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Scale Modeling of Water Storage Tanks to Improve Flow Circulation, Proceedings of the American Water Works Association, Water Quality Technology Conference, San Diego, California

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by

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Scale Modeling of Water Storage Tanks to Improve Flow Circulation

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I. INTRODUCTION

Why Study Flow Circulation in Tanks?

Increasingly stringent federal regulations have spawned increased interest in water quality in individual components of potable water distribution systems. One of the components of special interest is water storage tanks, because unlike pipelines, tanks are a "wide spot in the road" where plug flow cannot be assumed. Additionally, tanks are often "not a through street", but rather a "cul-de-sac" where "dead end" stagnation can occur. Understanding flow circulation in water storage tanks applies not only to distribution system storage structures, but also contact basins and clearwells at treatment plants.

The "macro" issue for flow circulation in water storage tanks is contact time for treatment processes such as chlorination. A relatively long contact time may result in inadequate chlorine residuals leaving the tank for the distribution system. In addition, chlorine by-products such as trihhalomethane pose certain health risks.[1] Conversely, if the tank is located near the treatment facility, a relatively short contact time may not allow sufficient time for disinfection. This not only poses potential health risks, but high chlorine residuals are also poorly received by the public. Thus, in the case of either relatively short or relatively long contact times, adequate disinfection of the water, and thus health, are a concern.

Regardless of treatment process, however, the "micro" issue is the degree to which the water passes through the tank in a uniform way. Because tanks are a "wide spot in the road," the last water in is not necessarily the last water out, so different zones or strata within the reservoir can contain water of different ages. Stagnant or "dead" zones result in relatively long localized detention times, while areas of rapid turnover or short-circuiting may have relatively short localized detention times.

The goal of the modeling performed for these studies was to determine flow characteristics within water storage tanks that are unfavorable to uniform mixing and to provide the required design features or baffles to most efficiently produce uniform flow in an economical manner.

Methods of Studying Flow Circulation in Tanks

Three common methods have been used to evaluate flow circulation in tanks. The first method is to perform tracer studies on existing tanks. A trace substance, such a fluoride, is introduced into or discontinued from a tank and the increasing or decreasing tracer concentrations are measured at the outlet. Plotting the changes in tracer concentration gives an indication of the overall rate of mixing in the tank. However, the tank is treated as a "black box" within the distribution system, so little information is provided on how mixing occurs *within* the tank. The data derived from such tests is valuable for evaluating existing tanks and perhaps for extrapolating to future, similar tanks. However, for information to be more broadly useful and for circulation within the tank to be better understood, some type of modeling is useful.

Recently much attention has been given to the use of Computational Fluid Dynamics (CFD) models, where finite element methods are employed to simulate mixing in the tank. These models have the advantage of being readily changed geometrically and not being subject to scaling factors. The disadvantages are that the results are subject to cell size limitations, imperfect boundary conditions and simplified flow theory models. [2]

A third method for evaluating flow circulation in tanks is to use scale hydraulic models. Scale models provide a tangible "feel" for mixing in tanks, but are locked into a specific geometry and are subject to scaling factors, especially with smaller models. This paper focuses on the use of scale models for evaluating flow circulation in three water storage tanks.

Scale Hydraulic Model Construction and Setup

In order to derive quantitative data from a scale hydraulic model, relationships between the prototype and model parameters such as length, flow and time must be established. For flow under atmospheric pressures characterized by turbulence, the Froude similitude relationship is the appropriate choice.[3] For Froude similitude, model lengths are scaled directly by the scale factor, so that, for example, at 48 scale, a 1 1/2-inch-diameter model inlet pipe corresponds to 72-inch prototype pipe. Flow rates for the model are scaled by the five-halves power and time is scaled by the one-half power.

The three scale models discussed in this paper were constructed largely of ½-inch acrylic sheets. The models were mounted on a wood frame at the U.S. Bureau of Reclamation Water Resources Research Laboratory in Lakewood, Colorado. Water was provided to the model inlets using a 250-gallon plastic supply tank in conjunction with a centrifugal pump and flexible plastic piping. Water was drawn through the outlet by means of a second pump and was discharged to the below-grade channel network in the lab. Inflow and outflow rates were measured and adjusted using valved, acrylic, panel-mount, water rotameters appropriate for the flow range considered.

Measuring and Evaluating Flow Circulation

Two primary methods were used to evaluate flow circulation in the scale models. Qualitative results were made possible by adding a yellow-green liquid powder tracing dye to the water in the supply tank which was then pumped into the model. The initial mixing in the models could be observed with this method. However, after approximately 30 minutes, all the water in the models was sufficiently dyed to prohibit further observation of mixing patterns. Quantitative means were thus needed to verify mixing.

For these studies, conductivity measurement was the quantitative means used to evaluate mixing. Fourteen conductivity probes were mounted at fixed locations in the supply tank and model. Tap water was introduced into the model initially filled with de-ionized water so that areas of lower ion concentrations in the model indicated a lower turnover rate than areas of higher concentrations. Zones of short-circuiting or stagnation could be located by calculating a "tracer breakthrough" at each probe at time, t, as follows:

$$\text{Tracer Breakthrough}(t) = \frac{\text{Conductivity}(t) - \text{Conductivity}(t=0)}{\text{Conductivity(Supply Tank)} - \text{Conductivity}(t=0)}$$

For each probe, time was plotted on the x axis and tracer breakthrough was plotted on the y axis. Time was expressed as a fraction of the hydraulic detention time, T, which is defined as the time for one complete exchange of water in the tank. The progress of mixing at a particular probe could then be evaluated from the graph by reading T_x/T values, where T_x is the time at which x percent of the inflow tracer concentration (tracer breakthrough) reached the particular probe. Overall mixing in tanks, clearwells and contact basins can be evaluated based on T_{10}/T at the outlet. The U.S. Environmental Protection Agency (USEPA) classifies the degree of mixing in basins based on T_{10}/T.[4]

Summary of Model Studies

Three scale hydraulic model studies were performed to evaluate flow circulation in potable water storage tanks. The first study was performed for Denver Water to investigate general aspects of flow circulation that could be applied to the designs of two new tanks. During five tests, three variables affecting mixing were evaluated: outlet configuration, water temperature and flow rate. A second study for the City of Fort Collins Utilities examined various baffle configurations to increase contact time at two similar 15 million gallon (MG) Reservoirs at the Water Treatment Facility. The third study for Denver Water investigated flow circulation issues related to planned modifications to Contact Basins 2 and 3 at their Marston Water Treatment Plant. The findings from the first two studies were incorporated into the research for the AWWA Research Foundation Project 260.[5]

II. DENVER WATER HYDRAULIC MODEL MIXING STUDY

Purpose of the Study

The purpose of this study was to arrive at specific design recommendations for the planned Chatfield and Colorow Reservoirs in the West Denver Metro Area. The study examined three parameters relating to mixing of water within tanks: outlet configuration, water temperature, and flow rate.

Model Description

The 1:22.75 scale model represented a 3.0 MG circular tank and was 8 feet in diameter, 12 inches tall and contained 16 columns and footings (see Figure 1). The inlet and outlet pipes were plumbed flush with the floor of the model so that the water entered and exited the model at a 90° angle. The outlet location was adjusted by plugging all the one-inch floor taps except the one at the desired location.

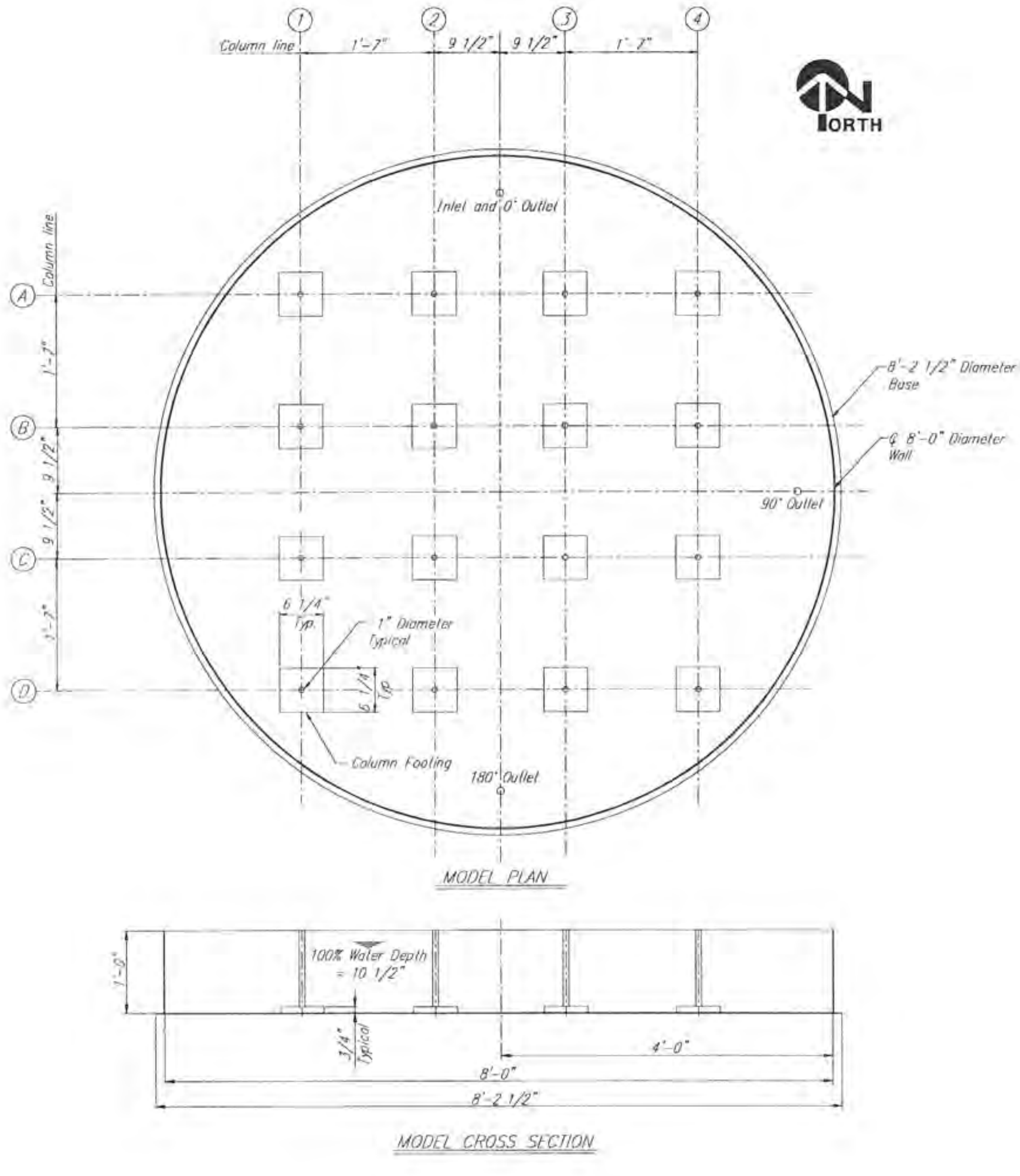

Figure 1. Denver Water Mixing Study - Model Dimensions

Flows in and out of the model were scaled to match the daily inflows and demands projected for the prototype tanks. The model inflow simulated a constant prototype pumping rate of 8 million gallons per day (MGD) into the tank. The system-wide daily demand hydrograph was normalized and "stepped" to simulate an average daily outflow of 8 MGD. The initial and final tank levels (75% full) were thus equal at the end of the 24-hour prototype day.

Tests Performed

The variables for each of the five tests completed are summarized in Table 1.

Table 1. Denver Water Mixing Study - Summary of Tests Performed

Test No.	Outlet Config.	Flow (MGD)	Temp Diff.
1	0°	8	No
2	90°	8	No
3	180°	8	Yes
4	180°	8	No
5	180°	2	Yes

"Outlet configuration" refers to the angle between inlet and outlet measured by an angle whose vertex is at the center of the model (see Figure 1). For zero degrees the inlet and outlet used the same piping. "Flow" indicates the average prototype inflow and outflow rate over the 24-hour prototype time period. "Temperature difference" means that a temperature differential of 2.2°C to 3.3°C was purposely induced between the model and inflowing water by allowing the water in the model to be warmed. For these tests, the colder inflowing water tended to "crawl" along the floor toward the outlet resulting in temperature stratification.

Results

Effect of Outlet Location

The effect of outflow on horizontal mixing was examined by comparing temperature data from Tests 1, 2 and 4. All three tests used the same flow rate (8 MGD) and no planned temperature differential between the inflow and model. Temperature data taken manually at the column opposite the 90° outlet was used to evaluate the effectiveness of the mixing patterns.

For the single (0°) inlet/outlet, the last area to experience complete mixing of the dye was in the southeast corner of the model. This was apparently due to slightly uneven flow velocities in the model favoring mixing on the west side. For the 90° case, the last area to experience mixing was the southeast corner of the model "behind" the outlet. For the 180° case, flows tended to move in both directions around the perimeter of the model so that the last area to fully mix was at the center. For each of the three cases, the columns and footings impacted the horizontal mixing because they tended to provide a "shadow" of poorer mixing away from the "sun" of the inflow.

Overall, the single (0°) inlet/outlet resulted in the poorest mixing because only the *difference* between the inflow and outflow rate stimulated circulation. The 90° case was improved due to larger turnover of water; however stagnant areas still developed 180° from the outlet. The most uniform mixing occurred with 180° of separation between the inlet and outlet.

Effect of Temperature Difference between Model and Inflow

The effect of a temperature difference between the model and the inflowing water was examined by comparing conductivity data from Test 3 and Test 4. Both tests had the same flow rates and the 180°

outlet configuration. However, in Test 3 a temperature difference between the model and the inflow was intentionally introduced where it was not in Test 4.

In order to evaluate the effects of the initial temperature difference in the model, a "percent stratification" term was defined as the difference in conductivity between the bottom of the model and the surface divided by the average model conductivity.

$$\text{Percent Stratification} = \frac{(C_{floor} - C_{surface})}{C_{average}} * 100$$

For the C_{floor} and $C_{surface}$ terms, conductivity data were averaged from four columns at the water surface and at the floor. The $C_{average}$ term was derived from the average of all eight readings. Higher values of percent stratification indicated more severe stratification.

Contrary to what was expected, the test with the initial temperature difference actually had about 40% percent lower maximum stratification than the test where inflows more closely matched model temperatures. The influence of varying laboratory air temperatures probably contributed to this anomaly.

During these tests, it was also observed that vertical mixing appeared to improve as flow moved from the inlet to the outlet. It might be surmised that the effect of dispersion across the model is more effective in "breaking up" the stratification than the turbulence produced at the inlet.

Effect of Flow Rate

The effect of inflow and outflow rates was examined by comparing conductivity data from Test 3 and Test 5. Both tests had a temperature difference between the inflow and the model and well as the same 180° outlet configuration, but Test 3 had an 8 MGD average inflow and outflow rate while Test 5 had an average of only 2 MGD.

Percent stratification for the two tests was plotted over time. The percent stratification at 2 MGD was 65% higher than at 8 MGD. The average model conductivity level for the 2 MGD test only reached about 60% of the value of the 8 MGD test. Thus, it appeared that rate of mixing in the model was approximately proportional to the square root of the flow rate.

It was also observed that higher inlet velocities caused by higher flow rates appeared to stimulate localized mixing at the inlet, but did not have a significant impact on tank-wide mixing patterns.

Conclusions

A summary of the results of the five tests is shown in Table 2.

Table 2. Denver Water Mixing Study - Summary of Mixing Factor Comparisons

Factor	Test Nos.	Measurement	Best Mixing	Relative Importance
Outlet Configuration	1,2,4	Temperature	180° separation	1
Temperature Difference	3,4	Conductivity	No temp. difference	3
Flow Rate	3,5	Conductivity	High flow rates	2

A single inlet/outlet resulted in the poorest mixing especially with small tank level fluctuations. The 90° case was improved due to larger turnover of water; but stagnant areas still developed 180° from the outlet. The ideal case is 180° separation. However, the geometric relationship between the inlet and outlet did not appear to be as significant as the fact that the inlet and outlet are separately piped. Small temperature differences between the inflow and the tank were believed to result in improved mixing. Low temperature differentials should permit less stratification to develop. In addition, higher flow rates resulted in more complete mixing. Based on observation of these tests, it appears that, in order of importance, the factors that most influenced mixing for this tank geometry were outlet location, flow rate and temperature differential.

III. FORT COLLINS UTILITIES 15 MG STORAGE RESERVOIRS BAFFLE STUDY

Purpose of the Study

The City of Fort Collins Utilities (FCU) potable water system includes two 15 MG storage reservoirs constructed without baffles in the mid-1960's at their Water Treatment Facility (WTF). Because these reservoirs are located at the WTF, FCU has been interested in maximizing the chlorine contact time in order to meet USEPA and State requirements for *Giardia* and other pathogens. This is especially true during periods of high flow and low reservoir levels when the chlorine contact time is relatively short. FCU felt that installing baffles in the reservoirs would provide some additional contact time.

A series of hydraulic model tests were conducted to find a baffle configuration for each reservoir that would efficiently increase the contact time. The results of a fluoride tracer test performed by FCU in 1996 on the East Reservoir were used during the model study as a basis for comparing model flows with the prototype. Tracer tests were also conducted by FCU in 1998 on both reservoirs after the proposed baffles had been installed and allowed for comparison of prototype and model study results.

Prototype and Model Descriptions

The dimensions of the two prototype 15 MG reservoirs are essentially identical. They have an inverted truncated pyramidal shape ("hopper bottom") with a 160-foot square bottom area and 6:1 side slopes. The top area is 284 feet square with 18-foot vertical walls. The piping for each reservoir, however, is different. The inlet and outlet pipes for the West Reservoir are located on adjacent walls whereas the inlet and outlet pipes for the East Reservoir are located on opposite walls. The West Reservoir has a 36-inch inlet, while the East Reservoir has a 48-inch inlet. Each inlet has a 90° elbow oriented vertically upward at the wall. Both reservoirs have 60-inch outlets which bend 90° downward into a sump, but the West Reservoir also has a 36-inch outlet adjacent to its 60-inch outlet.

Due to the geometric similarity between the two prototype reservoirs, testing of each was possible with a single hydraulic model. A scale factor of 1:48 was selected to keep the model to a size that could be readily transported and to permit use of standard plastic pipe fittings. The model was approximately 6-feet square in plan and had 196 columns constructed of 3/8-inch acrylic dowels. Baffles consisted of 1/8 acrylic sheets attached to columns with adhesive putty. The inlet pipes for the model consisted of 90° elbows oriented upward similar to the prototype inlet pipes. Since it was believed that the outlet pipe configuration would not significantly impact flow patterns, model outlet pipes were oriented horizontally, simplifying model construction.

Tests Performed

A total of 31 tests were performed on the model. The first five tests were performed on unbaffled reservoirs as a control and for comparison of the results with the fluoride tracer study. Eighteen tests involved the visual evaluation of mixing in each reservoir using a tracer dye. Conductivity tests were then conducted on the three most promising baffle configurations for each reservoir based on the results of the dye tests. Finally, two tests were conducted to determine if T_{10}/T varied with reservoir level and flow rate.

Results

Comparison of Unbaffled Prototype and Model T_{10}/T Times

Five tests were performed on the unbaffled reservoirs as a control and for comparison of the results with the February 26-28, 1996 fluoride tracer test on the East Reservoir (see Table 4). This tracer test was selected because it allowed for the comparison of an individual reservoir (the East Reservoir) and because the test was performed in an increasing tracer concentration mode (similar to the model tests). The specific flow rate and reservoir level used for each of the model tests (except Tests 29 and 30) were developed from the average flow rate and reservoir level for the fluoride tracer study.

The results of the fluoride tracer test were compared with the results of Tests 3 and 4 for the East and West Reservoirs. The results are shown graphically in Figure 2. It can be seen that the general shapes of all three curves are similar. However, the model tended to see faster tracer breakthroughs. The East Reservoir prototype T_{10}/T ratio was 0.34 while the East Reservoir model T_{10}/T ratio was 0.21, a 40% decrease. Although a West Reservoir prototype T_{10}/T ratio was not available, it was expected to be relatively low compared to the East Reservoir due to the proximity of its inlet and outlet. The model results indicated that the West Reservoir had an unbaffled T_{10}/T ratio of 0.18, 14% less than the East Reservoir model value.

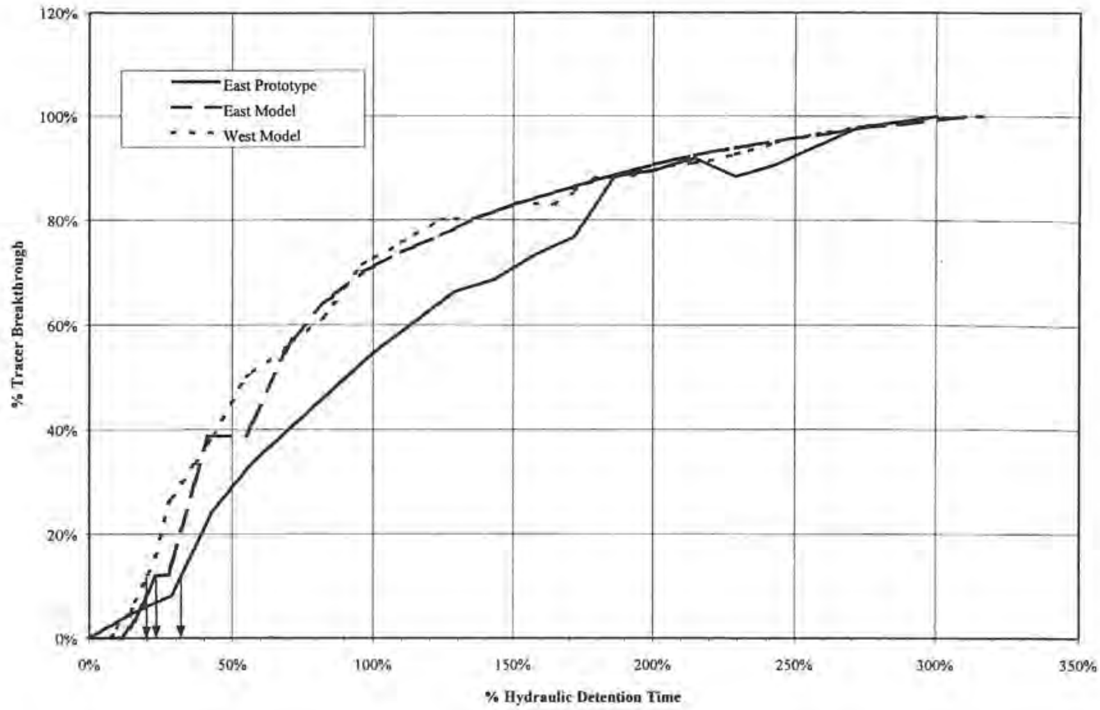

Figure 2. Fort Collins 15 MG Reservoirs - Comparison of Unbaffled Prototype and Model Tests

Since T_{10}/T is a dimensionless variable, in theory, prototype and model T_{10}/T times should have been equal. Differences between the two may be attributed to the sampling location differences between the prototype and model as well as to unscalable hydraulic phenomena occurring in the model, such as the impact of surface waves at the inlet. However, it was believed that the results of the model tests would produce conservative estimates of the prototype T_{10}/T since the model experienced shorter tracer breakthrough times. Relative increases in the model T_{10}/T due to the presence of baffles were expected to correlate to similar increases in the prototype T_{10}/T.

Dye Tests

Each reservoir was subjected to nine different baffle configuration dye tests to narrow the selection of baffle configurations for the longer conductivity tests. The configurations were developed based on what appeared to be reasonable means of slowing flow towards the outlet. This usually meant trying to develop a "front" of dye moving uniformly across the width of the model towards the outlet. The specific baffle configurations are illustrated in Figures 3 and 4. The arrows indicate the path of the first dye reaching the outlet.

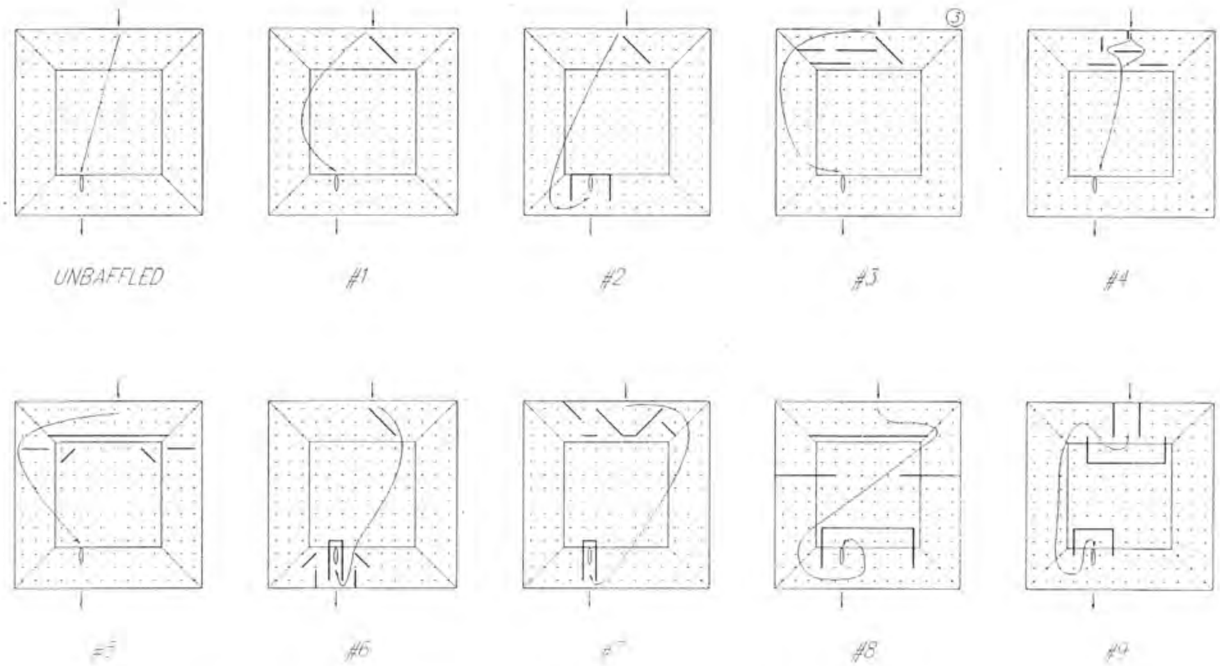

Figure 3. Fort Collins East 15 MG Reservoir Baffle Configurations

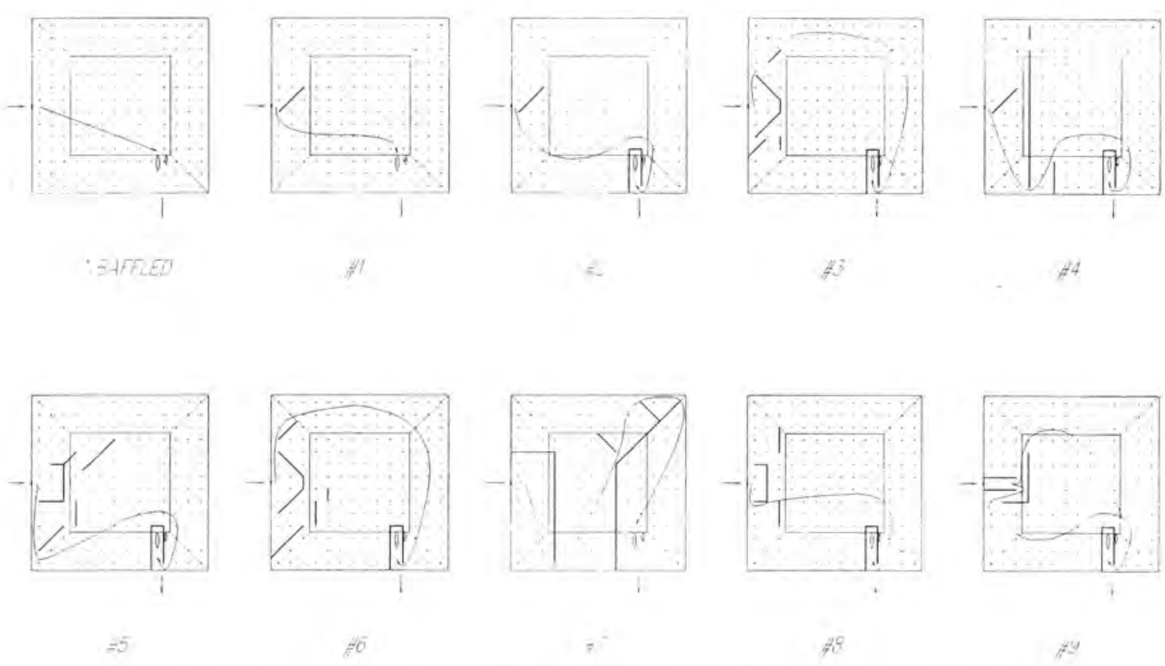

Figure 4. Fort Collins West 15 MG Reservoir Baffle Configurations

In the early stages of mixing, areas of poorer mixing (dead zones) could be identified by a lack of dye. These tended to occur at points distant from the most direct path between the inlet and outlet, behind very long baffles or at corners of the model. The first two of these phenomena could be dealt with successfully by modifying the baffle configuration or providing "windows" in the baffles. The dead zones at the four corners of the model were more difficult to manage because of the propensity of water to flow in curvilinear streamlines, rather than at right angles. This is an inherent problem of non-circular tanks. However, due to the relatively small volume of water in the corners of these reservoirs, this was not deemed a significant concern.

The observed times at which the dye first appeared at the outlet and its path were recorded for each baffle configuration. For the East Reservoir, Baffle 7 appeared to provide the greatest increase in contact time, followed by Baffles 8 and 3. For the West Reservoir, Baffle 3 was tested based on the apparent success of Baffle 7 on the East Reservoir. One modification was made so that the outlet was completely closed off on the side near the inlet. This configuration gave the best results for the West Reservoir, followed by Baffles 9 and 7.

Conductivity Tests

The three baffle configurations for each reservoir that produced the longest initial contact times during dye testing were selected to undergo conductivity testing for six hours (approximately 3T) to determine quantitatively which baffle configurations were most effective in increasing contact time. Tracer breakthrough curves were plotted for each conductivity test and the T_{10}/T's were calculated.

Although the dye contact time in the East Reservoir appeared to be better for Baffle 3 and Baffle 7, in reality T_{10}/T actually decreased for both configurations. Only Baffle 8 saw an increase in T_{10}/T, and the increase was significant. For the West Reservoir, the correlation between the dye testing and the conductivity testing was closer. All three baffle configurations saw improvements in T_{10}/T and the increases were relatively proportional to the increases in contact time observed in the dye tests.

Stability of T_{10}/T for Differing Flow Conditions

Two tests were conducted to determine if the T_{10}/T ratio varied with reservoir level and flow rate. The East Reservoir with Baffle 7 was selected as a control for these tests. In the first test, the flow was doubled to 23.0 MGD, resulting in a halving of the hydraulic detention time, T. In the second test, the reservoir storage volume was doubled, resulting in a doubling of T. Tracer breakthrough curves were plotted for each test and the T_{10}/T ratios were compared. When T was halved, the T_{10}/T increased by about 25%. When T was doubled, the T_{10}/T decreased by about 20%. Thus it appears that for these reservoirs, there is an inversely proportional relationship between T and T_{10}/T.

Final Baffle Selections

In order to compare the relative benefits of the various baffle configurations, the increase in the T_{10}/T over the unbaffled case was weighed against the length of baffle involved. Since the length of baffle would be approximately proportional to cost, this permitted an economic evaluation of the benefits of the various baffle configurations. Consequently a relationship was developed by dividing the increase in T_{10}/T over the unbaffled case by the length of baffle in hundreds of feet. The results are shown in Table 3.

Table 3. Fort Collins 15 MG Reservoirs - Final Baffle Selections

Reservoir	Test #	Baffle #	Baffle Length (feet)	T_{10}/T	Prototype $\Delta(T_{10}/T)/L$ (%/100')	Rating
West	5	None	0	0.18		
West	20	3	373	0.25	1.9	1
West	24	7	636	0.22	0.6	3
West	23	9	376	0.23	1.3	2
East	4	None	0	0.21		
East	31	3	217	0.14	-3.2	3
East	25	7	353	0.20	-0.3	2
East	27	8	624	0.33	1.9	1

For the West Reservoir, Baffle 3 resulted in the greatest improvement in T_{10}/T for the least amount of baffling. A 20-foot section of baffle was added to the configuration tested to enclose the 36-inch outlet, leading to a total baffle length of 393 feet. This configuration kept the baffles away from the center of the reservoir, which was expected to facilitate FCU washdown and maintenance activities. The final configuration is shown in Figure 5 and was expected to increase the T_{10}/T from 0.18 to 0.25, an increase of 39%.

For the East Reservoir, improving flow circulation patterns appeared to require relatively long baffle lengths. Since both the East and West Reservoirs are operated ("float") together, there appeared to be little value in improving the T_{10}/T in the East Reservoir beyond that of the limiting West Reservoir. Therefore a simple baffle configuration that would result in approximately the same T_{10}/T as the baffled West Reservoir was recommended for the East Reservoir. It was believed that this could best be accomplished by using a 140-foot baffle around the outlet (Figure 5) since closure baffles consistently provided small increases in contact time during the tests. This baffle was expected to direct flows towards the south wall where mixing would otherwise be minimal. Although the T_{10}/T was not known for this outlet closure acting alone, it was believed that it would increase the T_{10}/T for the East Reservoir into the range of the West Reservoir (from 0.21 to 0.25, an increase of 19%).

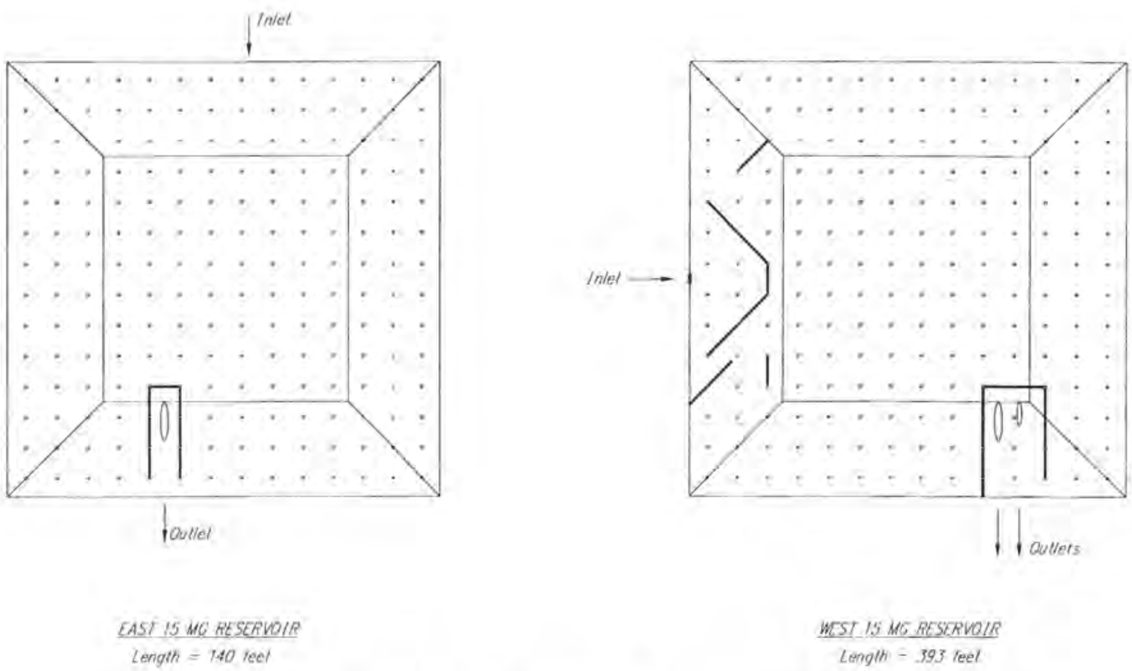

Figure 5. Fort Collins 15 MG Reservoirs - Final Baffle Configurations

Post-Baffle Fluoride Tracer Test Results

Based on the recommendations of the hydraulic model study, Hypalon® baffles were installed in the East and West Reservoirs during the fall and winter of 1997. The baffles extended from the overflow level to the floor. Due to limited roof loading capacity, the baffles were suspended from stainless steel angles mounted to the reservoir columns.

Fluoride tracer tests were subsequently performed by FCU on the West Reservoir, the East Reservoir, and on flow through both reservoirs operated in parallel. The conditions and results from these tests and the previous prototype tracer tests conducted by FCU are outlined on Table 4. The fluoride tracer tests showed a T_{10}/T of 0.45 for the West Reservoir, significantly higher than predicted by the scale model tests. This indicates that the new baffles installed in the West Reservoir are performing much better than predicted. However, the significance of this result is somewhat diminished by the outcome of the tracer tests for the East Reservoir and the combined reservoirs. The test for the East Reservoir indicated that the T_{10}/T ratio decreased by approximately 29% from the value of 0.34 obtained during the February 26-28, 1996 tracer test to the value of 0.24 obtained after the baffles were installed. The test on the combined reservoirs indicates that the new baffles resulted in an insignificant increase in the T_{10}/T ratio when the reservoirs are operated in parallel. Since the reservoirs are operated in parallel most of the time, this finding is the most important to the FCU.

Table 4. Fort Collins 15 MG Reservoirs - Summary of Fluoride Tracer Tests Performed

Test No.	Test Date	Reservoir	Avg. Flow (MGD)	Avg. Water Level (feet)	Avg. Reservoir Volume (MG)	Theoretical Detention Time, T (hours)	T_{10} (hours)	T_{10}/T
1[1]	June 5-9, 1995	East + West (unbaffled)	17.5	24	25	34	6.8	0.20
2[1]	Feb. 20-22, 1996	East (unbaffled)	17.8	21.3	10.8	14.6	3.6	0.25
3[1]	Feb. 26-28, 1996	East (unbaffled)	11.4	14.4	6.7	14	4.7	0.34
4[2]	Jan. 26-27, 1998	West (w/ baffles)	14.6	13.3	6.0	9.9	4.5	0.45
5[2]	Feb. 25-27, 1998	East (w/ outlet closure baffle)	14.0	14.3	6.6	11.4	2.8	0.24
6[2]	March 12-14, 1998	East + West (w/ baffles)	15.1	13.8	12.7	20.0	4.2	0.21

[1] Test performed under the direction of Process Applications, Inc., Fort Collins, CO
[2] Test performed under the direction of Judy Billica, Senior Process Engineer, City of Fort Collins Utilities

The fluoride tracer tests performed on the prototypes after the baffles were installed showed that the predicted improvements in contact time were significantly different than the actual contact times. It appears that, for the FCU reservoirs, the scale hydraulic model was not able to fully duplicate all the hydraulic phenomena occurring in the prototype. However, the model tests did allow visual observation of the potential impact of various baffle configurations. In addition, the model tests provided a systematic basis for evaluating a range of economic baffle configurations.

IV. DENVER WATER – MARSTON WTP BASIN 3 BAFFLE STUDY

Prototype Description and Purpose of Study

The Denver Water Marston Water Treatment Plant provides "peaking" capacity water treatment during periods of high summertime demand to supplement water treated at the Foothills and Moffat Water Treatment Plants. The plant treats approximately 10% of the water produced by Denver Water. At the end of the treatment process, the treated water passes through two contact basins (Basins 1 and 2) with storage volumes of 3.5 MG each. The water may then be routed into the distribution system or pass through a 10.4 MG clearwell (Basin 3) for temporary storage. These basins were constructed of reinforced concrete in the 1950's. Their relative orientations can be seen in Figure 6.

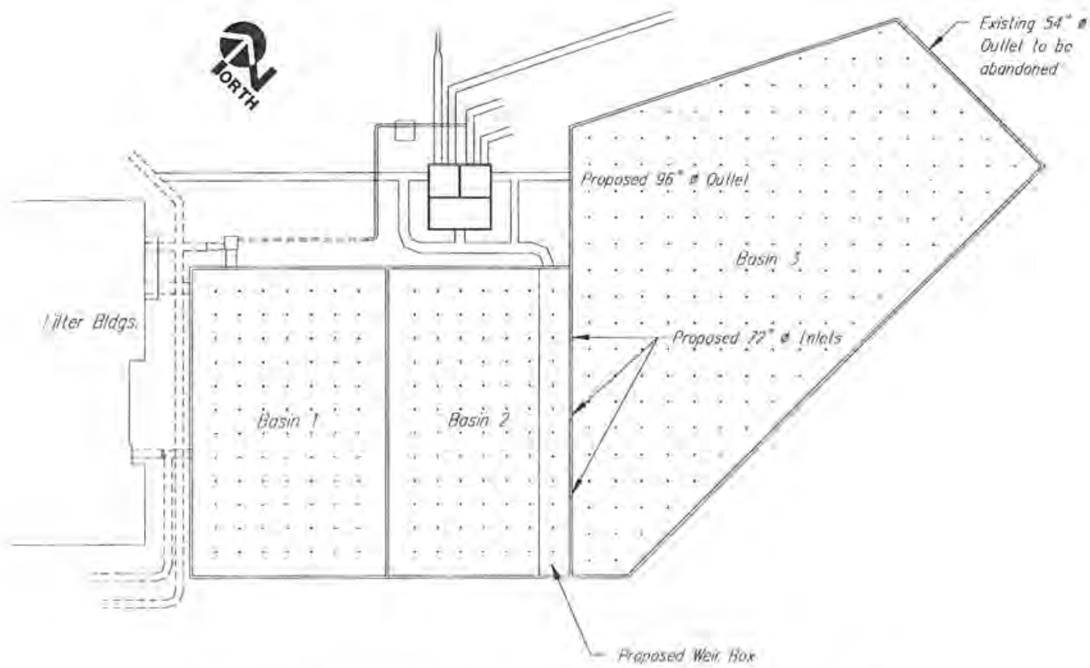

Figure 6. Denver Water Marston Treatment Plant Basins

Plans are currently underway to modify all three basins to increase chlorine contact time and eliminate "dead zones" within the basins. These modifications include adding labyrinth baffles in Basins 1 and 2 to provide more uniform flow, constructing a weir at the west end of Basin 2 to regulate flow into Basin 3 and modifying the inlet and outlet piping in Basin 3. The proposed Basin 3 inlet pipes would pass through the common wall with Basin 2 and the outlet would be moved from the north wall to the southwest wall.

Three hydraulic questions were raised by Denver Water in light of the proposed basin changes. The first asked if the weir at the west end of Basin 2 would work effectively. The second inquired what inlet configuration for Basin 3 would result in the most uniform mixing in the basin. The third question asked which baffle configuration in Basin 3 would minimize dead zones within the basin.

Model Description

The hydraulic model included the weir box in Basin 2 and all of Basin 3 (see Figure 7). In order to provide uniform flow into the weir box, a separate box was added adjacent to the weir box to stabilize flows coming from the pump. The sloping floor in the proposed Basin 2 weir box was replicated in the model. In order to keep the model to a size which could be readily transported and to permit use of scaleable PVC pipe fittings, a model scale factor of 1:48 was selected. The resulting model dimensions were approximately 8 1/2 feet by 9 feet. The 18-inch round prototype columns were modeled with 3/8-inch acrylic dowels. Baffles consisted of 1/8 acrylic sheets attached to columns with adhesive putty.

Five inlets were provided along the southwest wall: two 1 3/4-inch inlets (84-inch prototype) at the third points of the weir box and three 1 1/2-inch inlets (72-inch prototype) at the quarter points. A single 2-inch outlet (96-inch prototype) was placed along the southwest wall half way between the northern edge of the weir box and the west edge of the basin.

Tests Performed

A total of 16 tests were performed to answer the questions raised concerning modifications to Basins 2 and 3. The first two tests were performed to select an inlet pipe configuration for Basin 3. The mixing patterns of dyed water in the unbaffled basin were visually evaluated. Test 3 was a control conductivity test performed on the unbaffled basin. Tests 4 - 7, 9, 10 and 12 involved the visual qualitative evaluation of mixing in the basin using dye only. Eight different baffle arrangements were tested (See Figure 8). These tests were terminated when further visual evaluation was not feasible due to complete dye dispersion in the model. Tests 8, 11 and 13 involved the quantitative conductivity testing of the three most promising baffle configurations based on the dye test results. These tests were terminated when the outlet conductivity reached 90% of the inlet conductivity (approximately two hours). A constant inlet and outlet flow rate of 25 MGD was selected for the above tests to allow adequate time for reading conductivity data. The water level for all the tests was constant, since in the prototype, water level would be established by the weir wall height.

Since prototype flow rates are expected to vary from 20 to 150 MGD, Tests 14, 15 and 16 were performed to determine if T_x/T was constant for flow rates other than 25 MGD. Flows of 50, 100 and 140 MGD were examined. Baffle 8 was selected as a control configuration for these tests.

Results

Weir Box

During the initial model testing, an unexpected phenomenon occurred in the model weir box. When the water level in the inlet box (representative of Basin 2) was nearly level with the water level in the weir box and Basin 3, a turbulent rocking motion occurred in the short dimension of the weir box. This rocking motion eventually created relatively large surface waves in Basin 3. The phenomenon became a concern because of the potential impact of these waves in the prototype.

After discussion with Bureau laboratory personnel, it was concluded that this phenomenon was a result of the vacuum created along the downstream face of the weir as water flowed horizontally over the flat crest of the weir. This vacuum "sucked" the water in the weir box towards the weir wall. As the water level rose at the weir wall, the vacuum collapsed and the water sought to level itself by moving back away from the wall. Repetition of this process created the cyclic rocking motion. Laboratory personnel believed that this phenomenon might also be expected in the prototype.

Laboratory personnel recommended replacing the broad-crested weir (1/2-inch acrylic sheet) with a sharp crested weir. A 1/8-inch thick strip of sheet metal was used to simulate the sharp-crested weir. The rocking phenomenon was eliminated for all flow depths with this modification.

Inlet Configuration

Tests 1 and 2 were performed to select an inlet pipe configuration for Basin 3. The mixing patterns of dyed water in the unbaffled basin were visually evaluated for two inlet configurations proposed by Denver Water. The first configuration involved two 1 3/4-inch inlets (84-inch prototype) at the third points of the weir box. The second involved three 1 1/2-inch inlets (72-inch prototype) at the quarter points of the weir box.

During initial mixing, the spread of flow across the basin was wider with three inlets as would be expected. With three inlets, the zone between the inlet and outlet (Probe 4) appeared to be less well mixed, while with two inlets, the northwest wall (Probe 9) appeared to be less well mixed. Dye reached the furthest (northeast) corner (Probe 13) slightly faster with two inlets than with the three, probably due to the higher inlet velocities associated with the smaller overall inlet opening area.

Although there did not appear to be large differences in mixing between the three and two inlet configurations, a decision was made to use three inlets in order to better spread the initial flows and provide more flexibility in operation of the basin. The remaining tests were thus performed using the three inlets.

Unbaffled Conductivity Test

As a means for identifying dead zones in the basin and as a control for later baffled tests, an unbaffled conductivity test was next performed. One conductivity probe was placed in the supply tank and the other thirteen were placed as shown in Figure 7. In general flows tended to fan out from the inlet wall perpendicularly and gradually arc towards the outlet. This created a dead zone between the inlet and outlet at Probe 4 and at the furthest corner at Probe 13. A recirculation zone was also observed at Probe 3.

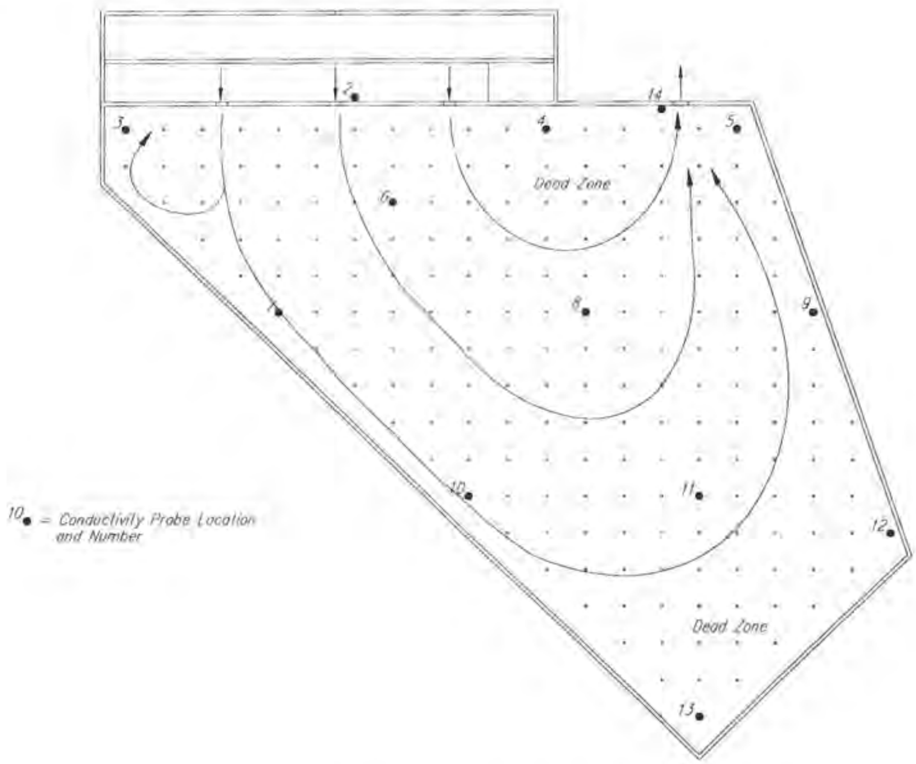

Figure 7. Denver Water Marston Basin 3 - Unbaffled Flow Lines

In general, the differences between the conductivities in the active and dead mixing zones in the basin were relatively higher than for other scale models tested by the authors. This was probably due both to the unusual geometry of the basin and the fact that the inlet and outlet are located on the same, rather than adjacent or opposite, walls.

Baffle Dye Tests

Based on the observations of dead zones in the unbaffled basin, eight different baffle configurations were dye tested to narrow the selection of baffle configurations for the longer conductivity tests (see Figure 8). These configurations were developed based on what appeared to be reasonable means of directing flows through dead zones. An attempt was made achieve this goal without the use of labyrinth-type baffles which are relatively expensive and create a maintenance liability. The guiding principle followed was to allow the basin to disperse flows where it was naturally able to and to train flows where it was not. The basic configuration involved creating a "wall" between the inlet and outlet areas. This "wall" was punctuated by short gaps to prevent creating additional dead zones behind the baffles.

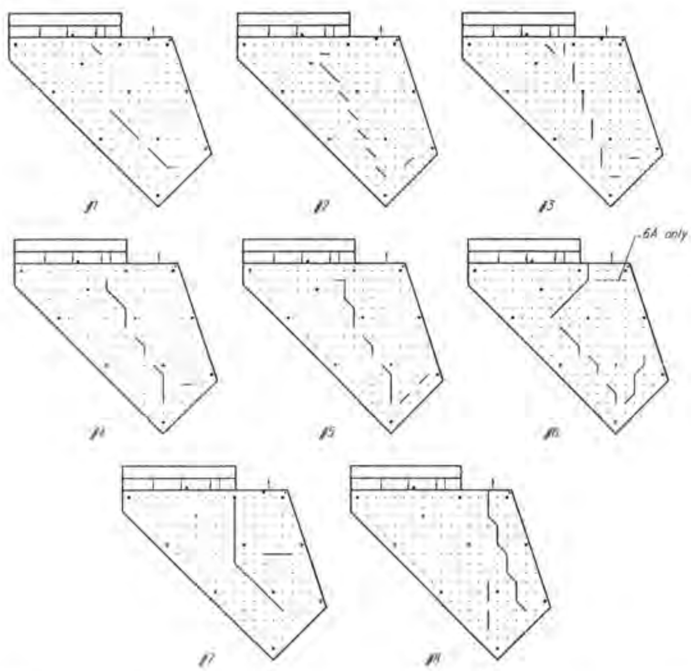

Figure 8. Denver Water Marston Basin 3 – Baffle Configurations Tested

Some general observations made in the course of these dye tests were:

1. The dead zone at Probe 4 could not be effectively eliminated by directing flows from the northernmost inlet through this area (Baffles 1, 2, 3 and 5).

2. Too many gaps in the baffle "wall" prevented the dead zone at Probes 12 and 13 from being eliminated (Baffles 1-5).

3. Baffle configurations which left a gap along the southwest wall (Baffles 1-5 and 7) allowed a basin-wide circular mixing pattern to develop. This proved counterproductive because some the water approaching the outlet was blended back in with the incoming flows. This water was thus forced to remain in the basin much longer than other water.

4. The area along the northwest wall did not tend to mix well unless flows were channeled along this wall (Baffle 8).

Overall, Baffle Configurations 6A and 8 appeared to provide the greatest improvement in overall mixing. The third best arrangement appeared to be Baffle Configuration 4.

Baffle Conductivity Tests

Baffle Configurations 4, 6A and 8 were selected to undergo conductivity testing for two hours to determine quantitatively which configuration was most effective in minimizing dead zones in Basin 3. Tracer breakthroughs were calculated for these three tests and the unbaffled test at the dead zones identified in the unbaffled test (Probes 4, 9, 12, 13) and at the outlet (Probe 14).

A relatively rapid increase in conductivity at Probes 4, 9, 12 and 13 was used as an indication of favorable mixing, since these were identified as dead zones. Baffles 6A and 8 tended to promote faster mixing at Probe 4. None of the baffles improved the mixing at Probe 9, except that Baffle 8 tended to produce more rapid mixing later in the testing. All three baffle configurations improved mixing at Probe 12, with Baffles 4 and 8 being most significant. The improvement in mixing at Probe 13 was dramatic and similar for all three baffle configurations, except that Baffle 6A gave the best long-term mixing.

A relatively slow increase in conductivity at the outlet (Probe 14) was also considered an indication of favorable mixing, because it signaled more uniform spreading of the flows into the basin prior to discharge. In general all the baffles produced slight increases over the unbaffled case early in the tests (up to T_{50}/T), but were similar in the long term.

Stability of T_{10}/T Times for Differing Flow Conditions

In order to ascertain the impact of the baffles over the flow range expected in the prototype, conductivity tests were run for Baffle 8 at 25, 50, 100 and 140 MGD. Tracer breakthrough graphs for Tests 13-16 showed strikingly similarities indicating that T_x/T was constant for the flow ranges expected in the prototype.

Final Baffle Selection

Since the goal of baffling Basin 3 was to eliminate dead zones, it was felt that the best means of evaluating the three baffle configurations was to quantify their performance at the probes identified in the unbaffled test as dead zones (Probes 4, 9, 12 and 13).

In order to weigh the impacts of the baffles over time for each test, the values of T_{10}/T, T_{50}/T and T_{90}/T for these four probes were determined from the graphs. The percent improvement of baffle "#" over the unbaffled case at a particular time was calculated as follows:

$$\%\ \text{Improvement}\ (\#) = \frac{T_x/T(\text{Unbaffled}) - T_x/T(\#)}{T_x/T(\text{Unbaffled})} * 100$$

In order to compare the relative benefits of the three promising baffle configurations, the average increases in T_{10}/T, T_{50}/T and T_{90}/T at the four probes were weighed against the length of baffle in hundreds of feet. Since the length of baffle was expected to be approximately proportional to cost, this permitted an economic evaluation of the benefits of the various baffle configurations. The results are shown in Table 5.

Table 5. Denver Water Marston Basin 3 – Final Baffle Selection

Baffle #	Baffle Length (feet)	T_{10}/T	T_{50}/T	T_{90}/T	Average % Improvement	Avg. % Improvement /100' Length	Rating
None	0	0.36	0.83	2.28	0.0%	0.0%	
4	253	0.29	0.59	2.11	18%	7.2%	2
6A	496	0.25	0.54	1.65	31%	6.3%	3
8	367	0.27	0.49	1.58	32%	8.8%	1

Baffle 6A provided the best initial mixing (T_{10}/T), but it was surpassed by Baffle 8 later in the tests (T_{50}/T and T_{90}/T). Overall, Baffle 8 has the greatest average improvement over length, followed by baffles 6A and 4.

Recommendations

The following recommendations were made for the improvements to Denver Water's Marston Treatment Plant Basins 2 and 3:

1. Use a sharp-crested weir for the Basin 2 weir based on its improved hydraulic performance.

2. Provide three 72-inch inlets in the common wall between Basins 2 and 3 at the quarter points of the wall. This arrangement provided improved distribution of flow in the basin over a two-inlet scheme.

3. Construct Baffle 8 for Basin 3. This configuration had the best overall ability to eliminate identified dead zones over time. The effectiveness of this baffling should be constant over the anticipated flow range for the basin.

These recommendations are expected to be implemented in the fall and winter of 1998.

V. CONCLUSIONS

Through having performed these three model studies, it is apparent to the authors that scale hydraulic models are a valuable tool for predicting the flow circulation patterns in water storage tanks. The authors believe that the conclusions based on their study can result in more efficient design of new tanks and modifications to existing storage facilities.

Although scale models are not readily modified geometrically, they can be easily adapted for changes to piping and baffles between tests as well as adjustments to the flow rate and flow depth during a single test. And though they are subject to scaling distortions, the authors believe that they provide a tangible "feel" for mixing that is unique to scale models.

The authors believe that scale hydraulic models best serve as a complement to prototype data and CFD model results. The insights gained from all three methods can be cross-calibrated with each other to produce a more complete understanding of flow circulation in water storage tanks.

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