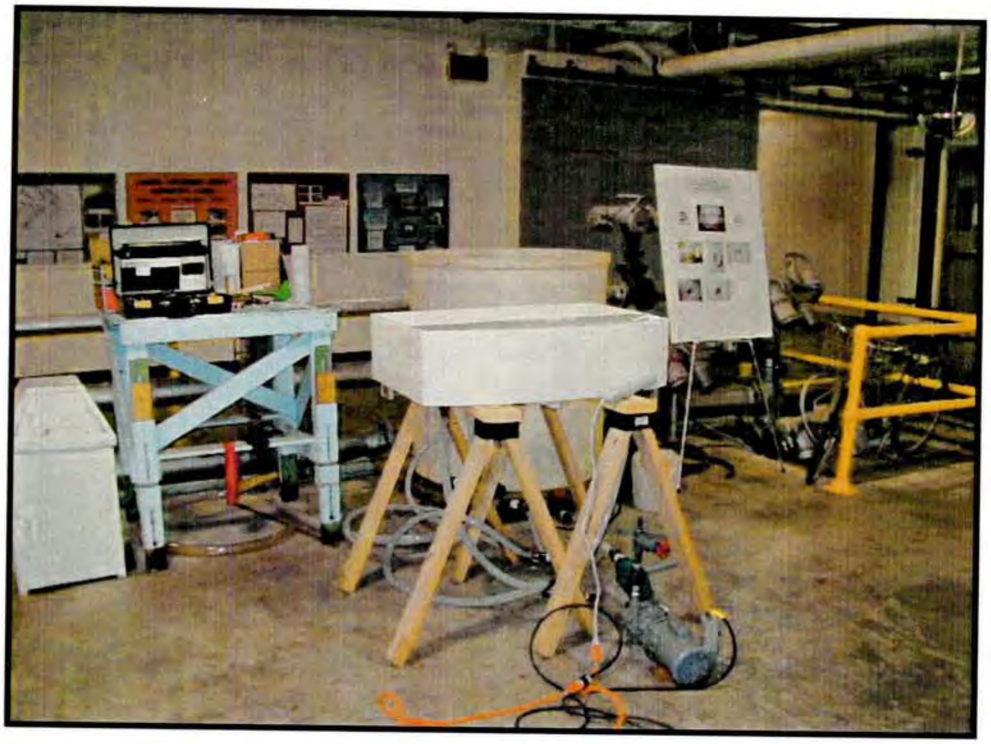
DENVER WATER

FOOTHILLS WATER TREATMENT PLANT

RESERVOIR OUTLET STUDY

November 1999



BATES
ENGINEERING

7333 W. Jefferson Avenue, Suite 155
Lakewood, Colorado 80235-2017
(303) 980-1212 Fax (303) 980-6300

PAP 829

ACKNOWLEDGMENTS

Lee Cesario of Denver Water and Robert Bates of Bates Engineering, Inc. developed the idea of testing the Foothills Water Treatment Plant Reservoir outlets while planning Reservoir 3. Jane Fisher served as the project manager for the Disinfection and Miscellaneous Improvements Project which incorporated the design and construction of Reservoir 3.

The hydraulic model was designed, installed and tested by David Woodward of Bates Engineering, Inc under the guidance of Lee Cesario and Robert Bates. The model was fabricated by AIA Plastics of Denver. Space rental, fabrication of antivortex devices, and miscellaneous testing equipment were provided by the U.S. Bureau of Reclamation Water Resources Research Laboratory and Research Lab Shop with the help of Dean Connor, Jerry Fitzwater and Dane Cheek under the oversight of Phil Burgi and Mike McDonald. Research information and antivortex device concepts were provided by Tracy Vermeyen, Research Hydraulic Engineer.

This report was prepared by David Woodward and reviewed by Robert Bates and Lee Cesario.

BATES
ENGINEERING

Letter of Transmittal

To:
Mr. Cliff Pugh, Acting Manager
Water Resources Research Laboratory (D-8560)
U.S. Bureau of Reclamation
P.O. Box 25007
Denver, Colorado 80225-0007

Date: November 17, 1999
Time: 9:01 AM

Project: Denver Water
Foothills WTP Reservoir Outlet Study
Re: Final Report

We are sending you: ☒ attached ☐ under separate cover by: Hand

Item No.	Quantity	Date	Description
1	1	11/19/99	Final Report

Purpose:
☐ For your approval ☐
☐ For your information ☐
☐ For your review and comment ☐
☐ As you requested ☐
☒ For your files ☐
☐ Return to your files ☐
☐ ☐

Remarks: Thank you again for all your help in performing this study!

Signed: David Woodward, P.E. Copies to: file

TABLE OF CONTENTS

EXECUTIVE SUMMARY

This report discusses the results of a hydraulic model study investigating formation of vortices at the outlets of Denver Water's existing and planned Foothills Water Treatment Plant Reservoirs. The purpose of the study was to recommend antivortex devices for both the existing Reservoirs 1 and 2 and for the planned Reservoir 3. The objective was to allow the reservoirs to operate at lower water levels by minimizing the detrimental impacts of vortices. This would effectively increase the usable storage in the reservoirs.

The model study was performed in cooperation with the U.S. Bureau of Reclamation using a 1:48 scale acrylic model. A total of 32 tests were performed from August 1999 through October 1999. The study recommends that either a horizontal grid be placed over the Reservoir 1 and 2 outlet sumps or that the sump be lengthened and partially covered. The study further recommends that the center of the outlet pipe for the planned Reservoir 3 be placed 18 to 24 feet from the reservoir wall and that a plate antivortex device be installed on the outlet pipe.

I. PURPOSE

The Foothills Water Treatment Plant currently has a capacity of 280 million gallons per day (MGD) and provides approximately 70% of the treated water produced by Denver Water. At the end of the treatment process, the water currently passes through two "hopper-bottom" reservoirs (Reservoirs 1 and 2) operated in a parallel configuration with gross storage volumes of 25 million gallons (MG) each. During a planned plant upgrade beginning in the year 2000, a third circular 25 MG reservoir will be added. The locations and orientations of these three reservoirs can be seen in Figure 1. The combined reservoirs will represent almost 20% of Denver Water's gross treated water storage of 372 MGD.

We understand that Reservoirs 1 and 2 are typically operated above the 15-foot level (measured from the floor) and rarely below the 10-foot level for three primary reasons. The first is that the reservoirs serve as a water quality buffer in case a change in demands produces a spike in chlorine, pH or other levels. The second is that since the two inlet pipes are located at the 15-foot level at the top of the sloping floor section, discharging below this level results in scour of treatment process debris near the inlet. The third reason is that vortexing occurs at the outlet at low water levels. The undesirability of operating in the lower ranges of the reservoir means that a significant amount of storage is effectively lost. Below the 10-foot level this amounts to about 8.2 MG or about one-third of the total storage. Denver Water estimates that system-wide more than 40% of the gross reservoir storage is lost for similar reasons.[1]

This report will solely address the issue of vortexing at the outlet. Issues of outlet scour and water quality buffering is beyond the scope of the study. In general, outlet vortexing is undesirable because of reduction in flow capacity, excessive air entrainment, turbulence and possibly vibration.[2] Denver Water is particularly concerned about its ability to blow off the entrained air in Conduit 27 which could lead to reduced flow capacity. In addition, operating the reservoirs at low levels can create problems with distribution system components. For example, treatment process debris drawn into the outlet by turbulent flows can clog downstream pressure reducing valve screens.

We understand from Foothills staff that air-entraining vortices occur at about the 8-foot water level. Based on our observations of Reservoir 1 on August 27, 1999, a well-defined swirl above the outlet was visible with water at the 23-foot level and 114 MGD flows.

Bates Engineering has previously performed two hydraulic model studies for Denver Water for the Colorow Reservoir and Marston Water Treatment Plant Basin 3. Due to the complexity of the vortexing problem at the Foothills Water Treatment Plant Reservoir outlets, a hydraulic model was also felt to be warranted to aid in the design of the antivortex devices. Bates Engineering proposed to provide research into vortex behavior followed by a laboratory hydraulic model study. The goal of the study is to recommend antivortex devices that maximize the usable storage in the reservoirs.

---

[1] Telephone conversation with Mr. Mike Ranger, Denver Water on September 3, 1999.

[2] U.S. Bureau of Reclamation, *Hydraulic Laboratory Techniques*, p. 80.

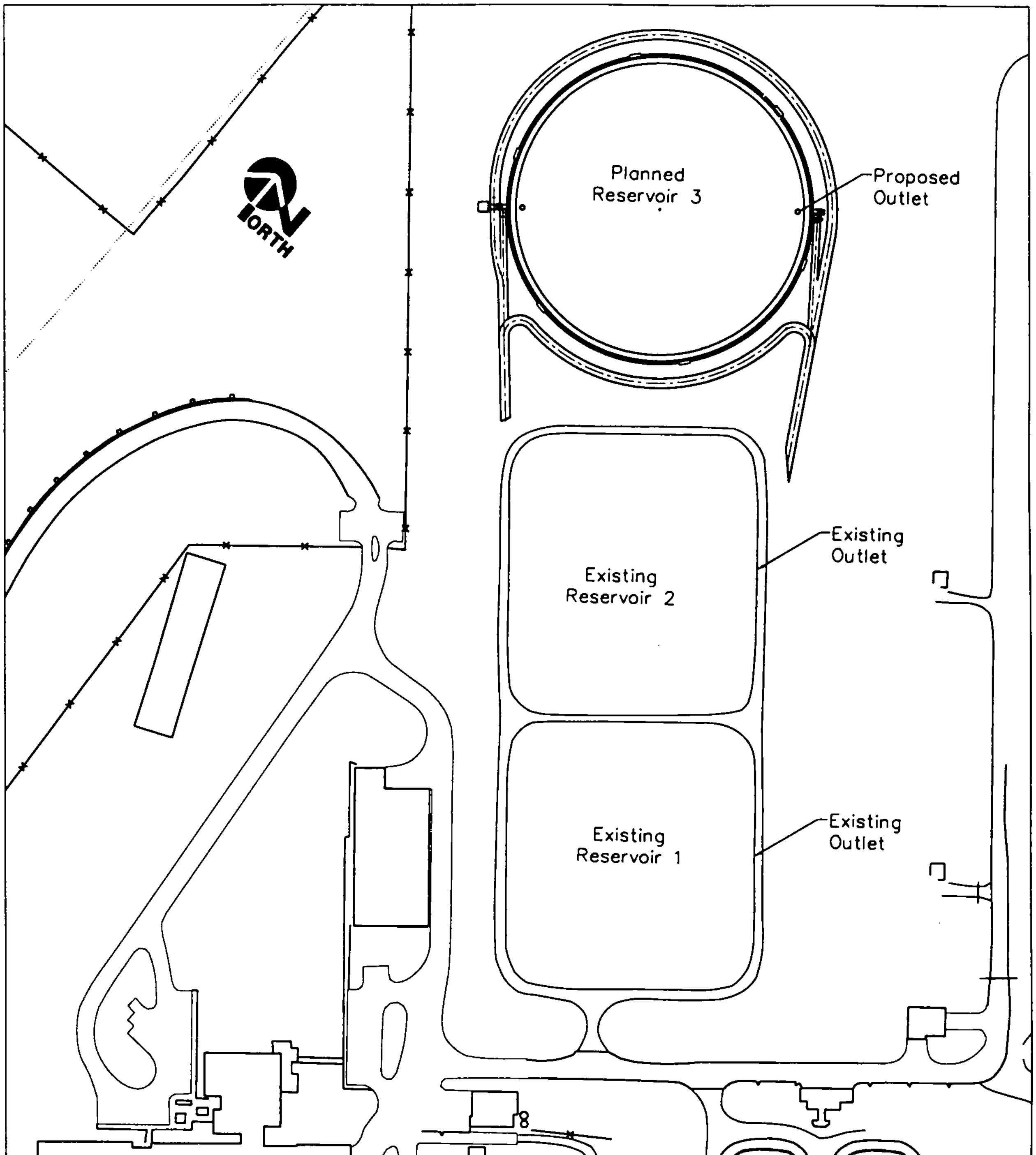
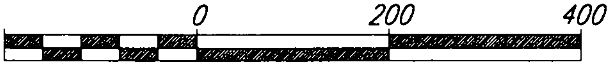


Figure 1
Foothills Treatment Plant Reservoirs



1" = 200'

II. VORTEX FORMATION AND CONTROL

Formation of Vortices

A vortex is defined as "a revolving mass of water in which the streamlines are concentric circles and in which the total head for each streamline is the same."[3] Vortices are part of a larger family of rotational flow phenomena that include swirls. The formation and mechanics of swirls and vortices is not completely understood. However, several interrelated factors are known to influence the extent of vortex formation in hydraulic structures. These include:

1. Outlet approach geometry
2. Outlet conduit size and orientation
3. Use of antivortex devices
4. Flow rate
5. Water depth

In general, swirls and vortices are related to eccentricities in the approach flow relative to the outlet.[4] These can be formed by an offset introduction of flow to the outlet (such as a sump), velocity gradients due to flow separation at changes in geometry of the approach flow, or obstructions, such as piers, near the outlet. Greater flow rates and lower water depths tend to increase the likelihood of vortex formation.

Researchers have documented six stages of vortex formation [5]:

1. Coherent surface swirl
2. Surface dimple
3. Dye core to intake
4. Trash to intake
5. Air bubble to intake
6. Full air core to intake

Stages 3 through 6 are defined by what the vortex is able to draw from the water surface down to the outlet, from tracer dye to a consistent air stream. An example of air bubbles being drawn into the model supply tank can be seen in Appendix A, Photo 3.

Vortices can be persistent or intermittent. They can be strong or they can be weak. Strength or severity is defined in terms of rotational speed, the quantity of rotating water, the size of the air core and the frequency of occurrence.[6] Though some vortices, particularly for pumps, can form from a submerged area, vortices affecting reservoir outlets will typically form from the free water surface to the outlet.

Detrimental Aspects of Vortices

Vortices can create detrimental hydraulic and structural conditions for hydraulic structures. Most of the difficulties are related to the turbulence and entrainment of air in the vortex. However, as one researcher points out, "it is relevant to remember that a vortex in itself is usually not the issue, but rather the

---

[3] American Water Works Assocation, *Glossary of Water and Wastewater Control Engineering*, 1981, p. 416.
[4] Knauss, p. 1.
[5] Knauss, p. 18.
[6] Zeigler, p. 10.

downstream flow characteristics it produces."[7] The following are specific problems have been associated with vortex formation on prototype structures.

1. Reduced discharge
2. Decreased efficiency of hydraulic machines
3. Movement of debris
4. Scour
5. Slug flow
6. Vibrations
7. Cavitation

Research has shown that discharge in conduits can be reduced by as much as 75% due to vortexing.[8] Air entrainment beyond three to four percent can reduce the efficiency of pumps.[9] The high local flow velocities associated with vortices can transport floating or settled debris resulting in scour or accumulation of debris in downstream conduits. Entrained air can accumulate in the downstream conduit, resulting in decreased flow capacity. Nevertheless, not all vortices result in these type of problems. Some hydraulic structures have experienced consistent formation of vortices without significant hydraulic or structural impacts.[10] The impacts of vortices also tend to decrease the further downstream the water travels as the flow becomes more uniform.[11]

We understand that the most persistent problems at the existing Foothills Reservoirs are the entrainment of air and the movement of treatment process debris.

Control of Vortices

Several approaches have been used to eliminate or control detrimental vortices. These are summarized below:

1. Maintain critical submergence over outlet
2. Deepen outlet
3. Alter approach geometry
4. Enlarge pipe size
5. Change pipe orientation
6. Provide antivortex devices

Critical submergence is defined as the depth of water over the outlet for which air-entraining vortices will not form. Various types of equations have been developed which attempt to define this depth in terms of outlet diameter, flow rate, velocity and Froude number.[12] However, these formulas tend to be general and do not result in a high degree of accuracy for the wide variation of outlet geometries existing.[13] In the case of a reservoir outlet, maintaining critical submergence is less desirable than other solutions due to the loss of storage associated with maintaining a large "dead" storage pool.

---

[7] Knauss, p. 140

[8] Posey, C.J. and Hsu, Hsieh-ching, "How the Vortex Affects Orifice Discharge," Engineering *News Record*, Vol. 144, No. 10, March 9, 1950.

[9] Knauss, p. 8.

[10] Hecker, p. 1255.

[11] Knauss, p. 140.

[12] Hecker, p. 1244.

[13] Knauss, p. 76.

Deepening the outlet is one means of maintaining a critical submergence without losing storage volume. Some researchers propose minimum sump dimensions for intakes.[14] The minimum submergence recommended for a horizontally exiting pipe is on the order of 1 1/2 D, where D is the outlet pipe diameter. For Reservoirs 1 and 2, this represents a minimum water level of 5 feet above the floor level. The minimum recommended width is 2D or 12 feet, which is greater than the current 10 feet. A wider sump would also keep average approach velocities closer to the recommended 1 foot/second. The minimum recommended sump length is 4D, or 24 feet, which is also greater than the 15 feet provided. Lengthening the sump is beneficial because it eliminates the turbulence associated with a vertical drop close to the outlet. At lower water levels the air which is entrained under the sump edge nappe can be drawn into the outlet. In the case of Reservoirs 1 and 2, altering the sump and outlet piping was expected to result in substantial expense, so this was not initially considered in the study.

Research has consistently shown that the approach geometry has a significant impact on the formation of vortices.[15] Reservoirs 1 and 2 have the disadvantage of being located adjacent to a tall vertical barrier (the wall). At low water levels, flows are effectively transported towards the outlet through a trapezoidal channel perpendicular to the wall. Thus the flow is required to make a sharp 90° left or right turn. This turning action provides the "seed" for vortex formation. Ideally, uniform, radial inflows are desired to prevent formation of vortices.[16] Making significant changes in the reservoirs' approach geometry was expected to be costly due to the large amount of interior concrete and earthwork which would be involved. For Reservoir 3, the ability to vary the outlet piping in the model and prototype gives some flexibility in inhibiting vortex action. The distance of the outlet piping to the adjacent wall also is an important factor in the approach geometry.[17]

Increasing the size of the outlet pipe decreases the average velocity through the pipe and would be expected to decrease the tendency for vortexing.[18] Again because Reservoirs 1 and 2 are existing, increasing the pipe size could be costly, so this option was also not pursued.

Many reservoir designers have attempted to inhibit vortex formation by placing 90° elbows on the outlet pipe oriented downward to the floor or into a sump. This effectively increases the flow path length (elongation of streamlines) which inhibits vortices. Though this has not decreased the *tendency* for vortices to form in previous model studies, it has proven effective in attenuating the persistent formation of air core vortices.[19] This outlet configuration would only be possible with the existing reservoirs if the sump were deepened. This alternate was not expected to be cost-effective compared with other antivortex solutions. For the planned Reservoir 3, this outlet configuration could be more easily achieved. However, in circular reservoirs, it is structurally undesirable to place large pipe openings through the lower portion of the wall. Other approaches were believed to be more efficient and cost-effective.

Based on the above considerations, control of vortices in the existing Foothills Reservoirs 1 and 2 initially focused on the use of antivortex devices. Vortex control for Reservoir 3 was planned to be approached by changing both the approach geometry (distance to the wall) and by providing an

---

[14] Prosser, p. 21.

[15] McBirney p. 19, Zeigler, p. 18.

[16] Amphlett, p. 9.

[17] Zielinski, p. 15, Amphlett, p. 9.

[18] Knauss, p. 154.

[19] Knauss, p. 149.

antivortex device at the outlet.

Antivortex Devices

Much of the information available on antivortex devices for outlets is based on hydraulic model research performed for pump intakes and morning glory spillways for large dams. Pump intakes are similar to Reservoirs 1 and 2 in that they are often placed in a sump and exit horizontally through an adjacent wall. Morning glory outlets are similar to Reservoir 3 in that flow moving primarily in a horizontal direction bends to pass through a vertical circular opening. The reservoir is different in that it will normally operate with a fully submerged crest so that pipe flow dominates rather than weir flow.

Antivortex devices commonly used for outlets can be broken into the following types[20, 21]:

1. Pipe End Modifications
   a. Cross
   b. Miter
   c. Bellmouth
2. Deflectors (fins) and Guide Vanes (piers)
3. Hoods (cover plates) and Horizontal Grids (rafts, grillages and lattices)
   a. Stationary
   b. Floating
4. Risers and Vertical Grids (outlet shafts, curtain walls)
5. Injectors

Pipe end modifications seek to disrupt the "tail end" of the vortex to prevent air from entering the outlet. Pipe crosses consist of orthogonal plates attached to the end of the vertically upward outlet pipe. Crosses are used as a standard antivortex device for high-velocity reservoir outlets designed by Bates Engineering. Two 18-inch high steel plates are welded at right angles at the center of the pipe to form the cross. Six inches of the plate extend downward into the pipe and 12 inches rise above the pipe. Though, one researcher recommends that the length of the antivortex plates be two pipe diameters or greater,[22] Bates Engineering has had successful experience with 12- to 48-inch-diameter reservoir outlets which extend a consistent six inches outside the pipe diameter. For pipes extending horizontally through a wall, vortex formation can be reduced by mitering the end of the pipe 45° so that the flow is forced to turn downward before exiting.[23] Bellmouths are used primarily for outlets facing vertically downward.[24]

Deflectors and guide vanes seek to make the flow more uniform upstream from the outlet in an attempt to inhibit vortex formation. Deflectors are typically flat plates placed near the outlet which disrupt flow patterns which encourage the formation of vortices. They can be oriented horizontally, vertically or at an angle. They are often placed at locations where flow separation leading to vortices is expected to occur. Vertical guide vanes are typically placed immediately around the outlet so that flow is encouraged to enter the outlet radially. By radially directing the flow inward, the vanes disrupt the circular flow patterns stimulating vortices. They are commonly used for low submergence outlets such as morning

---

[20] U.S. Army Corps of Engineers, *Hydraulic Design of Spillways*, p. 112.
[21] Zipparro and Hasen, p. 3.9.
[22] Zielinski, p. 7.
[23] Zielinski, p. 7.
[24] Zielinski, p. 9.

glory spillways, but can also be used for greater submergence depths.

Hoods and horizontal grids are horizontal surfaces placed above the outlet to suppress the most direct path from the water surface to the outlet. Hoods are solid members whereas grids allow water to pass through the horizontal surface. Thus hoods force any vortices to bypass the area, while grids can allow vortices through them depending on the grid sizing. Some researchers have suggested that hoods should be at least four pipe diameters wide.[25] The Bureau of Reclamation recommends that hoods and horizontal grids extend at least two diameters in front of and to each side of the outlet.[26] Horizontal grid openings should be sized so that the grid spacing is smaller than the vortex anticipated vortex diameter.[27] Hoods and horizontal grids can be located at a fixed height above the outlet or can be allowed to float with the water surface. Because grids allow water to pass, they can also be placed at the top of a sump without significantly increasing flow velocities near the outlet. Fixed, submerged grids were found more effective than floating grids in one study.[28]

Risers and vertical grids are vertical "conduits" above the outlet which isolate the outlet area from the approach area circulation patterns. Risers are solid conduits having discrete weirs or ports for inflows. Vertical grids have regularly-spaced openings. The conduit cross section can be circular, rectangular or curved depending on the approach condition and outlet type. Flows are directed inward through the openings and then downward to the outlet. Trashracks for large dams often function as vortex-suppressing vertical grids when relatively small opening sizes are used.[29]

Injectors introduce water into stagnant zones near the outlet to avoid low pressures leading to swirling of the water. They typically require a pumped injection system and thus are not necessarily practical for water storage reservoirs.

Many types of creative antivortex devices have been developed for specific outlet geometries which consist of variations and combinations of the above general types of antivortex devices. Often vertical and horizontal grids or hoods are combined in a single antivortex device.

Reservoirs 1 and 2 are currently equipped with hood over the outlet pipe in the sump. The hood is essentially one quarter of a steel drum with a diameter matching the 72-inch outlet pipe that extends four feet upstream from the valve. The half-moon bottom of the drum is oriented vertically so that flow has to pass under the long side of the half-moon. This devise effectively lengthens the flow path for vortex formation, but also congests the outlet sump and probably results in higher average velocities in the vicinity of the outlet pipe. Head losses are also believed to be relatively high with the existing hood compared with other types of antivortex devices. Nevertheless, in most outlet situations the head loss created by antivortex devices is of less concern than the impact of the vortices.[30]

Scale Modeling of Vortices

Both analytical and scale models are successfully used to predict prototype hydraulic behavior. However, due to the complexity of vortex formation, adequate computational fluid dynamic models are

---

[25] Zielinski, p. 11.

[26] U. S. Bureau of Reclamation, *Design of Small Dams*, p. 428.

[27] Zeigler, p. 26.

[28] Zeigler, p. 24.

[29] Zeigler, p. 16.

[30] Prosser, p. 16.

still in the early stages of development.[31] Consequently when vortex formation is of concern, designers have typically resorted to physical scale models.[32]

Four primary similitude laws govern scale modeling of vortices:

Froude - gravitational forces (deep open flow)
Reynolds - viscous forces (pipe flow)
Weber - surface tension (shallow open flow)
Kolf - circulation (shallow open flow)

Using water as a medium it is physically impossible to scale all four of these affects simultaneously due to the limited viscosity range of liquid water.[33] The majority of vortex models have been based on Froude scaling due to the predominance of gravitational and inertial forces. It is recognized that some "scale effects" may occur due to viscous effects, especially when antivortex devices are introduced. Some researchers have approached this by increasing Froude flow rates[34] or using correction factors.[35] Others have ignored the effects providing the Reynolds number at the outlet exceeds 3 x 10^4.[36] The Weber number for the majority of models will have an insignificant impact, especially in the Weber number is greater than 11.[37] It appears that the impact of the circulation number would only significantly influence outlets located near the center of circular tanks. In general, the larger the scale model, the less impact Reynolds, Weber and Kolf scale effects will have on the model results.[38]

Correlations between model and prototype vortex behavior have been studied by several researchers. In general there has been good correlation between the formation of vortices in Froude-scaled models and their prototypes. One author states that, "there is no reported case in which a negligible model vortex corresponded to a sufficiently strong prototype vortex that it produced operating problems."[39]

---

[31] Constantinescu and Patel, p. 537.
[32] Hecker, p. 1243, Knauss, p. 153.
[33] Knauss, p. 53.
[34] Hecker, p. 1253.
[35] Knauss, p. 85.
[36] Hecker, p. 1244.
[37] Knauss, p. 81.
[38] Jain, Raju and Garde, p. 1443.
[39] Hecker, p. 1255.

III. MODEL DESCRIPTION

Based on the experience of past research, Froude similitude was selected for this model. For Froude similitude, model lengths are scaled directly by the model scale factor, L_R. In order to permit use of scaleable PVC pipe fittings, a model scale factor of 1:48 was selected, so that, for example, a 1 1/2-inch diameter model outlet pipe corresponded to the 72-inch prototype outlet pipe. For Froude similitude, flow rates for the model are scaled by the five-halves power so that a 150 MGD prototype flow rate corresponds to a model flow rate of

$$Q_M = Q_P/L_R{}^{5/2} = 150 \text{ x } 10^6 / 48^{\,5/2}/(24*60) = 6.5 \text{ gallons per minute (gpm).}$$

Due to the relatively large model scale factor, the Reynolds number was 1 x10^4 which is less than the 3x 10^4 recommended to eliminate viscous scale effects and the Weber number was 8.2 which is somewhat less than the 11.0 recommended to eliminate surface tension scale effects. Thus the effects of viscosity and surface tensions could be expected to have some impact on the results, especially at the lower water levels.

In order to facilitate model testing, both Reservoirs 1 and 2 and Reservoir 3 were tested using a single model. Because the outlet approach geometry has a significant impact on the development of vortices,[40] a sizable area near the outlets was included in the model. One half of the model represents a 152-foot by 78-foot area around the Reservoir 1 and 2 outlets. The Reservoir 3 half of the model corresponds to a 152-feet chord of wall length with a clear distance to the wall of 97 feet. The resulting model dimensions were approximately 3 feet by 2 feet (see Figures 2 and 3). Columns were not expected to impact the vortexing action and were thus not modeled.

The model was fabricated from 1/2-inch white acrylic sheet. All of the wall and floor pipe penetrations were threaded with NPT threads for use with PVC pipe. Similar to the prototype Reservoirs 1 and 2, two 48-inch inlet pipe penetrations were located at opposite corners from the Reservoirs 1 and 2 outlet sump. However, the inlet pipe penetrations were drilled through the floor for simplicity. The Reservoirs 1 and 2 outlet pipe also served as the Reservoir 3 inlet pipe. Three 72-inch outlet pipe penetrations were drilled through the floor at 12, 24 and 36 scaled feet from the Reservoir 3 wall. Two wire cloth baffles were placed between the two halves of the model to dampen surface waves produced by the pumps.

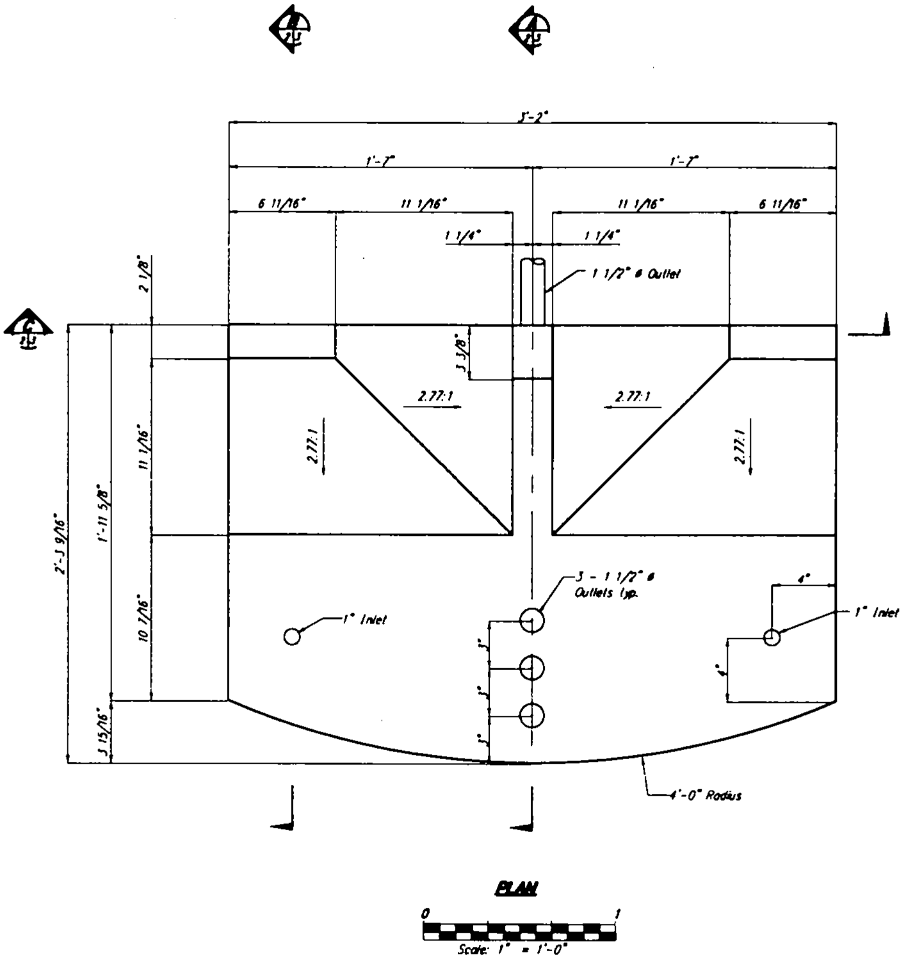
The model was placed on wood sawhorses at the U.S. Bureau of Reclamation Water Resources Research Laboratory in Lakewood, Colorado for testing (see Appendix A, Photo 1). Water was provided to the model using a 250-gallon plastic supply tank in conjunction with a 1/3 horsepower centrifugal pump. Water was drawn through the outlet with a 1/8 horsepower centrifugal pump and was discharged to a floor drain. Inflow and outflow rates were measured using valved, acrylic, panel-mount, 10-gpm King® rotameters. Plastic tubing and PVC fittings were used to connect the various model components.

The water level was generally set at 24 to 32 feet above the floor at the start of each test. Tests were typically run with an outlet flow of 6.5 gpm corresponding to the maximum normal prototype flow of 150 MGD. The inlet flow was generally set at 6 gpm so that the water level would fall gradually during the test. The inlet pump was occasionally turned off to speed up the testing process. Written observations of the mixing at the outlet were recorded at about two-foot intervals. Red Norlab® liquid powder tracing dye with a specific gravity of 1.0 was introduced with an eyedropper onto the water surface upstream from the sump and at another locations where flow patterns were to be observed. This

---

[40] Prosser, p. 40.

proved to be more effective in viewing flow patterns than using yellow or green dyes or confetti. Photographs were also taken periodically during the critical stages of the testing (see Appendix A). The tests were terminated when the outlet was no longer submerged (typically between a 0- and 4- foot water level).



Note: All dimensions are inside dimensions.

Figure 2
Foothills Reservoir Hydraulic Model Plan

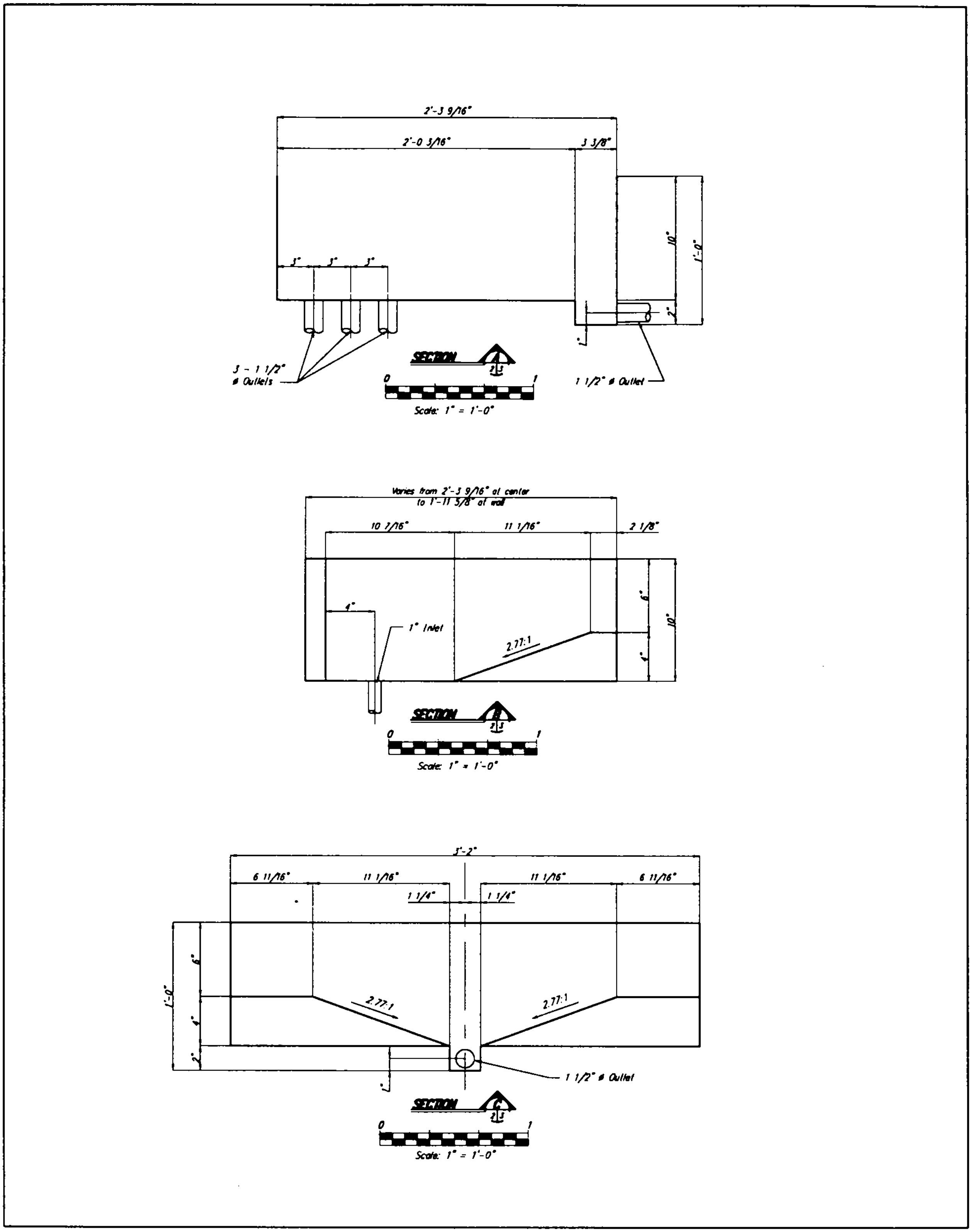


Figure 3
Foothills Reservoir Hydraulic Model Sections

V. RESERVOIRS 1 AND 2 TESTS

A total of 23 tests were performed to select an antivortex configuration for the existing Reservoirs 1 and 2 outlets. Two initial tests examined the existing reservoir outlet with and without the existing antivortex hood. Thirteen tests looked at various antivortex devices in lieu of the existing hood. At least one of each of the first four types of antivortex devices discussed above was tested. Because substantial performance improvements were not observed with the tested antivortex devices, the next four tests involved modifying the outlet sump geometry. The final four tests sought to verify the conclusions of the first 19 tests by examining the flow patterns near the outlet with the use of granular tracer materials.

Figure.4 summarizes the results of the tests performed for Reservoirs 1 and 2. The test number, antivortex device, prototype flow rate, water level at various vortex formation stages and general comments are listed. It should be noted that, contrary to the order of the six stages of vortex formation, the formation of a dye core in the model consistently preceded the formation of a dimple. In the figures, "bubbles" indicate that air was "blown back" through the outlet. "Turbulence" means that surface waves were visible in the model. "Collapse" means the outlet went from submerged orifice-type flow to open weir-type flow.

Detailed results and conclusions about each of the Reservoirs 1 and 2 tests are discussed below.

Existing Conditions (Tests 1 and 4)

The existing reservoir design includes a "shroud" or hood consisting of a 4-foot-long half cylinder mounted to the wall directly above the outlet pipe. The top of the 6-foot-diameter cylinder is flush with the top of the outlet pipe (Photo 6). This device appears to have been designed to minimize vortexing at the outlet. The model was tested both with and without the hood. The hood provides some swirl suppression at higher water levels (Photos 4 and 6) and vortex suppression at the lower water levels (Photos 5 and 7). However, the presence of the hood narrowed the flow path, so that the local flow velocities in the sump area were probably increased, resulting in increased turbulence and scour potential. In general though, the hood appeared to dampen rotational flow behavior.

These tests also clearly showed that vortices form at the outlet because the flow moving toward the sump is forced to turn to the left or right when striking the reservoir wall. The sharp turn creates a swirling motion that spawned vortices. As the water level decreased, flows were again required to make another right turn in the same direction as they struck the side slopes adjacent to the outlet. At very low water levels, the vortices tended to form in the two sump corners adjacent to the reservoir wall.

Pipe End Modifications (Tests 2 and 3)

These two tests extended the outlet pipe by adding a 90° upward pipe bend inside the sump in lieu of the existing hood. The model bend dimensions approximated the dimensions of an American Water Works Association Standard C208 72-inch, steel, five-piece bend. The addition of the bend alone actually encouraged vortex formation. The bend not only effectively raised the outlet elevation, but also provided a horizontal outlet surface which allowed the vortex to develop along a straight path between the water surface and the outlet (Photo 8). The second test added the standard antivortex plates used by Bates Engineering (Photo 9). The addition of antivortex plates improved the situation and decreased the swirl at higher water levels, but the performance at lower water levels was still less desirable than observed in the unmodified reservoir.

It should also be noted that the same antivortex plates were also briefly placed vertically at the mouth of the existing outlet pipe. This addition had little impact on the outlet hydraulics because the vortices easily passed around the plates.

Deflectors and Guide Vanes (Tests 7, 8, 10, 11, 13 and 14)

Various flow-directing schemes were modeled in an effort to counter the tendency for swirling and vortexing at the outlet.

Outlet channel modifications - Modifications to the floor geometry of the trapezoidal channel leading to the sump were the subject of two tests. The first involved placing a "check dam" in base of channel about half way between the upstream toe of the side slopes and the sump (Photo 13). The dam rose four feet above the channel floor and extended part way up the side slopes for a total width of 24 feet. It was believed that the addition of this deflector might slow the potentially high velocities along the floor of the channel which might scour reservoir debris into the sump. In fact, the dam only worsened the turbulence because it pushed water higher and then forced it around the barrier. The second test provided an approximately parabolic (ogee) crest from the upstream edge of the sump to the sump floor. The crest tended to smooth the flowlines at higher water levels, but only increased the turbulence at lower water levels due to the effective reduction in the sump length from about 13 1/2 feet to 10 1/2 feet.

Wall fins and piers - The addition of fins and piers along the reservoir wall in the corners of the sump where vortices were most commonly observed was the subject of two tests. The first placed thin, 8-foot-high, 2-foot-wide fins 45° from the wall both towards and then away from the sump. The second test added 7-foot-high, 4-foot-wide nose piers. Both devices simply moved the vortices inward into the sump, without appearing to decrease the intensity of these vortices.

Guide Vanes - In order to straighten the flow at the outlet sump, radial vanes were placed at 45° around the outlet which extended to a height of 6 feet above the floor based on recommendations of Bureau of Reclamation personnel. A solid hood was placed on top of the vanes (Photo 12). Vortexing continued to be a problem at higher water levels, but at lower levels, the vanes decreased the turbulence by guiding the flow more radially toward the outlet. Because the 6-foot guide vanes did not work effectively at higher flows, the guide vanes were extended up to 16 feet and the hood was extended an additional four feet from the wall (Photo 15). These taller and wider vanes performed more satisfactorily than the first vanes, but relatively strong vortices still formed near the walls and even between the vanes.

Hoods and Horizontal Grids (Tests 6, 9, 12 and 15)

A hood which matched the outlet sump size (10' x 13 1/2') was placed over the sump three feet above the floor level. Surprisingly, vortex formation started at higher elevations and was stronger at all water levels than the existing reservoir. This may have been due to the fact that the flow velocities entering the sump were higher than other comparable antivortex device configurations. Based on observations from other tests, it was believed that simply moving the hood up would only increase the likelihood of vortex formation. Extending the hood a certain number of pipe diameters beyond the limits of the sump was felt to be impractical due to the large size which would be required. It was thus concluded that simple hoods would not be effective in breaking up the vortex.

Horizontal grids were placed over the sump opening at the floor level. Based on results of previous studies, the grid size was initially set at about one fourth of the diameter of the outlet pipe.[41] Wire cloth with 1/4-inch x 1/4-inch openings corresponding to 1' x 1' openings in the prototype was tested. The test showed the same tendency for vortices to form at high water levels as the existing reservoirs, but these vortices were suppressed. In addition, the grid appeared to create a more uniform distribution of flow around the outlet sump at low water levels which was believed would result in less scour in the prototype (Photo 11). A 1/8-inch-square wire cloth corresponding to a 6" x 6" prototype grid was then tested to see if any improvement in performance could be obtained by a slightly tighter grid. The performance was similar to the 1' x 1' grid, so it was determined that there would no need for closer grid spacing.

A variation of the horizontal grid concept was the fanned grid. The grid was also 10' x 13 1/2' in plan, but rather than having square openings, the members were placed radially from a point above the sump (Photo 14). The depth of the radiating members was two feet. This configuration did tend to push the center of vortex formation away from the area immediately above the outlet, but it did not appear to decrease the intensity of the vortex for a given water level compared to the existing reservoir.

Risers and Vertical Grids (Test 5)

In general it was felt that risers and vertical grids would not be practical for Reservoirs 1 and 2 because of the complexity and cost of construction and operation of a structure that might be up to 40 feet in height. However, a vertical grid was tested which consisted of a 1/4 inch wire cloth placed vertically in the sump around the outlet pipe to a height of 20 feet. A square horizontal hood was placed above the wire cloth, because previous research had determined that this was necessary to prevent vortices from passing through the top.[42] The grid did have a positive impact in encouraging radial flow and lowering the elevation at which swirls were observed. However, at the 9-foot water level, a swirl developed inside the vertical grid (Photo 10). This was felt to be an unacceptable hydraulic behavior. No further attempts were made to improve this configuration.

Extended Sump (Tests 16 - 20)

The model sump was extended to the edge of the reservoir side slope. This lengthened the sump from 15 feet to 52 feet (Photo 16). Acrylic plates were used to cover the width of the sump over various lengths to determine is an optimal sump length and distance from the wall could be found.

In two tests, the sump was opened from 8 feet from the wall to 20 feet from the wall for a total open length of 12 feet, and from 16 feet from the wall to 32 feet from the wall for a total open length of 16 feet. Both of these configurations allowed relatively strong vortices to be carried into the open portion of the sump and down the covered portion of the sump without significant breakup of the vortex, although the more distant sump exhibited a slightly weaker vortex (Photos 19 and 20).

Another test left the sump 100% open from the wall (0 feet) to the edge of the reservoir side slope (52 feet). Weak vortices still formed near the outlet (Photo 17), but much more of the flow entered at the upstream end of the sump so that less flows were available for the rotating mass of water near the wall. At low water levels, most of the flow passed through the end of the sump and moved relatively uniformly down the sump to the outlet (Photo 18). A final test left the sump open from 32 feet from the wall to 52 feet from the wall for a total open length of 20 feet. This configuration eliminated the weak vortex near

---

[41] Zeigler, p. 26.

[42] Conversation with Tracy Vermeyen, U.S. Bureau of Reclamation Water Resources Research Laboratory, September 1999.

the wall which developed with the completely open sump. A vortex still did form at the downstream end of the open portion of the sump, but by the time this vortex had reached the outlet pipe at the wall, it had become completely "unbraided" so that flow was relatively uniform entering the outlet pipe (Photo 21).

Granular Tracer Testing (Tests 20-23)

Because of Denver Water concerns regarding scour of treatment debris into the outlet, the final set of tests on Reservoirs 1 and 2 were performed to observe the flow patterns in the area immediately around the sump. These were performed for the existing reservoir, the existing reservoir with the 1' x 1' grid and the 32'-52' extended sump. For the first two tests, both a pea gravel and a concrete sand were placed about 1/8 inch thick and in a 1-inch-wide band around the 32'-52' sump perimeter. The pea gravel did not move until the water level dropped to 3 feet, so then concrete sand was then tested. Sand began to flow into the outlet sump at the 5-foot level and was very turbulent at the 1-foot level (Photo 24). The next test was performed using concrete sand with the existing reservoir conditions including the hood. Sand began to move toward the outlet at 6 feet and was very turbulent at 3 1/2 feet (Photo 22). With the addition of the 1' x1' horizontal grid, the sand began to move at about 5 feet and was very turbulent at 2 1/2 feet (Photo 23). Thus, the addition of the grid improved the velocity distribution the equivalent of one additional foot of water. This verified the effectiveness of the grid. The 32'-52' sump exhibited even less turbulence. This is presumably due to the ability of water to more uniformly enter this larger sump. It was concluded that the grid helps reduce local turbulence, but an enlarged sump away from the wall is even more effective in producing uniform flow into the outlet pipe.

Figure 4
Foothills Reservoirs 1 and 2 Tests

		Outflow			Depth at Formation (feet)				Comments
Test #	Antivortex Device	(MGD)	Swirl	Dye Core	Dimple	Bubbles	Turbulence	Collapse	
1	None	150	22	16	4		6		
2	90° Bend	150			11				Encourages vortex formation
3	90° Bend/Antivortex Plat	150	12		10	6	4	3	
4	Existing Hood	150	20		6	5	4	2	Minimizes vortex; creates turbulence
5	Vertical Grid	150	9				3	2	
6	1' x 1' Horizontal Grid	150	16	6	10				
7	6' Guide Vanes	150	20	11	None		4	2	Smooths flow at lower water levels
8	Exist. Hood/Check Dam	150			6		6		Increase turbulence at lower water levels
9	Fanned Grid	150	23	15	8			3.5	Square grid more effective
10	Ogee crest	150							No improvement for flows under 4'
11	16' Guide vanes	150	24		5			3	Vortices at wall still form
12	6" x 6" Horizontal Grid	150							Similar to 1' x 1' Grid
13	Wall Deflectors	150							Only moves vortex
14	Wall Piers	150							Only moves vortex
15	Solid Hood	150		24	20				Worsens vortex
16	Sump (0-52 feet)	150	24	20	17	4	4	0	
17	Sump (8-20 feet)	150	24	16	10		4	1	Vortex more pronounced
18	Sump (16-32 feet)	150	24	24	20		5	2	
19	Sump (32-52 feet)	150	20	20	18		4	2	Vortex breaks up before reaching outlet
20	Sump (32-52 feet)	150							Pea gravel tracer
21	Sump (32-52 feet)	150							Concrete sand tracer
22	Existing Hood	150							Concrete sand tracer
23	1' x 1' Horizontal Grid	150							Concrete sand tracer

RESERVOIR 3 TESTS

A total of 9 tests were performed to select a wall offset and antivortex device for the planned Reservoir 3 (see Figure 5). The first, third and fifth tests looked at three offsets without any antivortex device. The second, fourth and sixth tests looked at these same three offsets with the standard antivortex plates. The final three tests verified the selected offset and antivortex plates for three other flow rates.

Variable Distance of Outlet to Wall (Tests 1, 3 and 5)

These tests were performed to determine the optimal distance from the wall for the outlet without the use of an antivortex device. With the outlet located closest to the wall (12 feet), the impact of the flow hitting the wall and being forced to turn was apparent as it was in Reservoirs 1 and 2. This turning motion tended to spawn the formation of a vortex (Photo 25). For the case of the outlet farthest from the wall (36 feet) the vortex tended to be "swept away" towards the wall due to the high surface flow velocities (Photo 26). However, an insidious broad swirl began forming at high water levels which reinforced vortex development as the water level dropped (Photo 27). Thus the distance from the wall also increased the tendency for the water to vortex because it allowed a large rotational mass of water to develop. One other negative aspect also developed at this large distance from the wall: a dead zone developed near the floor against the wall behind the outlet. The flow velocities in this zone were very slow. This tendency was also noted in previous model studies performed by Bates Engineering.[43] A compromise between the detrimental aspects of being either too close or too far from the wall was the 24-foot offset (Photo 28). The swirl and formation of the air core for this offset occurred at lower water levels than for either the 12-foot or 36-foot offsets.

Variable Distance of Outlet to Wall with Antivortex Plates (Tests 2, 4 and 6)

The addition of standard antivortex plates consistently lowered the water level where swirls, dye cores and dimples developed for all three wall offsets. It also completely eliminated the air core vortices that occurred in each of the unprotected outlets (Photos 29 and 30). No further investigation of other types of antivortex devices was thus felt to be warranted.

The relative improvement in hydraulic performance due to the addition of the antivortex plates was more marked as the outlet moved away from the wall. This presumably is the case because the antivortex plates perform optimally when the vortex is formed by a well-organized rotational mass as opposed to the more random flow patterns created by the turning motion at the wall.

Selected Outlet with Varying Flow Rates (Tests 7, 8 and 9)

Because it appeared that the 24-feet offset with the antivortex plates produced the best hydraulic performance, this configuration was tested at alternate flow rates of 50 MGD, 100 MGD and 175 MGD, in addition to 150 MGD. 175 MGD was the maximum flow permitted by the model outlet pipe pump. At 175 MGD the water surface flow velocities were increased such that the vortex had an even stronger tendency to be "swept away" towards the wall at higher water levels. Unlike the 150 MGD flow rate, some air was intermittently drawn into the outlet at water levels less than 6 feet. At 100 MGD and 50 MGD, swirls developed at progressively lower water levels. A surface dimple never formed. "Collapse" to weir-type flow occurred at the 1- to 1 1/2-foot level. Flows were generally very uniform and radial.

---

[43] Bates Engineering, Inc., "Treated Water Storage Reservoir Hydraulic Model Mixing Study," prepared for Denver Water, Denver, Colorado, November 1996.

Figure 5
Foothills Reservoir 3 Tests

		Outflow	Distance to		Depth at Formation (feet)				
Test #	Antivortex Device	(MGD)	Wall (feet)	Swirl	Dye Core	Dimple	Air Core	Collapse	Comments
1	None	150	12	32	20	10	6	2.5	Wall encourages tight swirl
2	Antivortex plate	150	12	18	20	9	none	3	
3	None	150	36	24	18	14	12	3	Broad swirl due to large wall distance
4	Antivortex plate	150	36		14	12	none	3	
5	None	150	24	21	14	14	4	2	
6	Antivortex plate	150	24	20	15	12.5	none		
7	Antivortex plate	175	24	26	16	12.5	intermittent	3	High surface velocities "wash away" swirl
8	Antivortex plate	100	24	20	12	none	none	1.5	
9	Antivortex plate	50	24	18	12	none	none	1	Flow very uniform and radial

VI. CONCLUSIONS

RESERVOIRS 1 AND 2

Many previously successful antivortex devices were tested on the Reservoirs 1 and 2 outlet with only moderate success. It was concluded that the primary factor influencing outlet hydraulics is the approach flow condition. The fact that the outlet is adjacent to a wall and that as the water level decreases flows are increasingly channelized so that strong rotational patterns are developed is difficult to overcome with the simple addition of antivortex devices. The pipe end modifications, deflectors and hood did not appreciably improve the performance. Horizontal and vertical grids and guide vanes did improve the performance at various flow levels. It is believed that the most economical improvement can be made with the addition of a horizontal grid over the outlet. Because the 6" x 6" grid did not show any observable improvement over the 1' x 1' grid, the latter size is appropriate. Some additional benefit may be derived by adding vertical depth to the grid.

Lengthening the sump allowed flow patterns to be improved significantly, but also involves more extensive construction and greater cost than the simple addition of an antivortex device. The further the sump is moved away from the wall toward the upstream toe of the reservoir side slope, the better will be the hydraulic performance of the outlet. A longer sump opening is preferable to a smaller sump opening.

In summary, antivortex devices will have some positive impact on flow performance of Reservoirs 1 and 2, but to significantly improve flow patterns at the outlet, some type of reconfiguration of the outlet approach geometry will be required.

RESERVOIR 3

Reservoir 3 represents an improvement in the conditions found in the existing Reservoirs 1 and 2. The constant height of the reservoir and the ability to locate the outlet at some distance from the wall improves the chances of developing uniform, radial flow at the outlet. This decreases the opportunities for vortex formation.

It appears that there are three primary factors influencing the selection of the distance of the outlet pipe from the wall. Broad rotational flow patterns and the creation of stagnant zones near the wall are detrimental phenomena that increase as the outlet wall offset increases. Strong, turbulent vortices immediately above the outlet are developed if the outlet is located too close to the wall. An intermediate offset between these two extremes should develop optimal hydraulic performance. Based on interpolations between the behaviors of the three offsets tested, the outlet pipe should be offset three to four pipe diameters from the wall.

The addition of the standard antivortex plates improved the outlet hydraulic performance at all offsets and water levels and eliminated the formation of air core vortices for flows up to 150 MGD. These antivortex devices are economical to fabricate, install and remove and should be used regularly when vortexing is anticipated at an outlet.

VII. DESIGN RECOMMENDATIONS

The following are recommended for Denver Water's Foothills Treatment Plant Reservoirs outlets:

RESERVOIRS 1 AND 2

There appears to be three levels of opportunity for minimizing the impacts of vortices in Reservoirs 1 and 2. They are listed in increasing order of construction complexity and cost. These three alternates are shown in Figure 6.

1. **No Changes** - Leave the existing hood in place. The hood does serve to suppress vortices to some extent.

2. **Horizontal Grid** - Place a 1' x 1' horizontal grid over the top of the sumps. Fabricating the grid one foot deep may provide additional breakup of high velocity and vortexing flows around the edges of the sump. The existing hood should be left if place. The grid will need to be designed around the existing valve stems, ladder and handrailing. Somewhat higher head losses through the outlet should be expected. This alternate is expected to decrease scouring of debris into the outlet by developing a more uniform flow velocity distribution.

3. **Longer, Covered Sump** - Extend the sump away from the wall as far toward the upstream toe of the reservoir side slope as possible. Cover as much of the top of the sump as possible, but leave at least 20 feet of length open at the upstream end of the sump. Remove the existing hood. This configuration is expected to develop an even more uniform velocity distribution at the outlet due to the lack of adjacent vertical barrier (the wall) and the minimization of channelized flow in the upstream channel. The rotational flow of the swirls and vortices which develop are expected to greatly diminish in energy by the time the flow reaches the outlet pipe due to the tendency for uniform flow conditions in the covered portion of the sump.

An evaluation of the potential costs for each of the options based on the expected benefits derived should permit selection of the appropriate alternate. If outlet flow conditions deteriorate over time due to increased demands or peak flows, the next opportunity level can be implemented.

RESERVOIR 3

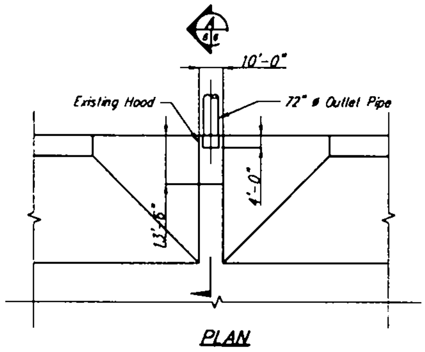
The Reservoir 3 outlet design should incorporate the following:

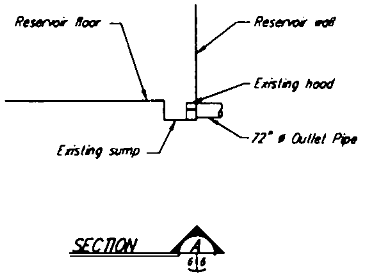
1. The center of the outlet pipe should be placed **18 to 24 feet from the reservoir wall.**

2. Standard **antivortex plates** should be installed on top of the outlet pipe.

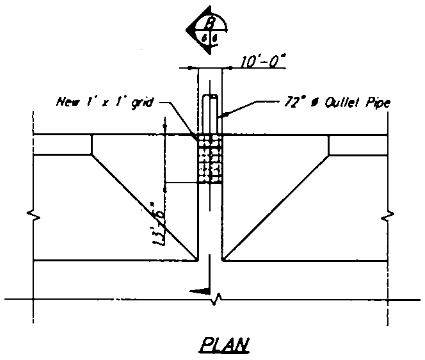
These two recommendations are shown in Figure 7. The recommendations are expected to minimize vortex behavior at the outlet.

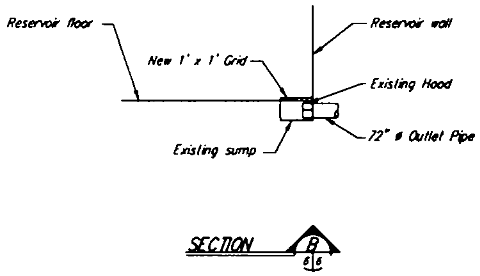
Alternate 1: No Changes



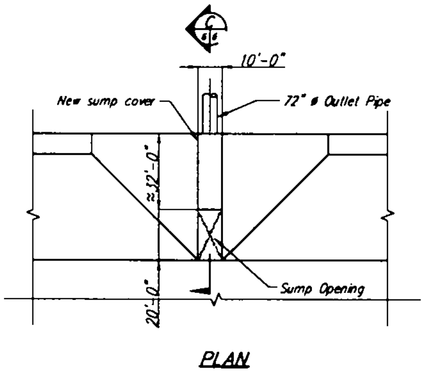


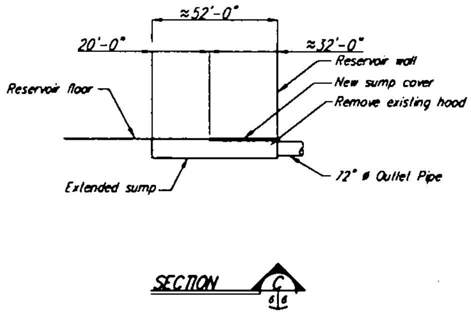
Alternate 2: Horizontal Grid over Sump





Alternate 3: Longer, Covered Sump





N.T.S.

Figure 6
Foothills Reservoirs 1 and 2 Recommendations

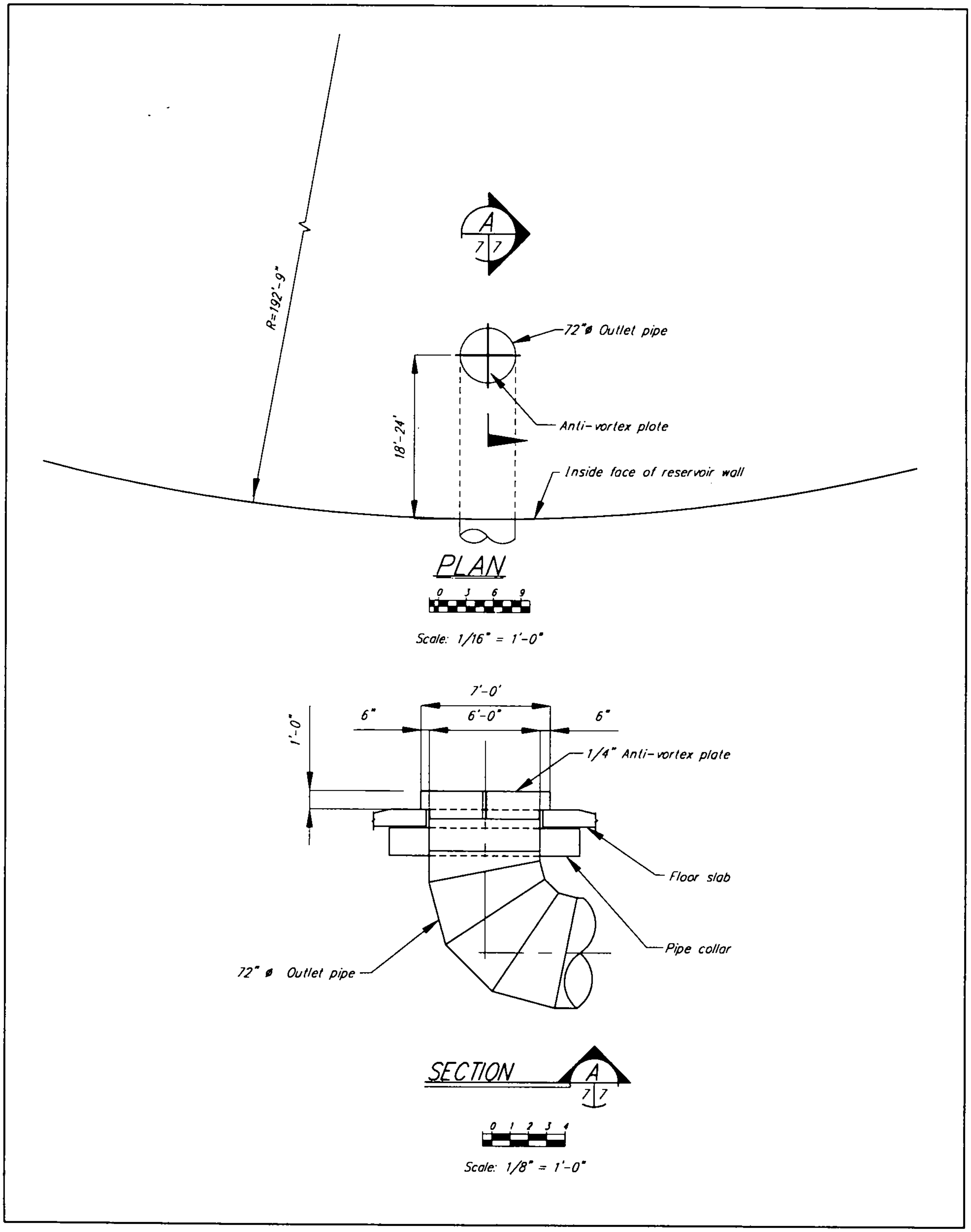


Figure 7
Foothills Reservoir 3 Recommendations

REFERENCES

Amphlett, M.B., *Air-Entraining Vortices at a Vertically Inverted Intake*, Hydraulic Research Station Report No. OD/17, Wallingford, England, September 1978.

Bates Engineering, Inc., "Treated Water Storage Reservoir Hydraulic Model Mixing Study," prepared for Denver Water, Denver, Colorado, November 1996.

Beichley, G.L., *Hydraulic Model Studies of the Morning-glory Spillway for Hungry Horse Dam, Hungry Horse Dam Project*, U.S. Bureau of Reclamation Hydraulic Laboratory Report HYD-355, April 23, 1954.

Bradley, Joseph N., "Morning Glory Shaft Spillways: Prototype Behavior," *Transactions* of the American Society of Civil Engineers, Vol. 121, 1956.

Constantinescu, G. and V.C. Patel, "Influence of Approach Flow Non-Uniformity on Vortices at a Pump Intake," *Proceedings* of the 27th Congress of the International Association for Hydraulic Research, San Francisco, California, August 10-15, 1997.

Daugherty, Robert L. and Joseph B. Franzini. *Fluid Mechanics with Engineering Applications*, 7th ed., McGraw Hill, 1977.

Johnson, Perry L., *Hydraulic Model Studies of the Forebay Reservoir Outlet-Outlet Structure for Mt. Elbert Pump-Storage Powerplant, Fryingpan-Arkansas Project, Colorado*, U.S. Bureau of Reclamation Engineering and Research Center Report No. REC-ERC-72-5, Denver, Colorado, January 1972.

Haindl, K., "Contribution to Air Entrainment by a Vortex," Eighth Congress of the International Association for Hydraulic Research, Montreal, August 24-29, 1959.

Hecker, George F., "Model-Prototype Comparison of Free Surface Vortices," *Journal of the Hydraulics Division*, American Society of Civil Engineers, Vol. 107, No. HY10, October 1981.

Jain, Akalank K., Kittur G. Ranga Raju and Ramachandra J. Garde, "Vortex Formation at Vertical Pipe Intakes," *Journal of the Hydraulics Division*, American Society of Civil Engineers, Vol. 104, No. HY 10, October 1978.

Knauss, Jost, editor, *Swirling Flow Problems at Intakes*, International Association of Hydraulics Research Hydraulics Structures Design Manual, A. A. Balkema, Rotterdam, Netherlands, 1987.

McBirney, W.B., *Hydraulic Model Studies of the Trinity Dam Morning-glory Spillway, Trinity River Diversion, Central Valley Project, California*, U.S. Bureau of Reclamation Hydraulic Laboratory Report HYD-447, April 22, 1960.

Posey, C.J. and Hsu, Hsieh-ching, "How the Vortex Affects Orifice Discharge," *Engineering News Record*, Vol. 144, No. 10, March 9, 1950.

Prosser, M.J., *The hydraulic design of pump sumps and intakes*, British Hydromechanics Research Association, Cranfield, Bedford, England, July 1977.

U.S. Army Corps of Engineers, *Hydraulic Design of Spillways*, Engineering Manual EM 1110-2-1603, March 31, 1965.

U.S. Bureau of Reclamation, *Hydraulic Laboratory Techniques*, Denver, 1980.

U.S. Bureau of Reclamation, *Design of Small Dams*, 3rd ed. Denver, 1986.

Zeigler, E.R., *Hydraulic Model Vortex Study - Grand Coulee Third Powerplant*, U.S. Bureau of Reclamation Engineering and Research Center Report No. REC-ERC-76-2, Denver, Colorado, February 1976.

Zielinski, Paul B., *Design for Elimination of Vortex Formation at Inlets*, American Society of Civil Engineers National Meeting on Water Resources Engineering Meeting Preprint 2160, January 21-25, 1974.

Zipparro, Vincent J., and Hans Hasen, *Davis' Handbook of Applied Hydraulics*, 4th ed., McGraw Hill, 1993.

APPENDIX A - PHOTOGRAPHS

PHOTO DESCRIPTIONS

1. Overall view of the model in the U. S. Bureau of Reclamation Water Resources Research Laboratory in Lakewood, Colorado. Model in center. 250-gallon plastic supply tank is at left. Outlet pump to left of supply tank. Inlet pump at bottom left.
2. Top view of the model. Reservoirs 1 and 2 sump at top. Three Reservoir 3 outlet alternates at bottom. Reservoirs 1 and 2 inlets at bottom right and left.
3. Classic air-entraining vortex seen in circular 250-gallon supply tank. Water depth is approximately 5 feet. Flow is 6 gallons per minute (gpm). Orifice diameter is approximately 1 inch.
4. Reservoirs 1 and 2 with existing hood removed (Test 1). Dye core vortex above sump at 12-foot level.
5. Reservoirs 1 and 2 with existing hood removed (Test 1). Swirls in corners of sump adjacent to reservoir wall at 2-foot level.
6. Reservoirs 1 and 2 with existing hood (Test 4). Dye core vortex above sump at 20-foot level.
7. Reservoirs 1 and 2 with existing hood (Test 4). Swirls in corners of sump adjacent to reservoir wall at 3-foot level.
8. Reservoirs 1 and 2 with 90° upward bend in outlet sump (Test 2). Strong air entraining vortex at 10-foot level.
9. Reservoirs 1 and 2 with 90° upward bend and plate antivortex device in outlet sump (Test 3). Weir flow at 3-foot level.
10. Reservoirs 1 and 2 with vertical grid antivortex device (Test 5). Swirl inside of grid at 12-foot level.
11. Reservoirs 1 and 2 with 1' x 1' horizontal grid (Test 6). Relatively uniform flow distribution at 3-foot level.
12. Reservoirs 1 and 2 with 6' guide vanes (Test 7). Dye core passing through vanes on right side of device at 7-foot level.
13. Reservoirs 1 and 2 with check dam in outlet channel (Test 8). Very turbulent flow downstream of dam at 7-foot level.
14. Reservoirs 1 and 2 with fanned grid antivortex device (Test 9). Swirl is pushed somewhat away from wall at the 20-foot level.
15. Reservoirs 1 and 2 with 16' guide vanes (Test 11). Distinct swirls still present at 24-foot level.
16. Overview of model with sump lengthened to edge of side slopes (52 feet from wall).
17. Reservoirs 1 and 2 with 0'-52' sump (Test 16). Weak dye core near wall at 18-foot level.

18. Reservoirs 1 and 2 with 0'-52' sump (Test 16). Relatively uniform flows moving down sump at 2 1/2-foot level.

19. Reservoirs 1 and 2 with 8'-20' sump (Test 17). Strong dye core entering center of sump at 25-foot level.

20. Reservoirs 1 and 2 with 16'-32' sump (Test 18). Medium dye core entering downstream edge of sump at about 24-foot level.

21. Reservoirs 1 and 2 with 32'-52' sump (Test 19). Dye core entering sump and "unbraiding" before reaching outlet pipe.

22. Reservoirs 1 and 2 with existing hood using concrete sand tracer (Test 22). All sand except corners against wall is completely removed.

23. Reservoirs 1 and 2 with existing hood and 1' x 1' horizontal grid using concrete sand tracer (Test 23). Sand in front of the sump is not completely removed.

24. Reservoirs 1 and 2 with 0' - 52' sump using tracer sand (Test 21). Sand removal is relatively uniform except at upstream sides.

25. Reservoir 3 with center of outlet pipe 12 feet from wall (Test 1). Strong dye core drifts toward wall at about 12-foot level.

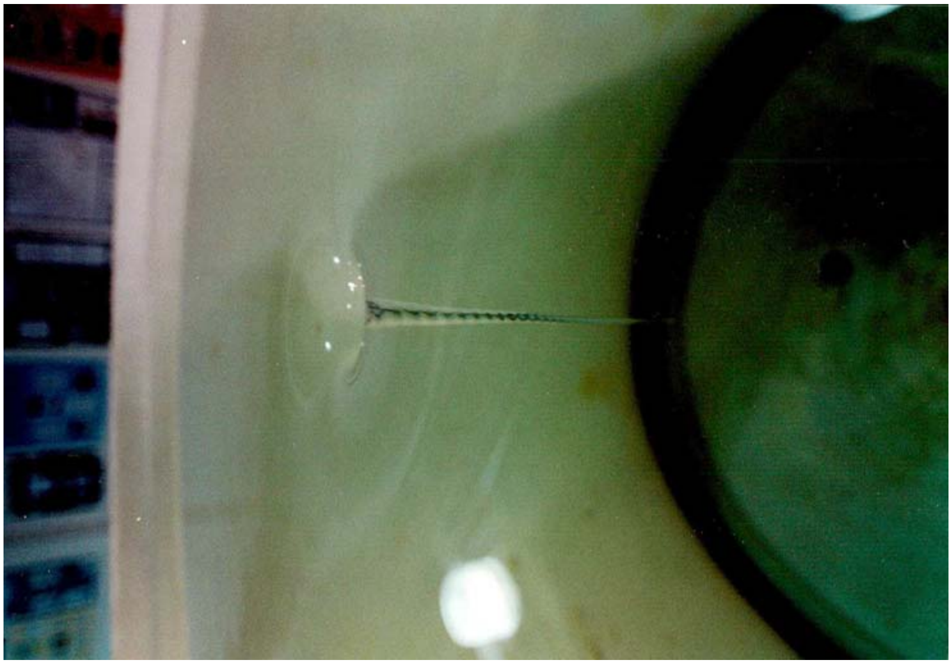
26. Reservoir 3 with center of outlet pipe 36 feet from wall (Test 3). Strong dye core drifts toward wall at about 18-foot level.

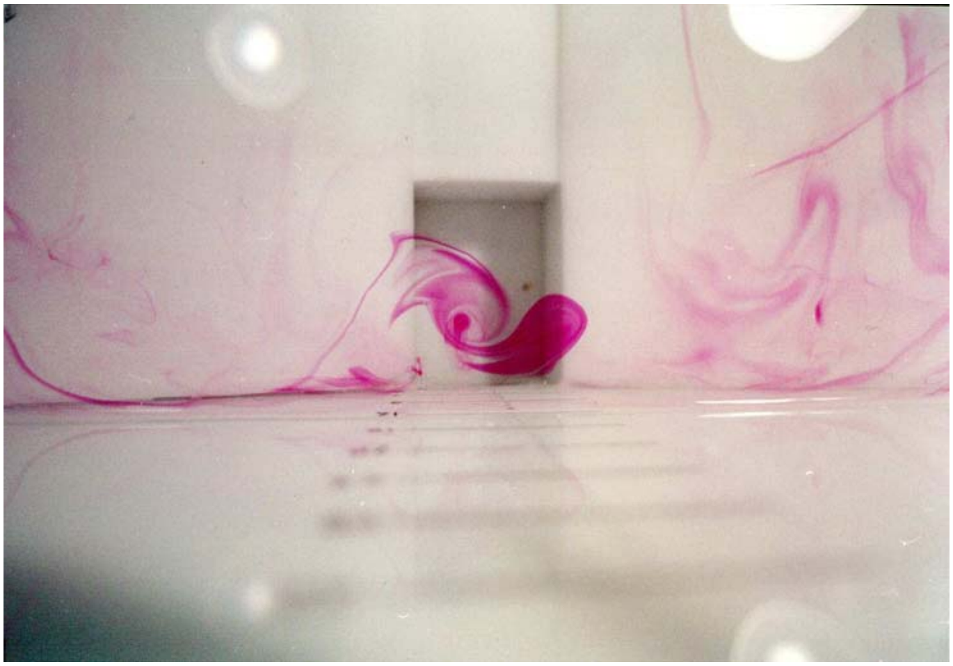
27. Reservoir 3 with center of outlet pipe 36 feet from wall (Test 3). Strong dimple and large swirl pattern at about 12-foot level.

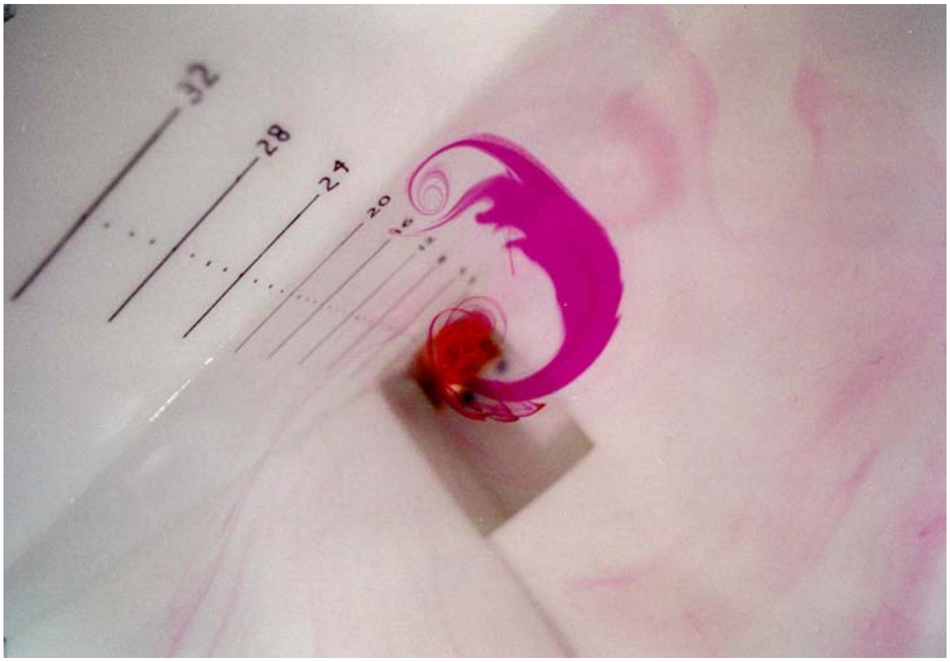
28. Reservoir 3 with center of outlet pipe 24 feet from wall (Test 5). Moderate dimple and moderate swirl pattern at about 14-foot level.

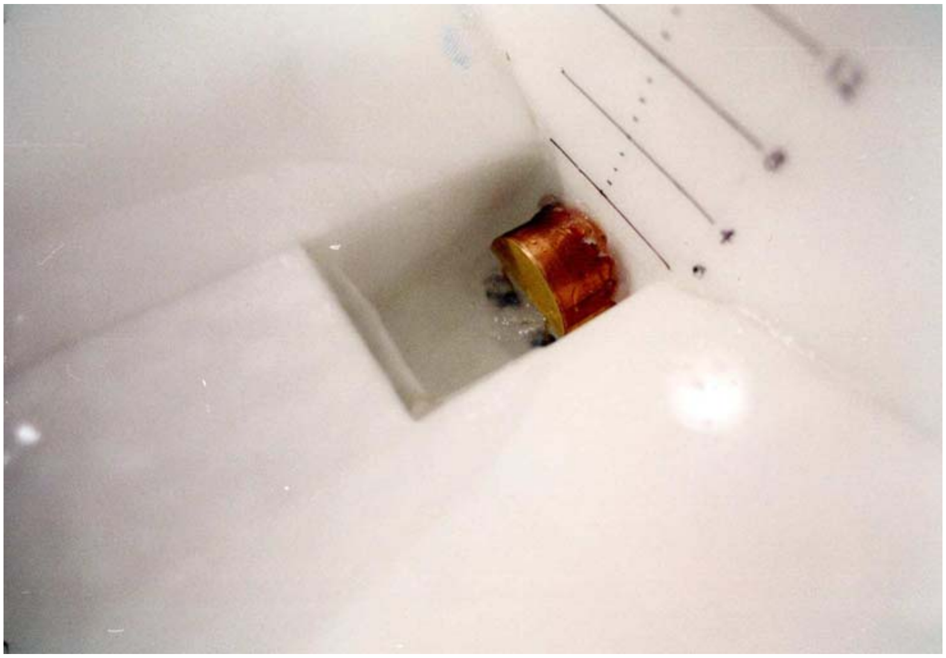
29. Reservoir 3 with center of outlet pipe 24 feet from wall and antivortex plates (Test 6). Moderate dye core at 15-foot level.

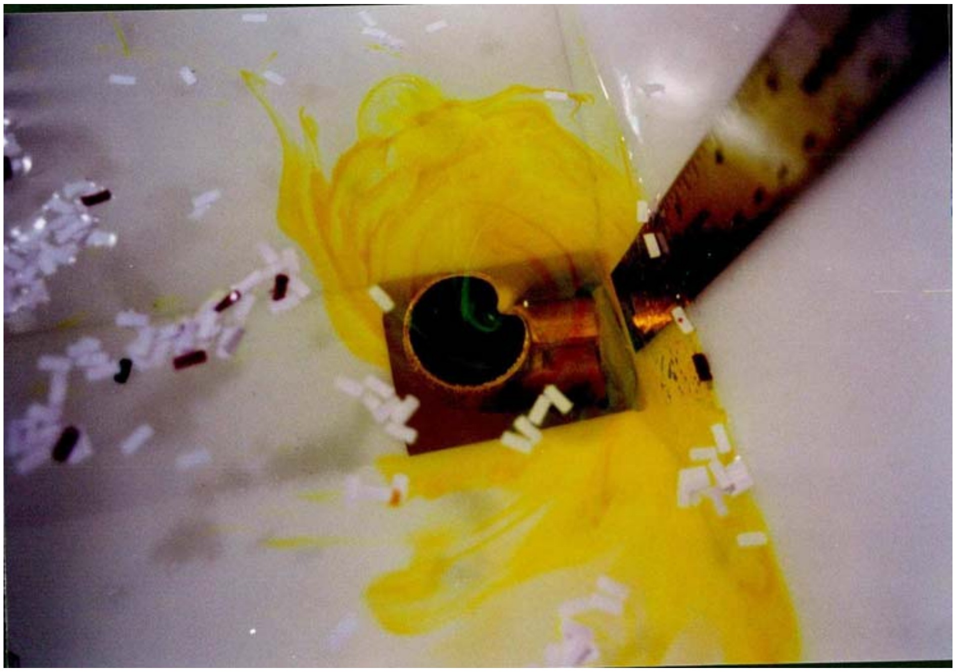
30. Reservoir 3 with center of outlet pipe 24 feet from wall and antivortex plates (Test 6). Relatively radial flow approaching outlet at 2-foot level.

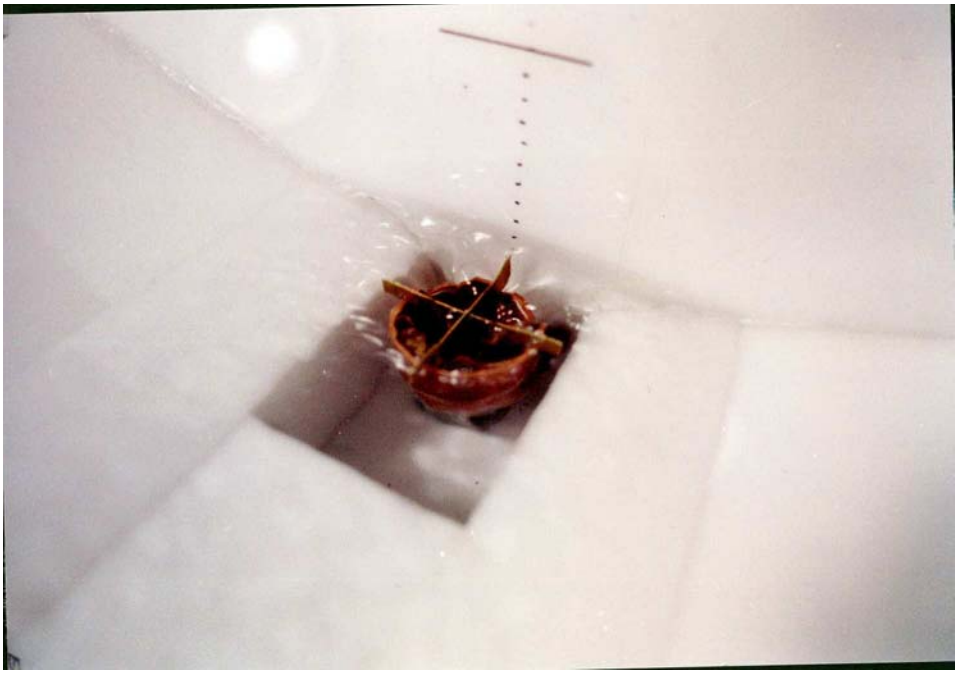


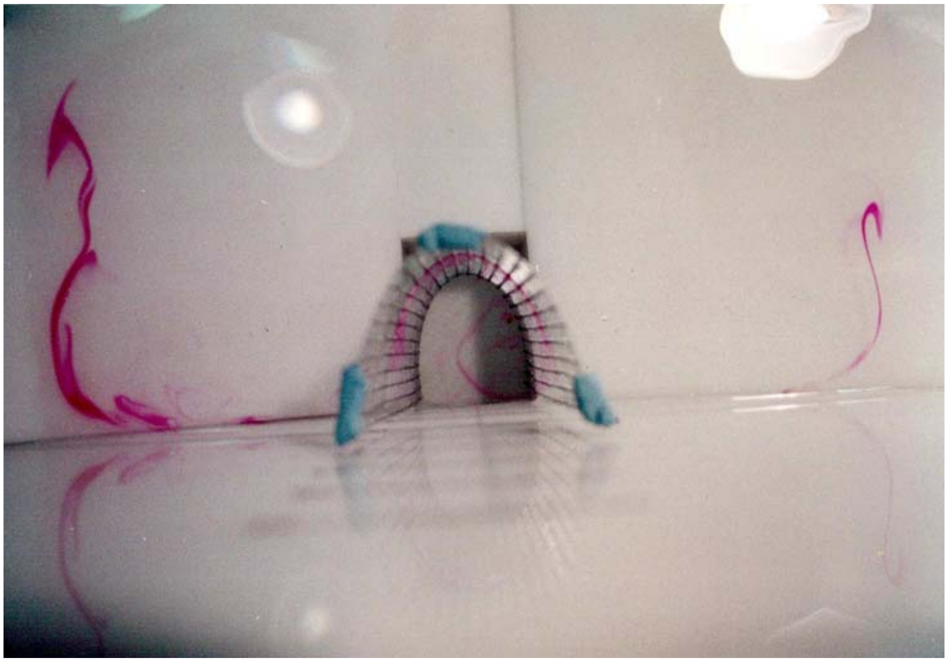


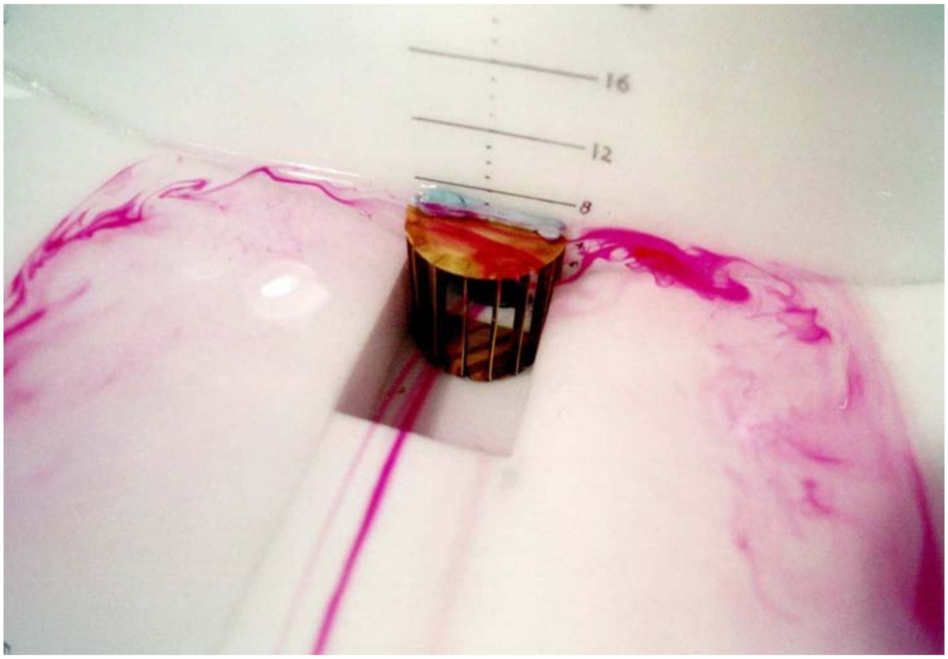

32
28
24
20
16
12
8

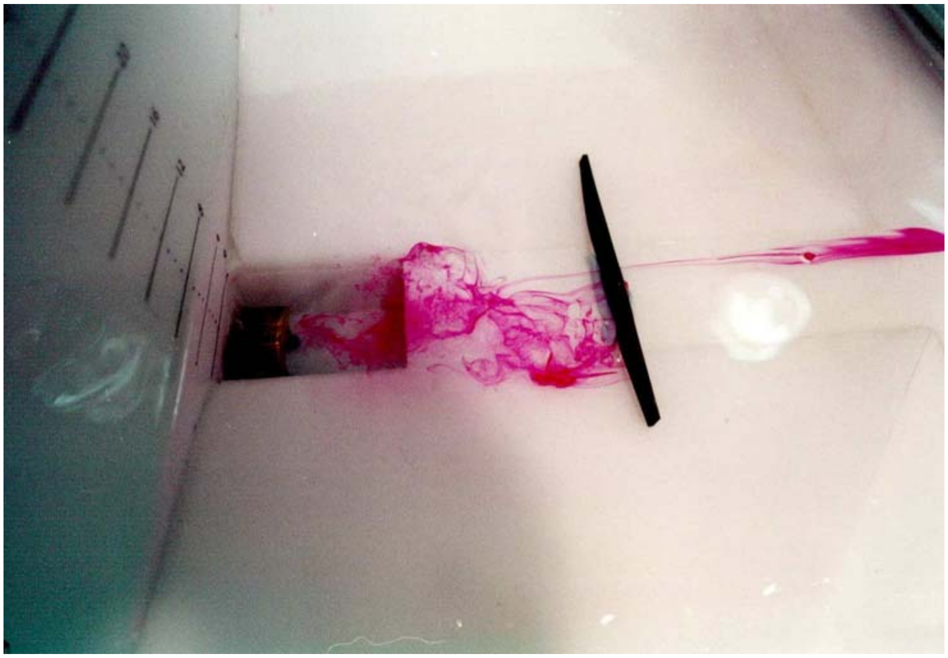


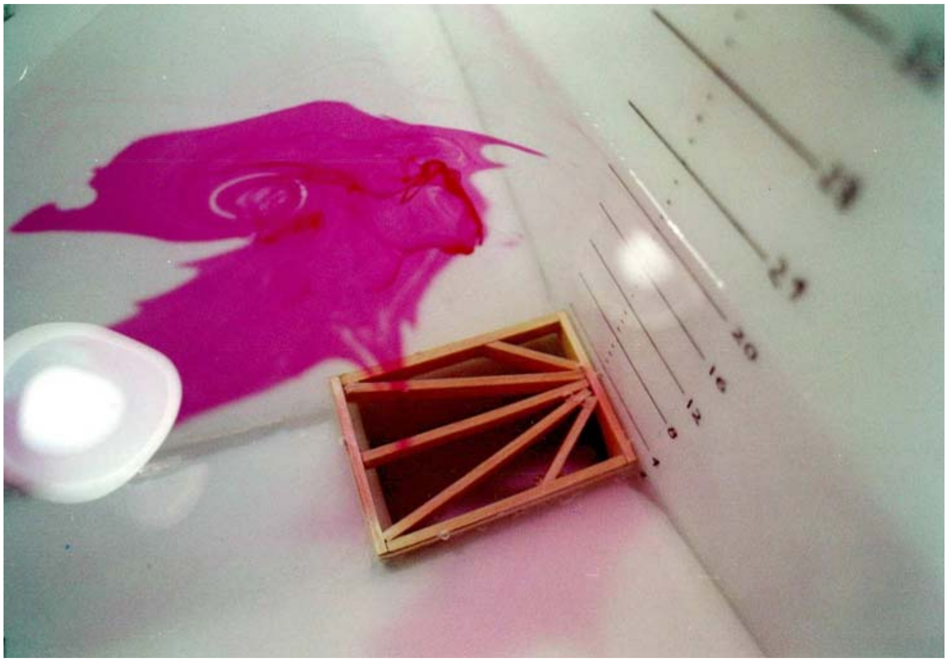


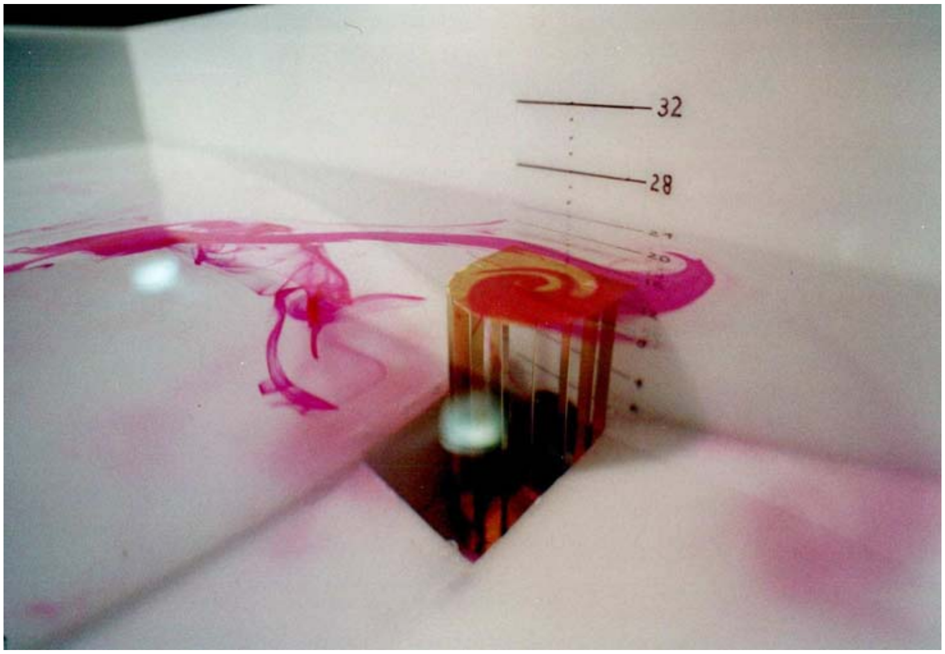


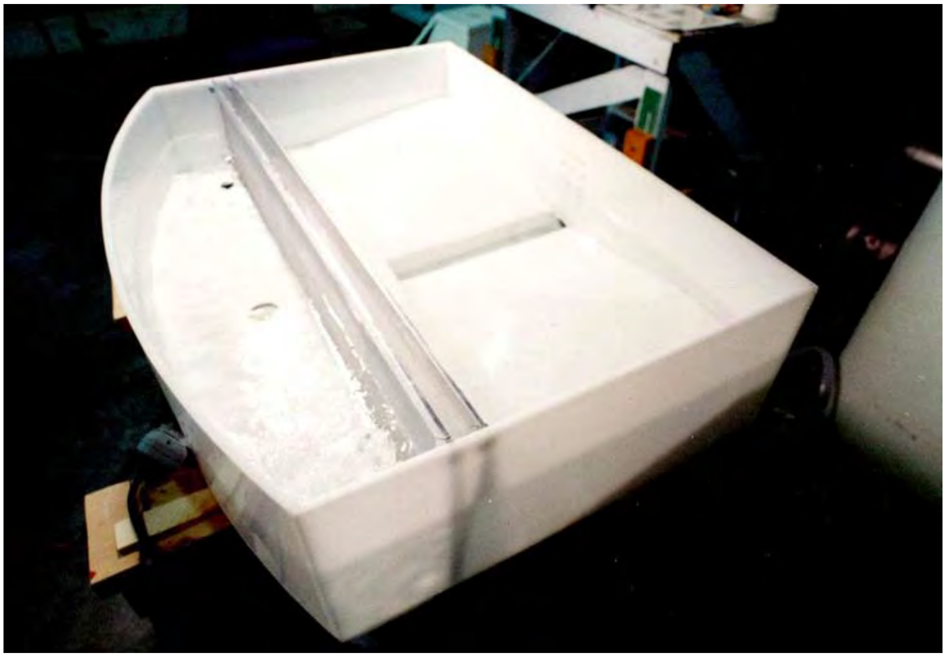


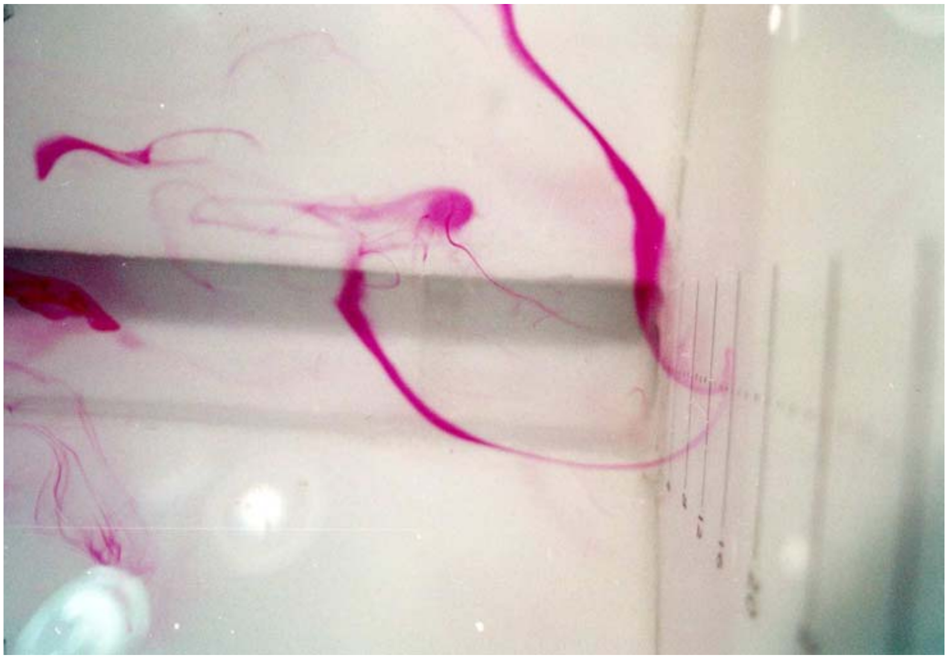

16
12
8

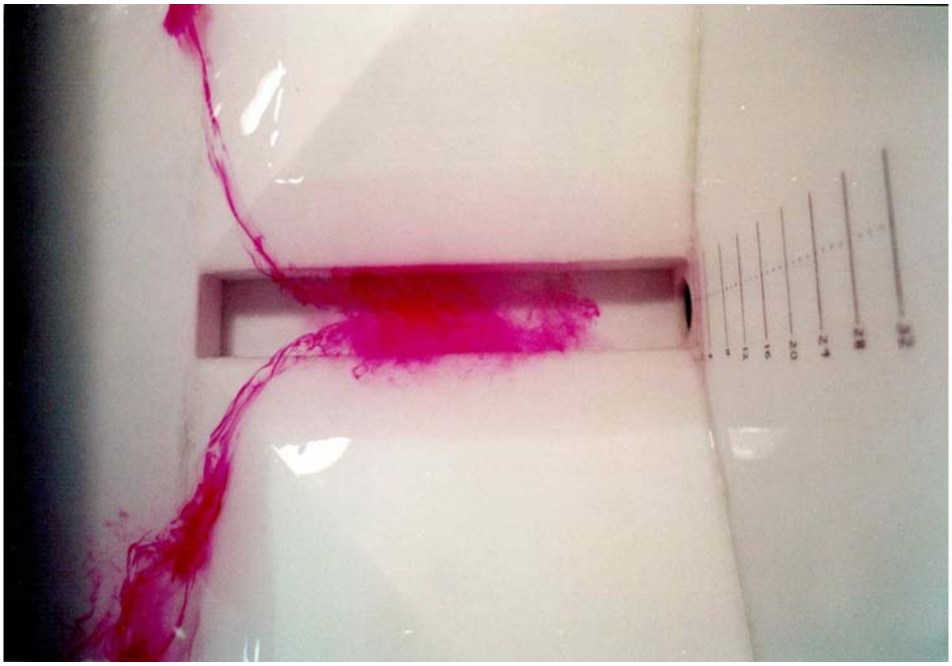


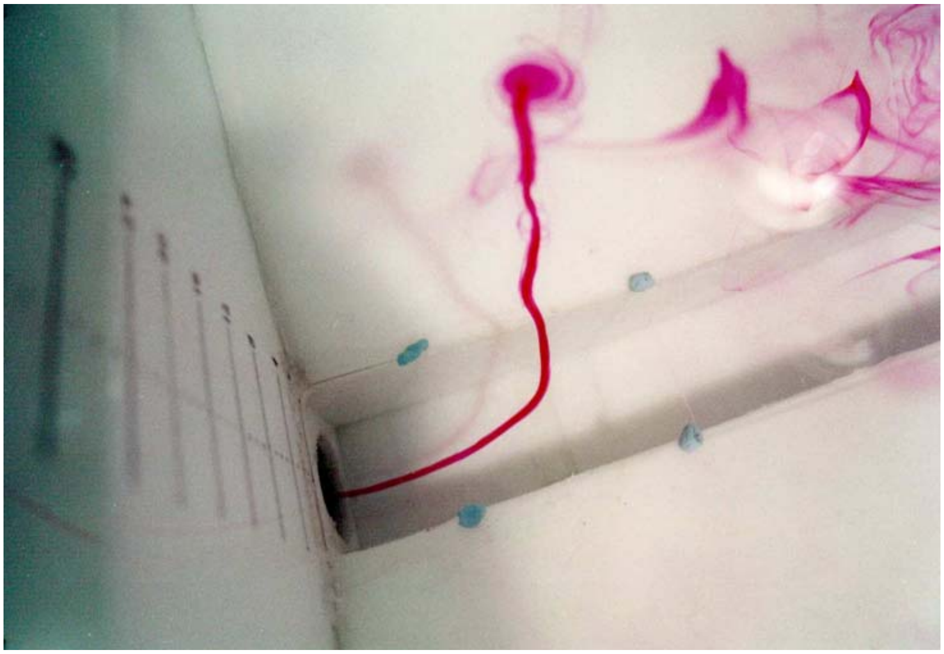

4
8
12
16
20
24

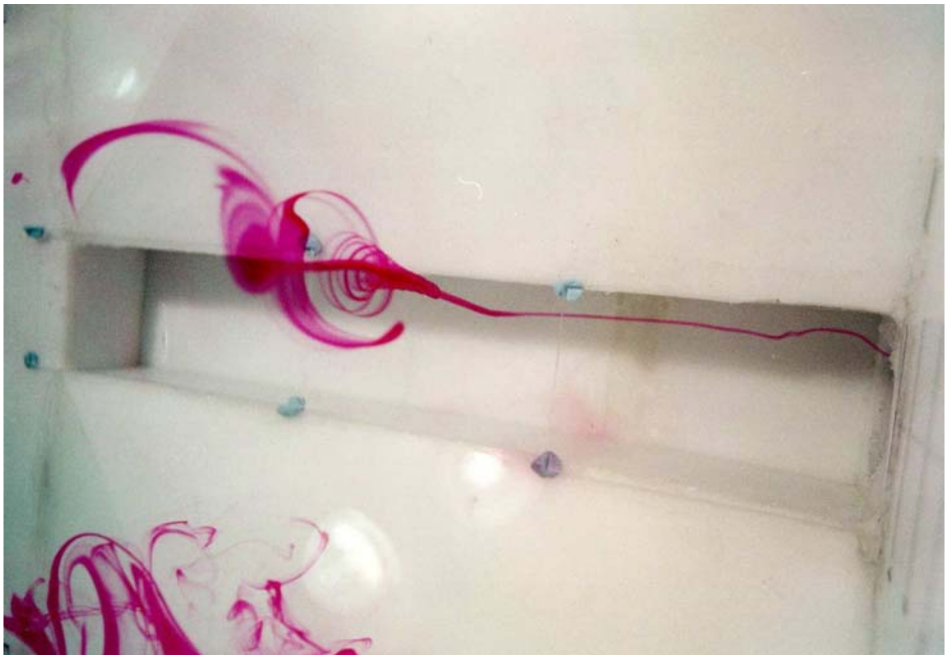

32
28
24
20

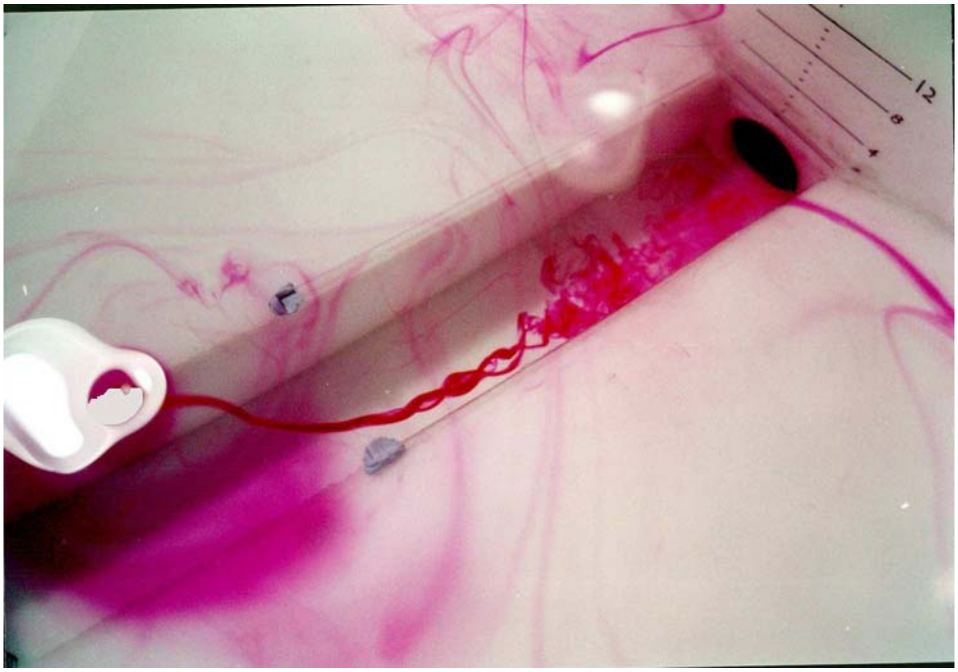




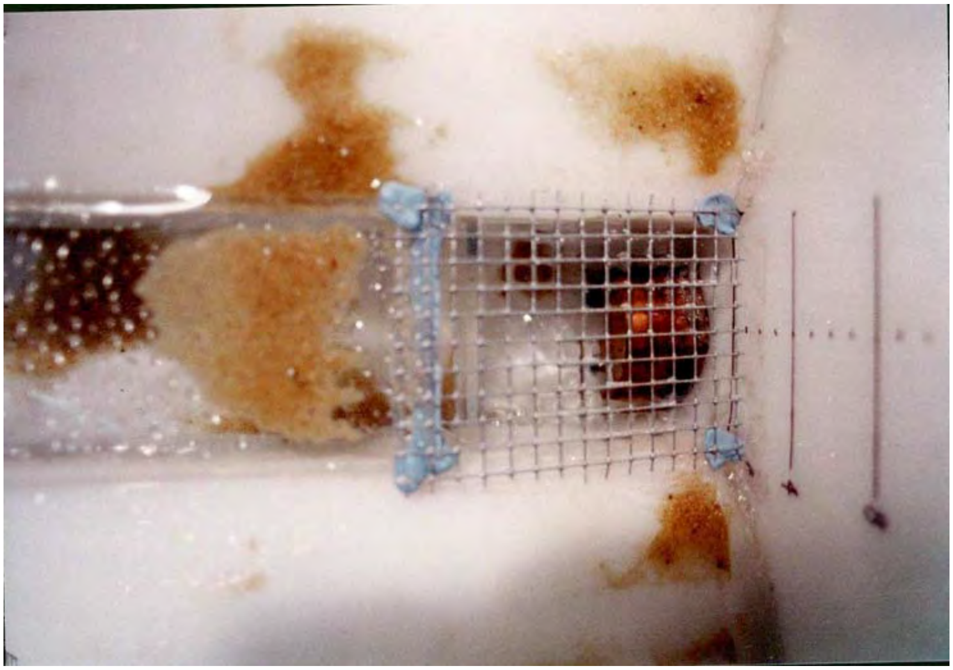

4
8
12
16
20
24
28
32

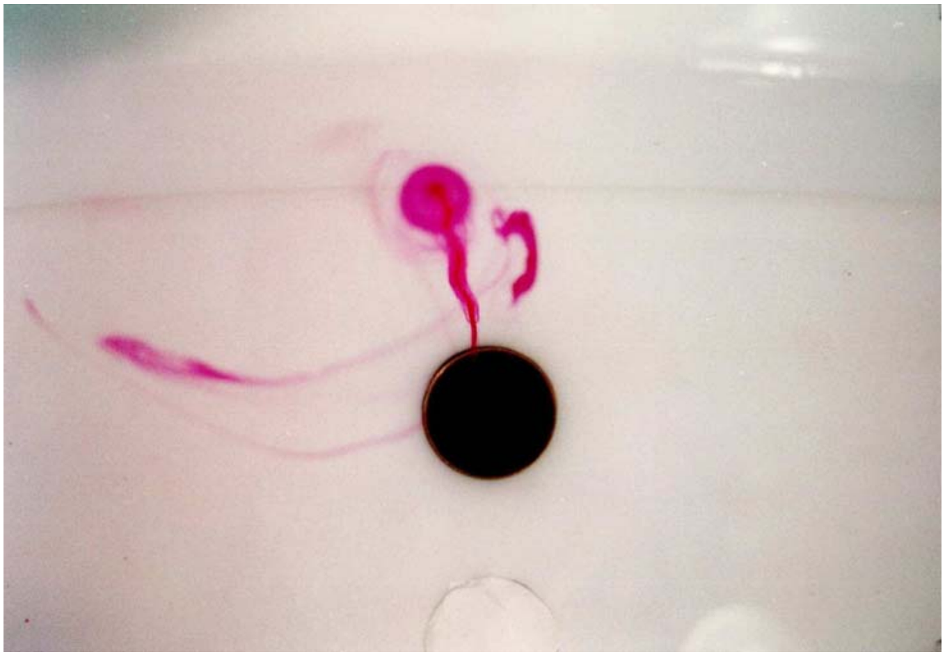


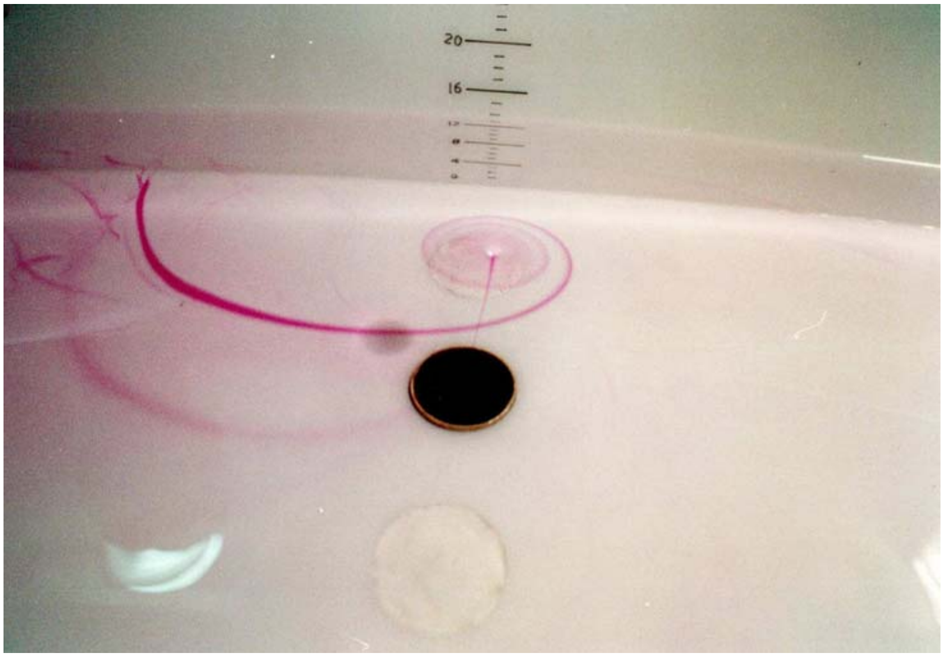


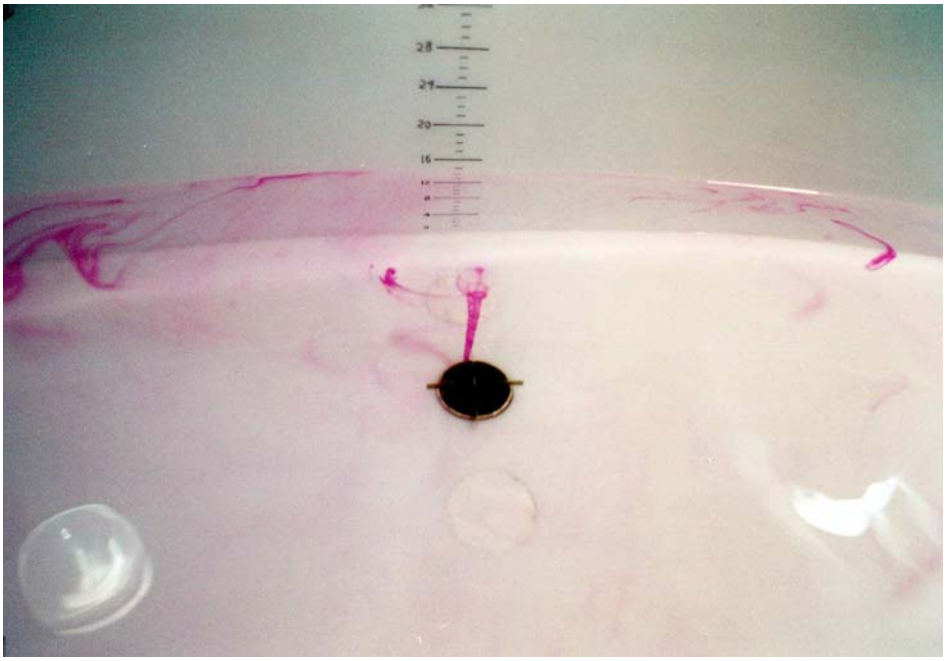

12
8
4


2
4
8






20
16
12
8
4
0


28
24
20
16
12
8
4


20
16
12
8
4