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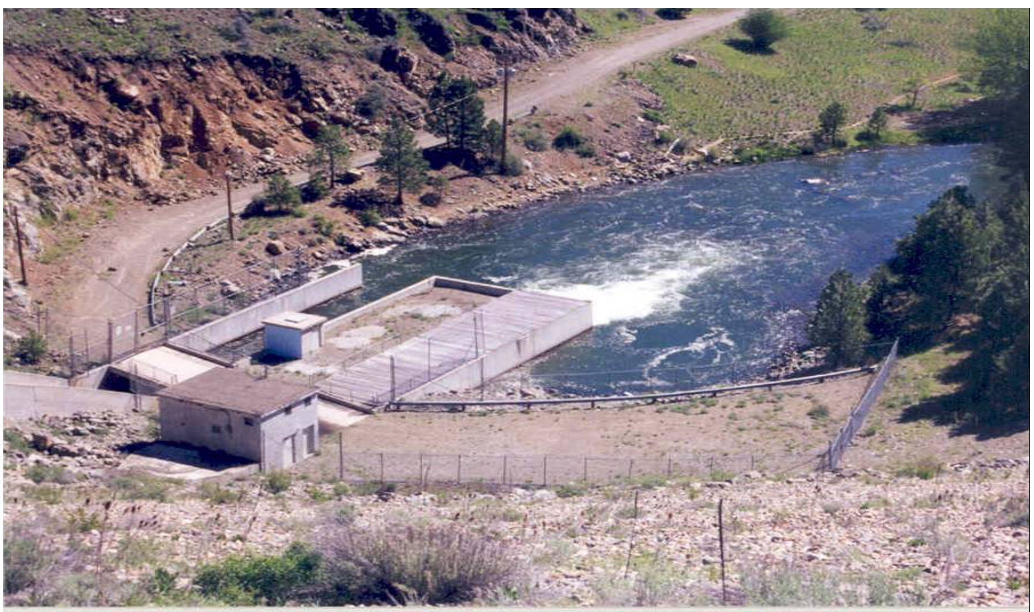
Hydraulic Laboratory Report HL-2005-01

Mason Dam Flow Deflectors for Preventing Stilling Basin Abrasion Damage



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Water Resources Research Laboratory
Denver, Colorado

October 2005

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14. ABSTRACT

Research sponsored by Bureau of Reclamation Science and Technology Program and conducted by the Water Resources Research Laboratory in Denver has demonstrated that flow deflectors can be used to mitigate abrasion damage commonly experienced by Reclamation Type II outlet works stilling basins and other standard basins of similar design. This will increase the life of the basins and reduce or eliminate the need for costly repairs.

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U.S. Department of the Interior
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Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

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

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Support provided by the Snake River Area Office including Karl Ames, Curtis Carney, Mark Albl and Steve Dunn was invaluable. The support of Jim and Jeff Colton of the Baker Valley Irrigation District was also appreciated and crucial to the success of this program. Thanks also to Bob Sund for providing the structural design for the prototype flow deflector and to Bill Baca for his dedication and attention to detail in model data acquisition.

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Disclaimer

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Purpose

A physical model study was conducted to evaluate the hydraulic characteristics of the Mason Dam river outlet works stilling basin and to design a flow deflector for the purpose of mitigating basin abrasion damage. In addition, the first prototype flow deflector design was implemented at Mason Dam in October 2002 to provide a field demonstration of this technology. Field monitoring, including dive inspections and velocity profile measurements were included in this study to verify the effectiveness of the deflector and to refine the final design.

Introduction

Stilling basin abrasion damage is a widespread problem for river outlet works at dam sites throughout the United States. Abrasion damage occurs when materials, such as sand, gravel, or rock, are carried into the basin by a recirculating flow pattern produced over the basin end sill during normal operation of a hydraulic jump energy dissipation basin (Figure 1). Once materials are in the basin, turbulent flow continually moves the materials against the concrete surface, causing severe damage, often to the extent that reinforcing bars are exposed. Then when repairs are made, many basins experience the same damage again within one or two operating seasons. Research conducted by Reclamation's Water Resources Research Laboratory (WRRL) in Denver has demonstrated that the installation of flow deflectors can improve flow distribution, thus minimizing or eliminating the potential for materials to be carried into stilling basins (figure 2). This can increase the life of the basins and reduce necessary repairs.

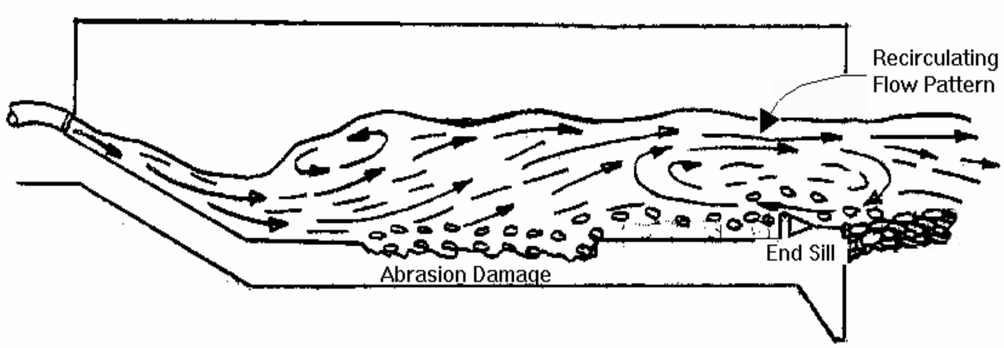

Figure 1. A recirculating flow pattern is produced over the basin end sill during normal operations.

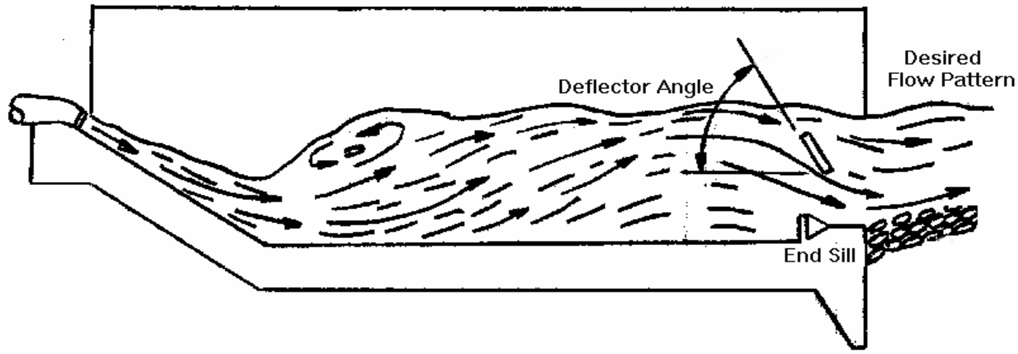

Figure 2. Desired flow pattern with flow deflector installed.

The Mason Dam outlet works stilling basin, a typical Reclamation Type II basin with a long history of abrasion damage and repeated repairs, was determined to be an excellent candidate for a field demonstration of this technology. Mason Dam is located on the Powder River in Baker County, Oregon, approximately 17 miles southwest of the city of Baker. The dam was constructed for irrigation, and for maintaining minimum flow in the Powder River. Flood control benefits are also provided for areas downstream from the dam. The dam is a 173 ft high zoned earthfill embankment with a crest length of 895 ft. The dam forms a reservoir 4.5 miles long covering 1962 acres. The tunnel outlet works and an ungated spillway are located on the left abutment. Reclamation owns Mason Dam; however, the Baker Valley Irrigation District (BVID) operates and maintains the facility under contract with Reclamation.

A physical model, constructed in the WRRL, was used to design a flow deflector for the Mason Dam outlet works stilling basin. In addition, a field evaluation was conducted after the prototype deflector was installed to verify the effectiveness of the design and to develop methodology for widespread application (a patent is pending on this technology).

Conclusions

Model Evaluation

1) Results from model investigations indicate that the installation of a flow deflector in the stilling basin can help improve flow conditions to minimize the potential for carrying materials into the basin, thereby extending basin life, and reducing long-term O&M costs.

2) Model investigations were used to design an effective flow deflector for discharges up to the maximum downstream river channel capacity of 500 ft^3/s, maximum discharge allowed by Standing Operating Procedures (SOP).

3) The investigations determined that the optimal deflector design was a 5 ft high deflector positioned 5 ft upstream from the end of the basin at elevation 3900 ft (referenced to the upstream lower edge of the deflector) and angled at 90 degrees (vertical).

4) The 5 ft high deflector spanning the 17 ft wide basin produced better performance than a 3 ft or 4 ft high deflector. However performance was acceptable for all three configurations.

5) Without a deflector in the basin, the average bottom velocities measured at the end of the basin were predominantly in the upstream direction and ranged in magnitude from -0.4 ft/s to -0.8 ft/s for gate openings ranging from 20% to 100% (negative values indicate velocities were upstream into the basin). Maximum upstream velocities measured were in the range of -2.0 ft/s to -3.0 ft/s. All dimensions and measurements reported here are scaled to prototype dimensions.

6) With the optimal deflector design in place, average velocities were directed downstream away from the basin. Maximum downstream bottom velocities measured at the end of the basin ranged from 3.0 ft/s to 5.0 ft/s for the range of operations tested. Velocities of this magnitude should not cause any significant erosion downstream from the basin.

7) Model investigations indicated that with a deflector installed in the basin, flow releases ranging from 30% to 60% gate opening can be used to flush materials from the basin. Without a deflector, releases at 100% gate opening (870 ft^3/s) are required to purge materials from the basin. However, since this exceeds the maximum downstream river channel capacity of 500 ft^3/s and SOP requirements, releases at 100% gate opening are not normally allowed. Therefore the basin cannot be flushed on a regular basis without a deflector. The exact size of materials that can be flushed from the basin with the deflector in place will depend on operations and have not yet been determined.

8) The difference in water surface profiles measured along the basin walls, with and without the deflector installed, was negligible.

9) Piezometer taps were used to measure the differential loading across the deflector for model operations up to 100% gate opening at maximum reservoir elevation. The maximum force on the prototype deflector due to static hydraulic loading was predicted to be about 12,600 lbs.

Field Evaluation

1) Average vertical velocity profiles measured at Mason Dam at the exit of the basin without a deflector correlated well with the velocities measured in the model, especially those velocities measured near the bottom where air entrainment was minimal. This demonstrated that the physical model provided an accurate representation of prototype conditions.

2) Average velocities measured at the basin exit with the deflector in place correlated well with the model for discharge releases up to 30% gate opening. Velocities measured at gate openings greater than 30%, with the deflector in place, were inconclusive due to high air concentration in the flow that interfered with data acquisition.

3) The dive team inspecting the basin in August 2004, after two seasons of operations with the deflector in place, found only a few stones in the basin and no indications of abrasion damage. The flaking off of a thin top layer of the new concrete was attributed to other causes. In June 2005, a subsequent dive inspection was conducted and there were still no signs of abrasion damage; thereby indicating the deflector was performing as desired. In addition, divers found no signs of erosion immediately downstream from the end of the basin.

4) The high correlation between model and prototype data indicates that the installation of a deflector in the basin can help improve flow conditions significantly to minimize the potential for entraining materials in the basin, thereby extending basin life, and reducing long-term O&M costs.

The Model

A 1:7 geometric scale was used to model the Mason Dam outlet works stilling basin. Froude scale similitude was used to establish the kinematic relationship between model and prototype because hydraulic performance depends predominantly on gravitational and inertial forces. Froude scale similitude produces the following relationships between the model and the prototype:

Length ratio $L_r = 1:7$

Velocity ratio $V_r = L_r^{1/2} = 1:2.65$

Discharge ratio $Q_r = L_r^{5/2} = 1:130$

The physical model was used to investigate hydraulic conditions in the Mason Dam stilling basin and to study the effect of deflector angle and position on flow patterns over the basin end sill (Figures 3 and 4).

Prototype features modeled included:

1) The two 33-in by 33-in high pressure regulating gates and upstream bifurcation.

2) The 17 ft wide hydraulic jump twin bay stilling basin with 2:1 sloping chutes, and dentated end sill.

3) Approximately 75 ft of topography downstream from the basin, constructed on a 5:1 slope.

Velocities were measured with a SonTek Acoustic Doppler Velocimeter (ADV) probe and were measured at the downstream end of the basin at its centerline. Tailwater elevation was set for each flow condition tested, using tailwater data obtained during Mason Dam outlet works operations. The deflector was modeled with a flat section of sheet metal spanning the 17 ft wide basin and mounted on guides attached to the basin sidewalls, to allow vertical movement of the deflector within the basin (Figure 4).

Figure 3. Looking through the plexiglass sidewall of the model operating at 40% gate opening.

Model Study Investigations

Model investigations were conducted to evaluate hydraulic conditions in the stilling basin and downstream apron area for the range of operating conditions expected in the prototype. The actual flow conditions tested are listed in Table 1. Both high pressure regulating gates of the twin bay design were operated symmetrically at all times as required by the SOP. Velocity data and dye streak data were collected and analyzed to define basin performance. This data was used to determine the most effective deflector angle and the best lateral and vertical locations within the basin. Although investigations were conducted up to the maximum possible discharge of 870 ft^3/s (100% gate opening at maximum reservoir, elevation 4077 ft), the optimum deflector design was based only on discharges up to 575 ft^3/s (60% gate opening at maximum reservoir). This is because Mason Dam's SOP limits outlet works discharges to the maximum downstream river channel capacity of 500 ft^3/s. Velocities were measured at numerous locations within and downstream from the stilling basin to map out resulting hydraulic flow patterns for each discharge tested. Initial measurements included mapping vertical velocity profiles measured at the downstream end of the stilling basin for gate openings of 20, 40, 60, 80 and 100 percent, with discharge based on maximum reservoir (Figure 5).

Velocities were measured at approximately 0.7 ft vertical increments starting 0.29 ft above the basin invert and continuing until air entrained in the flow prevented further measurements (all dimensions are prototype). Figure 5 demonstrates average velocities measured within the bottom 9 ft to 10 ft of the water column are directed upstream into the basin (negative values indicate average velocity is directed upstream). Early investigations showed that average velocities measured at the end of the basin, at its centerline, and 0.44 ft above the invert elevation provide a good representation of the bottom velocities that carry materials into the basin. Therefore, velocities measured at this location were used as a basis to determine deflector performance for all subsequent investigations.

In addition, 8 piezometer taps were installed equally spaced across the upstream and downstream faces of the deflector. The taps were connected to a manometer board to measure differential loading on the deflector for flow rates up to a maximum discharge of 870 ft^3/s at 100 % gate opening.

Figure 4. Looking upstream at stilling basin model with ADV probe and deflector installed near the end of basin.

Table 1 Prototype flow conditions tested in model.

Gate Opening %	Prototype Discharge Corresponding to Maximum Reservoir Elevation (ft^3/s)	Tailwater Depth (ft)
20	230	18.2
40	420	18.8
60	575	19.5
80	735	20.0
100	870	20.7

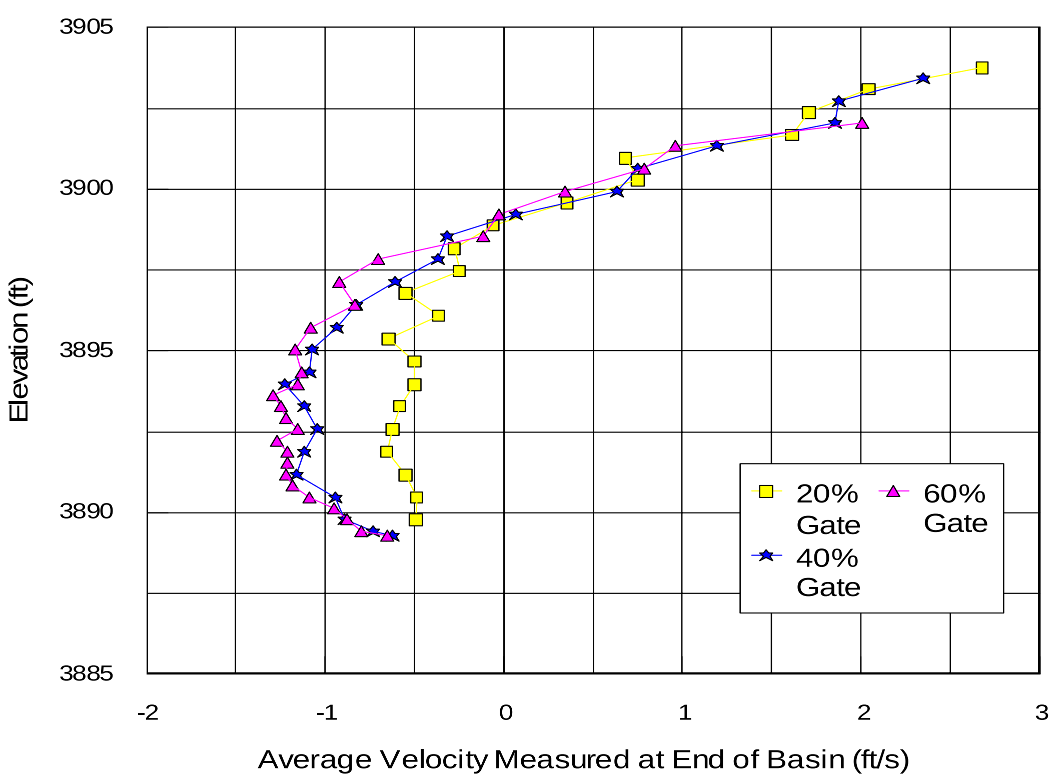

Figure 5. Vertical velocity profiles measured at the downstream end of basin without a deflector.

Model Results

Optimal Positioning and Size

Tests were initially conducted at 40 and 60 percent gate openings only, since these conditions produced the strongest upstream bottom velocities adjacent to the riprap apron, within the maximum operating range specified by the Mason Dam SOP. Four different parameters were investigated to determine what criteria would produce best deflector performance (all parameters are referenced to the bottom upstream edge of the deflector).

1) Lateral and Vertical Positioning - Initial investigations were conducted with a 5 ft high deflector, angled at 60 degrees and spanning the width of the basin. Lateral location was defined as the distance from the downstream end of the stilling basin (defined as the downstream end of the basin sidewalls) to the deflector. Lateral locations were varied from 0 ft to 14 ft. The best position for the deflector laterally along the length of the basin was determined by setting the deflector a specified distance from the end of the basin and then measuring average bottom velocities at the end of the basin. For each lateral position, the deflector was moved in vertical increments so that average bottom velocities could be measured for a range of deflector elevations for each flow condition tested. Deflector elevation was varied from 4 ft to 15 ft above the elevation of the basin floor (floor elevation 3889 ft).

Deflector performance was defined by comparing these velocities; i.e. the higher the velocity in the positive direction, the better the performance. Positive values indicated that average velocity was in the downstream direction, away from the basin.

Figures 6 and 7 show average bottom velocities measured as a function of deflector elevation for each lateral position tested for 40% and 60% gate opening, respectively. The figures demonstrate that best deflector performance occurs with the deflector located 5 ft to 6 ft upstream from the end of the basin walls and positioned at an elevation in the range of 3899 ft to 3901 ft.

2) Angle - Once the most effective range for lateral and vertical positioning was established, deflector angle was varied to determine best performance. For this case, lateral positioning was kept constant at 5 ft and deflector elevation was varied from 3896 ft to 3901 ft. Velocities were measured for deflector angles ranging from 40 to 90 degrees referenced from the horizontal plane as shown in Figure 2.

Figures 8 and 9 show that best performance occurs with the deflector angled at 80 or 90 degrees and with deflector elevation in the range of 3899 ft to 3901.

3) Size - The next step was to determine if the deflector could be reduced in size in order to reduce costs and still maintain performance. For this set of tests, deflector lateral positioning was kept constant at 5 ft and deflector elevation was kept constant at 3900 ft. Deflectors 3 ft and 4 ft in height were tested at 80 and 90 degrees. Figures 10 and 11 show that although performance is still acceptable for the smaller deflectors, it is reduced compared with the performance of the 5 ft deflector. After some discussion, it was determined the additional cost was insignificant compared to the increased confidence level in performance, and therefore the 5 ft deflector was selected for the final design.

As a result of these investigations, it was determined that best deflector performance, based on average bottom velocities measured at the downstream end of the basin, occurred with a 5 ft high deflector mounted 5 ft upstream from the end of the basin at elevation 3900 ft (11 ft above basin floor) and angled at 90 degrees.

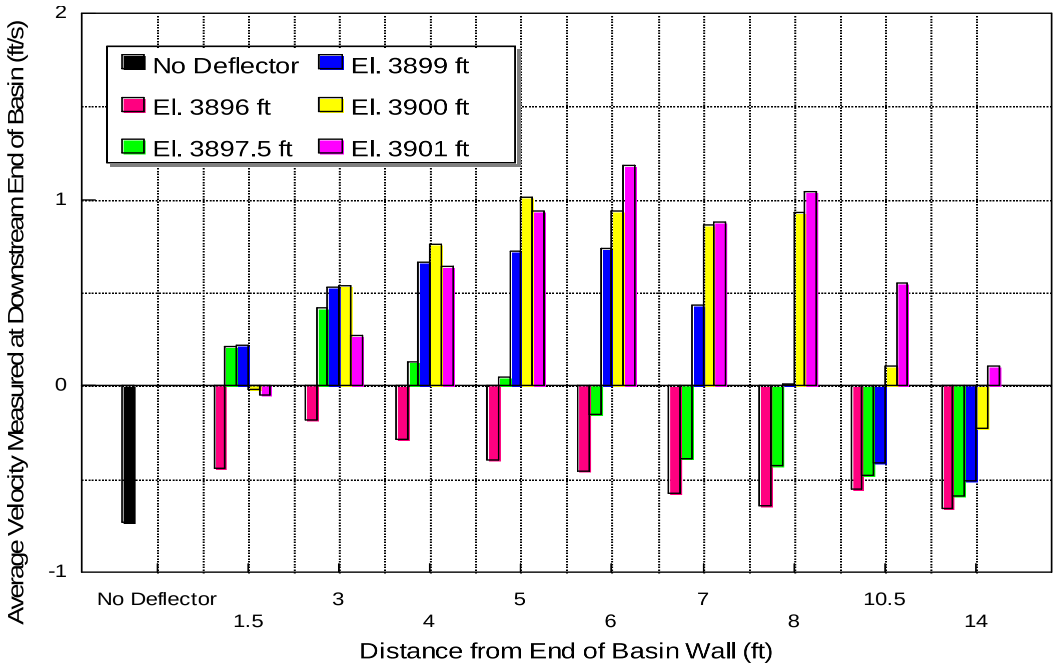

Figure 6. Average velocity versus lateral deflector positioning with deflector angled at 60 degrees and basin operating at 40% gate opening.

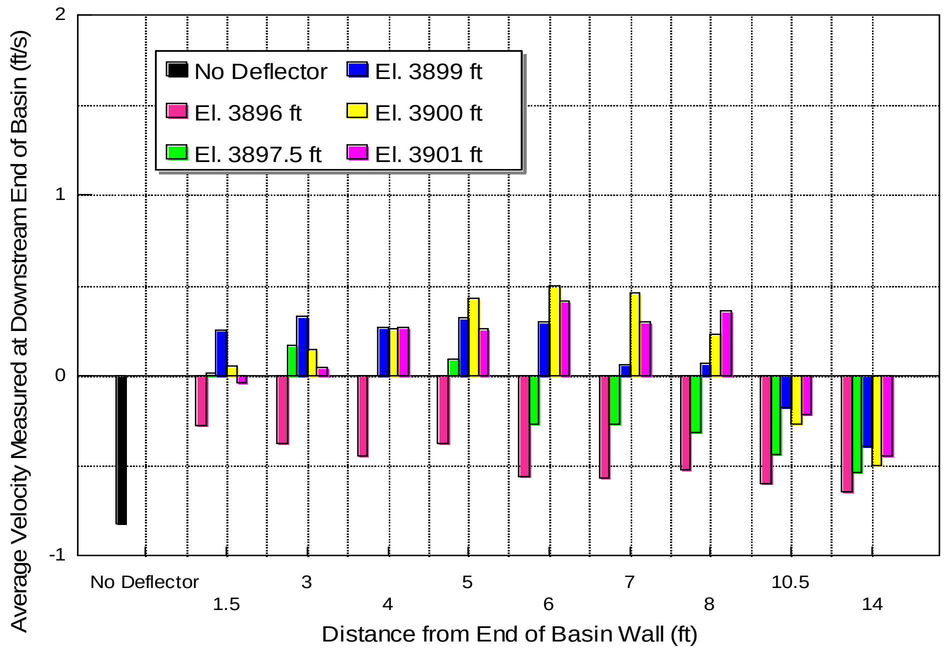

Figure 7. Average velocity versus lateral deflector positioning with deflector angled at 60 degrees and basin operating at 60% gate opening.

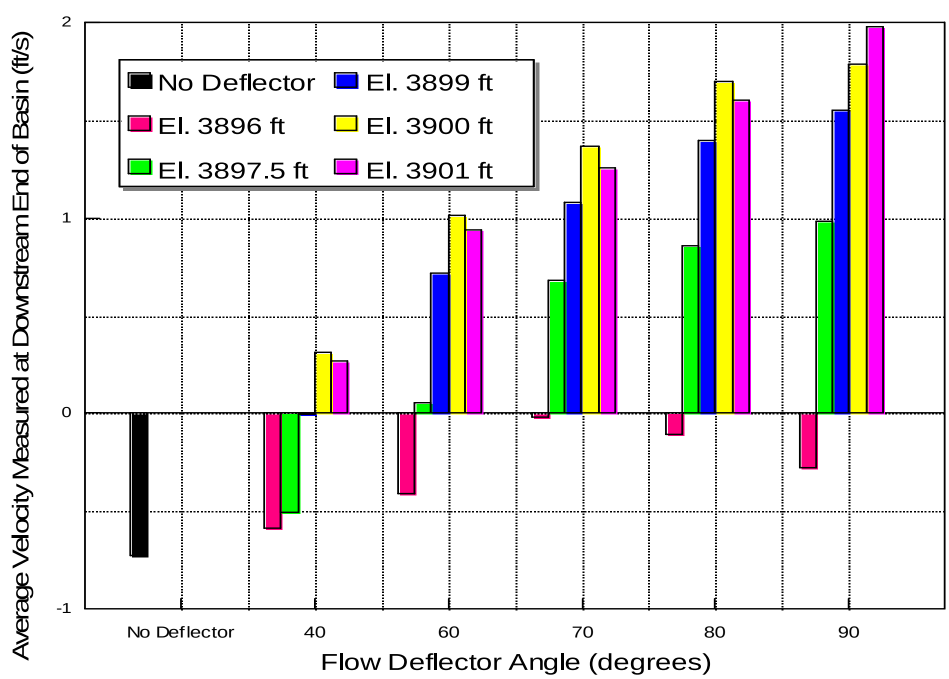

Figure 8. Average velocity versus deflector angle with deflector positioned 5 ft laterally and basin operating at 40% gate opening.

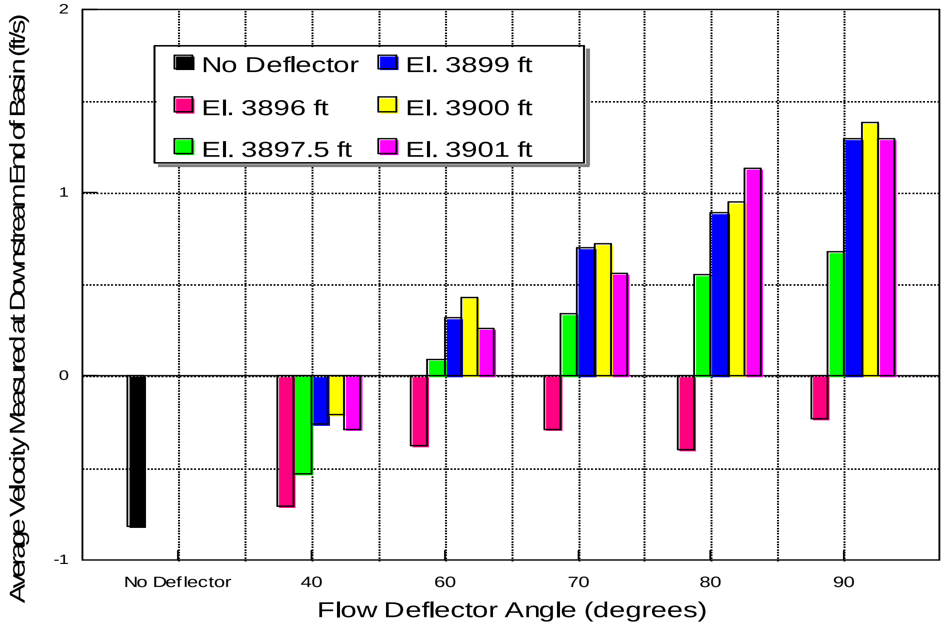

Figure 9. Average velocity versus deflector angle with deflector positioned 5 ft laterally and basin operating at 60% gate opening.

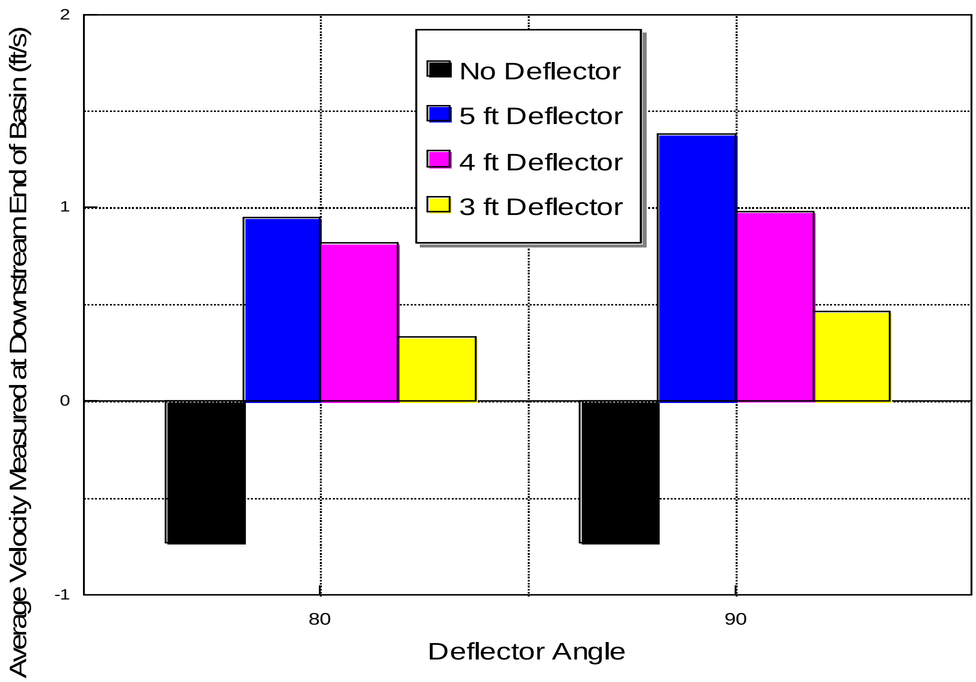

Figure 10. Average velocity as a function of deflector angled 80 and 90 degrees for a 3 ft, 4 ft, and 5 ft high deflector.

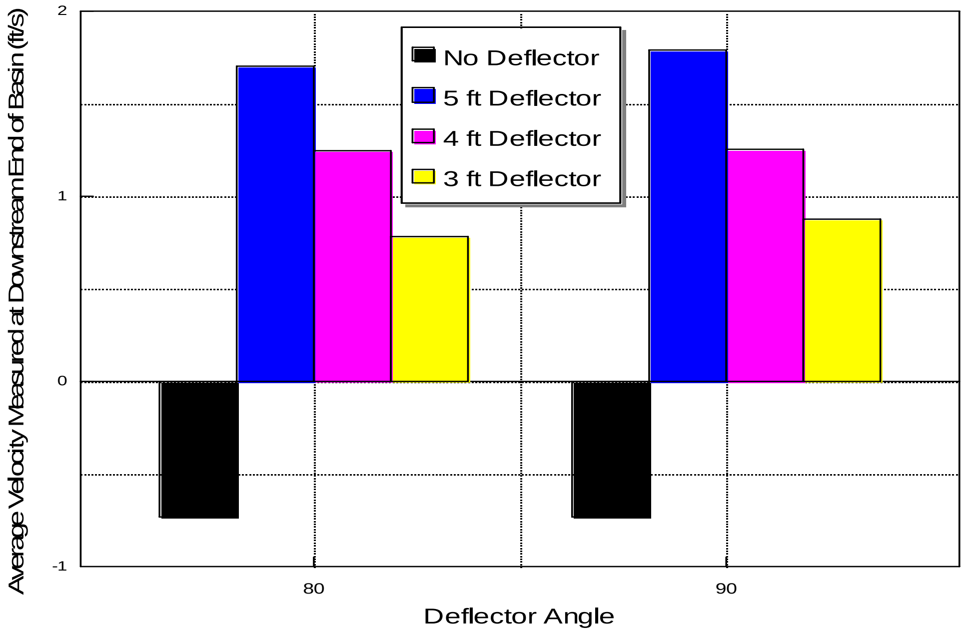

Figure 11. Average velocity as a function of deflector angled 80 and 90 degrees for a 3 ft, 4 ft, and 5 ft high deflector.

Deflector Loading

Piezometer taps installed on the upstream and downstream faces of the model deflector were used to measure differential loading. The maximum loads predicted for the prototype deflector were 6,000 lbs, 12,000 lbs, and 12,600 lbs respectively for basin operations of 60%, 80%, and 100% gate openings.

Overall Performance

After the optimal design parameters were set, it was important to look at deflector performance with the basin operating throughout the full range of possible discharges up to the maximum flow at 100% gate opening, in case unusual circumstances should require releases above those normally allowed while the deflector is in place. Table 2 shows the average bottom velocities measured without a deflector compared with those measured with the deflector set into optimal position for gate openings ranging from 20% to 100%. Table 2 shows that with the optimal deflector design in place, performance at gate openings ranging from 20% to 60% was very good. Average velocities for this range of discharge were greater than 1.0 ft/s and were directed in the downstream direction.

The table also shows that for gate openings of 80% and 100%, performance was reduced significantly; although still improved over having no deflector. Figure 12 demonstrates performance at higher discharges can be significantly improved by moving the deflector to a lower elevation. This could be accomplished with a mobile deflector supported on guides to allow vertical adjustments in position for operations at high and low discharges. However, since the outlet works will probably never be operated at these higher releases due to SOP limitations, the stationary deflector design positioned at elevation 3900 ft was determined acceptable.

Hydraulically Self-Cleaning Operations

Model investigations showed that without a deflector, materials can be flushed from the basin throughout the range of operations tested, due to the nature of the flow occurring within the basin. This phenomenon occurs because turbulence within the basin periodically tosses materials high enough into the water column to be caught and subsequently carried out by the main jet exiting the basin. However, these suspended materials often hit their fall velocity as they are exiting the basin and are deposited back onto the basin end sill; thereby making them readily accessible to be carried right back into the basin by the upstream current. As a result, for a large range of discharges, although materials are flushed out, the inflow of materials is constant, thereby resulting in significant abrasion damage.

Table 2. Basin performance with and without deflector.

	Average prototype velocity measured in model at end of basin with and without deflector (ft/s)	
Gate Opening (%)	No Deflector	Optimal Deflector at 3900 ft and angled at 90 degrees
20	-0.44	1.3
40	-0.73	1.8
60	-0.82	1.4
80	-0.88	-0.5
100	-0.69	-0.2

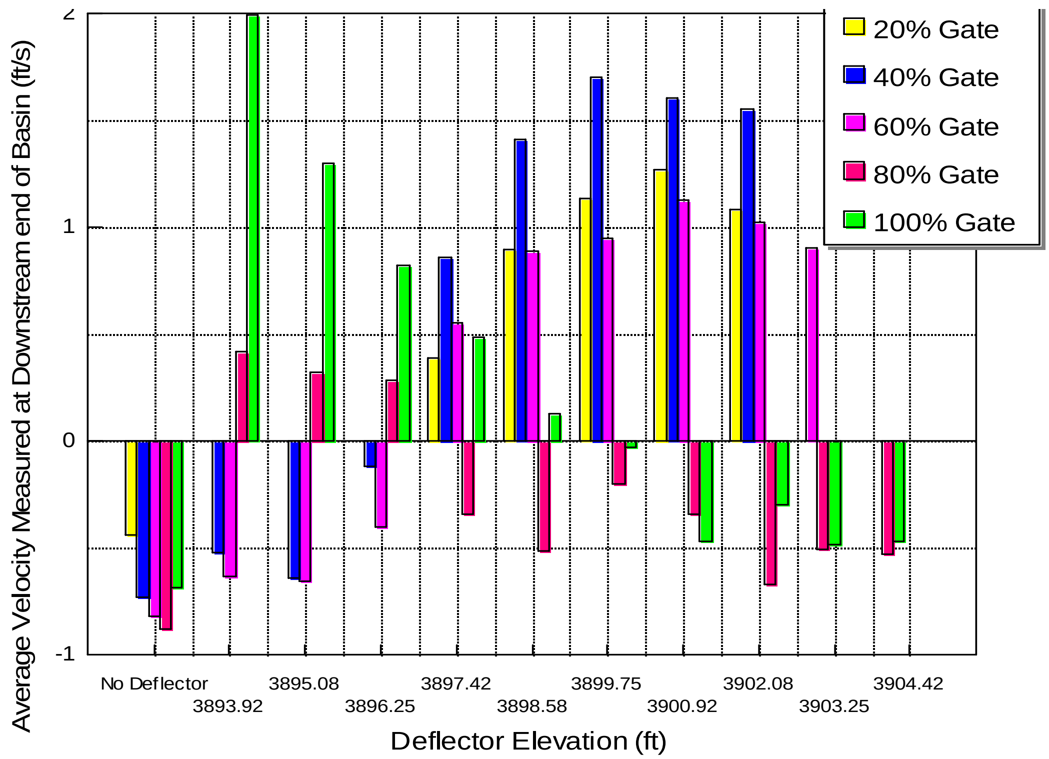

Figure 12. Average velocity versus deflector elevation (deflector angled at 80 degrees and positioned 5 ft laterally).

With the optimal deflector design in place, model investigations demonstrated that the upstream component of velocity at the end of the basin is no longer strong enough to carry a significant amount of material back into the basin; therefore most materials that are flushed from the basin will not be carried back in. As a result the basin potentially becomes hydraulically self-cleaning, thereby reducing abrasion damage significantly. The range of sizes of materials that can be flushed from the basin will depend on outlet works operations and will be determined more precisely in future studies.

Field Evaluation

The final prototype deflector for Mason Dam was designed with a set of guides that would allow the deflector to be manually adjusted in angle and elevation for testing purposes. The prototype flow deflector was delivered to Mason Dam and installed by the Baker Valley Irrigation District and Reclamation's Snake River Area Office in October of 2002 (Figure 13). In addition, basin abrasion damage was repaired with new concrete at the time the deflector was installed. In April of 2003, the deflector was set to optimal position as determined from the model study before seasonal operations began.

In August 2003, after nearly five months of basin operations with the deflector in place, a field evaluation and dive inspection were conducted to verify the effectiveness of the deflector.

An Acoustic Doppler Profiler (ADP) probe was installed by a dive team to measure exit velocities at the downstream end of the basin. The deflector was raised above the water surface and basin exit velocities were measured for outlet works operations ranging from 10% gate opening up to 60% gate opening at 10% increments. The same measurements were repeated with the deflector lowered to optimal position, with bottom elevation set to 3900 ft and angled at 90 degrees. Table 3 shows the discharge tested at Mason Dam compared with the discharge tested in the model for the same gate opening. The reason for the difference in values is because model study discharges were set based on maximum reservoir elevation, and the reservoir was actually 73 ft below that level at the time tests were conducted at Mason Dam.

Figure 13. Prototype flow deflector installation at Mason Dam in October 2002.

Figure 14 shows the average prototype velocities exiting the basin, measured at elevation 3891 ft (2 ft above the basin floor elevation) for each gate opening tested, with and without a deflector. The figure shows significant improvement in flow conditions at the downstream end of the basin with the deflector lowered into optimal position for gate operations from 10% to 30% gate opening. Average prototype velocities are greater than 0.75 ft/s and have changed from upstream in direction to downstream, with the deflector in place. However, for gate operations ranging from 40% to 60% gate opening, prototype velocities measured were inconclusive due to limitations of the ADP probe to accurately measure velocities when large quantities of air are entrained in the flow. The deflector was designed to redirect the main jet exiting the basin down toward the basin end sill. Therefore, at high discharges, when the jet is highly aerated, entrained air was also redirected downward towards the end sill where the ADP probe was located. As a result, accurate velocity measurements were not possible at the higher discharges.

Table 3. Prototype discharges tested in the model and at Mason Dam.

Gate Opening (%)	Prototype Discharge tested in Model - Corresponding to Maximum Reservoir (Elevation 4075 ft, ft^3/s)	Prototype Discharge tested at Mason Dam at Low Reservoir (Elevation 4005 ft, ft^3/s)
10	N/A	85
20	230	163
30	N/A	250
40	420	330
50	N/A	400
60	575	500

Divers conducting the initial underwater inspection in August 2003 found only a few small stones in the basin and noted that the new concrete was very smooth and in excellent condition, with no signs of any erosion or wear. A second dive inspection of the stilling basin was conducted in August 2004 after a second season of operations with the deflector in place. Again, the divers found only a few small stones (total of 4) throughout the entire basin. However, in addition they discovered that a thin layer of the new concrete (used to repair the basin in October 2002) was gone, exposing aggregate at its surface.

After spending some time examining photos of the basin floor and consulting with Reclamation concrete experts and divers who had conducted similar inspections, it was concluded there was no indication that the cause of the missing layer was due to abrasion. Several factors were sited as probable causes of this phenomenon including the fact that the concrete was exposed (despite an effort to protect it with a layer of hay) to temperatures well below freezing (5 degrees Fahrenheit) immediately following the laying of the new concrete. This likely caused the top layer to freeze before it had time to cure, thereby creating a weak top surface. In addition several dive team members had seen similar surfaces at Reclamation sites where there were no signs of abrasion damage or rocks in the basin, and erosion did not progress further in subsequent years.

A third dive inspection, conducted June 2005, showed no signs of abrasion damage and only a few stones in the basin, thus providing further evidence the deflector was performing as desired.

Figure 15 compares model and prototype average exit velocities, measured at elevation 3891 ft for each gate opening tested, with and without a deflector. The ADV probe used in the model study was not as sensitive to high air concentrations; therefore velocity measurements were possible for all gate openings tested. Although model and prototype discharges are not identical (due to low reservoir elevation during prototype testing) Figure 15 shows a strong correlation between model and prototype velocities measured at the same location for the same gate openings. Therefore, it would be reasonable to assume, with the field verified data already acquired, that the velocities measured in the model for gate openings ranging from 40% to 60% (with the deflector in place) are also a reasonable representation of prototype flow conditions; thereby demonstrating that the deflector is performing as desired, and reducing the potential for entraining materials.

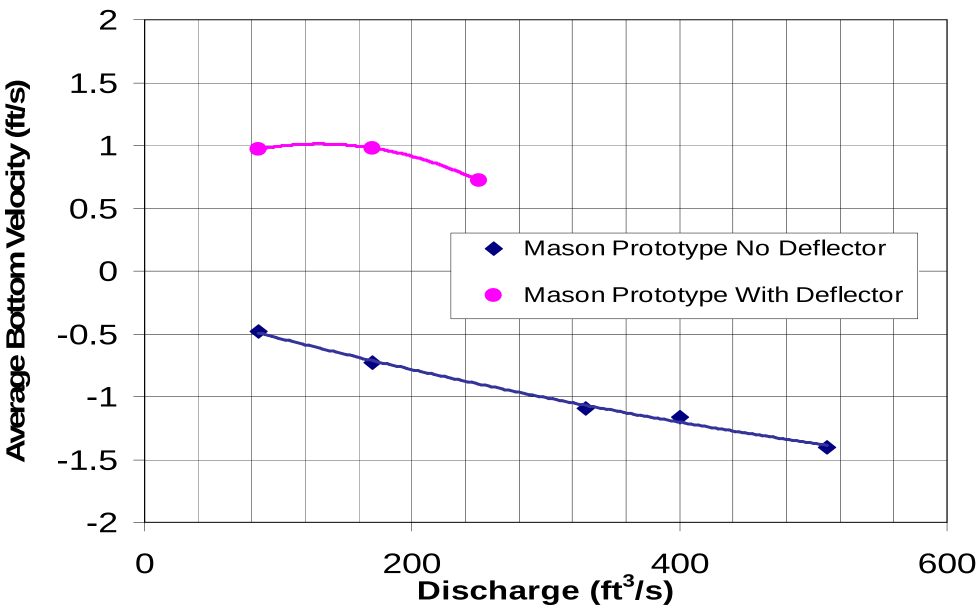

Figure 14. Average bottom velocity measured at El. 3891 ft at downstream end of Mason Dam tilling basin as a function of outlet works discharge.

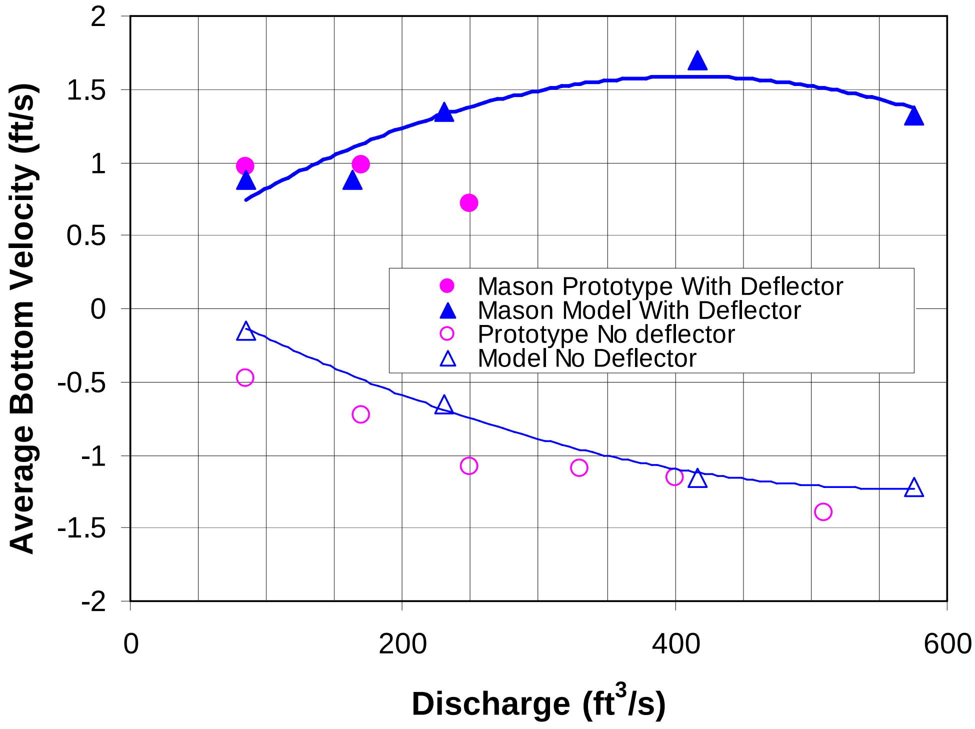

Figure 15. Comparison of average prototype exit velocities measured in the model and in the prototype with and without a deflector.

Generalizing Deflector Design for Widespread Applications

The model investigations and field evaluation were used to develop a method for generalizing flow deflector design for Reclamation Type II stilling basins and basins of similar design, based on velocity profiles measured at the end of the basin before a deflector is installed. In the future, velocity data measured on-site can be used to determine the optimal deflector design and location for a specific basin.

Optimal deflector design and position will vary over the operational range of most basins. Several practical approaches can be considered to achieve both economical and effective performance:

- One option is to design a stationary deflector to be effective for the most predominant range of basin operations. This would mean that when the basin was operated outside the deflector design range, materials may be drawn into the basin. In this case, it would be recommended that the basin be operated within the designated design range periodically, to help purge materials from the basin.

- A second option would be to design a moveable deflector supported on guides so that deflector elevation could be changed for different ranges of operations. In most cases this would require only two positions.

- A third option may be to install two separate deflectors staggered in position, both vertically and horizontally, so that flow conditions can be improved throughout the full range of operations without having to adjust deflector positioning. Preliminary research conducted by WRRL has demonstrated this may be a viable solution.

Implementation of any of the above options should significantly reduce the amount of damage caused by abrasion and the costs associated with basin repairs.

Details for determining optimal deflector design will not be released until after the patent has been awarded.

References

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