Evaluation of Travel Path Ratio as a Measure of Short-Circuiting Potential in Stormwater Quality Basins using Ideal Flow Modeling

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Abstract

Permitted Best Management Practices (BMPs) serving recent development in Harris County and the City of Houston were examined to select two basin-type BMPs for performance monitoring. Over 750 permits were examined and relevant permit details entered into a database management system; 440 were basin-type BMPs. Detailed examination of the engineering drawings for 440 basin-type BMPs discovered that many BMPs while trying to adhere with local design guidelines confused the meaning of length-to-width ratio as a geometric basin-shape requirement without regard to flow path through the basin. Thus some basins while long and slender have inlets and outlets located across from each other on the short dimension of the basin and arguably are likely to short-circuit. In the selection of the basins for performance monitoring a scoring criteria called Travel Path Ratio (TPR) was created to account for basins that otherwise met design guidelines but were likely to have short circuiting.

An ideal flow model was later constructed to test the relevance of this measure in the context of short-circuiting. The ideal flow model generates velocity potentials that are used in a particle-tracking model to create residence-time distributions for the basins. The residence time distributions of different geometric designs, all with the same volume are compared and demonstrate that the TPR criteria is a reasonable measure of the potential for short circuiting. Inclusion of such a criterion as a design guideline could provide both designers and reviewers a quick tool to evaluate short-circuits potential in future basin designs.

Introduction

In October 2001, the City of Houston and Harris County began enforcement of regulations that required permanent structural controls called Best Management Practices (BMPs) be constructed for all new development and significant redevelopment on 5 acre and larger tracts. Since then, many different types and designs have been developed and implemented. One of the most commonly used best management practices in Harris County is the dry detention pond; therefore two dry detention ponds with storm water quality features (SWQ) were selected for monitoring over a period of time to generate reliable data for performance analysis. The selection of the two BMPs was based upon a scoring system that assigned numerical values to different documented features of the BMPs thought to enhance water quality. Among the features, length to width ratio, inlet and outlet count, land use of served area, sampling feasibility, and an evaluation of short circuiting are considered.

Several hundred BMPs in both jurisdictions (City of Houston and Harris County) were entered into a scoring database and evaluated to select the two ponds. The database included scanned images of the engineering drawings associated with the individual permits, and many locations were actually visited during the study. Tables 1 and 2 summarize the contents of the permit database(s). The Harris County Permits database covers permits issued through December, 2004. The City of Houston permits database covers permits issued through June, 2005. About three to four years of permits are represented for each jurisdiction

Table 1. Harris County Permits Summary

	Wet/Dry Basins[3]	Oil-Grit Separators	Vegetative Filter Strips	Other[4]	Total
Permit Count[1]	264	96	15	11	386
Permit Fraction	68%	25%	4%	3%	100%
Acreage Served[2]	13,696	1,659	144	591	16,090
Area Fraction	85%	10%	1%	4%	100%

Table 2. City of Houston Permit Summary

	Wet/Dry Basins	Oil-Grit Separators	Vegetative Filter Strips	Other	Total
Permit Count[1]	176	174	7	8	365
Permit Fraction	48%	48%	2%	2%	100%
Acreage Served[2]	3,712	1,902	94	77	5,785
Area Fraction	64%	33%	2%	1%	100%

[1] Permit count is the number of permits in database with indicated classification
[2] Acreage served is acres reported in permit or project acreage
[3] Wet/Dry acreage has 12 permits without acres served
[4] Other has 3 permits without acres served.

The summaries illustrate that the principal structural BMP used in Harris County jurisdiction is the basin type BMP, while in the City of Houston jurisdiction the basin type and the oil-grit separators are equally common. The high fraction of oil-grit separators is attributed to the desire to minimize the BMP footprint within the City jurisdiction because of limited real estate availability. The total drainage area served by these BMPs collectively is about 35 square miles, with the majority of the area in the northwest part of the county. Of these 35 square miles of drainage area, about 25 square miles are served by some kind of pond-type BMP. For perspective, Harris County is roughly 1700 square miles – only about 2% of the entire area is served by any kind of BMP.

Figure 1 is a map of all basin type in both databases. The geographic extent is on the order of 60 miles in both North-South and East-West directions. Because the City of Houston extends outside of Harris County, there are BMPs included in this database that are located outside of the county. It is interesting to observe that because these BMPs represent post-2000 construction that most of the growth is occurring well outside the city center. The Pasadena area is excluded from both databases; absence of markers in this region is because of lack of data and not necessarily because of lack of BMPs.

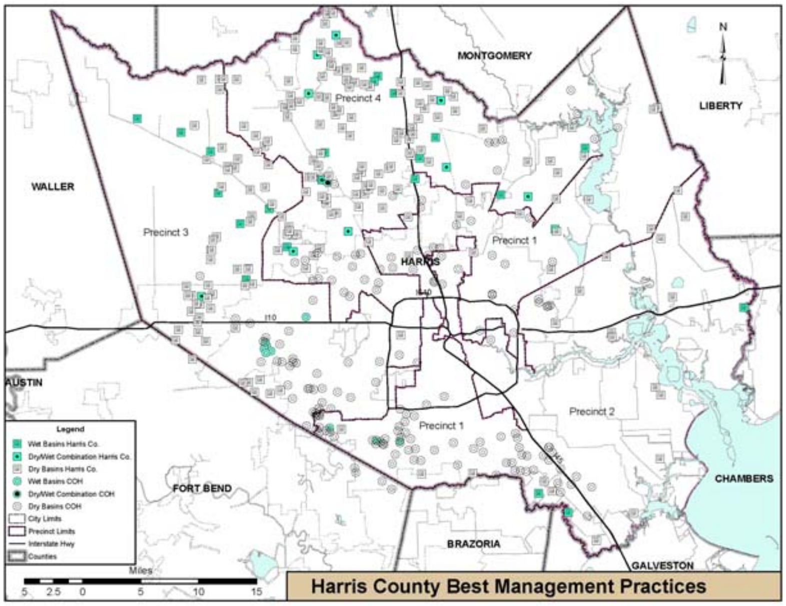

Figure 1. All Basin-Type in Harris County and City of Houston

A scoring system was developed based on the wide geographic distribution displayed in Figure 1 as it was clearly infeasible to visit every site in the database. Details of the scoring system and selection of the two monitored basins are in Orozco (2006).

The regional [Harris County and City of Houston] Stormwater Quality Guidelines (JTF, 2001a) provide design parameters that have a specific value assigned. For example, the design volume of the pond must hold and treat the first 0.5 inches of runoff from the drainage area that the pond serves (JTF, 2001b). This requirement along with a specific pond drainage rate establishes the required treatment volume. It also establishes the hydraulic retention time of the pond; independent of geometry. Geometric design parameters like the length-to-width ratio [3:1 is specified as best, although 2:1 are accepted] are also specified in the manuals. The manual further states that short-circuiting should be avoided and minimized for dry detention pond design.

During examination of the 440 basin-type permits we discovered that many basins were designed in a way that indicated consideration of a length to width ratio 3:1 [one dimension was three time larger than another dimension]; but the relative positions of inlet and outlet locations was such that a potential for short-circuiting exists in many permitted ponds.

To make short-circuiting potential measurable, a surrogate criterion named Travel Path Ratio (TPR) was developed during the study, and applied to the dry detention basins reviewed. TPR was used as a scoring criterion to predict pond performance for the purpose of selecting existing ponds for monitoring. Later, to test the relevance of this evaluation parameter, stormwater flow inside a detention basin was modeled. Different hypothetical basin geometries were evaluated and the residence time distribution of particles is calculated and used to evaluate performance. Several actual designs were examined to illustrate the application of the model to real basins and to justify the use of the TPR as a potential design criterion.

Literature Review

As part of a local or regional stormwater management program regulatory authorities typically prepare a “Minimum Design Criteria Manual” in order to help developers design BMPs and meet the design criteria for a stormwater quality program. These authorities then review the permit proposal presented by the developers, and if the design criteria established in the design manual are met, the corresponding storm water quality permit will be issued for the development.

The removal efficiency of the detention ponds is directly dependent to the time that pollutants stay inside the pond, where they can be removed by settling (Shaw et al, 1997). Around 60 to 90 percent of the pollutant removal of detention ponds is due to sedimentation and settling (Davis and others, 1978). Thus the design goal of such a pond is a high residence time. The design goal for chlorine contact tanks is similar; to provide long residence time in order to obtain good disinfection. The length-to-width ratio is one of the important criteria.

Table 3 summarizes selected design guidance relevant to short-circuiting and establishment of geometric guidelines to induce high residence time from several sources around the United States. These selected existing criteria suggest that all jurisdictions desire that the ponds behave as long, slender reactor vessels [like a chlorine contact tank].

The length-to-width ratio parameter for chlorine contact tanks is calculated as the ratio of the flow path inside the tank and the average width of the tank [perpendicular to the flow path]. Most chlorine contact tanks are designed using baffles to increment the residence time. The efficiency of 16 different chlorine contact tanks ranging from 3.2 to 120 length-to-width was measured concluding that the larger the length-to-width ratio, higher residence time, less dispersion and higher efficiency is obtained (Sepp, 1977). The New Jersey guidelines essentially adopt this definition of length-to-width ratio; the jurisdictions that define length as inlet to outlet distance are close to this definition as many ponds are approximately rectangular basins. Golden, Colorado specifically recognizes that ponds may require the use of baffles and other features to fit the idealized reactor vessel into an actual space; the other jurisdictions are more vague in this respect, yet they do recognize short-circuiting is an issue.

Table 3. Selected Design Guidelines from Different Locations in USA

Location	L/W	Length (L)	Width (W)	Reference
Harris Co./Houston	2:1 to 3:1	--	--	JTF 2001.[1]
Woodland, CA	2:1	--	--	City of Woodland, 2003
California (generic)	1.5:1	Inlet-to-Outlet	--	CASQA, 2003.
Virginia	2:1	Inlet-to-Outlet	Average width	VADOC, 1999
Tennessee	Ideal 4:1 2:1 minimum	Inlet-to-Outlet	--	TDEC, 2002
Connecticut	3:1	Inlet-to-Outlet	--	CNDEP, 2004
New Jersey	2:1 to 3:1	Flow path.	Average normal to path.	NJDEP, 2003
Aurora, Il	--	--	--	City of Aurora, 2003.[2]
Golden, Colorado	2:1 to 3:1	--	--	City of Golden, 2005[3]

[1] Distance between inlets and outlets to maximize flow path, minimize short circuiting, avoid dead space.

[2] Distance between inlets and outlets shall be maximized as feasible, and if possible they should be at opposite ends of the basin

[3] Modification of the inlet and outlet points, through the use of pipes, swales (baffles) or channels may be necessary to achieve this goal

In the present study it became apparent to the authors that the Harris County/City of Houston guidelines regarding the length-to-width ratio was misinterpreted in some permits as a geometric requirement independent from inlet and outlet orientation, hence the creation of the TPR as a measure of short circuiting potential.

Travel Path Ratio

A surrogate based on the inlet-outlet distance along a likely hydraulic path, and the inlet to outlet distance along the longest geometric path that follows the basin edge was developed. The criterion is called the Travel Path Ratio, and it is a hybrid concept of the inlet-to-outlet distance concept and the flow path concept. It was created because it was relatively simple to calculate from the drawings in the database, it accounts for inlet and outlet location relative to pond geometry, and penalizes “short-circuits”. For the pond selection exercise it was further decided based on engineering judgment that a TPR numerical value above 0.5 was acceptable, and below 0.5 was poor. The minimum required value of 0.5 for the TPR parameter is later demonstrated to be a useful value with the ideal flow modeling program.

The Travel Path Ratio (TPR) is calculated as the ratio between the most direct geometric path distance and the longest distance that the water could take from the inlet to the outlet along the sides of the pond. The longest distance is defined as the summation of the two main dimensions depending on the pond shape. Figure 1 is an example of how the TPR is determined in a rectangular pond with inlet and outlet at opposite corners. This metric is considered a measure of the short-circuiting potential of a pond. This criterion was implemented because many ponds in the database were designed to in a way that indicated adherence of length to width ratio 3:1; but the effect of inlet location related to the outlet was ignored.

For the non-rectangular ponds the TPR is computed using a characteristic polygon (i.e. triangle, rectangle or trapezoid), and appropriate characteristic dimensions to define the longest distance component. The travel path (TP) dimension is always the most direct geometric distance from the inlet to the outlet of the pond. For the triangular shape, the “A” distance (length) is the base of the triangle and the “B” distance (width) is the distance from the centroid to the base of the triangle. For trapezoid shapes, the “A” distance (length) is the average between the bases and the “B” distance (width) is the height of the trapezoid. The TPR value will always be less than 1 (unless the pond has baffles), so the higher the ratio, the higher the score will be assigned to the permit.

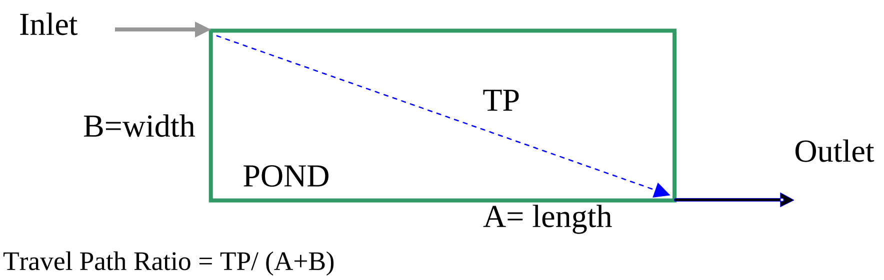

Figure 2. Travel Path Ratio Computation

The travel path distance in the case of a baffle is the shortest geometric distance from the inlet to the outlet, going around the baffle if necessary. The remaining terms are unchanged. The utility of this criterion is demonstrated to be useful for quantifying the short-circuiting potential in dry detention ponds and is discussed in detail later; at the time of pond selection, this ad-hoc criterion was simply a judgment-based criterion. Further details of the actual database construction, analysis, and pond selection are reported in Orozco (2006). The remainder of this paper discusses the post-selection examination of the TPR criterion.

Travel Path Ratio Evaluation

To examine the effectiveness of the TPR, the flow of water inside the basin is simulated to determine the residence time distribution of ideal tracer particles entering the pond. The residence time distribution of these particles is expected to change depending on the pond geometry design and the relative position of the inlet and outlet, as such the effect of different pond geometries can be compared. The TPR criterion accounts for the relative position of the inlet and outlet.

The hydraulics of a water quality detention basin are approximated by a velocity-potential, stream-function formulation with internal boundaries to allow the simulation of internal baffles (swales) in the basin. The hydraulic model assumes that the basin is full to its stormwater quality design depth (just before high-flow overflow) and this depth is maintained for sufficient time that a quasi-steady flow situation develops. In all simulations in the basin volume is assumed identical; thus the hydraulic retention time would be identical (Orozco, 2006)

The ideal tracer is simulated as an ensemble of particles initially distributed near the inlet. The particle's trajectory is determined from the local velocity for a short time step, the particle is allowed to move, its velocity recomputed, and the process repeated until the particle exits the basin. This tracking of particles is somewhat tedious and time consuming, but it provides a tool to approximate basin behavior. Because the principal mechanism of treatment in these basins is thought to be settling, the tracer arrival times obtained by this simulation convey valuable information about the probable performance of the basin based on its geometry and relative position of inlet and outlet.

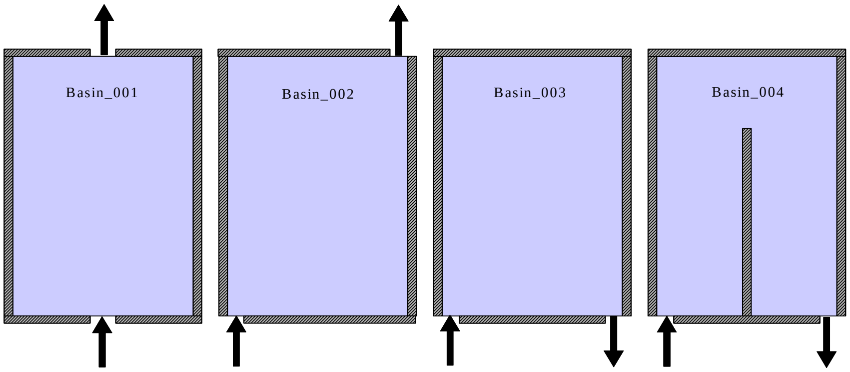

Figure 3 Four Basin Configurations with the Same Geometric Length/Width Ratio

The modeling approach is illustrated with four generic basins to illustrate the concepts in the model study; actual basins are examined later in the chapter. Figure 3 depicts four geometries simulated to illustrate the principles of the study. In each of the four basins the geometric length to width ratio is held at 3:1 as per typical design criteria (JTF, 2001a). Basins 1 and 2 are relatively common configurations, as is basin 4. Basin 3 is an intentional case of obvious short-circuiting.

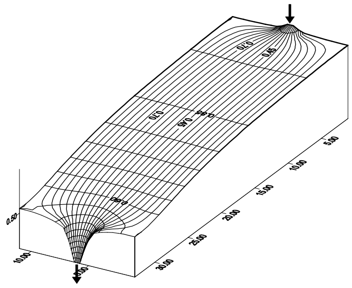

Figure 4a. Basin 1 Flownet

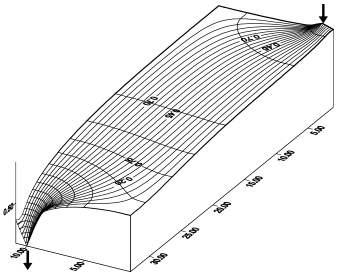

Figure 4b. Basin 2 Flownet

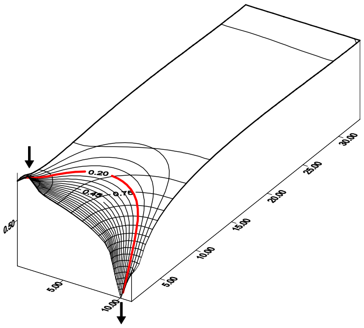

Figure 4c. Basin 3 Flownet

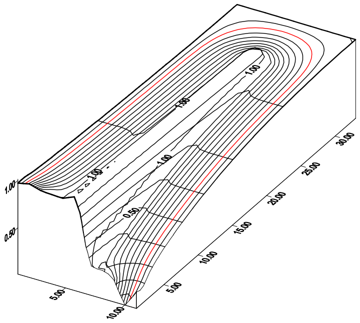

Figure 4d. Basin 4 Flownet

Figure 4 is a set flownets for each hypothetical basin that graphically illustrates the importance of inlet to outlet relative location. Figure 4a is the flownet for Basin 1, flow is uniform across much of the basin with streamline distortion apparent at only the inlet and outlet.   The inlet and outlet are centered on the short side of the basin, on opposite sides. The travel-path ratio for this basin is 0.76 and would satisfy this selection criterion in our study. The mean arrival time (a surrogate for residence time) is 2909 time units, and the standard deviation normalized by the mean is 0.08. This basin configuration is common in both the Harris County and City of Houston jurisdictions; and meets suggested geometric design criteria in the Harris County guidance manual.

Figure 4b is the flownet for basin 2. Flow is uniform across about 1/3 for the basin with streamline distortion apparent at the inlet and outlet.   The inlet and outlet are on opposite corners of the long side of the basin. The TPR for this basin is 0.79 and would satisfy this selection criterion in our study. The mean arrival time is 4332 time units, and the standard deviation normalized by the mean is 0.16. This basin configuration along with Basin 1 is quite common in both the Harris County and City of Houston jurisdictions; and meets suggested geometric design criteria in the Harris County guidance manual.

Figure 4c is the flownet for basin 3. Basin 3 is intended as an example of a poorly configured basin, although some basins with this configuration appear in the permit database. The bold streamline has stream function value 0.2; the value of the function along the short wall is 1.0; hence eighty-percent (1.0-0.2) of the flow is confined to the lower 1/6 of the basin with streamline distortion apparent at the inlet and outlet.   This result can be interpreted as either "short-circuiting" or the basin is hydraulically smaller than its geometry suggests.   The inlet and outlet are on opposite corners of the same short side of the basin. The TPR for this basin is 0.25 and would fail the selection criterion in our study.   The mean arrival time is 137 time units, and the standard deviation normalized by the mean is 0.34. This basin configuration is not common in the Harris County and City of Houston jurisdictions; it only meets design criteria in the Harris County guidance manual if the designer interprets the meaning of 3:1 length-to-width ratio as meaning that one dimension of the basin is three times larger than another - it does not meet the criterion related to “minimization of short-circuiting.”

Figure 4d is the flownet for basin 4. Basin 4 is identical to Basin 3 except a baffle wall is added to mitigate the “short-circuit” and is intended as an example of simple retrofit to a poorly configured basin. Several examples of this configuration are permitted in both jurisdictions. The same streamline as in Basin 3 is labeled and it is apparent in this case that the addition of the baffle wall changes the flow pattern so that the flow traverses the entire basin. The travel-path ratio for this basin is 1.5 and would satisfy this selection criterion in our study. The mean arrival time is 9369 time units, and the standard deviation normalized by the mean is 0.05.

Figure 5 is a plot of the cumulative tracer arrival time distributions for the 4 basins. The time axis is logarithmic and that the worst performing basin (Basin 3) in terms of residence time is over one order of magnitude lower time that the better performing basins. These hypothetical basins illustrate the impact of short-circuiting as well as the value of a simple retrofit (baffle) to an otherwise poor basin.

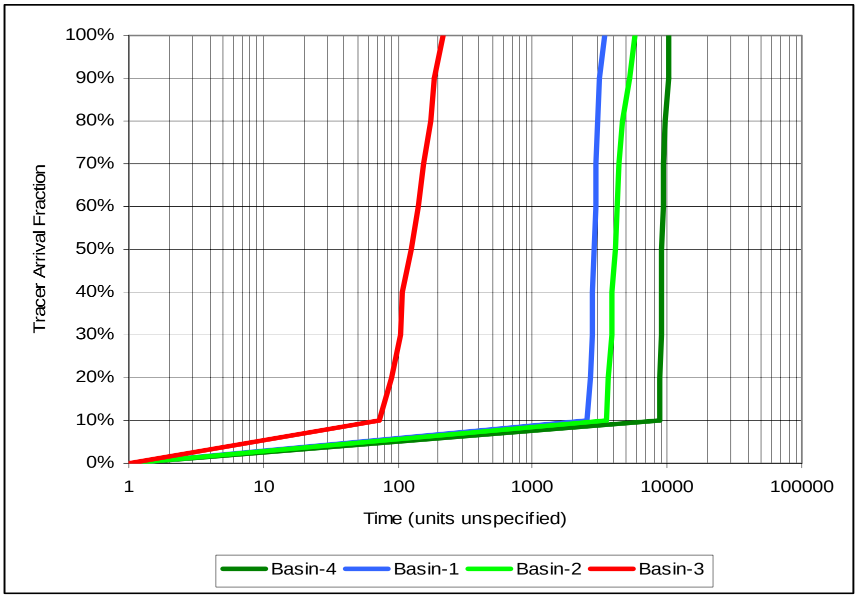

Figure 5 Tracer Cumulative Arrival Time Diagram for the 4 Study Basins

Application to Existing Ponds

The previous section illustrated the modeling concept on generic ponds; in this section actual geometries in the permit database are examined. Because the detention ponds are designed to be emptied in a 24 to 48 hours period, it is assumed that there is not change in the outflow during the particle travel interval (quasi-steady discharge). The intent of this work is to demonstrate the relevance of the new TPR parameter as a surrogate to avoid short circuiting, and also to demonstrate the importance of having a short circuiting criterion for storm water detention pond design.

Detention ponds are designed to treat at least the first 0.5 in of rainfall in the watershed served, so the ponds are assumed simulated to have the same base area. If the ponds have the same area, and assuming that the ponds are serving the same watershed area, the resulting runoff volume that the pond is treating is the same. For this reason, the water depth will also be the same for all of the ponds. Hydraulic Retention Time (HRT), which is defined as the volume of the pond over the flow, is also the same for all the pond designs studied. Therefore, only the geometry and inlet and outlet positions will be changed. The HRT is a classic wastewater requirement, but without the geometry design parameters the HRT becomes insufficient. For example surface loading and weir loading rates are used in wastewater engineering to supplement the HRT requirements. For this reason, the TPR and geometric L/W ratio parameters equally important for stormwater quality pond design.

Fifteen different stormwater quality and detention pond configurations were examined, many from the permit databases, several are variations of the actual configurations to suggest simple retrofits. Two are hypothetical cases using other state's suggested criteria. Several examples are examined in the following paragraphs.

Figure 6 is an image of the engineering drawing for the pond in permit 2003-0070. The pond has a L/W ratio of 2.0 and a TPR value of 1.07. These values suggest that the pond meets the criteria. This pond is similar to the Basin 4 hypothetical configuration.

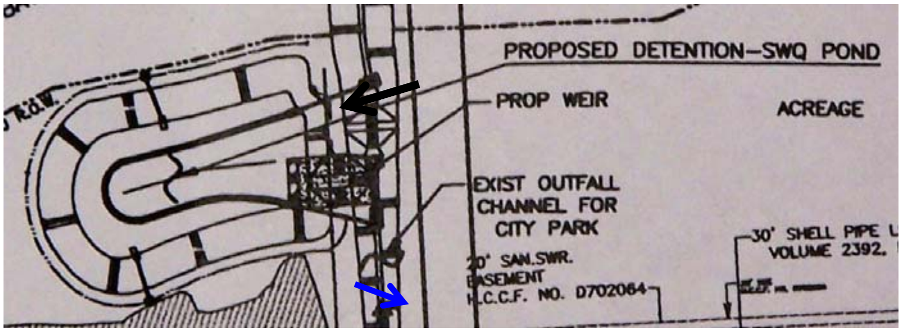

Figure 6 Engineering Drawing for Permit 2003-0070 from COH

The average residence time from the particle tracking program is 4597 time units. If the baffle wall is removed, geometry is unchanged but the TPR value is reduced to 0.33 and the pond will short circuit. The average residence time from the particle tracking program is 651 time units. Thus the baffle wall in this case increases residence time nearly seven fold, and more importantly the TPR value is greater than 0.5.

Figure 7 is an image of the engineering drawing for the pond in permit 8-279-9. The pond has a L/W ratio of 1.6, and a TPR value of 0.42. These values suggest that the pond will short circuit. This pond is similar to the Basin 3 hypothetical configuration. Figure 8 is the flownet for this pond.

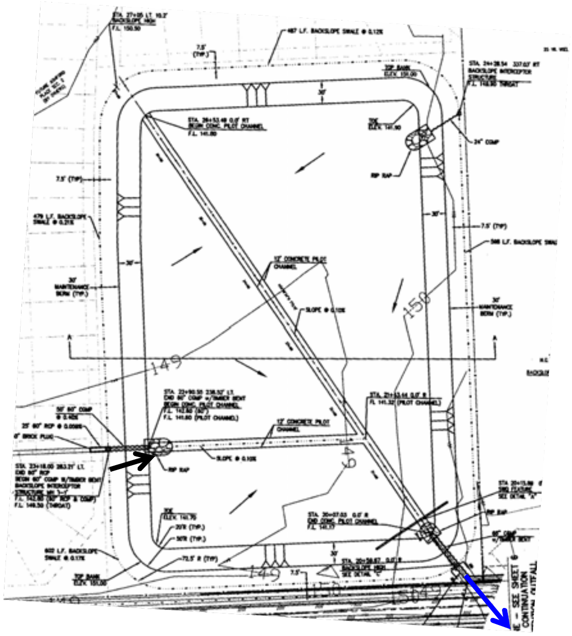

Figure 7 Engineering Drawing for Permit 8-279-9 (Harris County) SWQ Pond

Approximately 50% of the pond is wasted for pollutant removal. The TPR parameter is identifying short-circuiting and this pond does not comply with the criteria for stormwater quality pond design. The average residence time from the particle tracking program is 600 time units. Approximately 70% of the tracer particles will travel along the only one-third of the pond, and the other 30% use another 20% more of the pond, and around 50% of the pond is not used. This pond would be useful for flood water (peak attenuation) detention purposes, but according to the selected criterion is insufficient for water quality enhancement.

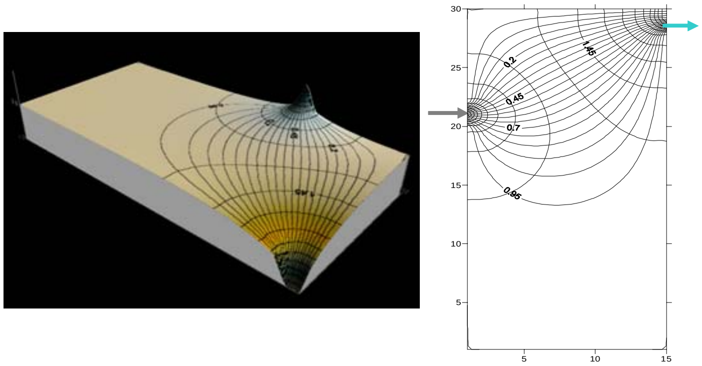

Figure 8 Flownets for 8-279-9

Figure 9 is an image of the engineering drawing for the pond in permit 8-262-4 from Harris County files. The pond has a geometrical L/W ratio of 1.0, and the TPR of 1.5. These values suggest that the pond meets the criteria. Because of the TPR value and the baffles contained in the pond, the L/W ratio can be less than 2.0 and good performance is achieved. The average residence time of this pond is 7357 time units, which is best time of any pond modeled.

Table 4 summarizes the results of the ponds studied in order increasing residence times. The first five designs do not meet the short circuiting design criteria, either because of a low geometrical L/W ratio (<2.0) or because the TPR parameter is not greater than 0.5. From these results, and applying the implemented TPR parameter and the geometrical L/W criterion, it was predetermined that mean residence time's less than 2500 time units do not provide good pond performance.

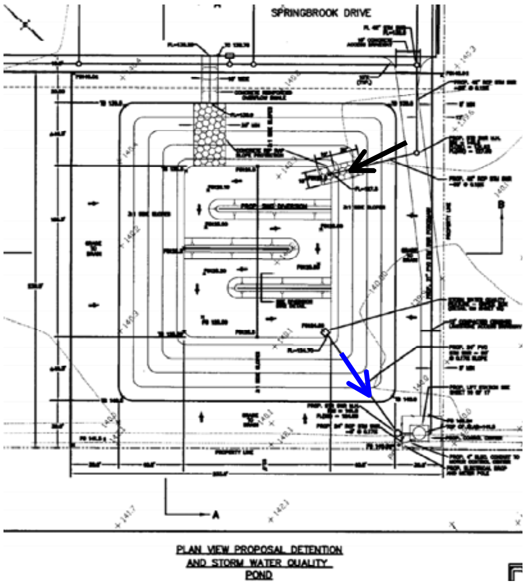

Figure 9. Engineering Drawing for Permit 8-262-4 (Harris County) SWQ Pond

Table 4 Summary Results of the Ideal Flow Modeling for the Pond Types Studied

ID	Basin Type	TPR	Geometrical L/W	Baffle	Residence Time
1	8-279-9	0.42	1.6	NO	600
2	2003-0070 without baffle	0.33	2.0	NO	651
3	2005-0080 model	0.48	21.0	NO	1172
4	2003-0117 model	0.50	1.0	NO	2413
5	Tennessee, (L/W)* =2.0	0.74	1.7	NO	2493
6	8-108-2	0.67	3.0	NO	2558
7	8-061-7	0.76	2.5	NO	2860
8	Connecticut, (L/W)* = 3.0	0.78	2.8	NO	2949
9	8-077-0	0.70	3.0	NO	3046
10	Basin with 1 baffle (L/W)=1.0	0.79	1.0	1	3322
11	8-169-8	0.75	3.0	NO	3411
12	2003-0070	1.07	2.0	1	4597
13	Basin with 2 baffle (L/W)=1.0	1.30	1.0	2	5507
14	2004-0040	0.92	11.0	NO	6863
15	8-262-4	1.50	1.0	3	7357
* =	L = TP for the L/W ratio calculation				

Figure 10 is a graphical representation of the information in Table 4. From Figure 11, four sections can be identified. These four sections show the different residence times ranges that can be achieved by changing the geometry of the pond, the inlet and outlet locations and by installing baffles.

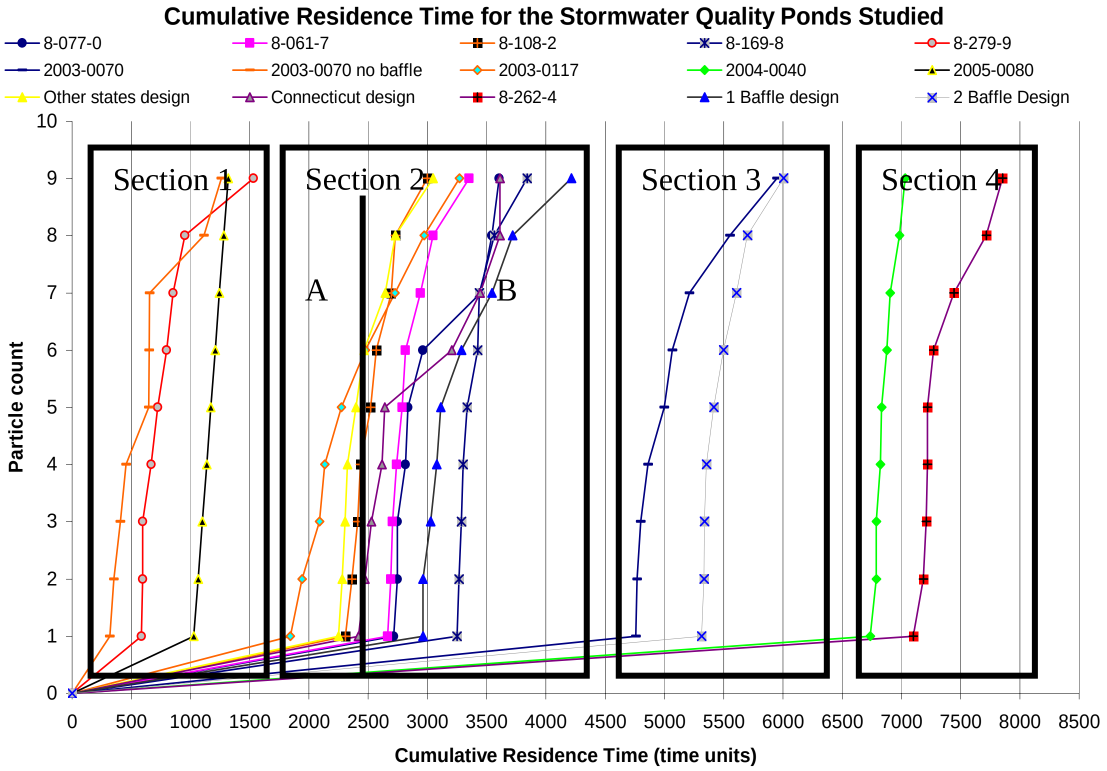

Figure 10 Cumulative Residence Time for the Pond Designs Studied

From left to right, the first section is produced by the ponds in permits 8-279-9, 2005-0080 and 2003-0070 without the baffle. Based on the residence time results, this section shows examples of poor or bad designs – generally these ponds are relatively square or inlets and outlets do not take advantage of pond shape.

Section two contains the minimum residence time established, this section is divided in two parts. The part A of section 2 is formed by permit 2003-0117 and the Tennessee design types. These ponds provide better residence time than the ponds in the first section, but are slightly under the minimum residence time established [in this study]. Part B contains the Connecticut state design type and various Harris County/City of Houston permitted designs. All these designs comply with the proposed criteria for stormwater quality pond design, their average residence time is greater than 2500 time units.

Sections three and four in Figure 10, contain various baffled designs and one moat-type pond. The residence time achieved in these designs is clearly greater than the other common pond designs.

Conclusions and Recommendations

The presence of permitted ponds in the Harris County and City of Houston databases with geometric length-to-width ratios of 2:1 to 3:1 and beyond, but with inlet and outlet locations not being located on opposite ends of the long axis of such ponds indicates that the guideline was unintentionally interpreted as a geometric requirement and not a hydraulic requirement. The guidance "minimize potential for short circuiting" is sufficiently vague as to allow such ponds.

The TPR calculation can rapidly evaluate short-circuit potential, is consistent with guidance from other state's manuals, and can be implemented with an engineering scale and calculator. From these studies a pond with a geometrical length-to-width ratio greater than 2.0 and a TPR parameter value greater than 0.5 will meet the existing local criteria of "minimize potential for short circuiting," and allow for innovative geometries to take advantage of surplus space in a subdivision.

The TPR parameter and the geometric requirement identified short-circuiting in all the study cases. Long shaped ponds [the ideal] have similar performance of ponds with baffles; baffles are a simple retrofit that can be employed to improve existing ponds.

Acknowledgments

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