DENVER WATER

MARSTON WATER TREATMENT PLANT

BASIN 3 BAFFLE STUDY

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ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

This report discusses the results of a hydraulic model study investigating mixing in Denver Water's Marston Water Treatment Plant Basins. The primary purpose of the study was to determine a baffle arrangement that would minimize "dead zones" in Basin 3 in light of changes made to the inlet and outlet locations. Secondary purposes were to evaluate the proposed weir box in Basin 2 and determine a satisfactory inlet pipe geometry for Basin 3.

The study was performed by Bates Engineering in cooperation with the U.S. Bureau of Reclamation using a 1:48 scale acrylic model. A total of 17 tests were performed in July and August 1997. The study recommends that the weir in Basin 2 be sharp-crested and that three 72-inch inlets be provided into Basin 3. A specific baffle configuration recommendation is made for Basin 3 which will improve mixing in potential "dead zones" by 32%.

I. PURPOSE

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 Million Gallons (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 three basins were constructed in the 1950's of cast-in-place concrete. Their locations and orientations can be seen in Figure 1.

Plans are currently underway to modify these basins to maximize their effectiveness. This is to be achieved by increasing the chlorine contact time in the contact basins and eliminating "dead zones" in the clearwell. Contact time is defined as the length of time for a slug of water to move from the inlet to the outlet of the basin. Dead zones are defined as specific areas within the basins where turnover of water is relatively slow compared with the average turnover in the basin.

Modifications to the basins include adding labyrinth baffles in Basins 1 and 2 to achieve plug flow, constructing a weir at the west end of Basin 2 to provide uniform flow into Basin 3 and modifying the inlet and outlet piping in Basin 3. The proposed Basin 3 inlet pipes will consist of steel pipe and butterfly valves through the common wall with Basin 2. The outlet will be moved from the north wall to the southwest wall.

Three hydraulic questions have been raised by Denver Water in light of these proposed changes to the basins:

- Will the weir at the west end of Basin 2 work effectively?

- What inlet configuration for Basin 3 will result in the most uniform mixing in the basin?

- What baffle configuration in Basin 3 will minimize dead zones in the basin?

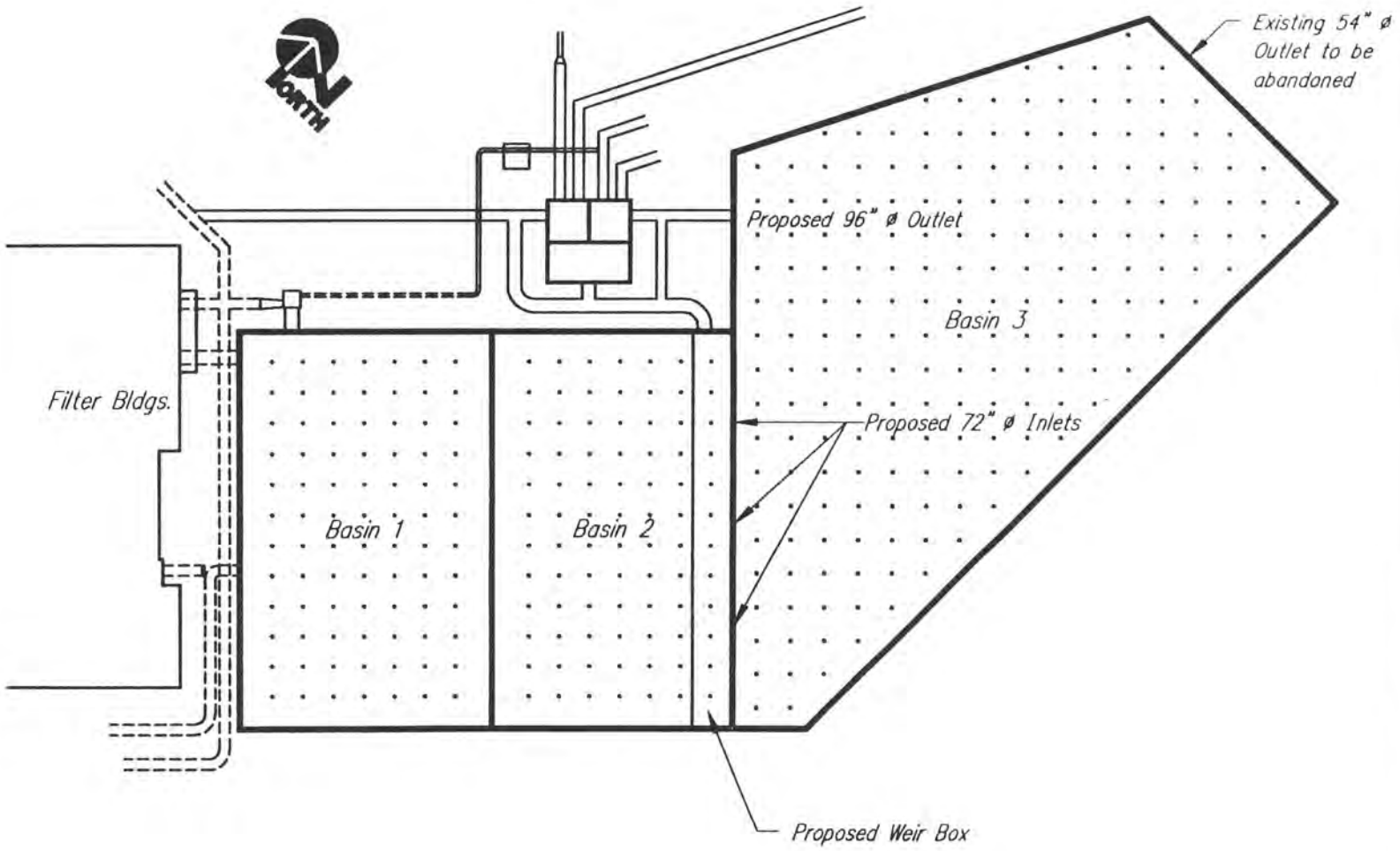The purpose of this study was to address these three issues.

Existing 54" ⌀
Outlet to be
abandoned

Proposed 96" ⌀ Outlet

Basin 3

Proposed 72" ⌀ Inlets

Filter Bldgs.

Basin 1

Basin 2

Proposed Weir Box

NORTH

Figure 1
Marston Treatment Plant Contact Basins

II.   USE OF HYDRAULIC MODELS

Recently, researchers have turned to scale hydraulic models to investigate mixing issues in potable water storage reservoirs.[1,2] These studies have been spearheaded by the American Waterworks Association (AWWA) Research Foundation Project 260, "Water Quality Modeling of Distribution System Storage Facilities". This research has previously been summarized in a report to Denver Water.[3]

Bates Engineering, Inc. has performed three hydraulic model studies related to mixing in potable water storage reservoirs. Each of these studies were performed using scale hydraulic models constructed of acrylic at the U.S. Bureau of Reclamation Water Resources Research Laboratory in Lakewood, Colorado. The findings from these studies have been incorporated into the knowledge base of AWWA Research Foundation Project 260.

The first study performed by Bates Engineering examined the effects of inlet piping configuration on mixing in a 3 MG reservoir under design in 1996 for the City of Aurora, Colorado. The number, size and location of the inlets were varied as well as the inlet pipe configuration itself. The results of this study were incorporated into the design of the reservoir now under construction.

A second study was performed for Denver Water to investigate general aspects of reservoir mixing that could be applied to the Hogback, Chatfield and Colorow reservoirs.[4] During six tests, the effect of four variables affecting mixing were evaluated: outlet configuration, water temperature, flow rates and the use of an air bubbler mixing system. The report concluded that the most important influences on reservoir mixing, and hence water quality, were: inlet/outlet geometry, flow rate and water temperature. An air bubbler mixing system effectively promoted mixing but required further evaluation.

A third study for the City of Fort Collins Water Utilities examined various baffle configurations to increase contact time at the twin 15 MG Reservoirs at their Water Treatment Facility. Baffle configurations were recommended for each reservoir that would increase the contact time by an average of 28%.[5] These baffles are currently under construction.

Denver Water saw the advantage of using a hydraulic model to address the issues related to modifications to their contact basins at the Marston Water Treatment Plant described in Part 1. They contracted with Bates Engineering, Inc. in June 1997 to perform a hydraulic model study. This report describes the model, the testing and the conclusions reached.

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[1]   Grayman, Walter M., et. al., "Water quality and mixing models for tanks and reservoirs," *Journal of the American Water Works Association*, Vol. 88, No. 7 (July 1996), pp. 60-73.
[2]   Telephone conversation with Lewis Rossman, U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, October 22, 1996.
[3]   Bates Engineering, *Denver Water Treated Water Storage Reservoir Hydraulic Model Mixing Study*, report prepared for Denver Water, November 1996.
[4]   ibid.
[5]   Bates Engineering, *Fort Collins Water Utilities 15 MG Reservoirs Baffle Study*, report prepared for Fort Collins Water Utilities, September 1997.

III. MODEL DESCRIPTION

The hydraulic model includes the weir box in Basin 2 and all of Basin 3. In order to provide uniform flow into the weir box, a separate box was added adjacent to the weir box to introduce flows from the pump. The level floor and walls of Basin 3 were fabricated using 1/2-inch acrylic sheet. 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 (L_R) of 1:48 was selected. The resulting model dimensions were approximately 8 1/2 feet by 9 feet (see Figures 2 and 3). 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 provided along the southwest wall half way between the northern edge of the weir box and the west edge of the basin. All the inlets and the outlet were placed at a minimum of 1/4 inch (1 foot prototype) above the floor.

The model was placed on a wood frame at the U.S. Bureau of Reclamation Water Resources Research Laboratory in Lakewood, Colorado for testing (see Photo 1, Appendix D). Mylar sheets were placed under the model to diffuse the fluorescent lights mounted below used for overhead photography.

Water was provided to the inlet box using a 250-gallon plastic supply tank in conjunction with a small centrifugal pump and flexible plastic piping. The water was diffused in the inlet box using a tee fitting (see Photos 4 and 5, Appendix D). Water was drawn through the outlet by means of two Little Giant® 1/25 HP magnetic drive centrifugal pumps in series and was discharged to a floor drain. Inflow and outflow rates were measured using valved, acrylic, panel-mount, 10 gallon per minute (gpm) King® rotameters.

Figure 2
Model Plan

Figure 3
Model Sections

IV.   MODEL SCALING FACTORS

In order to derive quantitative data from a hydraulic model, relationships between the prototype and model parameters such as length, flow and time must be established. These relationships are expressed in terms of similitude. For flowing water the choice of an appropriate similitude relationship is based on the forces which dominate the flow, whether inertia, friction, gravity, compressibility, surface tension or pressure.[6] For flow under atmospheric pressures characterized by turbulence, the Froude similitude relationship is the appropriate choice.

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.

For Froude similitude, flow rates for the model were scaled by the five-halves power so that 25 MGD corresponds to a model flow rate of

$$Q_M = Q_P/L_R^{5/2} = 25 \times 10^6/48^{5/2}/(24*60) = 1.09 \text{ gpm.}$$

This flow rate was selected as a control flow rate for the baffle selection tests to allow adequate time for taking conductivity data. The actual prototype flow rate for Basin 3 is expected to vary from 20 to 150 MGD. For Froude similitude, time is scaled by a factor of the one-half power. One minute in model time thus corresponds to

$$T_P = T_M*L_R^{1/2} = (1)(48)^{1/2} = 6.92 \text{ minutes}$$

in prototype time. Two hours of testing time in the model thus corresponds to 13.8 hours in the prototype.

For further details on model scaling, see Appendix A.

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[6]   Daugherty, Robert L. and Joseph B. Franzini. *Fluid Mechanics with Engineering Applications*, 7th ed., McGraw Hill, 1977, pp. 174-181.

V. DATA COLLECTION AND INTERPRETATION

Mixing in a hydraulic model can be visually observed by using a tracer dye. For this model, dye was introduced by adding yellow-green Norlab® liquid powder tracing dye to the water in the supply tank which was then pumped into the model. The initial mixing in the model could be observed and photographed with this method. However, after about 25 minutes, all the water in the model was sufficiently dyed to prohibit further observation of mixing patterns. Quantitative means were thus needed to verify mixing.

Conductivity can also be used to evaluate mixing. If tap water is introduced into a model full of de-ionized water, areas of low ion concentrations in the model indicate a lower turnover rate than areas of high concentrations. Dead zones could thus be located.

To utilize conductivity measurements, the model was filled with de-ionized (distilled) water and the supply tank was filled with tap water. De-ionized water has a theoretical conductivity of zero and the laboratory tap water had conductivity values in the range of 120 to 130 microSiemens per centimeter (μS/cm). An Orion® Model 105 conductivity meter was used to record conductivity from fourteen 5-pin Orion® 012010 conductivity probes mounted at fixed locations in the supply tank and model (see Appendix B for their locations). These 14 probes were bussed to a switching box with 14 channels so the probes could be read at a single location (see Photo 1, Appendix D). An additional 8-pin Orion® 010510 conductivity probe was used to independently verify conductivity measurements. This probe was also used to record temperatures in the model and the dye tank. In general, the dye tank and model temperatures were within 1° C of each other during conductivity testing so that temperature stratification was not created in the model.

The primary means for evaluating the effectiveness of a given baffle configuration with conductivity is by measuring the conductivity at a particular probe at a specific time and comparing it with the conductivity measured during the unbaffled test. The conductivity measurements can then be converted to a percent tracer breakthrough as follows:

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

For each probe, time can be plotted on the x axis and percent tracer breakthrough can be plotted on the y axis. Time is expressed in percent of hydraulic detention time, T, which is defined as the time for one complete exchange of water in the basin. For example, for flow in the model of 1.09 gpm and a water level of 2 13/16 inches (corresponding to approximately 69.1 gallons of storage, see Appendix A for details), one complete exchange of water in the model requires:

$$T = 69.1 \text{ gallons}/1.09 \text{ gpm} = 63.5 \text{ minutes}$$

The progress of mixing at a particular probe can then be evaluated from the graph by reading T_x/T values. T_x is defined as the time at which x percent of the inflow tracer concentration (tracer breakthrough) reaches the particular probe. For example, if 10% of the inflow tracer concentration reached the probe at 19 minutes, the resulting T_{10}/T is:

$$T_{10}/T = 19 \text{ minutes}/63.5 \text{ minutes} = 0.30 \text{ or } 30\%$$

Basins are routinely evaluated based on the T_{10}/T value at the outlet. In the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources*, the Environmental Protection Agency (EPA) has classified the degree of mixing in basins based on T_{10}/T time.[7] A modified version of their basin classification system is found below:

Basin Condition	T_{10}/T
Perfect Short Circuiting	0.00
Unbaffled (Completely Turbulent)	0.10
Minimal Baffling	0.30
Average Baffling	0.50
Superior Baffling	0.70
Perfect Mixing (Plug Flow)	1.00

While these guidelines appear to be more applicable to small basins than to large ones like Basin 3, they do provide some guidance on evaluating baffling configurations.

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[7] U.S. Environmental Protection Agency, *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources*, Washington D.C., March 1991, Table C-5.

VI.   SUMMARY OF TESTS PERFORMED

A total of 17 tests were performed to answer the questions raised concerning modifications to Basins 2 and 3. The variables for each of the 17 tests performed are summarized on Table 1.

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 4). These tests were terminated when further evaluation was not feasible due to complete dye dispersion in the model. Overhead photographs were taken for each test at regular intervals. A separate notebook of photographs has been provided to Denver Water along with this report.

Tests 8, 11 and 13 involved the quantitative conductivity testing of the three most promising baffle configurations based on the visual evaluation of the dye tests. The tests were terminated when the outlet conductivity reached 90% of the inlet conductivity (approximately two hours).

Tests 14, 15 and 17 were performed to determine if the T_x/T values were constant for other flow rates. Baffle 8 was selected as a control for these tests. Flows of 50, 100 and 140 MGD were tested (140 MGD was the maximum outlet pump capacity). Photographs for the 100 MGD test were taken separately in Test 16.

Table 1. Summary Of Tests Performed

Test #	Date	Baffle #	Baffle Length (feet)	Prototype Flow (MGD)	Test Duration (min.)	Overhead Photos	Conductivity Data	Comments
1	7/28/97	None	0	25	17	Yes	No	2-84" Inlets
2	7/28/97	None	0	25	17	Yes	No	3-72" Inlets
3	7/30/97	None	0	25	120	No	Yes	Unbaffled
4	7/30/97	1	190	25	25	Yes	No	Dye Test
5	7/30/97	2	246	25	25	Yes	No	Dye Test
6	7/30/97	3	248	25	25	Yes	No	Dye Test
7	7/30/97	4	253	25	25	Yes	No	Dye Test
8	8/4/97	4	253	25	120	No	Yes	Conductivity
9	8/4/97	5	321	25	25	Yes	No	Dye Test
10	8/4/97	6	438	25	25	Yes	No	Dye Test
11	8/11/97	6A	496	25	120	$t \geq 10$ min.	Yes	Conductivity
12	8/11/97	7	341	25	30	Yes	No	Dye Test
13	8/13/97	8	367	25	120	Yes	Yes	Conductivity/Dye Test
14	8/26/97	8	367	50	60	Yes	Yes	Conductivity
15	8/27/97	8	367	140	21:26	Yes	Yes	Conductivity
16	8/28/97	8	367	100	10	Yes	No	Dye Test
17	8/28/97	8	367	100	30	No	Yes	Conductivity

BAFFLE CONFIGURATION #3

BAFFLE CONFIGURATION #6

BAFFLE CONFIGURATION #2

BAFFLE CONFIGURATION #5

BAFFLE CONFIGURATION #8

BAFFLE CONFIGURATION #1

BAFFLE CONFIGURATION #4

BAFFLE CONFIGURATION #7
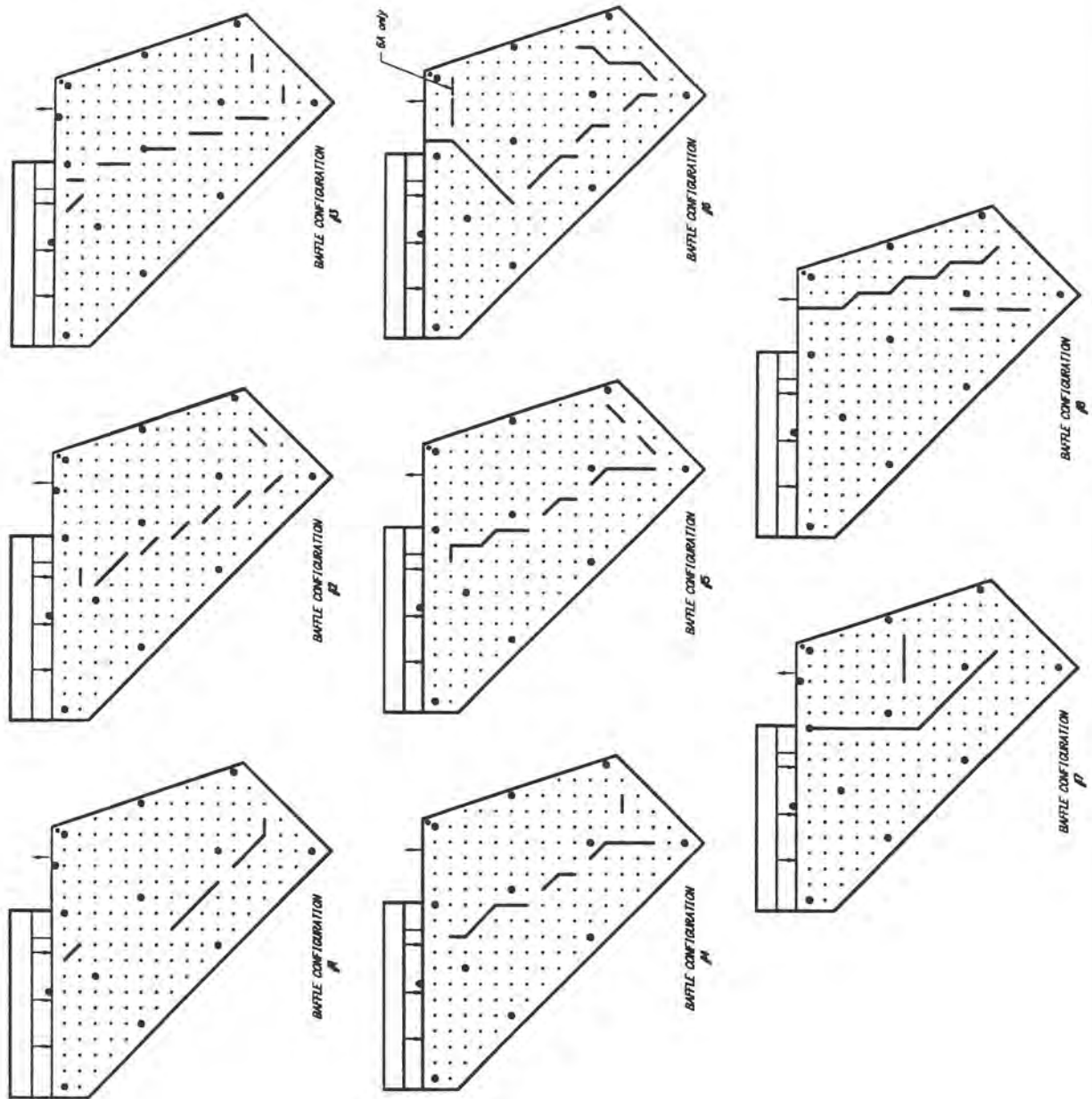
Figure 4
Baffle Configurations

VII. SUMMARY OF TEST RESULTS

A. 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 would occur in the weir box in the short dimension (see Photographs 4 and 5, Appendix D). This rocking motion eventually created relatively large surface waves in Basin 3. The phenomena 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 phenomena 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. The continuation 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. A sharp-crested weir is thus recommended for construction.

B.   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. Overhead photographs of these two tests can be found in the separate photograph binder.

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. Inlets not in use during the tests were sealed with 1/8-inch acrylic sheet and a submersible sealing lubricant.

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 farthest (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.

C.   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.

Prior to performing the test, it was assumed that the dead zones would be primarily located at the corners of the model away from the inlet and outlet (i.e. Probes 3, 12 and 13). In fact, conductivity readings at Probes 12 and 13 did indicate poor mixing. However, the area around Probe 3 appeared to be well mixed (see Photograph 7). Surprisingly, the "short-circuit" path between the inlet and outlet (Probe 4) also appeared to be poorly mixed. In general flows tended to fan out from the southwest wall perpendicularly and gradually arc to the north and bend back again south. This created a dead zone at probe 4. See Figure 5 below.
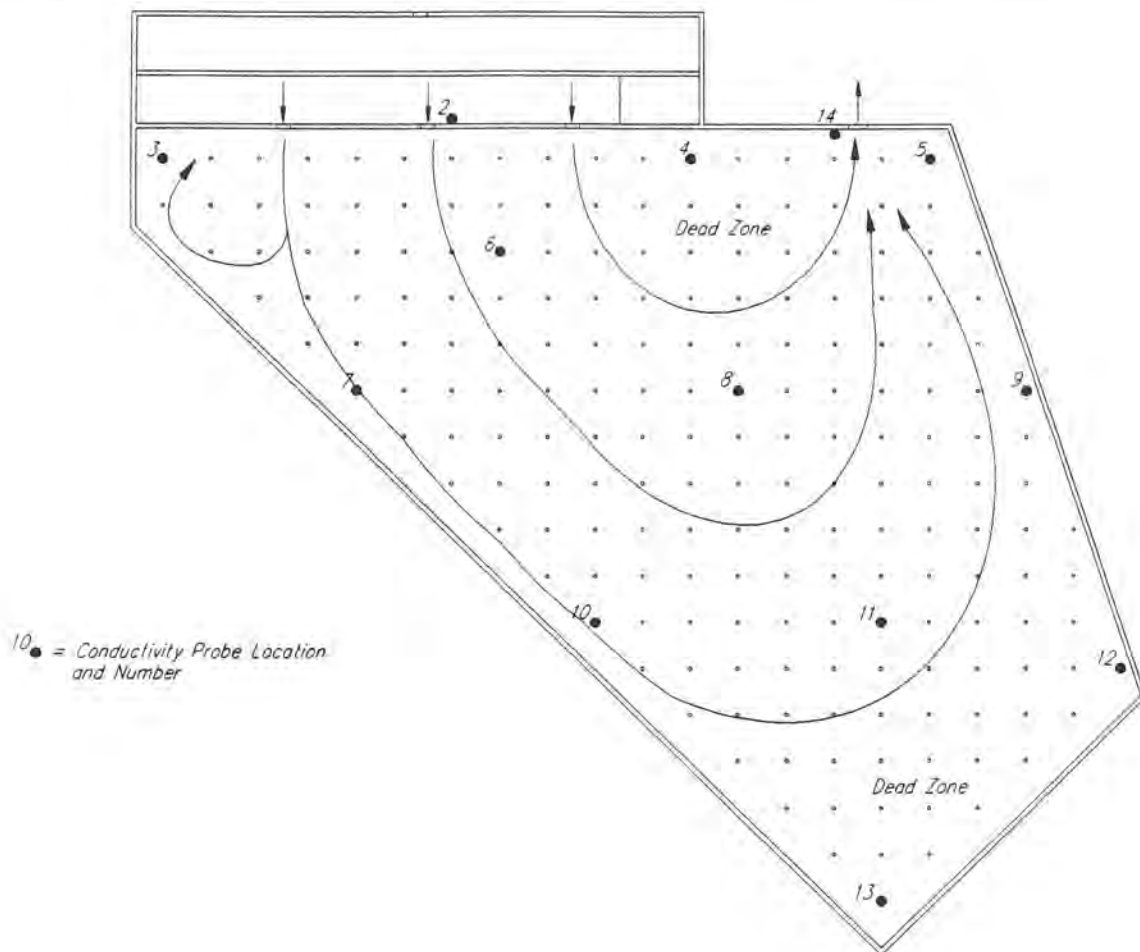
Figure 5. Unbaffled Flow Lines

In general, the differences between the conductivities in the active and dead mixing zones in the basin were relatively higher than for other models tested by Bates Engineering, Inc. This is undoubtedly 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.

D.   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. These configurations were developed based on what appeared to be reasonable means of directing flows through dead zones without creating new dead zones. An attempt was made achieve this goal without extensive plug-flow type baffles which are not only expensive, but also become 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 area and the outlet area punctuated by short gaps which would prevent creating new dead zones behind the baffles.

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 a minimum of twice as long as other water.

4. The area along the northwest wall does not tend to mix well unless flows are 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.

E.   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. For these three tests and the unbaffled test tracer breakthroughs were calculated at the dead zones identified in the unbaffled test (Probes 4, 9, 12, 13) and at the outlet (Probe 14). The calculations can be found in Appendix C. Tracer breakthroughs at these probes are graphed on the following pages. The graphs allow ready comparison of the effectiveness of each baffle configuration.

A relatively rapid increase in conductivity at Probes 4, 9, 12 and 13 is an indication of favorable mixing, since these are the 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) is also an indication of favorable mixing, because it indicates that flows have been spread more uniformly in the basin before they are discharged. In general all the baffles were slightly better than the unbaffled case early in the tests, but were similar in the long term.

Denver Water
Marston Basin #3 Baffle Study
Probe 4 Breakthrough
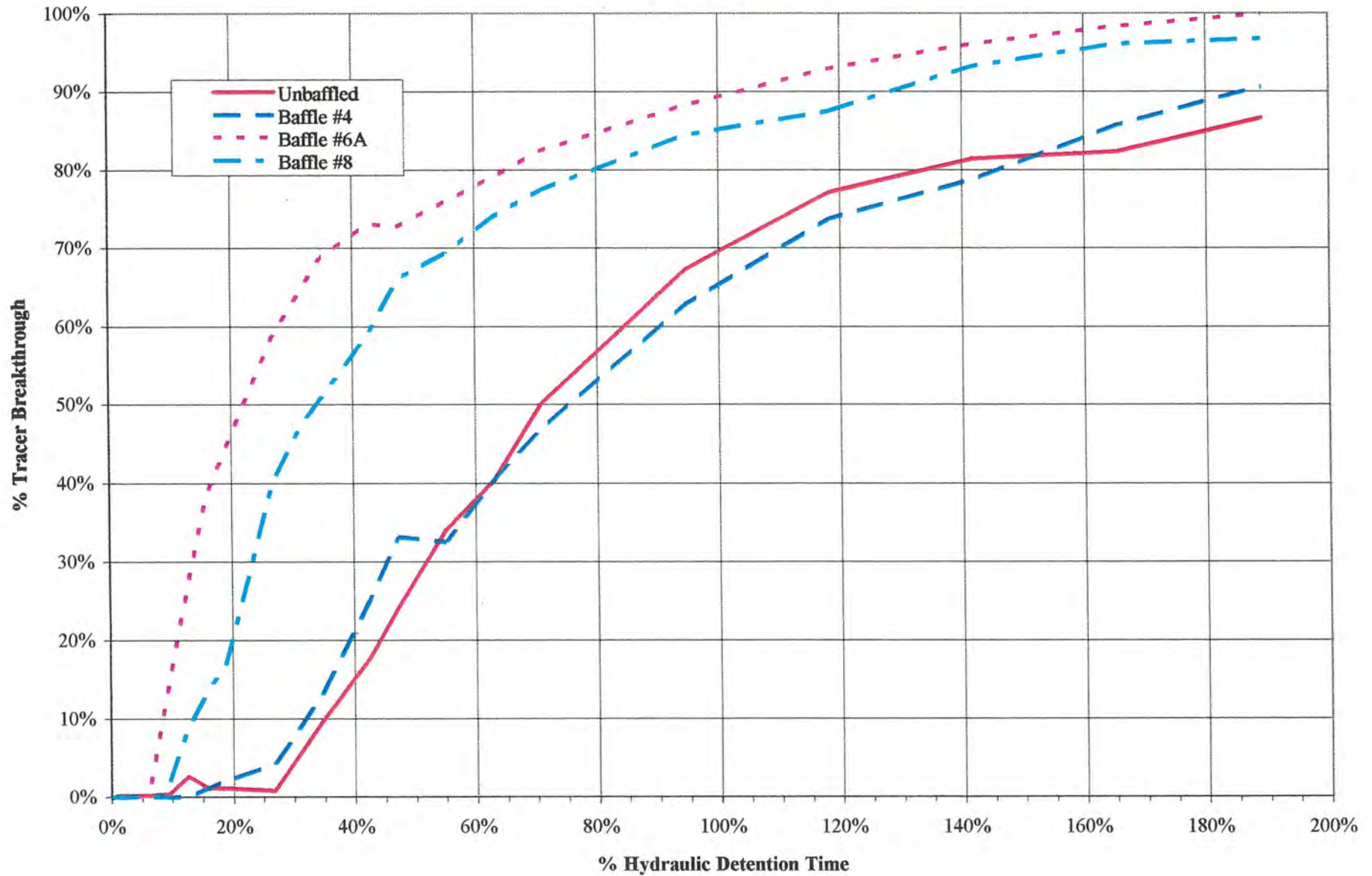
Denver Water
Marston Basin #3 Baffle Study
Probe 9 Breakthrough

Figure: Plot of % Tracer Breakthrough versus % Hydraulic Detention Time. Legend: Unbaffled, Baffle #4, Baffle #6A, Baffle #8.
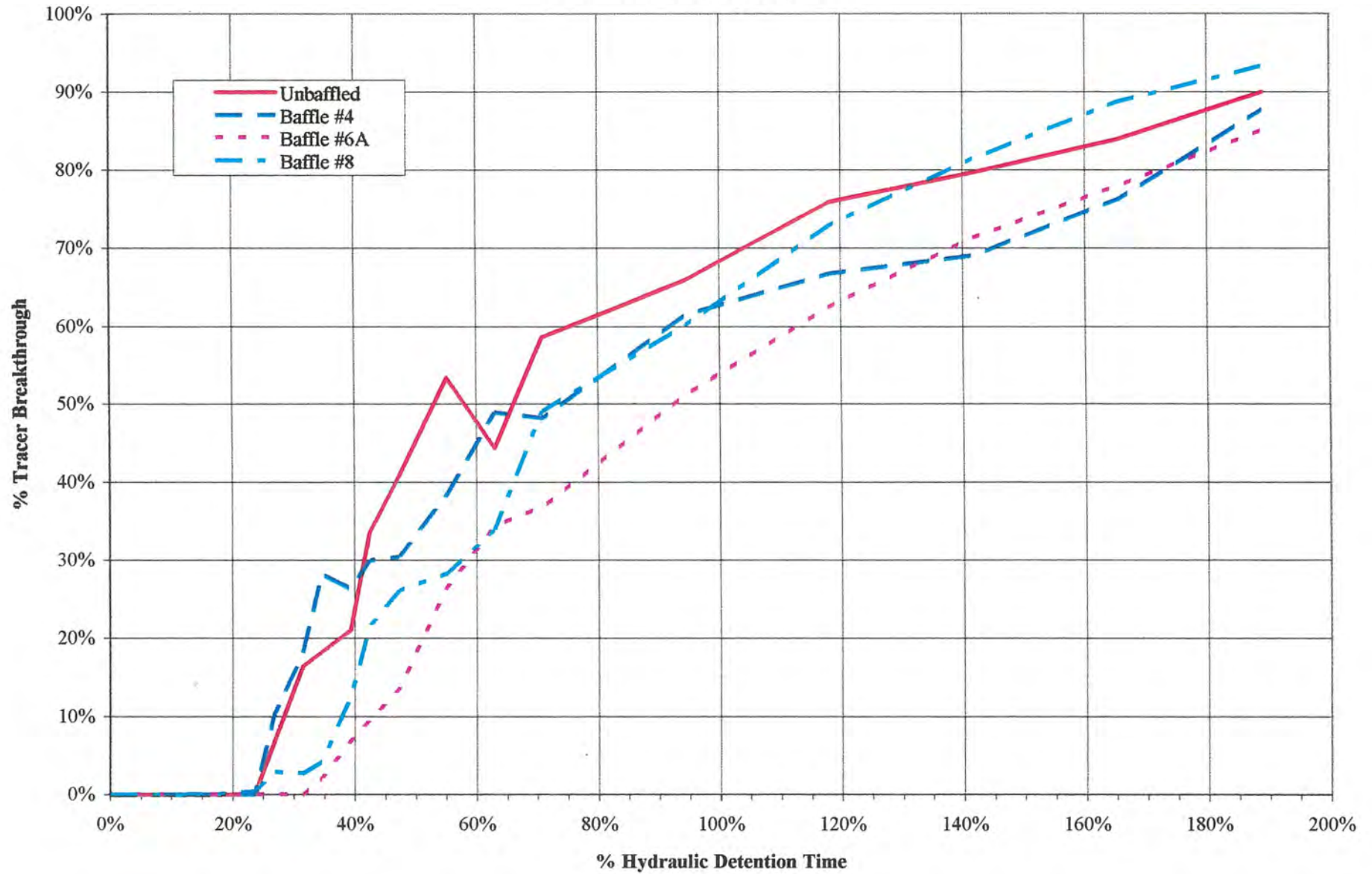
Denver Water
Marston Basin #3 Baffle Study
Probe 12 Breakthrough
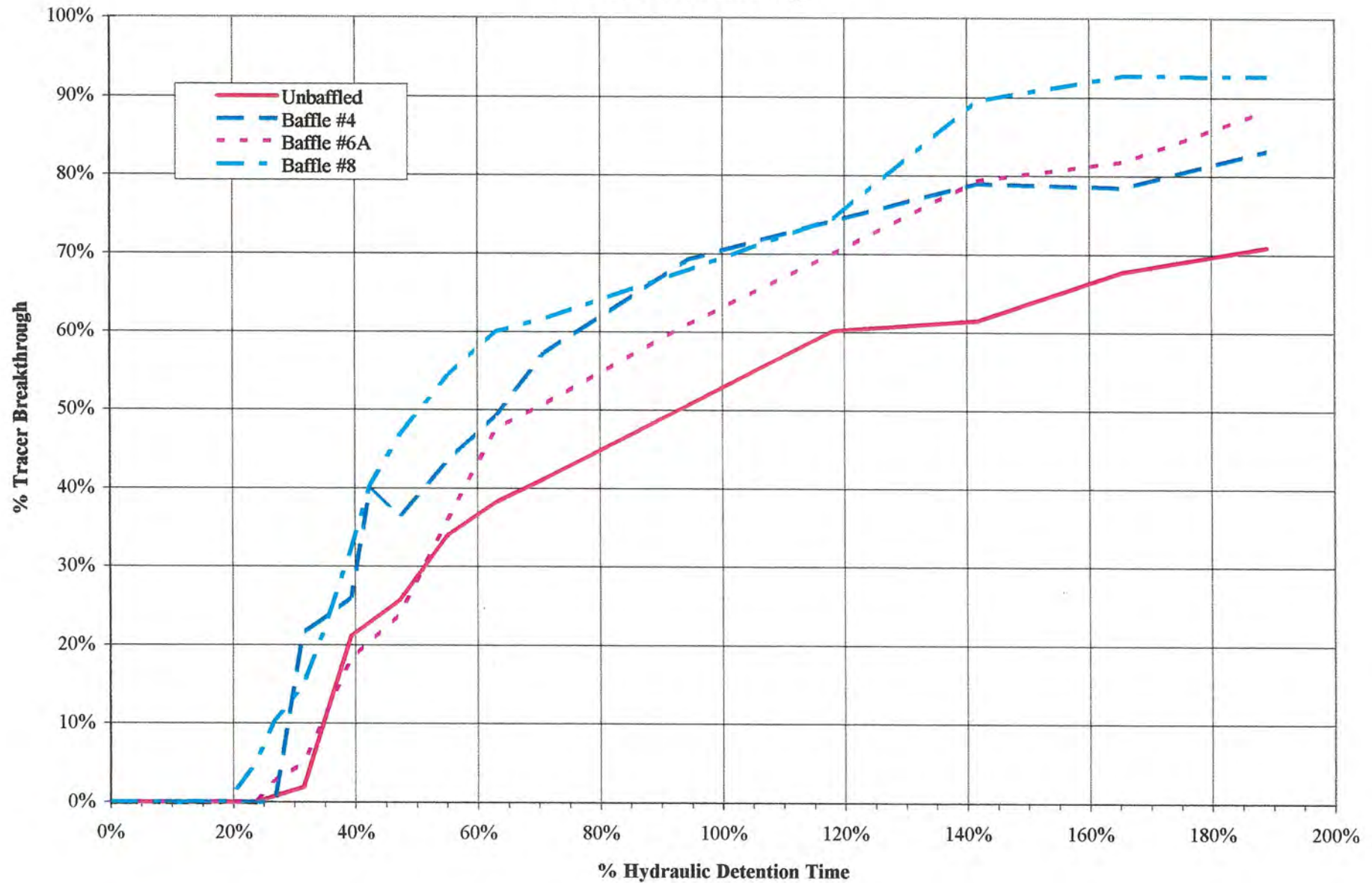
Denver Water
Marston Basin #3 Baffle Study
Probe 13 Breakthrough
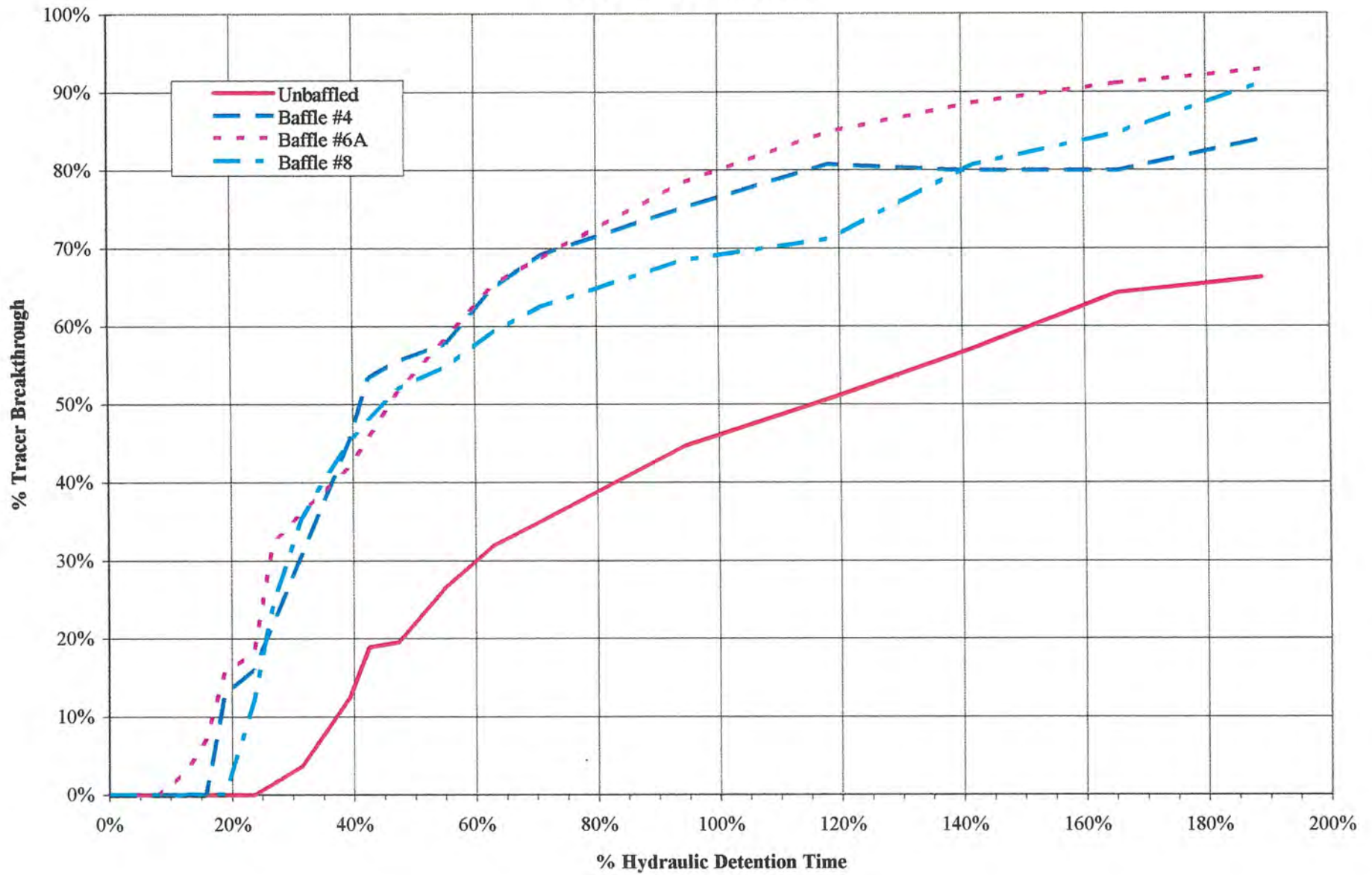
Denver Water
Marston Basin #3 Baffle Study
Probe 14 (Outlet) Breakthrough

Legend:
- Unbaffled
- Baffle #4
- Baffle #6A
- Baffle #8

Y-axis: % Tracer Breakthrough (0% to 100%)

X-axis: % Hydraulic Detention Time (0% to 200%)
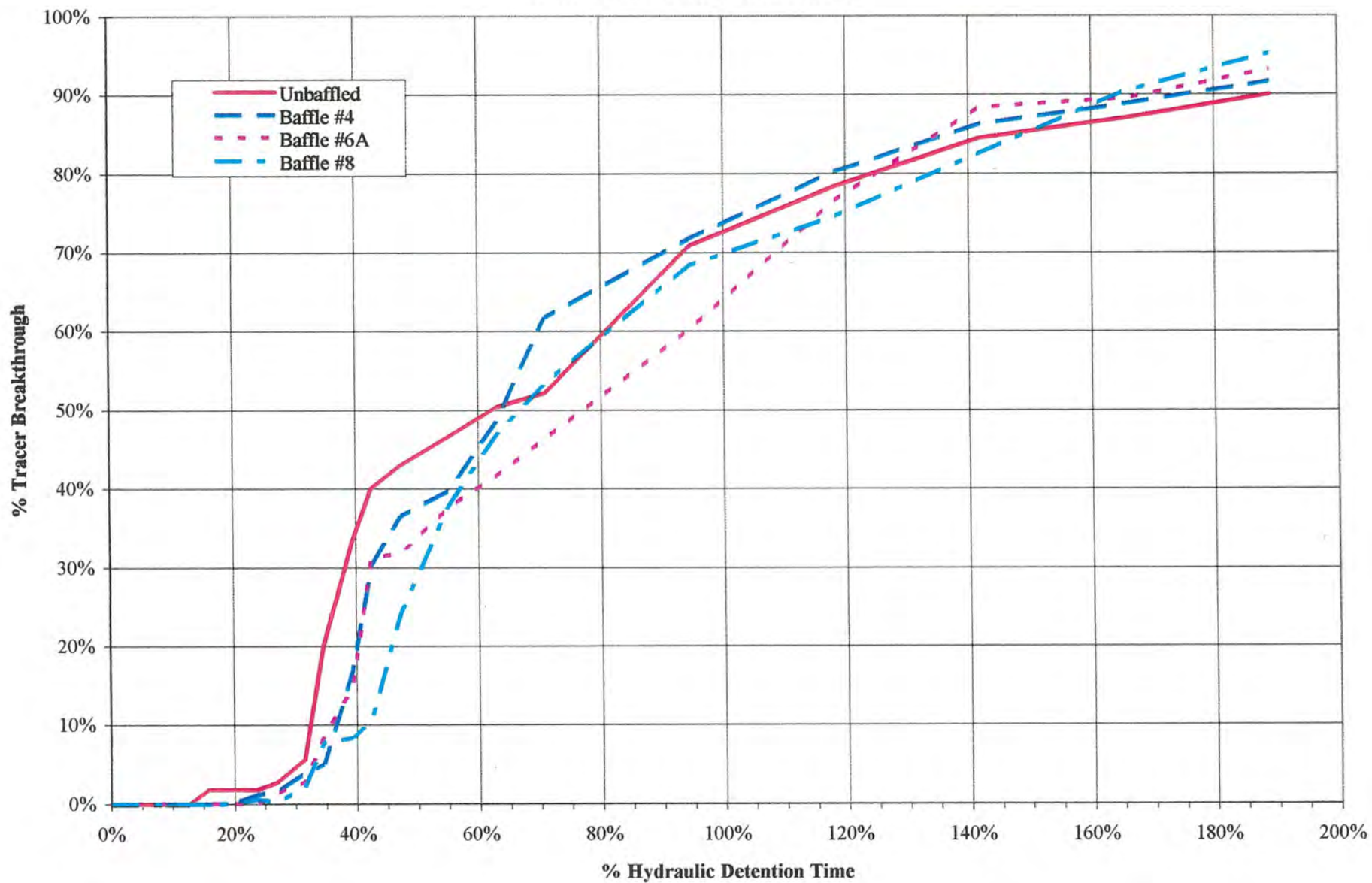
F.   Stability of T_{10}/T Times for Differing Flow Conditions

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. A comparison of tracer breakthrough for Tests 13, 14, 15 and 17 is shown graphically on the following sheet. The graphs are strikingly similar indicating that T_x/T is constant for the flow ranges expected in the prototype. Minor differences at the beginning of the tests are likely due to difficulty in making the rapid measurements required for the higher flows.

Denver Water
Marston Basin #3 Baffle Study
Baffle 8 - Outlet Breakthrough
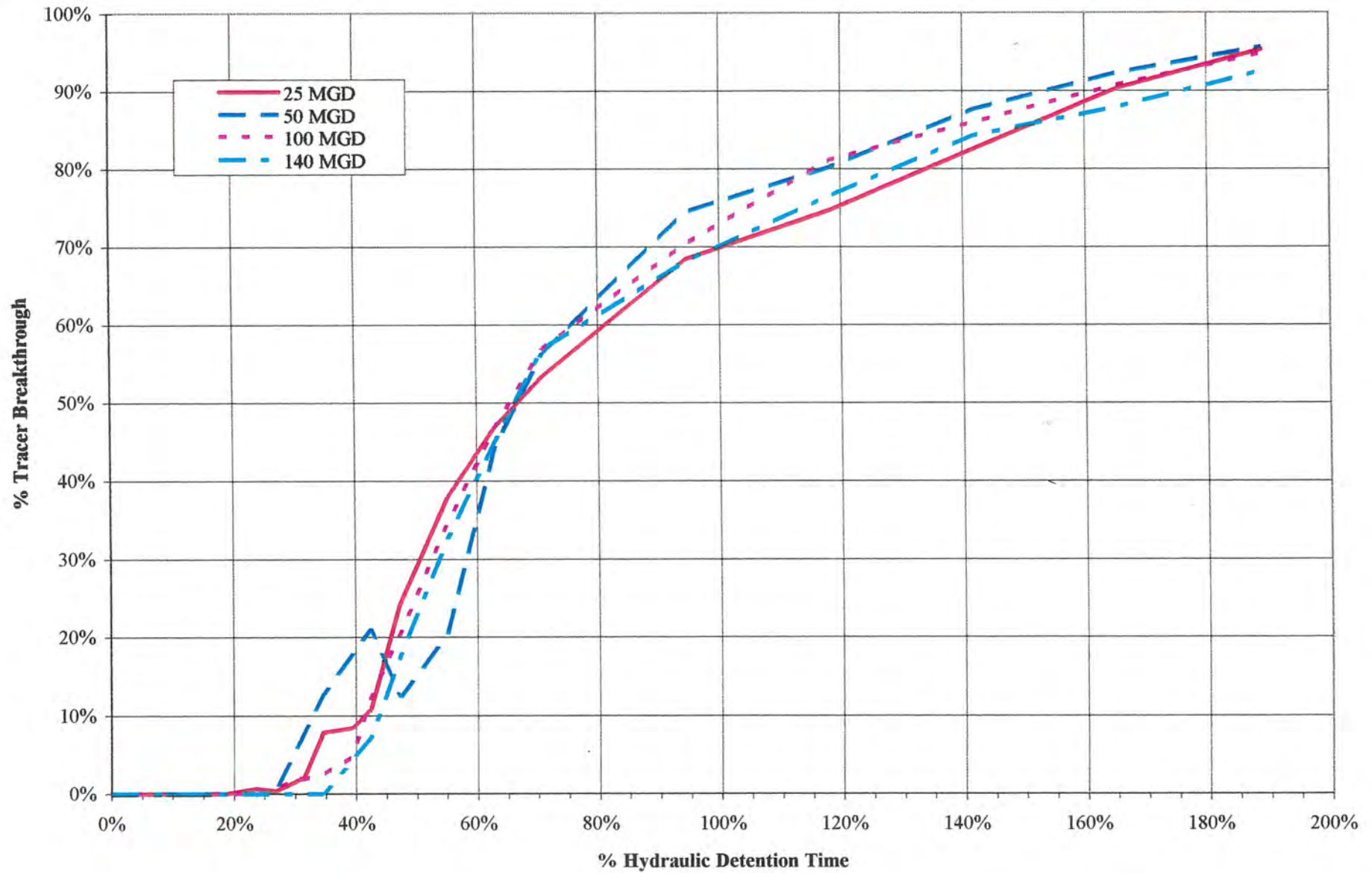
VIII. BAFFLE CONFIGURATION SELECTION

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. These are 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 various baffle configurations, the increases in T_x/T times were weighed against the length of baffle involved. Since the length of baffle will be approximately proportional to cost, this permits an economic evaluation of the benefits of the various baffle configurations. Consequently the percent improvement in tracer breakthrough was divided by the length of the particular baffle in hundreds of feet.

The length-relativized percent improvement for each baffle was then averaged for the three times, T_{10}/T, T_{50}/T and T_{90}/T. The results are shown on Table 2. Baffle 6A provides the best initial mixing (T_{10}/T), but it 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.** Even without relativizing the baffle configurations by their respective lengths, Baffle 8 is still superior to Baffle 6A. For these reasons Baffle 8 is the recommended baffle configuration.

Table 2. Evaluation of Top Three Baffles

10% Tracer Breakthrough (t = T_{10}/T)

| Baffle # | T_{10}/T (%) at Probe | | | | | Average | % | Baffle Length | % Impr./ Length |
	4	9	12	13	14*	4, 9, 12, 13	Improvement	(feet)	in 100's
None	44	28	35	37	**32**	36	0%	0	
4	38	27	34	18	**37**	29	19%	253	7.4%
6A	11	42	29	17	**36**	25	31%	496	6.3%
8	20	38	27	23	**42**	27	25%	367	6.8%

* T_{10}/T at outlet

50% Tracer Breakthrough (t = T_{50}/T)

| Baffle # | T_{50}/T (%) at Probe | | | | | Average | % | Baffle Length | % Impr./ Length |
	4	9	12	13	14	4, 9, 12, 13	Improvement	(feet)	in 100's
None	72	53	93	115	62	83	0%	0	
4	75	57	64	41	63	59	29%	253	11.4%
6A	22	77	70	46	76	54	35%	496	7.1%
8	34	67	50	45	66	49	41%	367	11.2%

90% Tracer Breakthrough (t = T_{90}/T)

| Baffle # | T_{90}/T (%) at Probe | | | | | Average | % | Baffle Length | % Impr./ Length |
	4	9	12	13	14	4, 9, 12, 13	Improvement	(feet)	in 100's
None	210	188	253	260	189	228	0%	0	
4	187	194	234	230	174	211	7%	253	2.9%
6A	103	205	196	155	170	165	28%	496	5.6%
8	129	172	144	186	165	158	31%	367	8.4%

Average % Improvement	Average % Impr./ Length in 100's	Rating
0%		
18%	7.2%	2
31%	6.3%	3
32%	8.8%	1

Figure 6
Recommended Baffle Configuration

IX. RECOMMENDATIONS

The following are recommended for the improvements to Denver Water's Marston Treatment Plant Basins 2 and 3:

1. A sharp-crested weir is recommended for the Basin 2 weir based on its improved hydraulic performance.

2. Three 72-inch inlets should be installed in the common wall between Basins 2 and 3 at the quarter points of the wall. This arrangement provides improved distribution of flow in the basin over a two-inlet scheme.

3. Baffle 8 is recommended for Basin 3. Of the baffle configurations tested, it had the best overall ability to eliminate identified dead zones over time. The effectiveness of this baffling will be constant over the anticipated flow range for the basin.

REFERENCES

Bates Engineering, *Denver Water Treated Water Storage Reservoir Hydraulic Model Mixing Study*, report prepared for Denver Water, November 1996.

Bates Engineering, *Fort Collins Water Utilities 15 MG Reservoirs Baffle Study*, report prepared for Fort Collins Water Utilities, September 1997.

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

Grayman, Walter M., Lecture Notes on "Modeling Tanks and Reservoirs", given at American Water Works Association Workshop on Distribution System Network Modeling, Denver, March 17, 1996.

Grayman, Walter M., et. al., "Water quality and mixing models for tanks and reservoirs," *Journal of the American Water Works Association*, Vol. 88, No. 7 (July 1996), pp. 60-73.

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

U.S. Environmental Protection Agency, *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources*, Washington D.C., March 1991.

APPENDIX A - HYDRAULIC MODEL SCALING FACTORS

Model Scaling Factors

Feature	Prototype Elev.* ft.	Prototype Depth ft.	Prototype Volume** (MG)	Model Depth (in.)	Model Volume** (gal.)	Flow	Prototype Flow (MGD)	Model Flow (gpm)
	5486.35	0	0.00	0.00	0.0		0	0.00
Outlet	5487.35	1	0.66	0.25	6.0		5	0.22
	5488.35	2	1.32	0.50	12.0		10	0.44
	5489.35	3	1.99	0.75	18.0		15	0.65
	5490.35	4	2.67	1.00	24.1	Minimum Flow	20	0.87
	5491.35	5	3.35	1.25	30.2	Tests 1-13	25	1.09
	5492.35	6	4.03	1.50	36.4		30	1.31
	5493.35	7	4.70	1.75	42.6		35	1.52
	5494.35	8	5.36	2.00	48.9		40	1.74
	5495.35	9	6.03	2.25	55.1		45	1.96
	5496.35	10	6.70	2.50	61.3	Test 14	50	2.18
	5497.35	11	7.37	2.75	67.5		55	2.39
Top of Weir	5497.60	11.25	7.54	2.81	69.1		60	2.61
							65	2.83
							70	3.05
							75	3.26
							80	3.48
							85	3.70
							90	3.92
							95	4.13
						Test 15	100	4.35
							105	4.57
							110	4.79
							115	5.00
							120	5.22
							125	5.44
							130	5.66
							135	5.87
						Test 16	140	6.09
							145	6.31
							150	6.53

* Basin #3 floor elevation varies from 5485.89 at south end to 5486.74 at north end

** Includes volume of weir box in Basin #2

At Q_{proto} = 25 MGD

T_{proto} = 7.2 hours

T_{model} = 63.5 minutes

APPENDIX B - CONDUCTIVITY DATA

BATES ENGINEERING, INC.
DENVER WATER MARSTON BASIN #3
HYDRAULIC MODEL STUDY

Test: 3 Date: 7/10 Inlet: 3-72" Baffle: Unbaffled Flow: 25 MGD

Time	Time (t)	Photo No(s)	Air Temp. (°C)	Supply Temp. (°C)	Model Temp. (°C)	Probe 1 Conduct. (µS)	Probe 2 Conduct. (µS)	Probe 3 Conduct. (µS)	Probe 4 Conduct. (µS)	Probe 5 Conduct. (µS)	Probe 6 Conduct. (µS)	Probe 7 Conduct. (µS)	Probe 8 Conduct. (µS)	Probe 9 Conduct. (µS)	Probe 10 Conduct. (µS)	Probe 11 Conduct. (µS)	Probe 12 Conduct. (µS)	Probe 13 Conduct. (µS)	Probe 14 Conduct. (µS)
7:13	0			21.8	20.8	132.8	2.7	2.0	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.6	2.3
7:14	1						20.0	2.0	2.0		2.1								
7:15	2						52.9	2.0			2.1								
7:16	3										10.1	2.3	2.0						
7:17	4						94.5	2.1	2.0		24.0	10.0	2.4		2.0				
7:18	5																		
7:19	6						107.5	8.1	2.3		22.8	40.5	3.4		11.8				
7:21	8						116.8	22.1	5.2		30.0	54.2	6.5		32.5				
7:23	10						121.3	28.4	3.3	1.8	38.5	71.6	7.9	1.8	39.2	1.8	1.7	1.6	5.0
7:25	12						124.4	39.5	3.2	1.8	48.0	75.5	15.6	1.8	47.0	2.0	1.8	1.6	6.7
7:28	15											76.6	24.4	1.9	36.6	2.1	1.8	1.6	4.7
7:30	17						124.9	62.2	2.8	34.6									5.8
7:33	20												29.3	23.4	25.8	7.5	4.3	6.5	9.7
7:35	22						126.8	69.1	14.4	56.3	49.4	94.6							28.7
7:38	25											93.7	63.8	29.4	31.7	16.8	29.6	18.1	45.7
7:40	27						126.9	80.3	250.0	58.6	59.2			45.9	58.7	24.8	31.9	26.4	54.6
7:43	30						127.1	87.3	33.5	69.7	72.2	98.6	80.3	55.3	56.6	31.7	35.5	27.2	58.4
7:48	35						127.9	89.4	46.5	85.0	93.2	98.6	89.1	71.7	65.5	44.0	46.4	36.7	63.2
7:53	40						127.9	93.2	54.7	83.5	93.1	100.2	91.3	59.9	86.1	52.9	51.9	43.6	68.1
7:58	45		23.4	21.9	22.1	133.0	127.8	101.1	67.5	84.7	106.6	97.1	94.4	78.6	92.6	62.7	55.8	47.7	70.4
8:13	60						128.2	102.2	89.9	93.0	105.2	108.0	102.2	88.2	102.7	82.0	68.2	60.3	94.8
8:28	75						129.1	109.6	102.8	102.6	113.8	112.3	108.0	101.2	106.5	91.7	80.6	68.1	104.6
8:43	90		23.9	22.0	22.4	132.0	129.7	117.7	108.5	106.3	110.6	120.2	114.9	106.2	113.6	101.0	82.4	76.5	112.6
8:58	105					132.8	129.5	123.7	109.7	112.5	116.7	124.3	117.6	111.8	118.0	105.5	90.5	86.0	115.8
9:13	120		23.9	22.2	22.6		130.3	125.8	115.3	118.6	119.7	127.5	121.9	119.7	122.4	112.3	94.7	88.5	119.7

BATES ENGINEERING, INC.
DENVER WATER MARSTON BASIN #3
HYDRAULIC MODEL STUDY

Test: 8 Date: 8/4 Inlet: 3-72" Baffle: #4 Flow: 25 MGD

Time	Time (t)	Photo No(s)	Air Temp. (°C)	Supply Temp. (°C)	Model Temp. (°C)	Probe 1 Conduct. (μS)	Probe 2 Conduct. (μS)	Probe 3 Conduct. (μS)	Probe 4 Conduct. (μS)	Probe 5 Conduct. (μS)	Probe 6 Conduct. (μS)	Probe 7 Conduct. (μS)	Probe 8 Conduct. (μS)	Probe 9 Conduct. (μS)	Probe 10 Conduct. (μS)	Probe 11 Conduct. (μS)	Probe 12 Conduct. (μS)	Probe 13 Conduct. (μS)	Probe 14 Conduct. (μS)
7:17	0		23.9	22.1	20.5	128.3	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.8
7:18	1																		2.8
7:19	2						7.7												2.8
7:20	3						62.1	2.2	2.2	2.3	13.4								2.8
7:21	4						96.8	3.9	2.3	2.2									2.8
7:23	5										25.4								2.8
7:25	6						115.4	9.6	2.2		17.6	32.7	2.2						2.8
7:27	8							17.7	2.3		23.9	45.8	2.5	2.2	30.4	2.2			2.8
7:27	10										33.8	60.7	2.4	2.2	35.8	2.2	2.2	2.2	2.8
7:29	12						125.7	36.7	4.9	2.2	41.6	70.8	3.0	2.2	37.5	2.2	2.2	18.4	2.8
7:32	15									13.1	43.3	82.1	2.9	2.2	46.7	2.2	2.2	22.1	4.8
7:30	17						126.3	43.3	7.4	25.3	58.5	85.1	12.0	14.8	54.2	13.5			4.8
7:37	20												24.0	24.7	52.8	18.0	29.0	14.4	7.8
7:39	22							64.1	18.5	47.5	69.8	88.8	39.0	37.3	61.3	32.4	31.1		9.1
7:42	25													34.9	59.2	39.2	34.5	58.4	23.6
7:44	27						128.3	80.1	33.3	65.5	81.6	96.1	55.1	39.5	69.7	42.2	51.8	68.4	40.2
7:47	30					125.5	128.8	87.7	43.3	78.4	87.5	99.7	60.9	40.0	77.5	52.1	47.2	71.1	47.9
7:52	35					125.5	128.9	86.1	42.6	80.4	87.4	101.9	76.9	50.0	89.6	52.8	56.3	73.7	51.8
7:57	40					125.4	128.9	93.0	52.4	82.2	89.0	102.7	84.9	62.9	94.1	64.5	63.3	82.7	62.9
8:02	45			22.1	21.9	125.3	128.9	101.4	60.5	85.0	100.6	104.7	93.3	62.0	94.4	83.7	73.2	87.9	79.0
8:07	60					126.1	129.0	103.0	80.1	91.3	106.1	108.6	97.7	78.5	106.1	94.2	88.1	95.4	91.4
8:32	75						129.0	104.9	93.6	96.7	112.8	108.5	105.2	85.0	106.3	92.3	94.2	102.3	101.8
8:47	90							107.3	99.9	97.6	117.5	110.9	108.0	87.8	111.1	99.0	100.1	101.2	109.2
9:02	105							114.6	108.5	109.2	121.3	117.8	108.5	96.7	113.9	105.9	99.5	101.2	112.3
9:17	120						128.9	117.6	114.5	109.6	122.5	121.0	119.4	111.0	117.2	110.8	105.3	106.3	115.9

Time	Time (t)	Photo No(s)	Air Temp. (°C)	Supply Temp. (°C)	Model Temp. (°C)	Probe 1 Conduct. (µS)	Probe 2 Conduct. (µS)	Probe 3 Conduct. (µS)	Probe 4 Conduct. (µS)	Probe 5 Conduct. (µS)	Probe 6 Conduct. (µS)	Probe 7 Conduct. (µS)	Probe 8 Conduct. (µS)	Probe 9 Conduct. (µS)	Probe 10 Conduct. (µS)	Probe 11 Conduct. (µS)	Probe 12 Conduct. (µS)	Probe 13 Conduct. (µS)	Probe 14 Conduct. (µS)
7:52	0		22.7	20.5	19.4	123.2	1.3	1.3	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.8
7:53	1						17.6												
7:54	2																		
7:55	3						68.1		1.4		21.5								
7:56	4						83.8		2.6		21.8	1.6							
7:57	5						98.1	2.1	10.5	1.3	39.1	9.9							
7:58	6						108.1	10.3											
8:00	8						116.0	19.6	33.8	1.3	50.5	30.0	1.8	1.3	39.8				
8:02	10	4					121.0	32.0	48.3		70.7	40.5	3.2	1.3	53.7	1.3			
8:04	12	5					123.2	58.5		1.3	74.7	50.3	5.9	1.3	62.8			20.6	
8:07	15	6									74.7	59.3	5.4	1.3	63.1	1.3	1.3	23.5	1.8
8:09	17	7					124.4	67.1	73.1	3.2		66.4	10.3	1.3	74.4	1.4	4.7	40.8	3.5
8:12	20	8								3.4	78.7	73.4	25.7	1.3	78.2	2.0	7.3	45.5	5.2
8:14	22	9					124.9	81.9	85.2	4.6	85.7	79.0	43.9	3.9	81.4	4.1			12.3
8:17	25	10											9.8		85.4	5.3	23.8	52.6	20.6
8:19	27						125.0	89.4	90.5	28.9	86.3	89.5	47.6						39.8
8:22	30					123.4	125.1	94.2	90.1	37.0	89.3	91.9	51.4	17.9	88.9	20.8	30.4	64.3	40.5
8:27	35						125.2	97.0	94.0	41.0	96.2	94.2	60.3	33.7	91.7	47.2	45.3	72.6	47.6
8:32	40				20.6	123.4	125.2	100.2	97.9	48.4	99.7	96.8	72.1	43.4	97.3	54.5	59.5	81.1	52.5
8:37	45						125.2	103.9	102.0	60.7	102.0	100.9	73.6	46.4	101.8	71.4	63.3	85.3	58.2
8:52	60					123.4	125.3	108.0	109.0	72.5	112.1	109.5	87.2	63.9	109.2	83.0	75.8	97.1	75.1
9:07	75			20.7	20.8	123.4	125.3	114.6	114.8	89.8	115.5	115.0	99.0	77.7	113.3	93.5	86.8	104.9	95.0
9:22	90						125.4	119.0	118.6	102.5	120.9	120.4	104.7	88.4	117.0	98.2	98.2	109.5	109.2
9:37	105						125.4	120.7	121.4	108.6	121.5	119.8	111.4	96.5	119.3	105.3	101.1	112.5	110.6
9:52	120						125.4	122.0	123.3	110.6	122.9	122.8	117.1	105.2	119.7	107.9	109.2	114.7	115.1

Time	Time (t)	Photo No(s)	Air Temp. (°C)	Supply Temp. (°C)	Model Temp. (°C)	Probe 1 Conduct. (µS)	Probe 2 Conduct. (µS)	Probe 3 Conduct. (µS)	Probe 4 Conduct. (µS)	Probe 5 Conduct. (µS)	Probe 6 Conduct. (µS)	Probe 7 Conduct. (µS)	Probe 8 Conduct. (µS)	Probe 9 Conduct. (µS)	Probe 10 Conduct. (µS)	Probe 11 Conduct. (µS)	Probe 12 Conduct. (µS)	Probe 13 Conduct. (µS)	Probe 14 Conduct. (µS)
8:01	0	2	22.9	19.8	18.2	121.2	3.5	3.4	3.4	3.4	3.4	3.3	3.3	3.3	3.3	3.3	3.3	3.3	4.2
8:02	1	3					5.0													
8:03	2	4					43.7	3.4	3.5		4.0									
8:04	3	5					84.1	3.4	3.5		25.9	3.8								
8:05	4	6,8					104.1	3.4	3.6		23.0	7.2								
8:06	5	7					112.4	3.7	3.7	3.4	29.2	14.5								
8:07	6	8					116.1	5.7	5.3		45.1	21.7	10.8		5.4					
8:09	8	9,9					119.5	21.1	13.7	3.4	38.7	41.5	11.6	3.4	32.2	3.4	3.4	3.4	4.2
8:11	10	10,10					120.7	37.7	19.3	3.4	62.6	60.4	29.1	3.4	42.8	3.4	3.4	3.4	4.2
8:13	12	11				120.6	121.8	53.3	23.4	3.4	73.2	63.9	34.9	3.5	47.7	3.4	3.4	3.4	4.3
8:16	15	12									69.2	65.9	52.5	3.9	64.4	6.2	9.2	17.5	5.0
8:18	17	13,11					122.3	65.2	50.6	3.6	75.7	75.9	65.6	6.8	61.5	10.2	15.5	31.9	4.6
8:21	20	14						71.5	59.1	4.2	69.8	69.5	73.9	6.6	70.4	20.0	20.8	44.9	6.7
8:23	22	15					122.7	71.6	63.0	14.2	82.3	78.6	75.7	8.4	72.6	30.9	28.4	49.9	13.4
8:26	25	16									80.5	77.4	81.4	18.1	76.2	40.9	41.2	56.4	14.0
8:28	27	17					122.9	81.7	72.7	25.0	89.2	84.3	81.3	28.7	80.0	44.5	50.9	59.8	16.9
8:31	30	18		19.8	19.5	120.4	123.0	83.3	80.9	31.8	84.5	81.0	90.1	34.0	82.2	53.8	58.4	64.4	32.5
8:36	35		21.2			120.5	123.2	82.4	84.8	41.7	92.9	86.9	93.5	36.6	87.9	60.7	67.3	67.6	48.4
8:41	40					120.5	123.2	85.8	90.3	47.4	94.4	88.5	95.3	43.3	91.3	68.5	73.8	72.9	58.9
8:46	45					120.6	123.3	90.6	94.3	53.9	100.8	89.0	99.3	61.0	91.6	74.9	75.7	76.8	66.5
9:01	60				20.1	120.7	123.5	101.9	102.5	69.1	104.5	101.8	105.8	74.1	97.4	89.7	83.1	83.8	83.9
9:16	75					120.7	123.6	107.7	106.1	83.6	109.6	110.2	108.9	89.0	109.7	101.3	90.8	86.9	91.2
9:31	90					120.8	123.7	114.8	112.8	94.7	113.7	116.0	114.4	99.0	112.5	105.9	108.5	98.1	100.4
9:46	105					120.8	123.8	118.9	116.2	103.5	116.8	119.8	118.1	107.5	116.3	111.8	112.2	102.8	109.5
10:01	120		23.2	20.4	21.0	120.7	124.0	121.1	117.0	110.4	119.1	121.6	120.2	112.9	119.1	111.8	112.1	110.3	115.2

BATES ENGINEERING, INC.
DENVER WATER MARSTON BASIN #3
HYDRAULIC MODEL STUDY

Test: 14 Date: 8/26 Inlet: 3-72" Baffle: #8 Flow: 50 MGD

Time	Time (t)	Photo No(s)	Air Temp. (°C)	Supply Temp. (°C)	Model Temp. (°C)	Probe 1 Conduct. (µS)	Probe 2 Conduct. (µS)	Probe 3 Conduct. (µS)	Probe 4 Conduct. (µS)	Probe 5 Conduct. (µS)	Probe 6 Conduct. (µS)	Probe 7 Conduct. (µS)	Probe 8 Conduct. (µS)	Probe 9 Conduct. (µS)	Probe 10 Conduct. (µS)	Probe 11 Conduct. (µS)	Probe 12 Conduct. (µS)	Probe 13 Conduct. (µS)	Probe 14 Conduct. (µS)
7:44	0	1	23.4	22.8	20.8	136.4	3.7	3.7	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	4.6
	1/2	2							3.7										
7:45	1	3							3.7										
	1 1/2	4							3.7										
7:46	2	5							3.7										
	2 1/2	6							3.7										
7:47	3	7							3.7										
7:48	4	8						28.7	3.7										
7:49	5	9							5.6										
7:50	6	10							11.0	3.7	60.2				67.0	4.2	3.6	3.6	4.5
	7 1/2	11							17.3					3.7		8.6	4.7	34.4	
	8 1/2	12							28.4					5.7		8.2	25.4	53.7	5.2
7:54	10	13							42.9					14.6		16.0			
7:55	11	14							53.8					20.8		28.5	45.8	69.3	21.5
	12 1/2	15							58.3					22.8		38.3	61.0		
	13 1/2	16												30.5		39.2	59.4	73.6	32.6
7:59	15	17							84.3					46.9		49.3	71.5	83.5	21.0
	17 1/2								92.0	66.3	103.4	106.4	94.0	54.2		66.9	77.4	88.1	31.8
8:04	20						139.4	105.8	95.4	79.7		109.5	98.7	65.4	103.7	76.7	83.9	93.5	63.4
	22 1/2			22.7	22.6	136.9	139.5	110.4	103.3	85.5	108.1	115.2	104.0	74.0	107.1	84.9	94.8	100.9	79.3
8:14	30					136.9	139.5	120.7	111.5	98.4	116.2	123.6	113.8	101.1	116.2	97.3	105.4	108.5	103.3
	37 1/2					136.9	139.6	128.8	118.4	108.0	118.5	129.6	120.4	113.4	124.5	109.2	115.5	116.5	110.8
8:29	45					137.0	139.6	132.8	124.0	115.8	123.1	134.1	123.6	119.0	128.0	119.8	120.8	123.4	120.7
	52 1/2					137.0	139.6	135.7	127.1	122.5	126.8	136.6	129.6	123.6	132.2	125.3	122.9	128.2	126.9
8:44	60						139.5	137.1	130.0	126.4	128.8	138.0	134.1	127.6	132.8	128.1	128.2	129.9	131.3

BATES ENGINEERING, INC.
DENVER WATER MARSTON BASIN #3
HYDRAULIC MODEL STUDY

Test: 15 Date: 8/27 Inlet: 3-72" Baffle: #8 Flow: 140 MGD

Time	Time (t)	Photo No(s)	Air Temp. (°C)	Supply Temp. (°C)	Model Temp. (°C)	Probe 1 Conduct. (µS)	Probe 2 Conduct. (µS)	Probe 3 Conduct. (µS)	Probe 4 Conduct. (µS)	Probe 5 Conduct. (µS)	Probe 6 Conduct. (µS)	Probe 7 Conduct. (µS)	Probe 8 Conduct. (µS)	Probe 9 Conduct. (µS)	Probe 10 Conduct. (µS)	Probe 11 Conduct. (µS)	Probe 12 Conduct. (µS)	Probe 13 Conduct. (µS)	Probe 14 Conduct. (µS)
9:40	0:00	18	22.3	21.3	19.9	130.7	3.0	3.0	3.0	3.0	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.8
	0:11	19																	
	0:21	20																	
	0:32	21																	
	0:43	22																	
	0:54	23																	
	1:04	24																	
	1:26	25							3.0										
	1:47	26							3.3										
	2:09	27							5.3										
	2:41	28							7.2										
	3:02	29							9.2									8.4	
	3:24	30																54.5	
	3:56	31															35.7		
	4:28	32												27.4					
	4:49	33							34.4										13.2
	5:21	34							41.0					60.9			74.9	84.0	
	6:15	35												79.5			83.1	96.6	45.5
	7:09	36							56.2									104.5	61.4
	8:02	37							59.0		88.6	122.6	72.4	87.0	113.6	72.1	104.4	106.3	76.4
	10:43							125.6	87.6	108.2		124.9	84.9	107.1	119.5	82.5	104.5	114.6	90.7
	13:24							127.9	97.5	113.3	110.4	124.7	90.7	114.5	120.1	94.2	115.0	118.8	101.4
	16:04							131.7	129.2	105.3	118.0	114.0	126.7	103.3	118.4	125.2	101.2	121.1	121.9	111.3
	18:45							131.5	129.9	110.3	121.8	119.0	127.5	107.4	121.9	126.6	107.7	122.5	124.5	116.0
	21:26			21.5	21.8			131.3	130.2	114.4	124.5	119.9	129.5	110.7	125.0	126.9	113.5	125.3	125.5	121.8

BATES ENGINEERING, INC.
DENVER WATER MARSTON BASIN #3
HYDRAULIC MODEL STUDY

Test: 17 Date: 8/28 Inlet: 3-72" Baffle: #8 Flow: 100 MGD

Time	Time (t)	Photo No(s)	Air Temp. (°C)	Supply Temp. (°C)	Model Temp. (°C)	Probe 1 Conduct. (μS)	Probe 2 Conduct. (μS)	Probe 3 Conduct. (μS)	Probe 4 Conduct. (μS)	Probe 5 Conduct. (μS)	Probe 6 Conduct. (μS)	Probe 7 Conduct. (μS)	Probe 8 Conduct. (μS)	Probe 9 Conduct. (μS)	Probe 10 Conduct. (μS)	Probe 11 Conduct. (μS)	Probe 12 Conduct. (μS)	Probe 13 Conduct. (μS)	Probe 14 Conduct. (μS)
9:33	0			20.7	19.3	120.1	3.1	3.1	2.1	2.1	2.1	1.9	1.9	1.9	2.0	2.0	2.0	2.0	2.6
	1/4								2.0										
	1/2								2.0										
	3/4								2.0										
9:34	1								2.0										
	1 1/4								1.9										
	1 1/2								2.3										
9:35	2								2.5								1.9	2.0	
	2 1/2								26.3								1.9	2.0	
9:36	3								13.2										
	3 3/4								27.3					1.9				2.0	
	4 1/4								20.8					2.3			12.6	53.6	3.7
9:38	5																		
	5 1/2								37.4									66.2	5.7
	6 1/4															36.6			8.2
	6 3/4													47.7		48.0		70.7	17.3
	7 1/2								53.3					54.5		58.9	62.9	80.7	26.8
	8 3/4								64.2					66.9		68.5	69.6	84.0	43.6
9:43	10											107.8	63.8	71.3	101.2	71.6	76.5	90.2	58.1
	11 1/4						120.7	122.6	111.3	84.2	75.0	85.4	108.7	82.4	82.8	97.0	74.3	88.1	98.8	70.0
9:48	15						120.1	122.4	116.4	91.0	87.5	98.6	116.3	85.8	92.7	108.0	94.9	95.7	101.2	85.9
	18 3/4						120.6	122.1	118.7	101.9	100.0	102.5	118.5	97.6	100.4	114.5	100.1	100.0	110.5	98.6
	22 1/2							121.8	119.9	106.5	107.0	107.3	120.1	101.3	108.2	116.5	107.3	108.7	112.6	104.3
	26 1/4					21.0		121.3	120.7	110.3	113.0	110.5	120.9	107.4	113.5	117.2	110.4	112.7	117.5	110.0
10:03	30			20.9		120.9	121.1		109.2	115.5	112.1	121.5	109.0	115.5	118.1	112.9	113.2	118.3	114.8

APPENDIX C - TRACER BREAKTHROUGH CALCULATIONS

Figure 7
Conductivity Probe Locations

Dye Tank
1●

2●

14●

3● 4● 5●

6●

7● 8● 9●

10● 11●

10● = Conductivity Probe Location
and Number

12●

13●

PLAN

TRACER BREAKTHROUGH CALCULATIONS
PROBE 4

Time (minutes)	Time t/T	Test 3 - Unbaffled Conduct. μS	Test 3 - Unbaffled Outlet %	Test 8 - Baffle #4 Conduct. μS	Test 8 - Baffle #4 Outlet %	Test 11 - Baffle #6A Conduct. μS	Test 11 - Baffle #6A Outlet %	Test 13 - Baffle #8 Conduct. μS	Test 13 - Baffle #8 Outlet %
0	0.0%	1.8	0.0%	2.2	0.0%	1.4	0.0%	3.4	0.0%
1	1.6%	2.0	0.2%	2.2	0.0%	1.4	0.0%	3.4	0.0%
2	3.1%	2.0	0.2%	2.2	0.0%	1.4	0.0%	3.5	0.1%
3	4.7%	2.0	0.2%	2.2	0.0%	1.4	0.0%	3.5	0.1%
4	6.3%	2.0	0.2%	2.2	0.0%	2.6	1.0%	3.6	0.2%
5	7.9%	2.2	0.3%	2.2	0.0%	10.5	7.5%	3.7	0.3%
6	9.4%	2.3	0.4%	2.2	0.0%	18.3	13.9%	5.3	1.6%
8	12.6%	5.2	2.6%	2.3	0.1%	33.8	26.6%	13.7	8.8%
10	15.7%	3.3	1.1%	3.6	1.1%	48.3	38.4%	19.3	13.6%
12	18.9%	3.2	1.1%	4.9	2.2%	55.4	44.3%	23.4	17.1%
15	23.6%	3.0	0.9%	6.4	3.4%	66.0	53.0%	39.7	31.0%
17	26.8%	2.8	0.8%	7.4	4.2%	73.1	58.8%	50.6	40.2%
20	31.5%	9.8	6.1%	14.1	9.6%	80.4	64.8%	59.1	47.5%
22	34.6%	14.4	9.6%	18.5	13.2%	85.2	68.7%	63.0	50.8%
25	39.4%	20.8	14.5%	27.4	20.3%	88.4	71.3%	68.8	55.8%
27	42.5%	25.0	17.7%	33.3	25.1%	90.5	73.0%	72.7	59.1%
30	47.2%	33.5	24.2%	43.3	33.2%	90.1	72.7%	80.9	66.1%
35	55.1%	46.5	34.1%	42.6	32.6%	94.0	75.9%	84.8	69.4%
40	63.0%	54.7	40.4%	52.4	40.5%	97.9	79.1%	90.3	74.1%
45	70.9%	67.5	50.2%	60.5	47.1%	102.0	82.5%	94.3	77.5%
60	94.5%	89.9	67.3%	80.1	62.9%	109.0	88.2%	102.5	84.5%
75	118.1%	102.8	77.1%	93.6	73.8%	114.8	93.0%	106.1	87.6%
90	141.7%	108.5	81.5%	99.9	78.9%	118.6	96.1%	112.8	93.3%
105	165.4%	109.7	82.4%	108.5	85.8%	121.4	98.4%	116.2	96.2%
120	189.0%	115.3	86.6%	114.5	90.6%	123.3	99.9%	117.0	96.8%

TRACER BREAKTHROUGH CALCULATIONS
PROBE 9

Time (minutes)	Time t/T	Test 3 - Unbaffled Conduct. µS	Outlet %	Test 8 - Baffle #4 Conduct. µS	Outlet %	Test 11 - Baffle #6A Conduct. µS	Outlet %	Test 13 - Baffle #8 Conduct. µS	Outlet %
0	0.0%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
1	1.6%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
2	3.1%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
3	4.7%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
4	6.3%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
5	7.9%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
6	9.4%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
8	12.6%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.4	0.1%
10	15.7%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.4	0.1%
12	18.9%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.5	0.2%
15	23.6%	1.9	0.1%	2.2	0.0%	1.3	0.0%	3.9	0.5%
17	26.8%	10.5	6.6%	14.8	10.2%	1.3	0.0%	6.8	3.0%
20	31.5%	23.4	16.5%	24.7	18.2%	1.3	0.0%	6.6	2.8%
22	34.6%	25.8	18.3%	37.3	28.3%	3.9	2.1%	8.4	4.3%
25	39.4%	29.4	21.1%	34.9	26.4%	9.8	7.0%	18.1	12.6%
27	42.5%	45.9	33.7%	39.5	30.1%	13.0	9.6%	28.7	21.6%
30	47.2%	55.3	40.8%	40.0	30.5%	17.9	13.6%	34.0	26.1%
35	55.1%	71.7	53.4%	50.0	38.6%	33.7	26.5%	36.6	28.4%
40	63.0%	59.9	44.4%	62.9	49.0%	43.4	34.5%	43.3	34.1%
45	70.9%	78.6	58.6%	62.0	48.3%	46.4	36.9%	61.0	49.1%
60	94.5%	88.2	66.0%	78.5	61.6%	63.9	51.3%	74.1	60.3%
75	118.1%	101.2	75.9%	85.0	66.8%	77.7	62.6%	89.0	73.0%
90	141.7%	106.2	79.7%	87.8	69.1%	88.4	71.3%	99.0	81.5%
105	165.4%	111.8	84.0%	96.7	76.3%	96.5	78.0%	107.5	88.8%
120	189.0%	119.7	90.0%	111.0	87.8%	105.2	85.1%	112.9	93.4%

TRACER BREAKTHROUGH CALCULATIONS
PROBE 12

Time	Time	Test 3 - Unbaffled		Test 8 - Baffle #4		Test 11 - Baffle #6A		Test 13 - Baffle #8	
		Conduct.	Outlet	Conduct.	Outlet	Conduct.	Outlet	Conduct.	Outlet
(minutes)	t/T	μS	%	μS	%	μS	%	μS	%
0	0.0%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
1	1.6%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
2	3.1%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
3	4.7%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
4	6.3%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
5	7.9%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
6	9.4%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
8	12.6%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.4	0.1%
10	15.7%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.4	0.1%
12	18.9%	1.8	0.0%	2.2	0.0%	1.3	0.0%	3.4	0.1%
15	23.6%	1.8	0.0%	2.2	0.0%	1.3	0.0%	9.2	5.0%
17	26.8%	2.8	0.8%	2.2	0.0%	4.7	2.8%	15.5	10.4%
20	31.5%	4.3	1.9%	29.0	21.6%	7.3	4.9%	20.8	14.9%
22	34.6%	14.4	9.6%	31.1	23.3%	13.9	10.3%	28.4	21.4%
25	39.4%	29.6	21.2%	34.5	26.1%	23.8	18.4%	41.2	32.3%
27	42.5%	31.9	23.0%	51.8	40.0%	26.4	20.6%	50.9	40.5%
30	47.2%	35.5	25.7%	47.2	36.3%	30.4	23.8%	58.4	46.9%
35	55.1%	46.4	34.0%	56.3	43.7%	45.3	36.0%	67.3	54.5%
40	63.0%	51.9	38.2%	63.3	49.3%	59.5	47.7%	73.8	60.1%
45	70.9%	55.8	41.2%	73.2	57.3%	63.3	50.8%	75.7	61.7%
60	94.5%	68.2	50.7%	88.1	69.3%	75.8	61.0%	83.1	68.0%
75	118.1%	80.6	60.2%	94.2	74.3%	86.8	70.0%	90.8	74.5%
90	141.7%	82.4	61.5%	100.1	79.0%	98.2	79.4%	108.5	89.6%
105	165.4%	90.5	67.7%	99.5	78.5%	101.1	81.7%	112.2	92.8%
120	189.0%	94.7	70.9%	105.3	83.2%	109.2	88.4%	112.1	92.7%

TRACER BREAKTHROUGH CALCULATIONS
PROBE 13

Time (minutes)	Time t/T	Test 3 - Unbaffled		Test 8 - Baffle #4		Test 11 - Baffle #6A		Test 13 - Baffle #8	
		Conduct. μS	Outlet %	Conduct. μS	Outlet %	Conduct. μS	Outlet %	Conduct. μS	Outlet %
0	0.0%	1.6	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
1	1.6%	1.6	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
2	3.1%	1.6	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
3	4.7%	1.6	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
4	6.3%	1.6	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
5	7.9%	1.6	0.0%	2.2	0.0%	1.3	0.0%	3.3	0.0%
6	9.4%	1.6	0.0%	2.2	0.0%	2.5	1.0%	3.3	0.0%
8	12.6%	1.6	0.0%	2.2	0.0%	5.0	3.0%	3.4	0.1%
10	15.7%	1.6	0.0%	2.2	0.0%	10.0	7.1%	3.4	0.1%
12	18.9%	1.6	0.0%	18.4	13.1%	20.6	15.8%	3.4	0.1%
15	23.6%	1.6	0.0%	22.1	16.1%	23.5	18.2%	17.5	12.1%
17	26.8%	3.6	1.5%	29.4	22.0%	40.8	32.4%	31.9	24.4%
20	31.5%	6.5	3.7%	40.3	30.8%	45.5	36.2%	44.9	35.4%
22	34.6%	11.1	7.3%	47.5	36.6%	48.3	38.5%	49.9	39.7%
25	39.4%	18.1	12.6%	58.4	45.4%	52.6	42.0%	56.4	45.2%
27	42.5%	26.4	18.9%	68.4	53.4%	57.3	45.8%	59.8	48.1%
30	47.2%	27.2	19.5%	71.1	55.6%	64.3	51.6%	64.4	52.0%
35	55.1%	36.7	26.8%	73.7	57.7%	72.6	58.4%	67.6	54.8%
40	63.0%	43.6	32.0%	82.7	65.0%	81.1	65.4%	72.9	59.3%
45	70.9%	47.7	35.1%	87.9	69.2%	85.3	68.8%	76.8	62.6%
60	94.5%	60.3	44.7%	95.4	75.2%	97.1	78.5%	83.8	68.6%
75	118.1%	68.1	50.7%	102.3	80.8%	104.9	84.8%	86.9	71.2%
90	141.7%	76.5	57.1%	101.2	79.9%	109.5	88.6%	98.1	80.7%
105	165.4%	86.0	64.3%	101.2	79.9%	112.5	91.1%	102.8	84.8%
120	189.0%	88.5	66.2%	106.3	84.0%	114.7	92.9%	110.3	91.1%

TRACER BREAKTHROUGH CALCULATIONS
PROBE 14 (OUTLET)

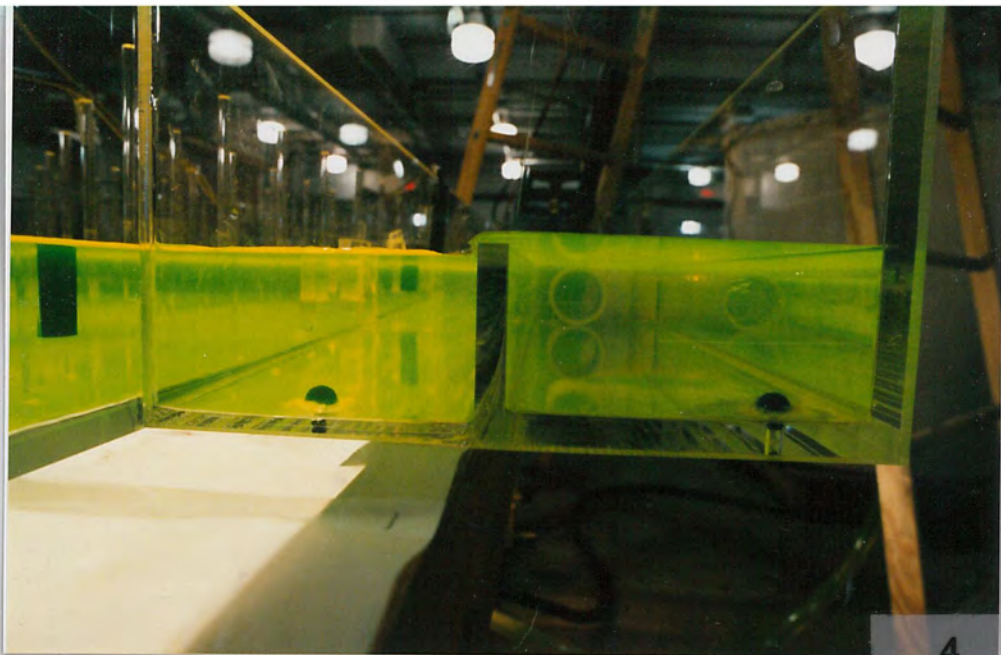| Time (minutes)	Time t/T	Test 3 - Unbaffled Conduct. μS	Outlet %	Test 8 - Baffle #4 Conduct. μS	Outlet %	Test 11 - Baffle #6A Conduct. μS	Outlet %	Test 13 - Baffle #8 Conduct. μS	Outlet %	Test 14 - Q = 50 MGD Conduct. μS	Outlet %	Test 17 - Q = 100 MGD Conduct. μS	Outlet %	Test 15 - Q = 140 MGD Conduct. μS	Outlet %
0	0.0%	2.3	0.0%	2.8	0.0%	1.8	0.0%	4.2	0.0%	4.6	0.0%	2.6	0.0%	3.8	0.0%
1	1.6%	2.3	0.0%	2.8	0.0%	1.8	0.0%	4.2	0.0%	4.6	0.0%	2.6	0.0%	3.8	0.0%
2	3.1%	2.3	0.0%	2.8	0.0%	1.8	0.0%	4.2	0.0%	4.6	0.0%	2.6	0.0%	3.8	0.0%
3	4.7%	2.3	0.0%	2.8	0.0%	1.8	0.0%	4.2	0.0%	4.6	0.0%	2.6	0.0%	3.8	0.0%
4	6.3%	2.3	0.0%	2.8	0.0%	1.8	0.0%	4.2	0.0%	4.6	0.0%	2.6	0.0%	3.8	0.0%
5	7.9%	2.3	0.0%	2.8	0.0%	1.8	0.0%	4.2	0.0%	4.6	0.0%	2.6	0.0%	3.8	0.0%
6	9.4%	2.3	0.0%	2.8	0.0%	1.8	0.0%	4.2	0.0%	4.6	0.0%	2.6	0.0%	3.8	0.0%
8	12.6%	2.3	0.0%	2.8	0.0%	1.8	0.0%	4.2	0.0%	4.6	0.0%	2.6	0.0%	3.8	0.0%
10	15.7%	4.7	1.8%	2.8	0.0%	1.8	0.0%	4.2	0.0%	4.6	0.0%	2.6	0.0%	3.8	0.0%
12	18.9%	4.7	1.8%	2.8	0.0%	1.8	0.0%	4.3	0.1%	4.6	0.0%	2.6	0.0%	3.8	0.0%
15	23.6%	4.7	1.8%	4.3	1.2%	1.8	0.0%	5.0	0.7%	4.6	0.0%	2.6	0.0%	3.8	0.0%
17	26.8%	5.8	2.7%	4.8	1.6%	3.5	1.4%	4.6	0.3%	5.2	0.5%	3.7	0.9%	3.8	0.0%
20	31.5%	9.7	5.7%	7.8	4.1%	5.2	2.8%	6.7	2.1%	15.0	7.8%	4.9	1.9%	3.8	0.0%
22	34.6%	28.7	20.2%	9.1	5.1%	12.3	8.6%	13.4	7.9%	21.5	12.8%	5.7	2.6%	3.8	0.0%
25	39.4%	45.7	33.3%	23.6	16.9%	20.0	15.0%	14.0	8.4%	28.2	17.8%	8.2	4.7%	9.4	4.4%
27	42.5%	54.6	40.1%	40.2	30.3%	39.8	31.3%	16.9	10.9%	32.6	21.1%	17.3	12.4%	13.2	7.4%
30	47.2%	58.4	43.0%	47.9	36.6%	40.5	31.8%	32.5	24.3%	21.0	12.4%	26.8	20.5%	26.1	17.5%
35	55.1%	63.2	46.7%	51.8	39.7%	47.6	37.7%	48.4	37.9%	31.8	20.5%	43.6	34.7%	45.5	32.7%
40	63.0%	68.1	50.4%	62.9	48.7%	52.5	41.7%	58.9	47.0%	63.4	44.4%	58.1	46.9%	61.4	45.2%
45	70.9%	70.4	52.2%	79.0	61.8%	58.2	46.4%	66.5	53.5%	79.3	56.4%	70.0	57.0%	76.4	56.9%
60	94.5%	94.8	70.9%	91.4	71.9%	75.1	60.3%	83.9	68.4%	103.3	74.5%	85.9	70.4%	90.7	68.2%
75	118.1%	104.6	78.4%	101.8	80.3%	95.0	76.6%	91.2	74.7%	110.8	80.2%	98.6	81.1%	101.4	76.5%
90	141.7%	112.6	84.5%	109.2	86.3%	109.2	88.3%	100.4	82.6%	120.7	87.7%	104.3	86.0%	111.3	84.3%
105	165.4%	115.8	87.0%	112.3	88.8%	110.6	89.5%	109.5	90.4%	126.9	92.4%	110.0	90.8%	116.0	88.0%
120	189.0%	119.7	90.0%	115.9	91.7%	115.1	93.2%	115.2	95.3%	131.3	95.7%	114.8	94.8%	121.8	92.5%

APPENDIX D - SELECTED PHOTOGRAPHS
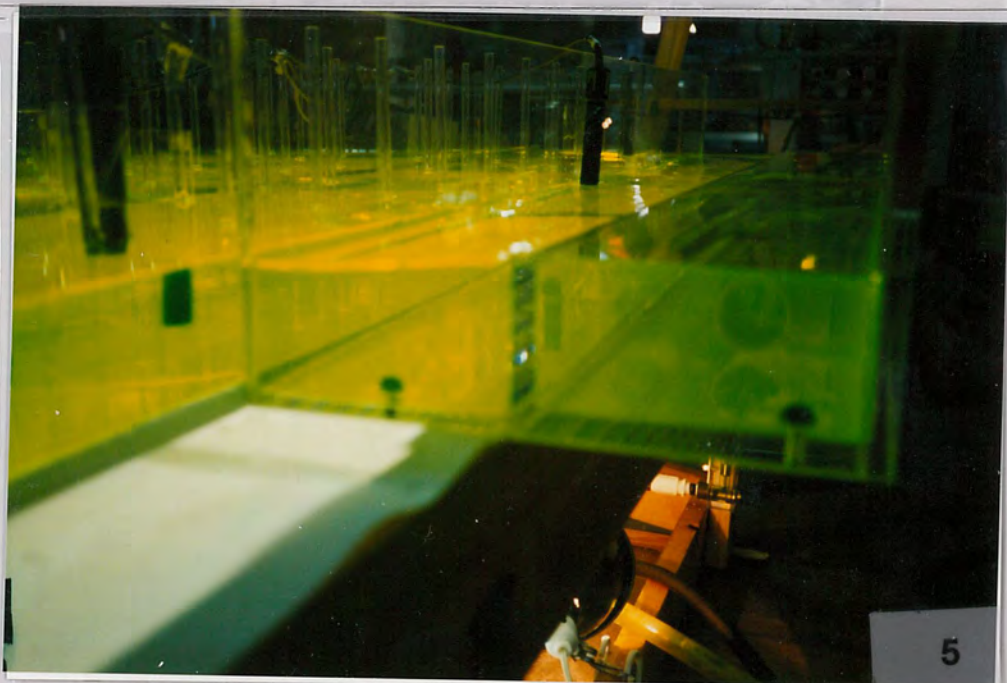
Photo Captions

1. Overall view of the model in the Water Resources Research Laboratory. The 250-gallon plastic supply tank is at left. Fourteen black conductivity probes are secured to columns and are fed to an electric switching box and conductivity meter (left center). Ladders were used to support camera mount for overhead photographs.

2. Close-up of model at the completion of Test 17 showing conductivity probes and baffles.

3. Filling of the model with de-ionized model prior to Test 17.

4. Close-up of inlet box (right) and weir box (left) during normal flow conditions.

5. Close-up of inlet box (right) and weir box (left) during a submerged weir condition. Note water "tipping" to the left in the weir box as the vacuum on the downstream side of the weir draws water to the right. When the vacuum breaks water again tips to the left. The complete cycle took about 1/2 second.

6. Initial dye penetration of the basin with three 1 1/2-inch (72-inch prototype) outlets (Test 8, t=1 minute).

7. Initial mixing at Probe 3. Note clockwise swirl around the probe (Test number unknown).

8. Initial mixing at Probe 4 with Baffle Configuration 6. Note counterclockwise swirl around the probe (Test 10, t=3 minutes).

9. Detail showing the tendency of the flow to "curve" around corners (Probes 13 and 12 at top and bottom center respectively) and to bypass zones behind baffles (right center). (Test 12, t=11 minutes).

10. Short-circuiting of dyed flow between the inlet and outlet (bottom center) with Baffle Configuration 7. As flow arrives from the north (top) a counterclockwise flow pattern is developed in the basin as water passes through the gap in the baffling at the right and re-mixes with water discharged from the inlet.(Test 12, t=17 minutes).

11. Fanning of flows into the outlet (bottom center) with Baffle Configuration 6. This tendency kept conductivity measurements at Probes 5 and 9 (bottom left and top left respectively) from rising as quickly as other probes. (Test 10, t=20 minutes).

12. Close-up of Baffle Configuration 8 along northwest wall (Test 13, t=17 minutes).

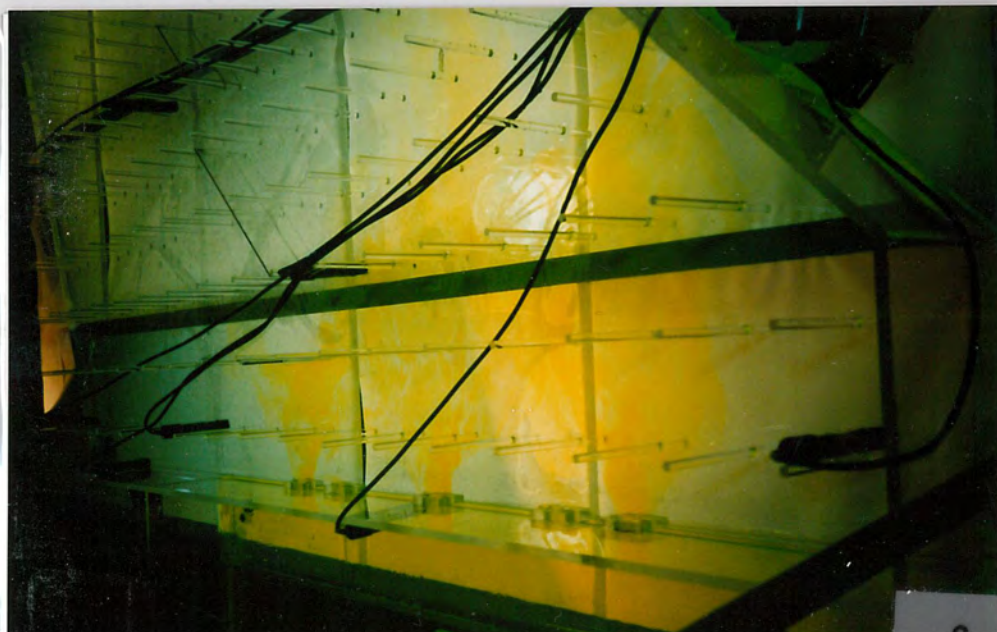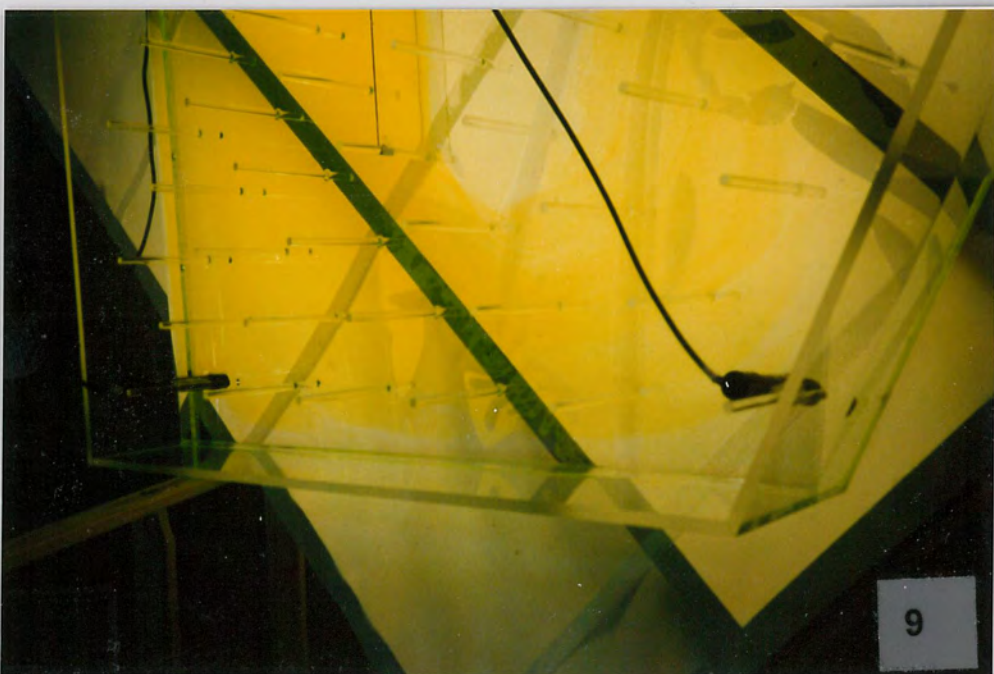Note: Photographs taken above the model at regular time intervals are included in a separate binder.

TEST 1
BAFFLE #8
Q= 100 MGD
8/28/97

4

5

10

11

12