depended largely on the initial location of the jam. Jams that began in the piers would shift towards the transition as the test progressed. However, these would be less impactful to the reservoir WSE because usually one or two debris pieces would pass through to the mouth than debris jams that began in the transition of the pipe and obstructed a larger portion of the conduit. Transition or mouth jams that occurred at the beginning of a trial would often have multiple pieces lodge into the transition simultaneously, causing a large impact to WSE almost immediately. These jams would often stay in the same location throughout the duration of the test.

Crest jams that form past the piers occurred at all flow rates and was nearly the exclusive location of jams once the morning glory spillway entered orifice flow (Table 2). In weir flow, the contraction of the streamlines (and resultant acceleration of flow) around the piers was found to pull many jams apart, resulting in many pieces entering the spillway individually even if they came from a cluster in the reservoir. This yielded a higher probability of forming a jam in the mouth or transition of the spillway. After the transition into pipe flow, nearly all debris remained buoyant and would not enter the morning glory, instead remaining in the piers above.

Table 2 Location of jams for individual log testing with piers. A combination jam was counted when there were jams at two or more of the reported locations for a given test. Please note, less iterations were run at flow rates greater than 2300 ft3/s due to the negligible impact of debris on WSE.

Flow Rate (ft^3/s)	Crest or Piers	Mouth	Transition	Combination
500	2	5	3	0
1020	4	0	6	0
1250	2	5	2	1
1510	2	6	0	3
1730	5	1	2	2
1910	3	2	2	3
2060	2	3	3	2
2130	3	5	2	0
2200	4	4	0	2
2240	7	0	0	3
2270	7	0	2	1
2300	5	0	0	0
2500	4	0	0	0
Total	50	32	22	17

Without Piers

Impacts to the discharge capacity for crest structures without piers were larger than the configuration with piers during weir flow and had the largest range of potential impacts in pipe flow. Without the piers there was nothing to potentially prevent larger pieces of debris from entering the mouth of the morning glory. Thus, more debris was able to enter the mouth and transition since no pieces were captured by the piers which caused a 45-54 percent reduction to discharge at these locations. Discharge reduction was calculated using the theoretical clearwater discharge method for Equations 2 and 3.

After the transition from weir to pipe flow began at approximately 2400 ft^3/s, a vortex formed (Figure 11 and Figure 12). When the vortex was present, there was such significant down-pull that all utilized pieces of debris including those larger than the critical length (up to 3 feet in diameter and 35 feet in length) were able to pass through the transition of the morning glory spillway due to the force of the water bending the dowel rod. This included the primary log, which theoretically exceeded the maximum length that could pass through the transition of the morning glory spillway. Therefore, with the presence of the vortex, the primary log was able to pass through the transition by bending. To minimize the impacts of bending, the diameter was increased from 6 inch to 9.5 inch and the length was increased by an additional 3 feet. However, the larger primary log was still observed to pass through the spillway by snapping due to the force of the water. During these tests where all debris passed without forming a jam, impacts to discharge were between a 5-29 percent reduction due to the vortex formation (Figure 14).

The formation of the vortex created an unstable reservoir that had fluctuations of up to 0.5 feet model for a single tested flow rate. This continued to progress as flow increased until the clearwater WSE would never properly stabilize (Figure 13). The unstable WSE is due to changes in vortex size, where higher WSE created a smaller vortex which would rapidly lower the WSE to a point where the vortex increased in size. The WSE would then cycle back up to a higher WSE and repeat. Furthermore, WSE would also vary based on the hysteresis within the model. Hysteresis is the natural variation in WSE that can occur as a result of whether the water is ascending or descending. Since the flow would never fully stabilize, repeatability of tests in this zone was difficult. Therefore, testing in this area was disregarded and is represented as hatching on Figures 14 through 16.

Figure 11 Vortex above morning glory spillway when piers are not present.

Figure 12 Vortex in morning glory spillway from side-view.

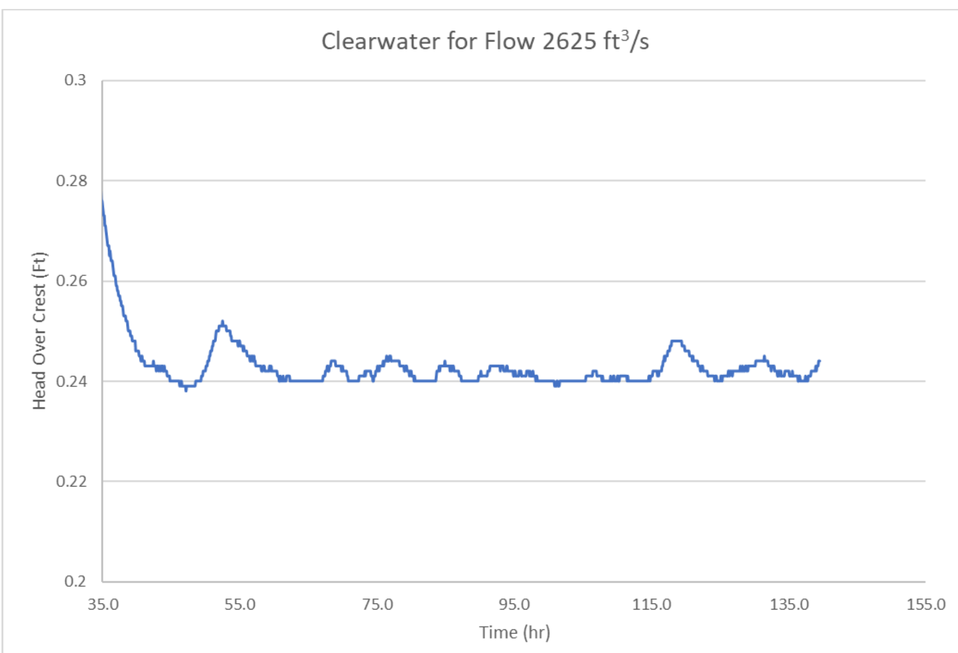

Figure 13 Clearwater (without debris) plot for flow rate where vortex creates a fluctuating water surface. The instability is accentuated due to the relatively small volume of water in the model reservoir. Vertical fluctuation may occur in the prototype but would have a significantly longer cycle time due to the reservoir volume.

In several iterations for flow rates with the vortex, the vortex pulled down multiple pieces of debris at the same time, causing a jam to form in the transition of the pipe. Those jams, including combination jams with a portion of the jam in the transition, would cause a significant reduction to the discharge capacity and would ultimately result in flows passing over the model emergency spillway. The percent discharge reduction cannot be estimated since the test never reached an equilibrium WSE with flows through the morning glory. Therefore, even though these points are still shown on the figures, the anticipated impact to flow reduction would be considerably larger. These two scenarios, where all debris passes or where debris jammed necessitating the emergency spillway created a divide in the discharge impacts for a given flow rate where impacts could range from 0-40 percent for a given flow rate (Figure 11). However, on average, these impacts to discharge created two separate linear curves, weir flow and pipe flow, where the greatest impact to flow rate was observed at lower flow rates (Figure 12).

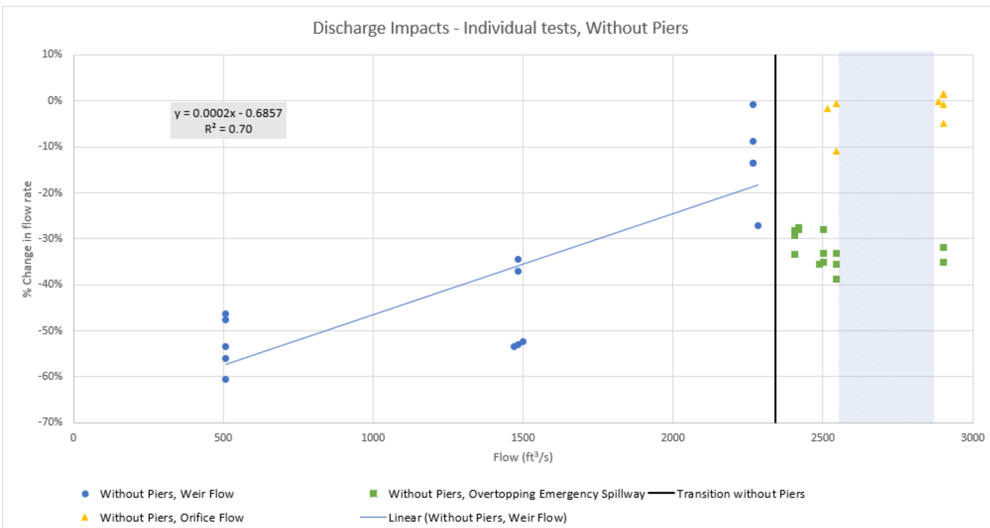

Figure 14 Percent change in flow rate for all test iterations without piers. Green square points represent iterations that overtopped the emergency spillway in the model and were not included in the data for the trendline equation. Therefore, while WSE and impacts to discharge capacity were calculated, these were based on WSE that was influenced by an auxiliary spillway. The hatched area represents unstable flow for the without piers condition due to the presence of a vortex (Figure 14 and Figure 15).

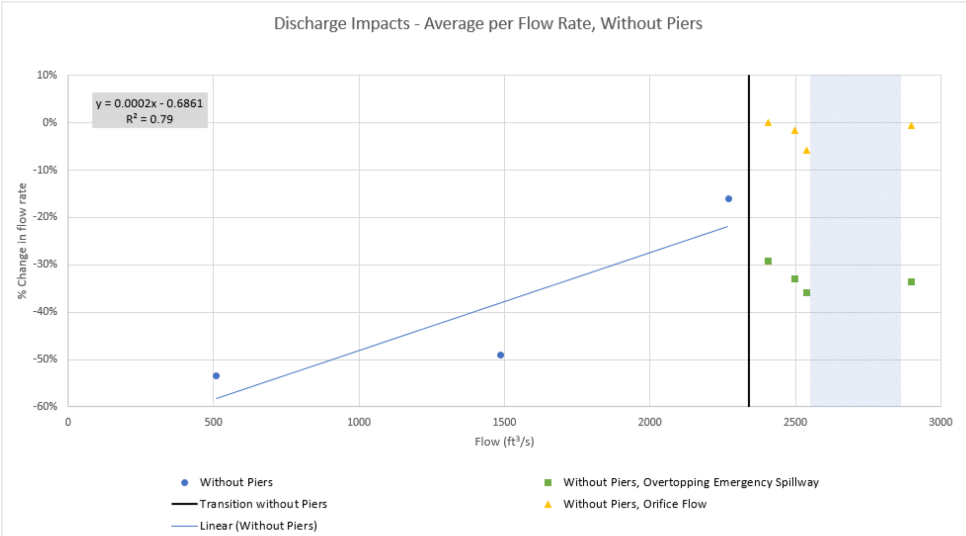

Figure 15 Average percent change in discharge over each flow rate without piers. Green square points represent iterations that overtopped the emergency spillway in the model. Therefore, while WSE and impacts to discharge capacity were calculated, these were based on WSE that was influenced by an auxiliary spillway. The hatched area represents unstable flow for the without piers condition due to the presence of a vortex (Figure 14 and Figure 15).

While some jams in weir flow did increase the WSE significantly, none of these iterations actually activated the emergency spillway. However, nearly every jam that was able to form in pipe or orifice flow did result in the emergency spillway being utilized (Figure 16). This was due to the jams being combination jams, successfully obstructing the mouth and transition of the pipe during these iterations (Table 3). Location of jams were also subject to the presence of the vortex. Due to the efficiency of streamlines in pulling debris into the mouth of the morning glory spillway and without piers to block the larger pieces from entering the spillway, the majority of jams in the weir flow regime were within the mouth or transition of the pipe. Once the vortex formed however, either the debris was simultaneously pulled into the morning glory, causing jams to build into every section of the spillway, or no jam occurred because all debris was forced through the pipe.

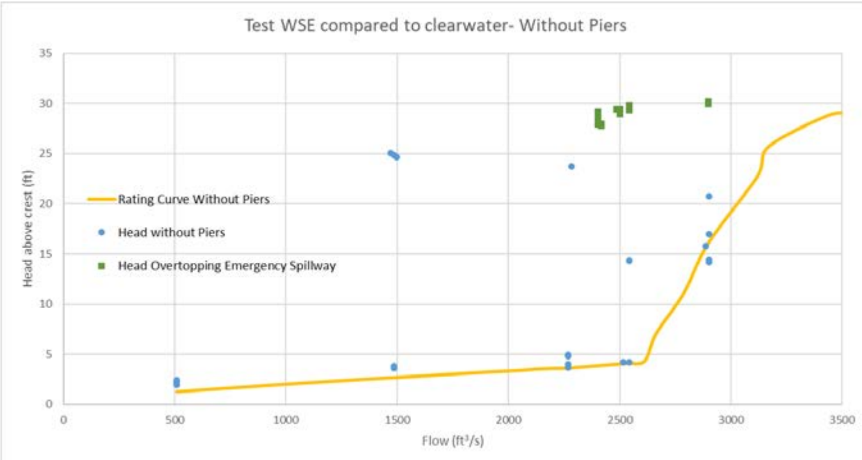

Figure 16 Water surface elevations (WSE) for individual tests without piers. Green square points represent iterations that overtopped the emergency spillway in the model. Therefore, while WSE and impacts to discharge capacity were calculated, these were based on WSE that was influenced by an auxiliary spillway.

Table 3 Location of jams for individual log testing without piers.

Flow Rate (ft^3/s)	Crest	Mouth	Transition	Combination	No Jam
500	0	1	2	2	0
1500	0	2	3	0	0
2300	1	0	2	2	0
2400	0	0	0	5	0
2500	0	0	1	4	0
2550	0	0	4	1	0
2900	2	0	1	0	4
Total	3	3	13	14	4

The timing of debris impacts depended largely on the vortex. When the vortex was operating with its largest air core, occupying nearly 40 percent of the diameter of the transition, the vortex was very efficient at removing all debris and clusters. The down-pull of the vortex would remove even the largest pieces of debris (35 foot length and 3 foot diameter, prototype), occasionally shattering thinner pieces in the process. When the vortex was not fully formed for the initial introduction of debris pieces, the debris could form a buoyant mat floating on top of the water. This would delay the formation of a jam within the morning glory. However, as time progressed the vortex would eventually form and begin pulling debris into the morning glory. This process created the worst jams by bringing in a larger pulse of debris at one time than would normally occur in pipe or weir flow. Jams in weir flow tended to have debris enter the morning glory gradually. During the pulsing caused by the vortex, approximately 10-20 pieces of debris would enter the morning glory at once and compact to form a dense jam that cannot be formed piecemeal by single piece additions. These jams pose a unique and dangerous threat to operations.

Log Cluster Testing

With Piers

For the with piers configuration, two sets of tests were utilized. In the first test, a pre-formed cluster was introduced into the model and the water level was allowed to stabilize to ascertain the final change in WSE. Out of the flow rates tested, only two clusters were not broken apart by the piers out of the 20 iterations performed at the varied flow rates to form jams in the mouth or transition (Table 4). While infrequent, when the pre-formed clusters passed the piers intact, flow was greatly obstructed in the transition of the pipe and WSE would rise rapidly. For the two tests that did cause transition jams, one activated the emergency spillway and the other raised the WSE almost 17 feet.

Table 4 Average change in WSE for cluster tests with piers. Red font denotes transition jams, black font denotes jams that remained in piers.

Flow Rate (ft^3/s) (1)	Average Change in WSE (ft) (2)
500	0.94
1020	1.64
1370	Emergency Spillway Activated
1510	1.91
1730	1.91
1910	2.07
2060	2.14
2130	1.33
2200	16.94

The second "rapid" test was devised to establish the frequency with which the jams would occur at the different locations of the morning glory spillway (Table 5) and the test was not run long enough for the water surface to stabilize. As observed in the previous pre-formed cluster test, jams were most likely to form around the piers. However, for the test where the WSE stabilized and for the "rapid test" both had an elbow jam at 1370 ft^3/s, the only flow rate to do so. This flow rate was in weir flow, which typically had a higher chance of forming elbow or mouth jams. Therefore, weir flow also poses the highest risk for cluster testing. Furthermore, in both tests, the piers prevented large clusters from entering the spillway in two ways. Predominantly, piers broke apart the clusters on impact, allowing individual pieces of debris to pass through the mouth and transition without getting lodged. Secondly, the piers restrained the larger clusters from entering the spillway. In pre-formed clusters, risk of major changes to WSE is relatively low unless individual pieces of debris that break off from the cluster wedged within the transition of the pipe.

Table 5 Frequency with which jams would occur at a certain location for twenty "rapid" tests at a given flow rate.

Flow Rate (ft^3/s) (1)	Number of Jams in the Crest (2)	Number of Jams in the Mouth (3)	Number of Jams in the Transition (4)
1020	20	0	0
1374	19	0	1
1910	20	0	0
2130	20	0	0
2200	20	0	0

Without Piers

During the testing for the without piers configuration, only the "rapid" cluster tests were performed. For the first few flow rates, the head over the crest was too low for clusters to pass over the crest of the spillway (Table 6). Clusters would generally become stuck on to the lip of the morning glory crest, occasionally spilling into the transition to form jams in the transition. This pattern was repeated until the emergence of the fully formed vortex. As the vortex caused the water surface to oscillate, the relative success of the cluster causing a jam depended largely on the strength of the vortex. When the vortex caused the spillway to shift into orifice flow, resulting in air occupying a significant portion of the transition of the pipe, the vortex would either break apart the cluster or pull down and pass the whole cluster, both resulted in no jam forming (Figure 17). Once control shifted into full pipe flow with a weaker vortex, clusters were able to form jams in the transition of the pipe as there was not enough down-pull to break apart the cluster. The location of a cluster jam depended largely on the strength of the vortex.

Figure 17 Cluster lodged onto the crest of the morning glory spillway without piers.

Table 6 Frequency with which jams would occur at a certain location for ten rapid tests at a given flow rate. Cluster success depends largely on vortex, if vortex can pull larger clusters then will probably jam in elbow. Otherwise, will break apart clusters in momentum and pass individual pieces.

Flow Rate (ft^3/s) (1)	Number of Jams in the Crest (2)	Number of Jams in the Mouth (3)	Number of Jams in the Transition (4)	Jam did not occur (5)
509	5	0	0	
1485	4	0	1	
2268	2	1	2	
2406	3	1	1	
2502	3	2	0	
2557	1	4	0	
2639	4	0	1	
2900	0	1	2	2

Simulated Flood Routing

With Piers

For the with piers configuration, two iterations of the simulated flood routing were conducted. During the first iteration, several logs formed a jam in the transition of the morning glory spillway starting at approximately 1,900 ft^3/s (Figure 18). This caused a spike in the WSE to approximately 19 feet, almost activating the emergency spillway. This is a higher increase to WSE than impacts to the WSE seen in individual log testing at similar flow rates in pipe flow. For individual log tests in pipe flow, transition jams were unlikely to happen as the debris would often float on top of the piers. As the transition jam in the first iteration of the simulated flood routing occurred in weir flow, it had a greater impact to the WSE once the morning glory transitioned into pipe flow due to the restriction in flow passage caused by transition jams.

During the second iteration, the jam occurred in the piers around 2,200 ft^3/s. As this jam occurred during the shift to pipe flow, the debris clog interrupted the transition into pipe flow normally seen in clearwater conditions at this flow rate. As the morning glory was unable to shift into pipe flow, the WSE was lower than at the corresponding clearwater flow rate. However, as jams at 2,200 ft^3/s had a high rate of occurrence within the piers and thus a low impact to WSE, this was not out of the ordinary. The variation in jam location and subsequent impact to WSE makes debris impacts during flood routing difficult to predict.

For both tests, no new debris entered the morning glory spillway as flows descended even though debris was still introduced on the descending portion of the curve.

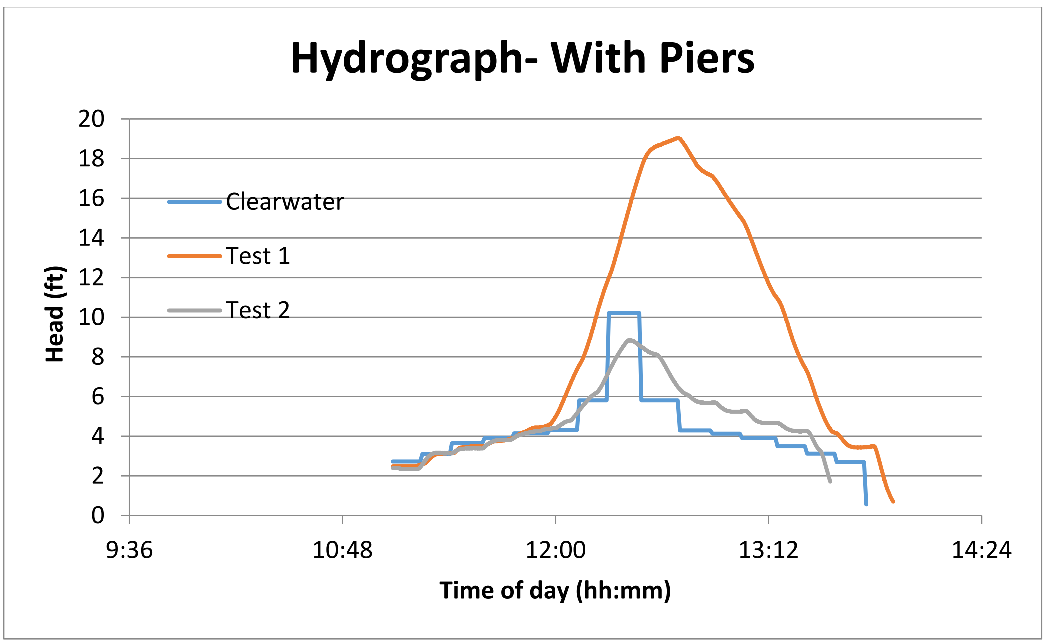

Figure 18 Simulated flood routing for Foss Dam, head is in prototype feet. Clearwater is plotted as a theoretical curve.

Without Piers

During the first simulated flood routing test, a crest jam occurred (Figure 19). The crest jam, which occurred prior to the start of peak flow, interrupted the normal transition point for the flow from weir to pipe flow, similar to the second iteration of the with piers testing. In addition, the flow was not given enough time to fully transition into pipe flow due to the ten-minute model time period before the stepped hydrograph flows were adjusted. This interrupted the change in flow regime, yielding a lower WSE on the increasing side of the curve and preventing the vortex from ever forming (Figure 20). For the descending flow rates, however, the jam prevented the shift back into weir flow thus raising the WSE. Therefore, preventing the vortex from forming and keeping the morning glory in orifice flow resulted in a lower WSE when compared to full pipe flow. Additionally, no new debris entered the morning glory spillway as flows descended even though debris was still introduced on the descending portion of the curve.

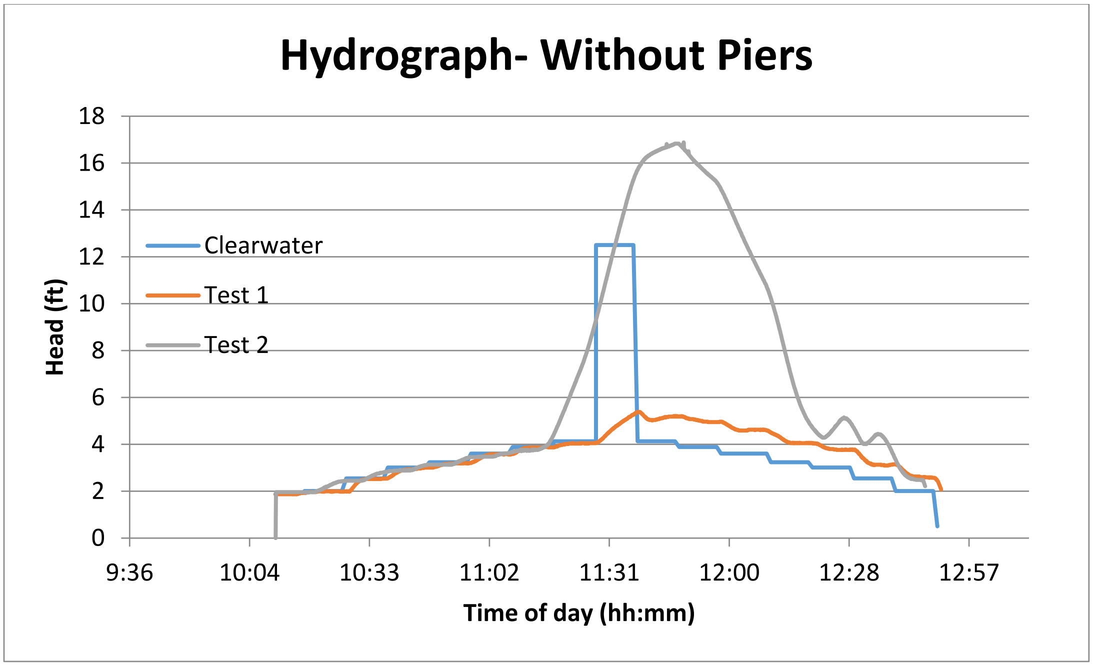

Figure 19 Simulated flood routing, head is in prototype feet. Clearwater is plotted as a theoretical curve.

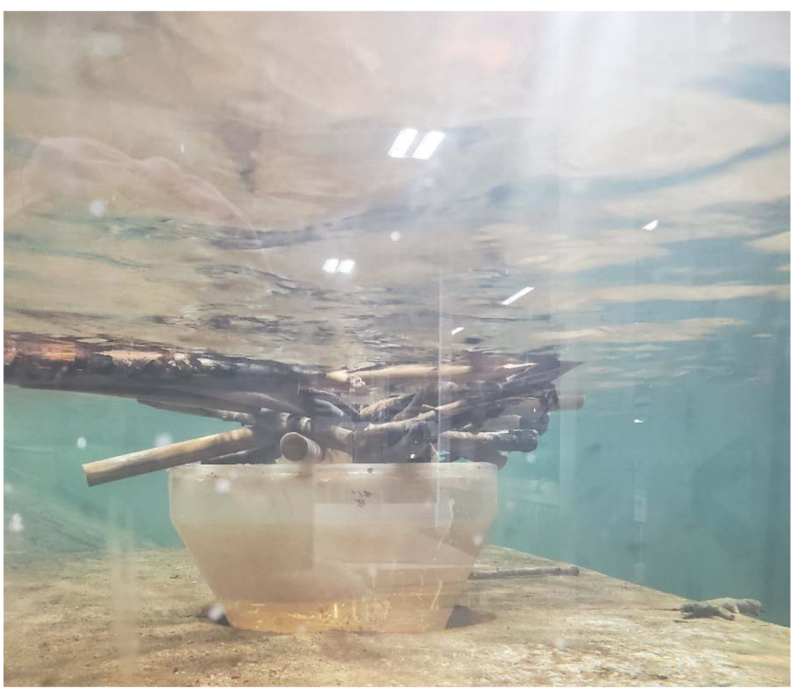

Figure 20 Crest jam during the first simulated flood routing test for the morning glory without piers during the step from 2500 to 2800 ft^3/s.

For the second iteration of the simulated flood routing, no debris jams occurred in weir flow allowing the morning glory to fully transition into pipe flow. The WSE rose beyond that expected by the clearwater simulated hydrograph test (Figure 19) due to debris floating on the surface disrupting vortex formation which had previously reduced the efficiency of the spillway. This trend continued as the flow rates decreased again until the WSE was low enough that the debris would be impacted by the crest of the morning glory. As debris would shift, a vortex would temporarily form, causing oscillations in the WSE, as seen in clearwater testing. This continued until the flow regime completely shifted back into weir flow.

Conclusion

The purpose of this study was to ascertain the risk debris clogging poses to morning glory spillways over a range of flow rates. The morning glory spillway was configured utilizing Reclamation's Foss Dam both with and without piers on the spillway crest. The relationship between the location of the debris clog and the change to WSE with the subsequent decrease in discharge capacity in the reservoir was assessed. While the model tests were performed on a scale representation of one of Reclamation's spillways that had a narrow crest diameter, the results of this study should be applicable to any morning glory design. During a risk analysis, the design of the transition should be examined, as some dams utilize more than one section to orient the flow near horizontal. In addition, some dams have a large vertical drop from the crest before a transition occurs which could create forces high enough to break up debris on impact. Results from this study are as follows:

With Piers, Including Air Vent

- Individual Log impacts to discharge capacity and WSE
  - Discharge reduction in weir flow: Average range of 13-52%.
  - Discharge reduction in pipe flow: Average range of 0-1%.
  - Average reservoir WSE increase in weir flow was 1-21 ft
  - Average reservoir WSE increase in pipe flow was 0.1-8 ft
  - Weir flow produced the most significant impacts to discharge and WSE
  - During orifice and pipe flow, debris mainly remained on the water surface; therefore, impacts to discharge capacity and WSE were lower.
- Log Clusters
  - Piers were often able to divide log clusters and prevent larger debris from entering the mouth of the morning glory.
  - If a fully intact cluster entered the morning glory spillway, it would create a jam as the spillway transitioned to the conduit and cause significant impacts to the WSE.
- Jam Location
  - Debris clogs occurring in the mouth or transition areas were more impactful to discharge and WSE than jams at the crest.
  - During weir flow, 66% of jams occurred in the mouth or transition.

    - During orifice and pipe flow, debris would remain in the piers due to the natural buoyancy of the logs, only 3% of jams were in locations other than the piers.
- Flood Routing
    - Impacts can vary considerably and depend on where the jam occurs (e.g. crest or transition).
    - When a jam occurred in weir flow, WSE increased by 19 ft.
    - When a jam occurred in pipe flow, the debris prevented a shift into pipe flow, lowering WSE.

Without Piers, No Air Vent

- Individual Log impacts to discharge capacity and WSE
    - Discharge reduction in weir or transitional flow: Average range of 16-54%.
    - Discharge reduction in pipe flow: Average range of 5-29%.
    - Average reservoir WSE increase in weir or transitional flow was 0.9-25 ft
    - Average reservoir WSE increase in pipe flow was 4-20 ft
    - Debris clogs most likely to occur in weir flow, all tests conducted in weir flow resulted in some kind of clog.
    - During orifice and pipe flow, a vortex formed which pulled most debris pieces through the morning glory without forming a jam.
    - Most debris passed through the morning glory spillway, but debris that was not successfully cleared caused significant increases to the WSE.
    - Combination jams resulted in WSE activating the emergency spillway.
- Log Clusters
    - Log clusters either caught at the crest at low flows or were broken apart by the vortex at higher flows.
- Jam Location
    - More combination jams occurred because piers weren't there to obstruct debris from entering the mouth of the spillway.
    - Jams continued to occur in the mouth and transition of the morning glory spillway even after the transition into pipe flow due to the presence of the vortex.
    - During weir flow 95% of jams occurred in the mouth, transition, or a combination of locations; 5% of jams occurred on the crest. During orifice flow 65% of jams occurred in the mouth, transition, or a combination of locations, 12% occurred on the crest, and 23% of tests yielded no jam.
    - If a jam shifted during a test, it was a result of the vortex, not the change in flow regime.
- Flood Routing
    - Impacts can vary considerably and depend on where the jam occurs (e.g. crest or transition).
    - Debris loading can disrupt vortex formation. This has the potential to prevent the shift into orifice flow improving discharge capacity or maintain orifice flow but without a vortex, depending on when the debris clogging occurs.

Recommendations

Physical model tests were performed on a morning glory spillway with and without piers to determine the impacts reservoir woody debris has on WSE behind a dam and the discharge capacity of the spillway structure. It is recommended that the simulated flood routing be repeated with longer time intervals to allow the flow regimes to fully shift into pipe flow both with and without piers on the morning glory. Other recommendations include future testing on morning glory spillways of different shapes and diameters. This would enable comparisons to be made about the formation of jams and impacts to discharge capacity and corresponding WSE across multiple configurations resulting in the creation of a dimensionless parameter. This parameter could be utilized to better inform future risk assessments.

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Appendix I: With Piers Test Data

Table A- 1 With piers, all individual log test data.

	Model						Prototype			
Test	Model Flow (cfs)	Initial WSE (ft)	Final WSE (ft)	Δ WSE	Proto Δ WSE	Corresponding Clearwater Q (cfs)	Initial H (ft)	Final H (ft)	Proto Q (ft)	Percent Reduction of Flow
5	0.37	0.09	0.14	0.05	0.86	0.66	1.67	2.54	506	-44%
	0.37	0.09	0.14	0.05	0.88	0.67	1.69	2.57	508	-45%
	0.37	0.09	0.15	0.06	1.13	0.74	1.64	2.77	509	-50%
	0.37	0.09	0.16	0.07	1.24	0.79	1.64	2.88	509	-53%
	0.37	0.09	0.18	0.09	1.55	0.93	1.67	3.22	509	-60%
	0.37	0.09	0.13	0.04	0.72	0.60	1.67	2.39	509	-39%
	0.37	0.09	0.15	0.06	1.08	0.73	1.66	2.74	509	-49%
	0.37	0.10	0.14	0.05	0.86	0.67	1.71	2.57	511	-45%
	0.37	0.09	0.14	0.05	0.88	0.65	1.64	2.52	511	-43%
	0.37	0.10	0.14	0.05	0.81	0.65	1.71	2.52	512	-43%
4	0.74	0.15	0.24	0.09	1.67	1.48	2.65	4.32	1017	-50%
	0.74	0.15	0.22	0.07	1.30	1.27	2.63	3.92	1017	-42%
	0.74	0.15	0.21	0.06	1.08	1.16	2.65	3.73	1017	-36%
	0.74	0.15	0.25	0.10	1.73	1.53	2.68	4.41	1017	-52%
	0.74	0.15	0.23	0.08	1.46	1.37	2.65	4.10	1017	-46%
	0.74	0.15	0.24	0.10	1.73	1.49	2.61	4.34	1017	-50%
	0.74	0.15	0.27	0.13	2.25	1.57	2.61	4.86	1017	-53%
	0.74	0.15	0.22	0.08	1.35	1.31	2.65	4.00	1017	-43%
	0.74	0.15	0.24	0.09	1.62	1.44	2.61	4.23	1017	-48%
	0.74	0.15	0.35	0.20	3.60	1.63	2.61	6.21	1017	-55%
6	0.91	0.16	0.26	0.09	1.66	1.55	2.95	4.61	1246	-42%
	0.91	0.16	0.22	0.05	0.95	1.26	2.95	3.91	1250	-28%
	0.91	0.17	0.25	0.09	1.60	1.55	2.97	4.57	1250	-41%
	0.91	0.17	0.26	0.10	1.73	1.56	2.99	4.72	1250	-42%
	0.91	0.17	0.81	0.64	11.56	1.87	3.01	14.56	1252	-51%
	0.91	0.17	0.28	0.11	1.94	1.57	3.06	5.00	1252	-42%
	0.91	0.17	0.57	0.41	7.34	1.75	2.99	10.33	1253	-48%
	0.91	0.17	0.24	0.08	1.35	1.51	3.02	4.37	1254	-40%
	0.91	0.17	0.25	0.08	1.42	1.55	3.02	4.45	1255	-41%
	0.91	0.17	0.21	0.04	0.74	1.19	3.04	3.78	1256	-23%
3	1.05	0.19	0.24	0.05	0.95	1.49	3.38	4.34	1443	-30%
	1.06	0.19	0.39	0.20	3.65	1.66	3.38	7.04	1457	-36%
	1.06	0.19	0.89	0.70	12.60	1.90	3.33	15.93	1457	-44%
	1.07	0.19	1.18	1.00	17.98	2.04	3.33	21.31	1471	-48%
	1.07	0.19	0.49	0.30	5.47	1.71	3.40	8.87	1471	-37%

Test	Model Model Flow (cfs)	Initial WSE (ft)	Final WSE (ft)	Δ WSE	Proto Δ WSE	Corresponding Clearwater Q (cfs)	Prototype Initial H (ft)	Final H (ft)	Proto Q (ft)	Percent Reduction of Flow
3	1.09	0.19	0.29	0.10	1.87	1.58	3.37	5.24	1498	-31%
	1.10	0.19	0.33	0.14	2.47	1.61	3.40	5.87	1512	-32%
	1.10	0.19	0.36	0.18	3.20	1.64	3.35	6.55	1512	-33%
	1.10	0.19	0.76	0.57	10.33	1.85	3.35	13.68	1512	-40%
	1.12	0.19	1.34	1.15	20.63	2.14	3.40	24.03	1540	-48%
	1.13	0.19	0.37	0.18	3.24	1.64	3.35	6.59	1553	-31%
7	1.25	0.20	1.25	1.05	18.81	2.07	3.60	22.41	1714	-40%
	1.25	0.20	1.19	0.99	17.77	2.04	3.58	21.35	1717	-39%
	1.26	0.20	1.05	0.85	15.30	1.97	3.60	18.90	1728	-36%
	1.26	0.20	1.21	1.01	18.23	2.05	3.60	21.83	1729	-39%
	1.26	0.21	1.33	1.13	20.27	2.13	3.71	23.98	1732	-41%
	1.26	0.21	0.48	0.27	4.84	1.70	3.74	8.59	1732	-26%
	1.26	0.21	0.26	0.05	0.86	1.55	3.73	4.59	1732	-19%
	1.26	0.21	0.23	0.02	0.38	1.38	3.74	4.12	1732	-8%
	1.26	0.21	0.53	0.32	5.80	1.73	3.74	9.54	1732	-27%
	1.26	0.21	0.28	0.07	1.21	1.57	3.78	4.99	1732	-20%
8	1.39	0.22	1.39	1.16	20.95	2.19	3.98	24.93	1911	-36%
	1.39	0.22	1.39	1.17	20.97	2.19	3.96	24.93	1911	-36%
	1.39	0.22	1.39	1.17	20.97	2.19	3.96	24.93	1911	-36%
	1.39	0.22	1.39	1.17	21.02	2.19	4.00	25.02	1911	-37%
	1.39	0.22	1.39	1.17	20.97	2.19	3.96	24.93	1911	-36%
	1.39	0.22	1.39	1.17	21.10	2.19	3.92	25.02	1911	-37%
	1.39	0.22	1.39	1.17	20.97	2.19	3.96	24.93	1911	-36%
	1.39	0.22	1.39	1.17	21.01	2.19	4.00	25.00	1911	-37%
	1.39	0.22	1.39	1.17	21.01	2.19	3.92	24.93	1911	-36%
	1.39	0.22	1.39	1.17	21.01	2.19	3.98	24.98	1911	-36%
9	1.50	0.23	1.14	0.91	16.42	2.02	4.14	20.56	2062	-26%
	1.50	0.23	1.27	1.04	18.67	2.09	4.16	22.82	2062	-28%
	1.50	0.23	1.29	1.06	19.12	2.10	4.12	23.24	2062	-29%
	1.50	0.23	1.13	0.90	16.25	2.01	4.14	20.39	2062	-25%
	1.50	0.23	1.24	1.01	18.09	2.07	4.16	22.25	2062	-27%
	1.50	0.23	0.90	0.67	12.04	1.91	4.16	16.20	2062	-21%
	1.50	0.23	1.16	0.93	16.65	2.02	4.14	20.79	2062	-26%
	1.50	0.23	0.78	0.55	9.86	1.86	4.14	14.00	2062	-19%
	1.50	0.23	0.31	0.08	1.51	1.60	4.14	5.65	2062	-6%
	1.50	0.23	0.25	0.02	0.40	1.55	4.18	4.57	2062	-3%
10	1.55	0.24	0.28	0.05	0.85	1.58	4.25	5.09	2131	-2%
	1.55	0.23	1.36	1.13	20.27	2.16	4.21	24.48	2131	-28%
	1.55	0.23	1.27	1.04	18.65	2.09	4.21	22.86	2131	-26%

Test	Model Model Flow (cfs)	Initial WSE (ft)	Final WSE (ft)	Δ WSE	Proto Δ WSE	Corresponding Clearwater Q (cfs)	Prototype Initial H (ft)	Final H (ft)	Proto Q (ft)	Percent Reduction of Flow
	1.55	0.23	1.09	0.86	15.46	1.99	4.21	19.67	2131	-22%
10	1.55	0.23	1.19	0.96	17.26	2.04	4.19	21.46	2131	-24%
	1.55	0.24	0.82	0.59	10.57	1.88	4.27	14.83	2131	-17%
	1.55	0.24	1.30	1.07	19.19	2.10	4.27	23.45	2131	-26%
	1.55	0.24	0.57	0.34	6.03	1.75	4.23	10.26	2131	-11%
	1.55	0.24	1.21	0.97	17.41	2.05	4.37	21.78	2131	-25%
	1.55	0.24	1.23	0.99	17.84	2.06	4.23	22.07	2131	-25%
11	1.60	0.28	1.06	0.79	14.15	1.98	4.97	19.12	2199	-19%
	1.60	0.27	0.43	0.16	2.83	1.68	4.88	7.70	2199	-5%
	1.60	0.29	0.40	0.11	2.00	1.66	5.17	7.16	2199	-4%
	1.60	0.29	0.33	0.05	0.86	1.62	5.13	5.99	2199	-1%
	1.60	0.28	0.36	0.08	1.49	1.64	4.95	6.44	2199	-2%
	1.60	0.29	1.31	1.02	18.38	2.11	5.24	23.62	2199	-24%
	1.60	0.28	0.61	0.33	6.01	1.77	5.04	11.05	2199	-10%
	1.60	0.28	1.07	0.80	14.33	1.99	4.99	19.31	2199	-19%
	1.60	0.29	0.33	0.04	0.65	1.61	5.26	5.90	2199	-1%
	1.60	0.28	1.32	1.04	18.74	2.12	4.99	23.72	2199	-24%
15	1.63	0.35	0.36	0.01	0.18	1.64	6.25	6.43	2241	0%
	1.63	0.35	1.33	0.98	17.69	2.13	6.21	23.90	2241	-23%
	1.63	0.35	0.37	0.02	0.38	1.65	6.34	6.71	2241	-1%
	1.63	0.34	0.42	0.07	1.31	1.67	6.17	7.49	2241	-2%
	1.63	0.34	0.72	0.38	6.84	1.83	6.16	13.00	2241	-11%
	1.63	0.35	0.39	0.04	0.77	1.65	6.21	6.98	2241	-1%
	1.63	0.34	0.89	0.55	9.90	1.90	6.14	16.04	2241	-14%
	1.63	0.34	0.43	0.09	1.53	1.68	6.19	7.72	2241	-3%
	1.63	0.34	1.10	0.76	13.72	2.00	6.16	19.87	2241	-18%
	1.63	0.34	0.82	0.47	8.51	1.87	6.19	14.71	2241	-13%
12	1.65	0.36	0.39	0.03	0.54	1.65	6.43	6.97	2268	0%
	1.65	0.37	0.39	0.01	0.23	1.65	6.71	6.95	2268	0%
	1.65	0.37	0.61	0.24	4.32	1.77	6.73	11.05	2268	-7%
	1.65	0.37	0.36	0.00	-0.04	1.64	6.59	6.55	2268	1%
	1.65	0.37	0.37	0.01	0.16	1.65	6.57	6.73	2268	0%
	1.65	0.36	0.39	0.03	0.54	1.66	6.55	7.09	2268	0%
	1.65	0.36	0.41	0.05	0.86	1.67	6.55	7.42	2268	-1%
	1.65	0.37	0.39	0.02	0.40	1.65	6.59	6.98	2268	0%
	1.65	0.36	0.41	0.04	0.76	1.66	6.55	7.31	2268	-1%
	1.65	0.36	0.45	0.10	1.71	1.69	6.46	8.17	2268	-2%
14	1.68	0.46	0.45	0.00	-0.04	1.69	8.21	8.17	2309	-1%
	1.68	0.45	0.44	-0.01	-0.14	1.68	8.08	7.94	2309	0%
	1.68	0.44	0.45	0.01	0.16	1.69	7.96	8.12	2309	0%

Test	Model						Prototype			
	Model Flow (cfs)	Initial WSE (ft)	Final WSE (ft)	Δ WSE	Proto Δ WSE	Corresponding Clearwater Q (cfs)	Initial H (ft)	Final H (ft)	Proto Q (ft)	Percent Reduction of Flow
	1.68	0.45	0.49	0.04	0.63	1.71	8.10	8.73	2309	-1%
13	1.81	0.70	0.70	0.01	0.09	1.82	12.58	12.67	2488	-1%
	1.82	0.70	0.71	0.01	0.13	1.82	12.56	12.69	2502	0%
	1.82	0.70	0.70	0.01	0.09	1.82	12.53	12.62	2502	0%
	1.82	0.70	0.70	0.00	-0.04	1.82	12.64	12.60	2502	0%

Table A- 2 With piers individual log test average per flow rate.

Test #	Model Q	Initial WSE	Final WSE	Percent Reduction	Proto Q	Initial H	Final H	Proto Δ WSE
3	1.09	0.19	0.60	-39%	1493	3.4	10.9	7.5
4	0.74	0.15	0.25	-52%	1017	2.6	4.4	1.8
5	0.37	0.09	0.15	-48%	509	1.7	2.7	1.0
6	1.00	0.18	0.48	-41%	1378	3.2	8.6	5.4
7	1.26	0.20	0.78	-32%	1728	3.7	14.0	10.3
8	1.39	0.22	1.39	-36%	1911	4.0	25.0	21.0
9	1.50	0.23	0.95	-22%	2062	4.1	17.0	12.9
10	1.55	0.24	1.03	-21%	2131	4.2	18.6	14.4
11	1.60	0.28	0.72	-13%	2199	5.1	13.0	7.9
12	1.65	0.37	0.42	-1%	2268	6.6	7.5	0.9
13	1.82	0.70	0.70	0%	2498	12.6	12.6	0.1

Table A- 3 With piers, simulated flood routing test matrix. Please note, primary dowel added at 11:20 and orifice flow began at 11:55.

Time	Proto T, hr	Percent Debris Added	Q (Model)	Time	Q (Proto)	Clear water Head
0	0.00	0	0.72	11:05	990	0.15
			0.72	11:14	990	0.15
10	0.71	2%	0.8	11:15	1223	0.17
			0.89	11:24	1223	0.17
20	1.41	5%	1.1	11:25	1540	0.20
			1.12	11:35	1540	0.20
30	2.12	5%	1.26	11:36	1732	0.22
			1.26	11:45	1732	0.22
40	2.83	7%	1.39	11:46	1911	0.23
			1.39	11:57	1911	0.23
50	3.54	10%	1.4	11:58	2034	0.24
			1.4	12:07	2034	0.24
60	4.24	15%	1.6	12:08	2213	0.32
			1.6	12:17	2213	0.32
70	4.95	20%	1.7	12:18	2406	0.57
			1.75	12:28	2406	0.57
80	5.66	25%	1.61	12:29	2213	0.32
			1.61	12:41	2213	0.32
90	6.36	10%	1.4	12:42	2021	0.24
			1.4	12:52	2021	0.24
100	7.07	1%	1.3	12:53	1897	0.23
			1.3	13:02	1897	0.23
110	7.78	0%	1.2	13:03	1732	0.22
			1.2	13:14	1732	0.22
120	8.49	0%	1.0	13:15	1471	0.19
			1.07	13:24	1471	0.19
130	9.19	0%	0.9	13:25	1237	0.17
			0.90	13:34	1237	0.17
140	9.90	0%	0.7	13:35	976	0.15
			0.71	13:44	976	0.15
150	10.61	0%	0.00	13:45	0	0.03

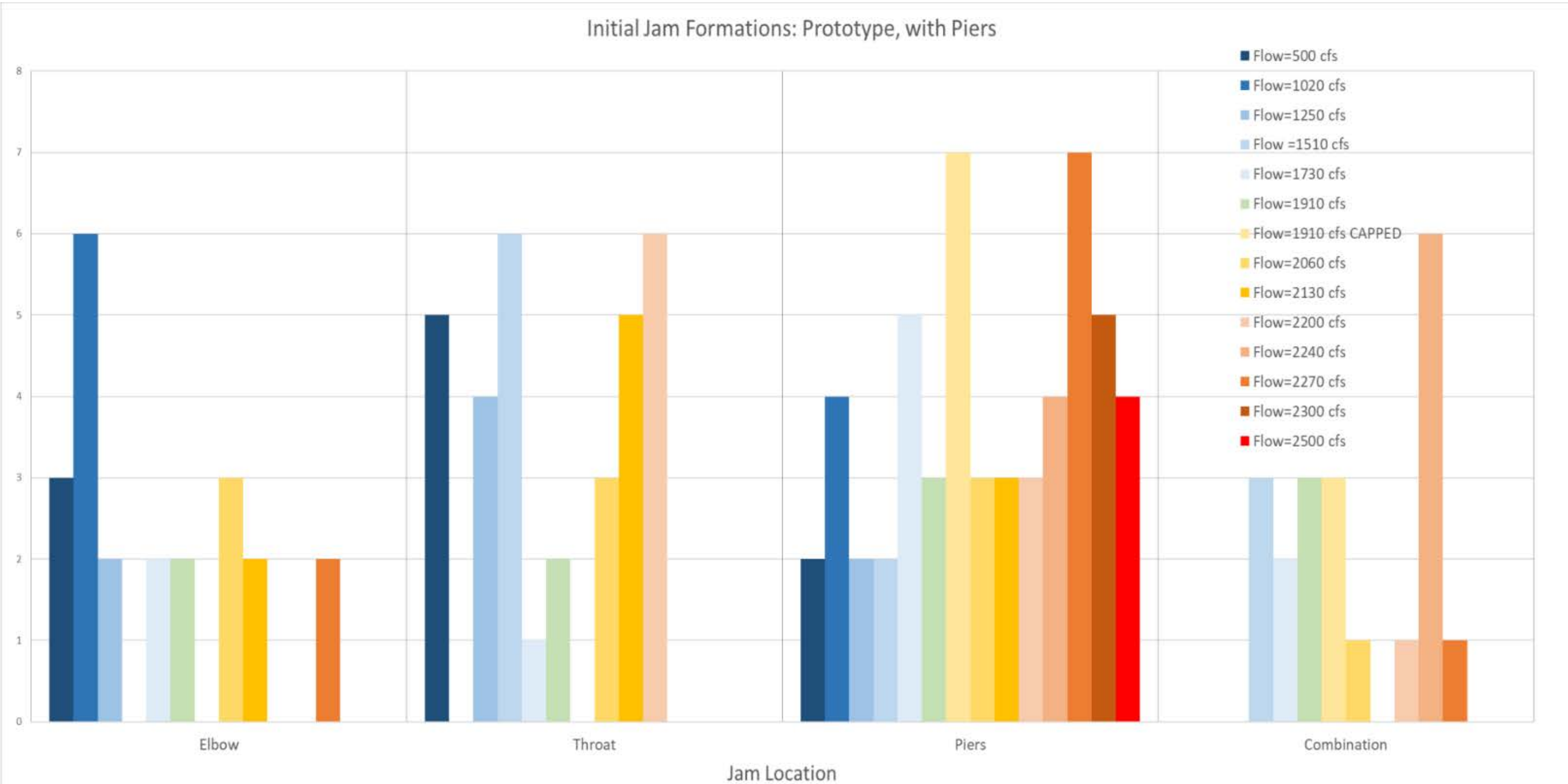

Figure A- 1 Location of jams, with piers. Cooler colors represent weir flow with warmer colors representing pipe flow.

Appendix II: Without Piers and No Air Vent Test Data

Table B- 1 Without piers, all individual log test data

	Model						Prototype			
Test	Model Flow (cfs)	Initial WSE (ft)	Final WSE (ft)	Δ WSE	Proto Δ WSE	Corresponding Clearwater Q (cfs)	Initial WSE (ft)	Final WSE (ft)	Proto Q (cfs)	Percent Reduction of Flow
3	1.08	0.15	0.20	0.05	0.94	1.65	2.70	3.64	1484.58	-35%
	1.08	0.15	1.38	1.23	22.19	2.29	2.66	24.86	1484.58	-53%
	1.09	0.15	1.37	1.22	21.94	2.29	2.70	24.64	1498.33	-52%
	1.08	0.15	0.21	0.07	1.17	1.72	2.63	3.80	1484.58	-37%
	1.07	0.14	1.39	1.25	22.46	2.30	2.59	25.06	1470.84	-53%
5	0.37	0.07	0.11	0.04	0.74	0.71	1.24	1.98	508.61	-48%
	0.37	0.07	0.14	0.07	1.22	0.94	1.21	2.43	508.61	-61%
	0.37	0.07	0.11	0.04	0.70	0.69	1.24	1.94	508.61	-46%
	0.37	0.07	0.13	0.06	1.04	0.84	1.21	2.25	508.61	-56%
	0.37	0.07	0.12	0.05	0.92	0.80	1.24	2.16	508.61	-54%
12	1.65	0.20	0.20	0.00	0.05	1.66	3.62	3.67	2268.12	-1%
	1.65	0.20	0.27	0.06	1.13	1.91	3.67	4.81	2268.12	-13%
	1.65	0.20	0.27	0.07	1.26	1.91	3.65	4.91	2268.12	-14%
	1.66	0.21	1.32	1.11	20.02	2.28	3.69	23.71	2281.86	-27%
	1.65	0.20	0.22	0.02	0.38	1.81	3.65	4.03	2268.12	-9%
18	1.75	0.21	1.58	1.37	24.64	2.48	3.83	28.48	2405.58	-29%
	1.76	0.22	1.54	1.33	23.87	2.43	3.89	27.76	2419.32	-28%
	1.76	0.22	1.55	1.34	24.07	2.44	3.87	27.94	2419.32	-28%
	1.75	0.21	1.62	1.41	25.29	2.62	3.82	29.11	2405.58	-33%
	1.75	0.21	1.55	1.34	24.07	2.44	3.82	27.88	2405.58	-28%
13	1.82	0.22	1.63	1.40	25.27	2.72	4.00	29.27	2501.80	-33%
	1.81	0.22	1.63	1.41	25.38	2.80	4.03	29.41	2488.05	-35%
	1.82	0.23	1.63	1.41	25.33	2.80	4.09	29.41	2501.80	-35%
	1.82	0.23	1.61	1.38	24.86	2.53	4.05	28.91	2501.80	-28%
	1.83	0.23	0.23	0.01	0.09	1.86	4.09	4.18	2515.55	-2%
14	1.85	0.23	0.23	0.00	0.02	1.86	4.16	4.18	2543.04	-1%
	1.85	0.23	0.80	0.57	10.22	2.08	4.09	14.31	2543.04	-11%
	1.85	0.23	1.66	1.43	25.70	3.02	4.09	29.79	2543.04	-39%
	1.85	0.23	1.64	1.41	25.40	2.87	4.12	29.52	2543.04	-35%
	1.85	0.23	1.63	1.40	25.24	2.77	4.12	29.36	2543.04	-33%
17	2.11	0.90	0.94	0.04	0.74	2.13	16.22	16.96	2900.44	-1%
	2.11	0.94	1.15	0.21	3.85	2.22	16.88	20.74	2900.44	-5%
	2.10	0.93	0.88	0.05	0.86	2.10	16.65	15.79	2886.69	0%
	2.11	0.89	1.68	0.79	14.22	3.25	15.97	30.19	2900.44	-35%
	2.11	0.87	1.66	0.79	14.20	3.10	15.73	29.93	2900.44	-32%
	2.11	0.85	0.79	0.06	1.12	2.08	15.32	14.20	2900.44	2%
	2.11	0.88	0.80	0.08	1.40	2.08	15.82	14.42	2900.44	1%

Table B- 2 Without piers, individual log test average per flow rate.

	Model				Prototype			
Test #	Q	Initial WSE	Final WSE	Percent Reduction	Q	Initial WSE	Final WSE	Proto Δ WSE
3	1.08	0.15	0.91	-49%	1485	2.66	16.40	13.74
5	0.37	0.07	0.12	-53%	509	1.23	2.15	0.93
12	1.65	0.20	0.46	-16%	2268	3.66	8.23	4.57
18	1.75	0.21	1.57	-29%	2406	3.84	28.23	24.39
13	1.82	0.23	1.35	-21%	2498	4.05	24.24	20.19
14	1.85	0.23	1.19	-17%	2539	4.11	21.43	17.32
17	2.11	0.89	1.13	-5%	2898	16.08	20.32	4.23

Table B- 3 Without piers, simulated flood routing test matrix.

Time	Proto T, hr	Percent Debris Added	Q (Model)	Time	Q (Proto)	Clearwater Head	Notes
0	0.00	0%	0.72	10:18	989.72	0.11	
			0.72	10:18	989.72	0.11	
10	0.71	2%	1.00	10:28	1374.62	0.14	1/2" Dowel added at 10:28
			1.00	10:28	1374.62	0.14	
20	1.41	5%	1.26	10:38	1732.02	0.17	
			1.26	10:38	1732.02	0.17	
30	2.12	5%	1.39	10:48	1910.72	0.18	All introduced debris still passing
			1.39	10:48	1910.72	0.18	
40	2.83	7%	1.61	10:58	2213.13	0.20	One stick in elbow with 1/2" dowel
			1.61	10:58	2213.13	0.20	
50	3.54	10%	1.75	11:08	2405.58	0.22	Oscillation of weir flow begins. Logs in elbow passed
			1.75	11:08	2405.58	0.22	
60	4.24	15%	1.85	11:18	2543.04	0.23	
			1.85	11:18	2543.04	0.23	
70	4.95	20%	2.05	11:28	2817.96	0.69	Transition to orifice flow. Crest jam on top of MG
			2.05	11:28	2817.96	0.69	
80	5.66	25%	1.85	11:38	2543.04	0.23	Crest jam interfering with transition point
			1.85	11:38	2543.04	0.23	
90	6.36	10%	1.75	11:48	2405.58	0.22	See above
			1.75	11:48	2405.58	0.22	
100	7.07	1%	1.61	11:58	2213.13	0.20	Transition to weir flow beginning in between jam.
			1.61	11:58	2213.13	0.20	
110	7.78	0%	1.39	12:10	1910.72	0.18	
			1.39	12:10	1910.72	0.18	
120	8.49	0%	1.26	12:20	1732.02	0.17	
			1.26	12:20	1732.02	0.17	
130	9.19	0%	1.00	12:30	1374.62	0.14	
			1.00	12:30	1374.62	0.14	
140	9.90	0%	0.72	12:40	989.72	0.11	
			0.72	12:40	989.72	0.11	
150	10.61	0%	0.00	12:50	0.00	0.03	

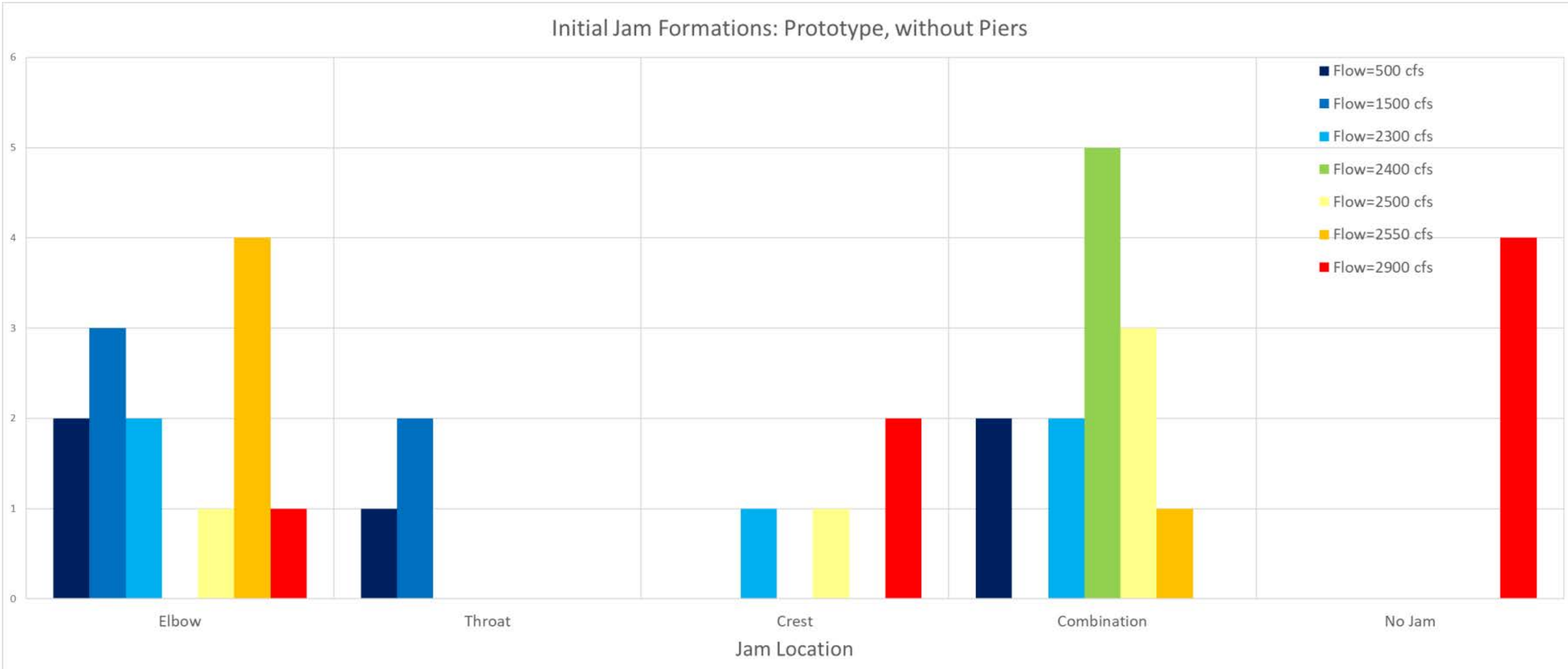

Figure B- 1 Jam locations without piers for a given flow rate. Cooler colors represent weir flow with warmer colors representing pipe flow.