EVALUATION OF THE EFFECTIVENESS OF SHORT CIRCUITING CRITERION FOR STORMWATER QUALITY BASINS DESIGN USING IDEAL FLOW MODELING

A Thesis

Presented to

the Faculty of the Interdisciplinary Graduate Program

in Environmental Engineering

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in Environmental Engineering

by

Samuel Orozco

August 2006

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EVALUATION OF THE EFFECTIVENESS OF SHORT CIRCUITING CRITERION FOR STORMWATER QUALITY BASINS DESIGN USING IDEAL FLOW MODELING

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ABSTRACT

In order to select the best two dry detention basins within the Harris County jurisdiction for sampling and monitoring their performance, the characterization of the existing and permitted Best Management Practices currently used within Harris County limits was performed. All Permits that have been issued by Harris County through December 2004 and the City of Houston through June 2005 were reviewed. BMP permit information was collected, analyzed and stored in a database for further analysis. Design parameters relevant to the performance and functionality of the BMPs were used as classification guidelines.

Two dry detention ponds were selected for the sampling based upon their total score for a number of parameters. Dry detention basins were classified as serving both residential and non-residential land use. Other parameters used in the scoring included: the length to width ratio (at least 3.0); the number of inlets (maximum of 1); the number of outlets (maximum of 1); and a short-circuiting criteria developed throughout the investigation named "Travel Path Ratio" (at least 0.5).

Harris County and the City of Houston have standardized many of their regulations for the Storm Water Quality Permits, and therefore the types of systems permitted are very similar. The distribution of permitted BMP types is presented along with maps of both Harris County and City of Houston permits that illustrate where BMPs have been constructed.

During the examination of the dry detention ponds, a Travel Path Ratio (TPR) criterion was implemented and used as a surrogate to measure short-circuiting. Dry detention ponds should avoid and minimize short-circuiting (Joint Task Force, 2001), and

this ad-hoc criterion determines if the design geometry of the ponds was generating short-circuiting or not. To determine the relevance of this measure, an ideal flow model program is used to model the stream flow within the basin and provide stream-flow lines and velocity potentials. Then, a particle tracking program is used to model the particle behavior within the basin using the stream-flow lines and velocity potential. With the particle tracking program residence time distributions of the particles are calculated. Different types of basin design geometries are evaluated and the residence time distribution is used to measure the ideally efficiency of the ponds. About 90% of contaminant removal in detention ponds is done by settling, thus the more time the particles spend inside the pond the better the removal efficiency. Therefore, the performance of the basins is assumed to be improved by increasing the residence time of the particles. The residence time distribution of different geometric designs are calculated and compared to analyze the relevance of the travel path ratio criterion implemented as a surrogate for short-circuiting.

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Chapter 3 presents the construction of the database used to both display the spatial distribution of BMPs and to select the two candidate ponds for matching and analysis by other parties.

Chapter 4 presents the scoring system used and explains the logic behind the TPR criterion used as ad-hoc measure of short circuit potential.

Chapter 5 is the analysis of different pond design types and the evaluation of performance using ideal flow modeling programs.

Chapter 6 presents the conclusions of the thesis.

CHAPTER 1 INTRODUCTION

1.1 Background

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.

These technological requirements are often criticized because of limited local performance data on both generic and proprietary structural BMPs. In response to this criticism, the Environmental Protection Agency (EPA) awarded a grant to Harris County for measuring Best Management Practices (BMP) effectiveness.

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. These data were collected in the format required by ASCE for publication in their national BMP data base (Urbonas, 1994; Strecker et al., 2004).

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 ad-hoc short circuiting criterion (called Travel Path Ratio) 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 details of this scoring system are discussed as part of this thesis.

Following the selection of the two BMPs using the scoring system, the rigor of the TPR criterion was tested by ideal flow modeling to establish that the TPR score excluded ponds with obvious short circuiting and included ponds whose geometrical length to width ratio was unfavorable, but with the presence of internal baffles could perform the water quality enhancement intended of a BMP. The details of this modeling constitute the other component of this thesis.

1.2 Objectives

The objectives of this thesis are threefold:

The first is to document the spatial distribution of permitted BMPs in Harris County and the City of Houston jurisdictions as well as the relative proportion of different types of BMPs in current service.

The second is to document the scoring system used to select the candidate ponds for monitoring by Carter & Burgess on behalf of Harris County for the performance analysis.

The third is to evaluate the TPR scoring criterion using ideal flow modeling and particle tracking to test the effect of pond geometry on these design criteria in other jurisdictions.

1.3 Problem Statement

This thesis presents the examination of the BMPs currently permitted within the unincorporated Harris County and incorporated City of Houston, using the specific design characteristics that are expected to produce good BMP performance. Ponds meeting prescribed criteria are screened using a database management system and selected for possible field monitoring. Of the feasible ponds, two representative dry detention ponds, one serving residential and one serving non residential development, are recommended for water quality sampling to determine pond performance.

The Stormwater Quality Guidelines (JTF, 2001a) states that short-circuiting should be avoided and minimized for dry detention pond design. In order to make short-circuiting measurable, a surrogate criterion named Travel Path Ratio (TPR) was developed during the study, and applied to the dry detention basins reviewed. TPR was taken as a reference to predict pond performance. As a way to demonstrate the relevance of this design parameter, the ideal flow of stormwater inside a detention basin was simulated and modeled. Different basin geometries are evaluated and the residence time distribution of the hypothetical particles is calculated and used to evaluate performance.

Currently the short circuiting criterion is evaluated with the length to width ratio in several states and cities in Stormwater Quality Manuals. Some states and cities define the length of the pond as the straight distance between the inlet and the outlet, and the L/W ratio criterion is mixed with the short circuiting criterion. Other jurisdictions, for example the state of New Jersey and the Joint Task Force don't specify the length of the pond as the distance from the inlet to the outlet, they just state that short circuiting should be avoided and minimized.

In the present work, the design criteria to avoid short circuiting in the stormwater detention ponds are defined with two parameters: the length to width ratio (L/W), and the "Travel Path Ratio" (TPR). With these two parameters satisfied, the pond is expected to perform well for pollutant removal. The removal efficiency of the detention ponds is directly dependent to the time that particulates 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 et al., 1978). In the present work, the L/W of the pond is proposed to be calculated as drawn on engineering drawings, the length of the pond over the average width of the pond, independently of the location of the inlet and the outlet. L/W ratio value must be greater than 2:1. The TPR criterion is calculated as the ratio of the most likely flow path inside the pond, and the summation of length and width distances. The TPR value must be greater than 0.5.

Simulation of several designs taken from actual permits in Harris County and the City of Houston are performed, and the retention times calculated to measure ideal performance. The other states and cities design criteria are also evaluated and compared with the proposed criteria design, to demonstrate the relevance of the new criterion for short circuiting measurement.

CHAPTER 2 LITERATURE REVIEW

2.1 Definitions

2.1.1 Best Management Practices (BMPs)

Best Management Practices (BMPs) are effective methods intended to reduce the amount of water pollution generated by non-point sources. Non-point sources include water pollution by natural processes, (i.e., runoff), and are not traceable to any identifiable source location such as a pipe. BMPs are divided into two types: Non-Structural controls and Structural controls.

2.1.2 Non-Structural BMP

Non-structural controls are practices that are designed to prevent or reduce the potential contact of storm water runoff with pollution-causing activities. Examples of this kind of control are: household hazardous materials storage/disposal, litter control, landscaping practices, frequent street cleaning and similar maintenance and administrative procedures.

2.1.3 Structural BMP

Structural Controls are constructed facilities that are designed to reduce pollutant levels in storm water runoff. Structural BMPs are selected and designed based on contributing drainage area, soil type, vegetative and impervious cover, and type of expected pollutant from the site.

2.1.4 Detention Basins

For new development and significant redevelopment, a storm water quality system has to be installed in order to be permitted and the construction to proceed. Permitted in this context means that the system designs have been submitted, examined, and approved by the permitting authority, in the current study these authorities are Harris County Stormwater Quality Permits and the City of Houston Stormwater Permits depending on where the development occurs. The permits are issued for a fixed interval of time and must be renewed every few years. For large developments, detention ponds are commonly used to satisfy flooding issues and designed with a storm water quality (SWQ) feature to provide pollutant removal in addition to flood control. Detention ponds can be classified as wet ponds and dry ponds. Both, wet and dry ponds work on the same principle for providing detention and water quality enhancement. The treatment principle of the ponds is mostly the settling of suspended solids. Screening is used to manage floatable trash. Because the removal of suspended solids is the principal treatment, dry detention basins don't provide much dissolved materials removal other than a fraction of materials that strongly sorbs to either the settling solids or the floating trash. However, for wet detention ponds, it has been found a reduction between 63 to 77 for Nitrate and phosphate respectively (Mallin et al., 2002). Removal of total suspended solids by detention basins has been calculated to vary between 60 to 90 percent (Barrett et al., 2005; Davis et al., 1978). Therefore, well designed ponds must allow solids to stay within the pond long enough to promote sedimentation and pollutant removal. The design challenge is much like primary clarification design for wastewater, with the added challenge that the systems are passive and unattended.

2.1.5 Short Circuiting

The longer solids stay inside the pond the better the removal efficiency of the pond will be. For this reason, short circuiting of detention ponds should be avoided. Short-circuiting happens when the storm water enters the detention pond, along with the pollutants, and exits rapidly from the pond. When short circuiting happens, insufficient time elapses for the solids to settle, reducing the removal performance of the pond. Short circuiting is commonly caused by two main design reasons:

- When the inlet is located too close to the outlet in a hydraulic sense. Design criteria recommendation is to locate the inlet as far as possible from the outlet (JTF, 2001a); this criterion assumes that the pond will not have internal baffles.
- When the length/width ratio of the pond is not met. The design criteria value for the length/width ratio is set by the regulatory agencies and its value varies from state to state, and even between political subdivisions within a state. L/W is recommended to be 3:1 or higher by JTF Minimum Design Criteria for BMP Design Manual.

Despite the guidelines to prevent short-circuiting, there are permitted ponds in service that do not meet these theories; recall the criteria are "recommendations."

2.2 Regulations

The stormwater discharges from non-point sources are not yet regulated by the EPA, but different approaches like the watershed-based National Pollutant Discharge Elimination System (NPDES) have been proposed by EPA to control pollution (EPA, 2003). In the watershed-based program, non-point sources can be an important factor to control in order to be permitted. At this time, there are few if any regulations for non-point source pollution but eventually there will be, and a well designed detention pond can be the key to achieve the pollution removal desired.

2.3 Dry Basin Design Criteria for Short Circuiting

Regulatory authorities such as Harris County and City of Houston have prepared a "Minimum Design Criteria Manual" in order to help developers design BMPs and meet the design criteria for stormwater quality program. Regulatory agencies will review the permit proposal presented by the developers, and if the design criteria established on the design manual is met, the corresponding storm water quality permit will be issued for the development.

For dry and wet stormwater quality basins, there are some design parameters that have a specific value assigned. For example, the design volume of the pond must be enough to handle the first 0.5 inches of rainfall over the watershed that the pond is serving (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. Geometry design parameters like the length/width ratio are also specified in the manuals. However, to improve treatment performance with detention ponds, short circuiting has to be avoided as well. Some states have already established a design parameter as a surrogate tool to quantify short circuiting potential.

2.4 Pond Geometry and Short Circuiting Criteria in Other Jurisdictions in USA

In California, the California Stormwater Quality Association (CASQA) has defined the length/width ratio differently. The length is defined as the distance between the inlet and the outlet, and the width is just the width of the pond presumably perpendicular to the length of the measurement (CASQA, 2003). In this way, no matter what the geometry of the pond is, the length to width/ratio will in some sense take into account the potential for short circuiting. California regulatory agencies require that a “length/width” ratio of 1.5 minimum has to be met on the pond design.

The state of New Jersey also has a surrogate for measuring short circuiting. In the ”New Jersey Stormwater Best Management Practices Manual”, under “Flow Paths”, the New Jersey Department of Environmental Protection has stated that flow paths lengths should be maximized and long, narrow basin configurations with length to width ratios from 2:1 to 3:1 should be utilized (NJDEP, 2003). In this manual, the criteria for short circuiting is also mixed with the length/with ratio parameter, but in this case the length is not defined as the distance between the inlet and outlet as it is defined in the “California Stormwater Handbook” , but instead considers a “hydraulic” length.

Tennessee Department of Environmental and Conservation in the Division of Water Pollution Control has published under basin shape, that the effective length to width ratio should be 4:1 and no less than 2:1, and they define the length as the distance between the inlet and outlet (TDEC, 2002). Again, the two parameters have been combined like in the California Stormwater Handbook.

In Virginia, the Virginia Department of Conservation & Recreation has stated that the length-to-width ratio of 2:1 through the marsh should be maintained, and they define the length-to-width ratio to be calculated dividing the straight line distance from the inlet to the outlet by the average width (VADOC, 1999). This is the same concept as in California and Tennessee.

The Stormwater Ordinance of The City of Aurora in the State of Illinois states under the Inlet and Outlet Orientation for both wet and dry basins, that the distance between inlets and outlets shall be maximized as feasible, and if possible they should be at opposite ends of the basin (City of Aurora, 2003). Here, the short circuiting problem is recognized as an important factor for basin design, but a specific parameter for measuring short circuiting is not proposed.

For the City of Golden in the state of Colorado as stated under the "Basin Shape", the pond shape should be a gradual expansion from the inlet and a gradual contraction toward the outlet to minimize short circuiting. They suggest a length to width ratio between 2:1 to 3:1, and explain that a modification of the inlet and outlet points, through the use of pipes, swales (baffles) or channels may be necessary to achieve this goal (City of Golden, 2005). It is clearly implied that the short circuiting needs to be avoided, but a parameter to quantify if the pond is complying or not with this goal is not provided.

The City of Woodland in the state of California has stated under the Extended Detention Basin Design Criteria section, that the length to width ratio should be 2:1, and larger ratios are preferred (City of Woodland, 2003). The inlet and outlet positions are not mentioned, and the definition of the length is not provided either. Therefore, it can be argued that the length of the pond is independent of the inlet and outlet, which could eventually lead to an obvious short circuiting design; even with the length to width ratio criteria under the specification, but with the inlet and outlet very close to each other allowing short circuiting in the pond.

In Connecticut the "Design Criteria for Stormwater Ponds" states that a minimum ratio of 3:1 for Length/Width ratio must be satisfied for the pond design (CNDEP, 2004).

The length of the pond is defined as the straight distance between the inlet and the outlet. This is the same concept of the other states storm water design manuals explained above, where the L/W ratio is mixed with the short circuiting criterion, but in this case the L/W is more conservative with the value of 3:1.

This review of existing criteria for other jurisdictions as well as for Harris County and the City of Houston demonstrate that all jurisdictions desire that the ponds behave as long, slender reactor vessels.

The City of Golden, Colorado specifically recognizes that such behavior may require the use of baffles and other features to fit the idealized reactor vessel into an actual space; the other jurisdictions are vague, yet they do recognize short circuiting is considerably more an issue.

In the present work it became apparent that to select candidate ponds the L/W ratio alone is not a sufficient criterion to avoid short circuiting and another parameter needs to be implemented to select good performance.

2.5 Other Studies Relevant to Stormwater Quality Basin Design

2.5.1 Chlorine Contact Tanks Design

The design criteria evaluated in this thesis for stormwater quality basins can be compared with the design criteria for chlorine contact tanks. The chlorine contact tanks are designed to provide high residence time in order to obtain good disinfection. Therefore, the L/W ratio parameter is one of the most important criteria used. Since the main objective is to provide higher residence time, the stormwater quality basins can be approximated to a chlorine contact time. The L/W ratio parameter for chlorine contact tanks is calculated from as the ratio between the flow path inside the tank, over the average width of the tank. 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 L/W ratio (using baffles to increase the L/W ratio) was measured concluding that the larger the L/W ratio, higher residence time, less dispersion and higher efficiency is obtained (Sepp, 1977). This concept can be also applied to the stormwater quality basin design, where the higher the residence time, higher settling will occur and the potential for pollutant removal is increased. Based on this fact, another solution to the short circuiting issue (found in the design manuals mentioned on section 2.4 on this thesis) could be to redefine the length distance on the L/W ratio calculation to the total flow path that the water follows to exit the pond, and provide some design recommendations to increase this length by implementing baffles on the stormwater quality pond.

2.5.2 Detention Basin Retrofit: Optimization of Water Quality Improvement

In this study, a detention basin in Morris Township, NJ was retrofitted and analyzed to study the effect of tradeoff between water quality benefits and increases in flooding problems (ASCE/WEF, 1998). The pollutant removal efficiency of the pond was intended to be increased by lowering the diameter of the outflow riser holes, which increased the retention time of the water. Then, using a hydrologic/hydraulic modeling program, the retrofit changes were evaluated (Marcoon et al., 2004). This is an example of a different way to obtain higher retention time, but with the inconvenience of increasing the flooding problems. This study also evaluated the design of a sub-surface flow gravel-bed wetland system, consisting of a shallow basin with an underground seepage bed with surface wetland plants. It was concluded that the high cost of an underground concrete type forebay system needed a bigger area to provide enough storage volume as well, making the retrofit not feasible. Incorporation of retrofits into existing basins could improve the water treatment potential, but may have negative hydrologic effects.

2.5.3 Inertial Separation Alternative

Another technique that could be implemented in detention basins as an alternative to sedimentation is the "Inertial Separation Process." This separation technique uses the inertia of solids moving through a liquid to effect separation in accelerating flow. This study showed performs similar to sedimentation basins and also provides other advantages including, 1) reduction in short-circuiting, 2) less inlet-outlet turbulence, 3) better utilization of the tank volume and 4) an increase in particle detention time (Sterling et al., 1985).

CHAPTER 3 HARRIS COUNTY & CITY OF HOUSTON PERMITS DATABASE AND SCORING SYSTEM

3.1 Database Construction

During this study all the permits issued by Harris County and The City of Houston from 2001 through mid-summer of 2005 were reviewed and selected data were entered into a Microsoft Access database for each jurisdiction.

The current Harris County permit database was modified to incorporate scoring information extracted by manual review of permit documents such as drawings, calculations and letter reports supplied to the county with the permit applications. These documents are scanned and stored electronically by Harris County.

The City of Houston database mimics the county's structure except that the scoring information was extracted by review of actual paper documents housed at City offices; at the time of this work the City did not maintain electronic images of permit application documents. Relevant documents were photographed and are stored with the University of Houston's copy of the City database.

All the BMPs in both databases include location information for spatial representation.

In the Harris County database most of this information was already collected by the county, while for the City of Houston database this information was collected by the research team from the street address and verified using geo-referenced satellite images, digital orthoquadrant images and similar remote sensing products. The spatial resolution of these images is on the order of 1 to 15 meters and is comparable with handheld global positioning system (GPS) values.

Many BMP locations were visited and the latitude and longitude in the field were obtained using a hand-held GPS receiver. The GPS estimated prediction error ranged from 3 to 10 meters; hence locations in the database reflect this level of location error.

Thus BMP locations in the database are approximate, but accurate enough to locate BMPs for spatial analysis and mapping.

Figure 3.1 is a representative permit record from the Harris County database with both permit information and scoring information.

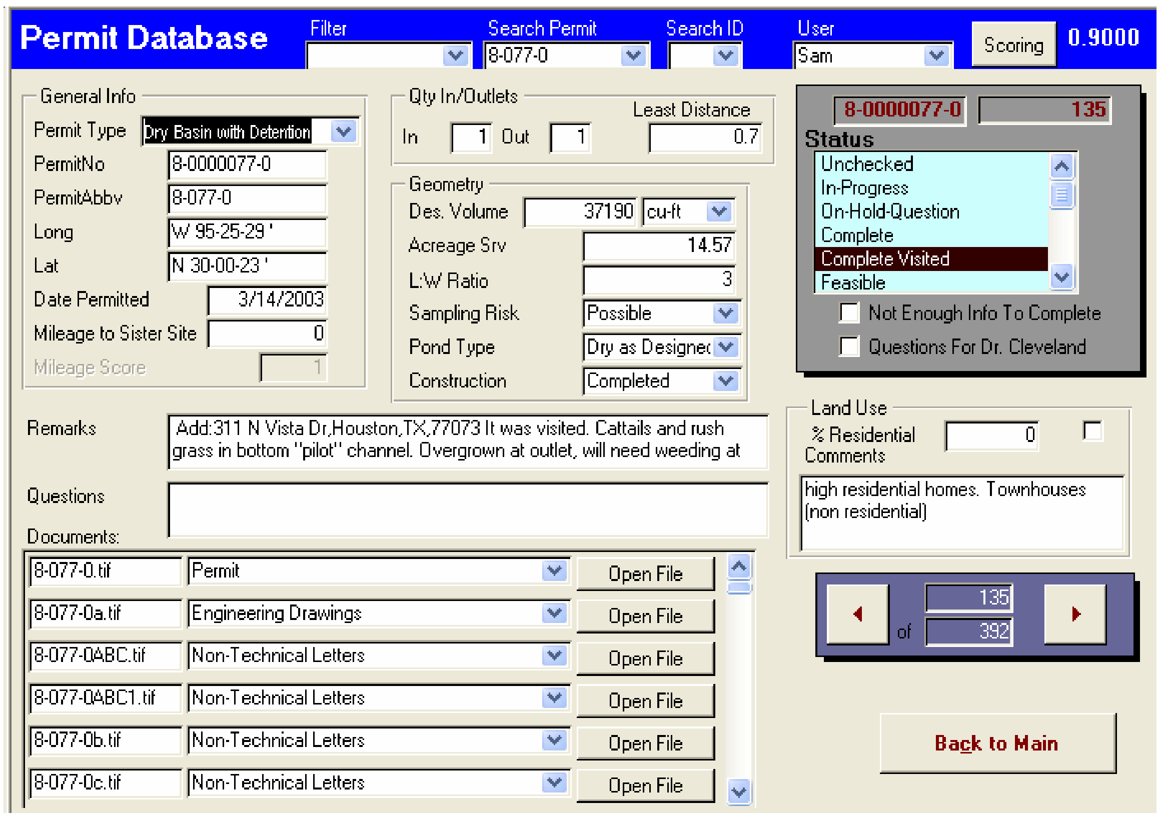


Figure 3. 1 Permit Record from Harris County

Figure 3.2 is a similar permit record from the City of Houston database.

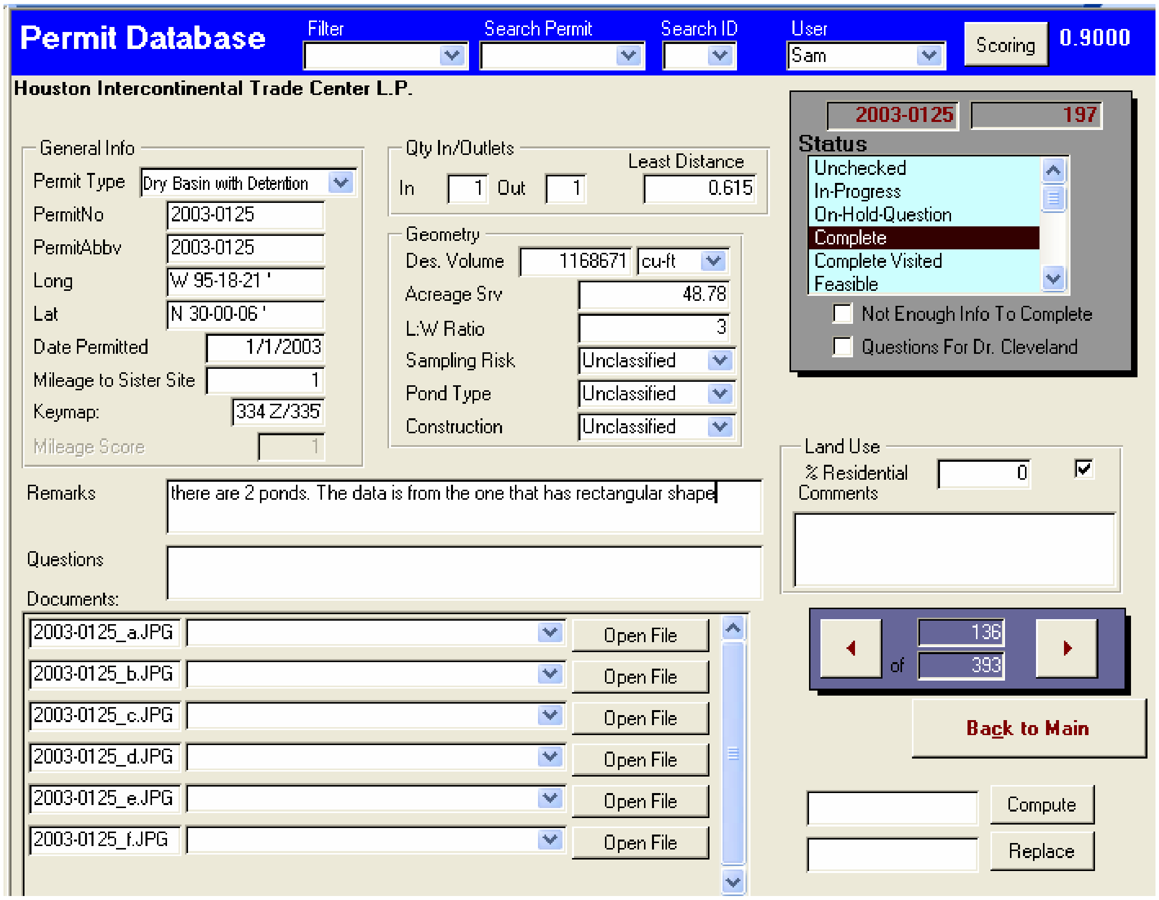


Figure 3. 2 Permit Record from City of Houston

3.2 Database Analysis and BMP Types in Service

Once the databases were prepared the data were used to generate summary statistics regarding the type of BMPs in use as well as spatial information.

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. The classification of the actual BMPs in Harris County and the City of Houston is presented on Table 3.1 and Table 3.2.

Table 3. 1 Harris County Permits Summary

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

Table 3. 2 City of Houston Permit Summary

	Wet/Dry Basins	Oil-Grit Separators	Grass Swales and Vegetative Filter Strips	Other	Total
Permit Count[1]	176	174	7	8	365
Fraction of Permits	48%	48%	2%	2%	100%
Acreage Served[2]	3,712	1,902	94	77	5,785
Fraction of Area	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 support the original assumption that the principal structural BMP used in Harris County jurisdiction is the basin type BMP.

In the City 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. In the southwest part of the city basin types are more common, while oil-grit separator types dominate inside the 610 loop.

3.3 BMP Mapping

In addition to summary queries the database was used to generate theme maps to illustrate the spatial distribution of BMPs in the study region by both entity and BMP type. Entities are identified using different markers, and the BMP types are mapped separately. The databases were used for sorting the distribution and relationships.

Figure 3.3 is a map of all permitted BMPs in Harris County. The BMPs permitted are concentrated in the north/northwest area of the County.

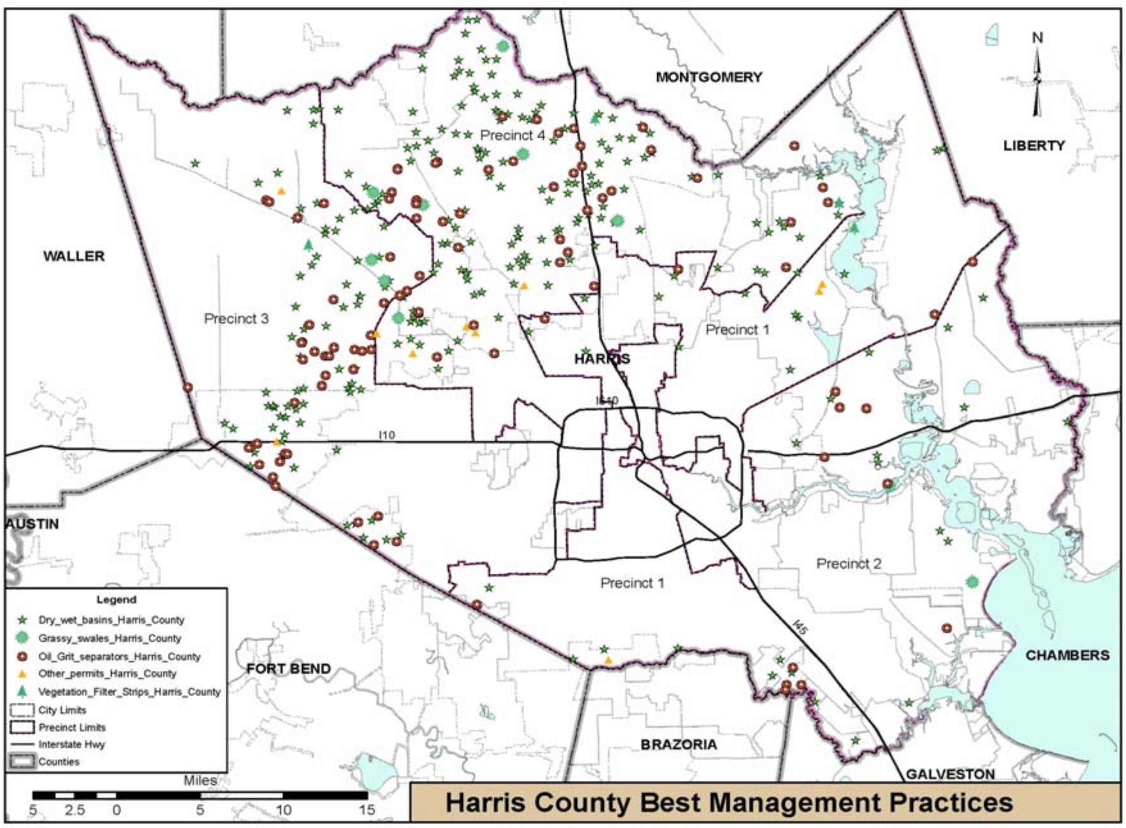


Figure 3. 3 All BMPs by Type from Harris County Database

The extreme northwest limit of the county is not very well covered by BMPs or indicates that the northwest area of the County has less recent development as of January

2005, however the area is developing and in several years one can expect the markers to populate this region. The north-east area of the county exhibits the same relative lack of BMP coverage, perhaps for the same reason.

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 3.4 is a map of all permitted BMPs in the City of Houston. The BMPs distribution in the City of Houston generally occurs in areas in the city under development/ redevelopment. There are not large developments occurring in downtown, whereas the south and southwest area is urbanizing, demanding a lot of BMP coverage. Recall that developments completed before 2001 are not included in the database.

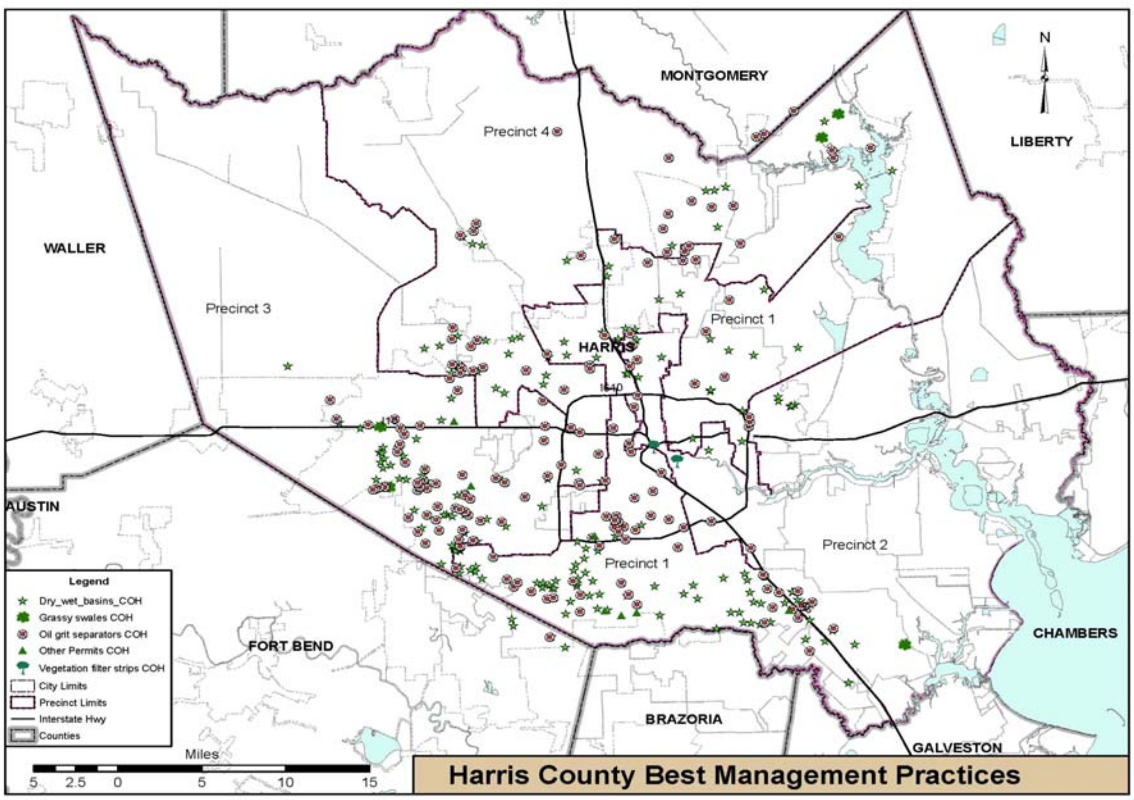


Figure 3. 4 All BMPs by Type from City of Houston Database

Figure 3.5 is a map of all permitted BMPs in both databases. The geographic extent is on the order of 60 miles in both North-South and East-West directions. This map presents BMPs without regard to type, thus ponds, oil-grit separators, and swale types are all represented on the map. 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 610 loop. The extreme north-west is known to be developing, but these BMPs are not yet permitted and in the databases.

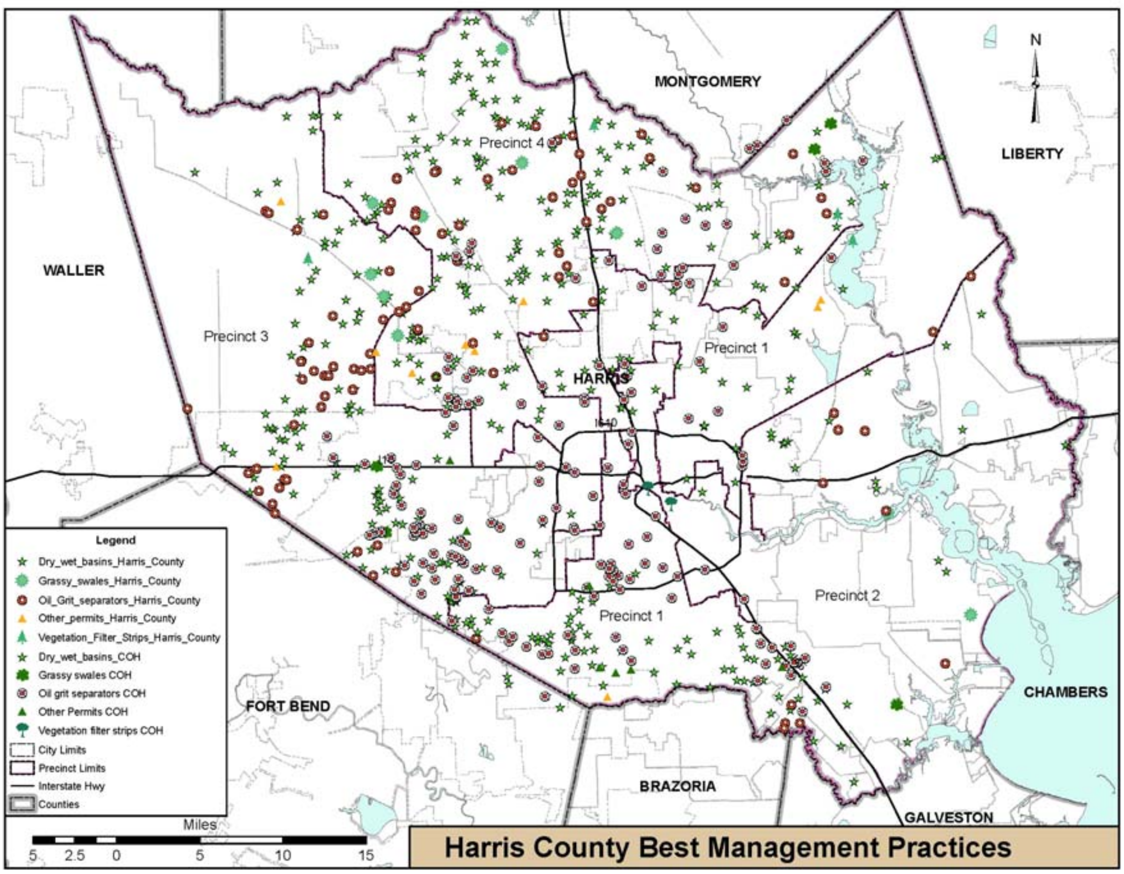


Figure 3. 5 All Permitted BMPs in Harris County and City of Houston Databases

Figure 3.6 is a map of all basin type in both databases. The absence of swale and grit separators from the map removes significant coverage within the City of Houston jurisdiction and mostly within the highly urbanized inner-loop area.

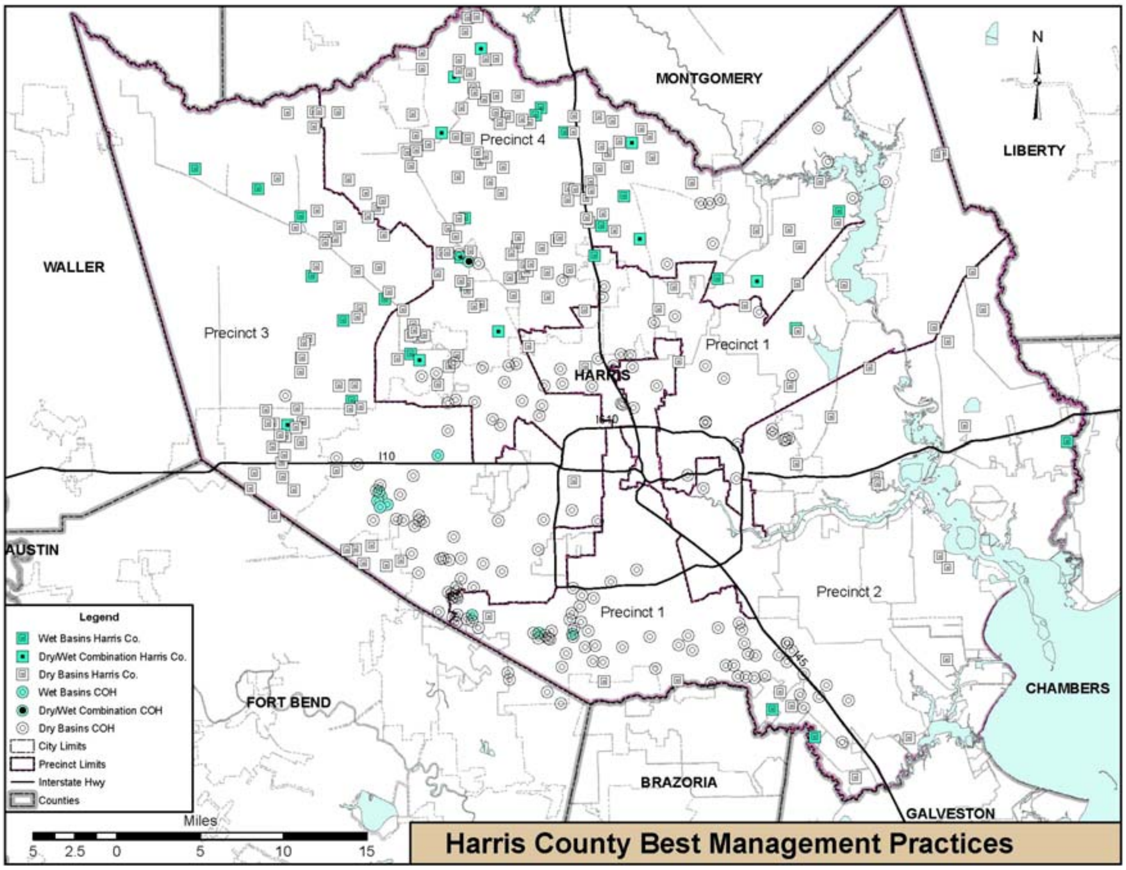


Figure 3. 6 All Basin-Type in Harris County and City of Houston

Figure 3.7 is a map of all Oil-Grit Separators in Harris County and the City of Houston. The Oil-Grit separators are very well distributed in the center area of the city limits due to the smaller space available in the city where the Oil-Grit separator type of BMP might be the best option. For Harris County, the Oil-Grit Separators only represents 25% of all BMP permitted and are mostly located in the north area of the county.

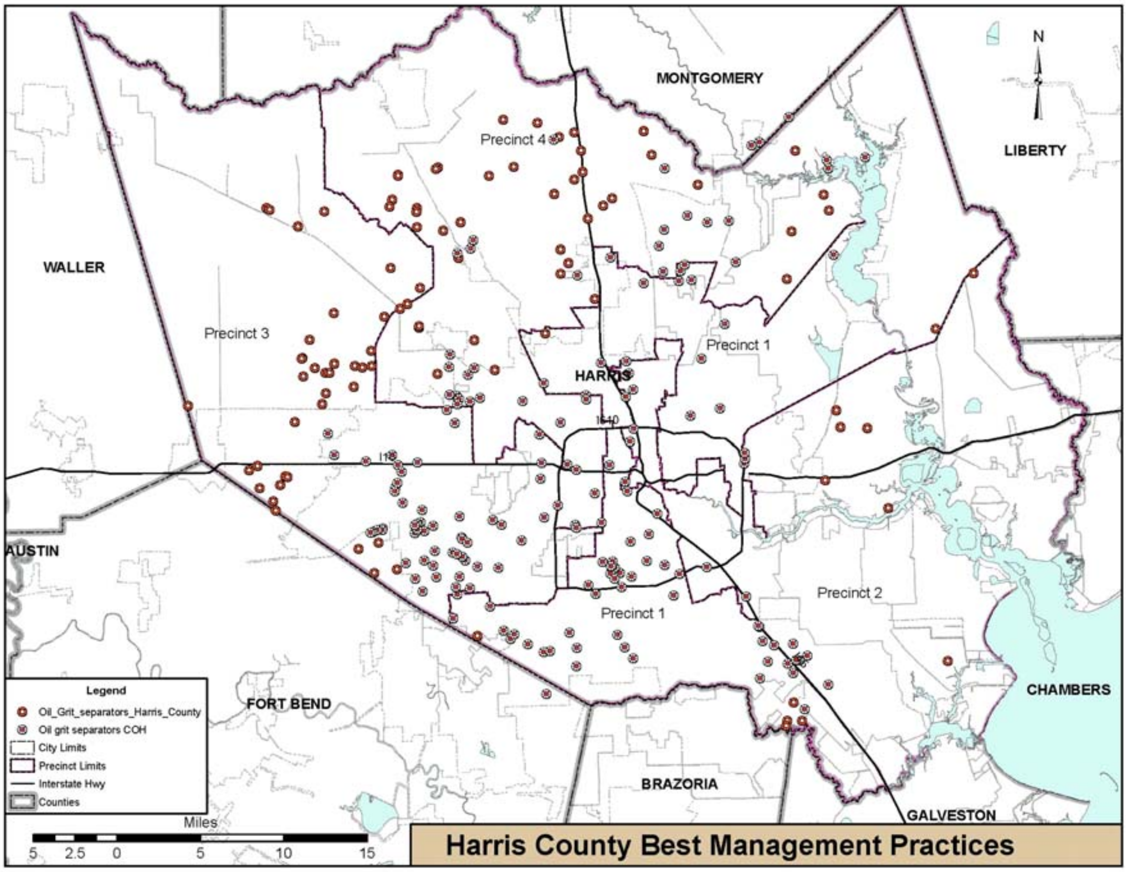


Figure 3. 7 All Oil-Grit Separators for Harris County and City of Houston

The scoring system in the next chapter was developed based on the wide geographic distribution displayed in Figure 3.6 as it was clearly infeasible to visit every site in the database. The dry/wet basins from the Harris County database are distributed in the north and north-west area of the county, outside of the city limits where the area to implement detention basins is comparatively vast. The basins appear almost equally distributed between north and south. The basins are not implemented in the center area or densely developed urban areas where the space to build and implement detention basins is reduced.

CHAPTER 4 SCORING SYSTEM AND SITE SELECTION

A scoring system was developed to reduce the set of candidate ponds to a handful for site visits and ultimately to two ponds for monitoring.

The ad-hoc criteria presented in Table 4.1 were used to characterize the permits in the database, and each criterion was used as a reference for database lookup and design scoring. The term “well designed” used in this thesis means the BMP adheres to design principles in various criteria manuals and is configured in a fashion suitable for monitoring to evaluate performance. The criteria were applied to the ponds that have an obvious water quality control feature and not simply quantity control. The developments served were defined as 100% residential or 100% non-residential. The measures are assigned numerical values according to the score rules in Table 4.1. These ad-hoc criteria are incorporated into a scoring system coded into the two research databases. The scoring system assigns a numerical score to the permit based on various metrics reported in the permit, as well as logistical metrics to reflect the ease or difficulty of monitoring.

All the permitted BMPs in each database were geo-referenced for spatial display by a variety of techniques including address matching, field visiting and in most of the City of Houston database by manual interpretation.

Table 4. 1 Initial Score Assignment Rules

Measure	Criteria	Score
A. Number of Inlets[1]	1	1
	More than 1	0
B. Number of Outlets[1]	1	1
	More than 1	0
C. Type of BMP[2]	Dry Pond	1
	Any other	0
D. Travel Path Ratio (TPR)[3]	More than 0.5	1
	Less or equal to 0.5	0
E. Length/Width Ratio (L/W)[4]	$X \geq 3$	1
	$2.5 \leq X < 3$	0.8
	$2.0 \leq X < 2.5$	0.5
	$X < 2$	0
F. Date of Permit[5]	2002	1
	2003	0.9
	2004	0.6
	2005	0.1

[1] The dry pond should have 1 inlet and 1 outlet (side swale collectors were not counted as inlets)
[2] The BMP type is a dry detention pond, others not considered
[3] The inlet is sufficiently far from the outlet, explained in narrative.
[4] The length-to-width ratio along the central flowline should be at least 3:1
[5] Surrogate for degree of construction completion.

The scoring system was created to designate good candidates for sampling. A good candidate must be: a dry detention pond, serve a homogeneous drainage area, be in an area that is well stabilized with respect to earth disturbing activities (construction), as the purpose is to determine post construction effectiveness, be constructed in general compliance with the design criteria (JTF, 2001a), and be cost effectively sampled. Cost effective sampling requires one inlet and one outlet. Degree of stabilization is estimated by the time since the permit was issued.

The initial score for a permit is the product of the scores from Table 4.1 (i.e. Score = A*B*C*D*E*F). The score "A" selects ponds with only 1 inlet, the score "B" selects ponds with only 1 outlet, the score “C” selects only dry ponds, the score “D” selects ponds with a TPR higher than 0.5, the score “E” assigns a weighted score based on the length to width ratio of the pond and the score “F” assigns a weighted score based on the year the project was permitted. The maximum possible score is 1 and the minimum is 0.

In order to increase the residence time and produce better contaminant removal, “well designed” ponds should have the length to width ratio (L/W) greater than 3.0, but (L/W) ratios of minimum 2:1 are also accepted. Based on these concepts, high values are assigned to ponds that have an L/W ratio greater than 3.0 and lower values to the ponds with L/W ratios between 2.0 and 3.0, neglecting the ones that have less than 2.0 as an L/W ratio. This particular criterion is related with the TPR; if the TPR is less than 0.5, the inlet is considered too close to the outlet and the length to width ratio criterion becomes irrelevant. Therefore, ponds with TPR values of less than 0.5 are considered inefficient and neglected in the score D. Also, because of the need of immediately sampling, older (2002–2003) permits are assigned higher scores because the writer assumed that they would be completely finished or almost finished, while newer (2004-2005) permits are assigned lower score values to reflect the likely still in-progress construction activities.

Initial score products greater than 0.5 were selected as candidates for field investigation. Selecting scores greater than 0.5 eliminates permits with ponds that have more than one inlet, more than one outlet and ponds with a TPR values less than 0.5. It also selects permits with dry ponds only, permits of 2004 or older, and permits with ponds that have a length to width ratio greater than 2.0. It is important to notice that the scores assigned for the year of the permit is only for selection purposes, and it does not mean that the ponds are not well designed, just that the permits might be too recent and immediate sampling would not be feasible. Candidates are listed in a descending order of score and this order is used as the order to be visited and field investigated (See Appendix I and II). Selected "well designed" ponds as determined by the scoring system from both databases were visited to verify information in the database and evaluate suitability for monitoring.

From the first visits, two candidates were selected; permit 8-169-8 (residential) and 8-077-0 (non-residential). These candidates were relatively far away from each other; 31 miles and around 44 min. driving. Pond performance is assumed to depend only on the shape of the pond (i.e. if it is well maintained and has established grass) and the other selection parameters established in the scoring system; so pond pair location within the region is not expected to have measurable impact on performance. However, it was attempted to select a pair of permits that were closer together for sampling logistics, but unfortunately no closer pair was found.

During the site visits, photographs were obtained along with the latitude and longitude for selected features.

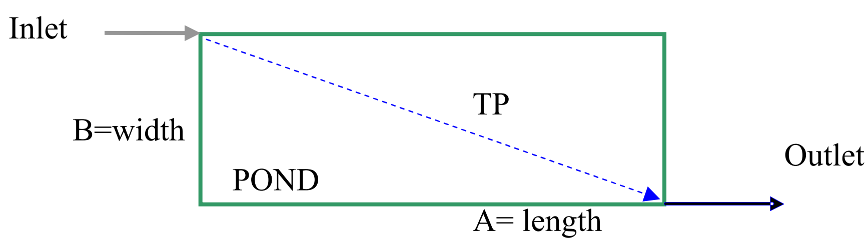
4.1 Travel Path Ratio Criterion (TPR)

The "Minimum design criteria for implementation of Certain BMPs" published by Joint Task Force in 2001, specifically states that the length to width ratio should be at least 3:1, but values of 2:1 are still accepted. It is also vague on how that ratio is determined. Other manuals (California, Tennessee and others) define the ratio as the inlet to outlet distance divided by the average basin width, and have different value requirements for that ratio.

A surrogate based on the inlet-outlet distance along a likely hydraulic path, and the inlet to outlet distance along the shortest geometric path that follows the basin edge was developed. The criterion is called the Travel Path Ratio and it was further decided based on engineering judgment that a 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 when the inlet and outlet are at opposite sides in the pond. The longest distance is defined as the summation of the two main dimensions depending on the pond shape. Figure 4.1 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 short circuiting potential of a pond. Therefore, the reason for this new parameter is to evaluate and give credit to the actual ponds that have large distances between the inlet and the outlet, which increases the residence time of the water in the pond, and to prevent short circuiting for future pond design. This criterion was implemented because many ponds in the database were designed to function 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. Therefore, the inlet-outlet location is causing short-circuiting.

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, so the higher the ratio, the higher the score will be assigned to the permit.



Travel Path Ratio = TP/ (A+B)

Figure 4. 1 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 in Chapter 5; at the time of pond selection, this ad-hoc criterion was simply a judgment-based criterion.

The results of applying the scoring system are the basins on permits 8-169-8 and 8-077-0 which are Harris County permits. Table 4.2 shows the complete characterization of these two ponds.

Table 4. 2 BMPs Selected for Monitoring

Permit Number	8-169-8	8-077-0
Name of the Project	Oak Landing	North Vista Apartments
Address	20900 FM 529, Cypress, TX 77449	311 North Vista Dr., Houston, TX 77073
Date Permitted	3/14/03	10/17/03
Inlets	1	1
Outlets	1	1
L/W Ratio	4	3
Travel Path Ratio (TPR)	0.8	0.7
Area Served (acres)	42.54	15.57
% Residential	100	0
% Non-residential	0	100
Final Score	0.9	0.9

CHAPTER 5 EVALUATION OF TPR AND OTHER DESIGN CRITERIA BY IDEAL FLOW MODELING

5.1 The Effect of Basin Geometry and Inlet/Outlet Location

In order to demonstrate the effectiveness of the TPR, the flow of water inside the basin is simulated with a LaPlace solver program. Then, a particle tracking program is applied to determine velocity potential lines and simulate the residence time distribution of the 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. For this reason, the effect of different pond designs can be calculated and compared. The TPR criterion accounts for the relative position of the inlet and outlet. Therefore, when the criterion is applied to a specific design, a value of 0.5 or greater must be satisfied for the travel path ratio in order to prevent short-circuiting. If the TPR is less than 0.5, the inlet is considered too close to the outlet and the length to width ratio criterion becomes irrelevant. Ponds with a TPR less than 0.5 are considered inefficient and the design of these types of basins must be avoided.

5.2 Simulation of Basin Hydraulics by Ideal Flow

The hydraulics of a water quality detention basin can be approximated using an ideal flow model. In the present work the flow in a basin is 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 study 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 this thesis the basin volume is assumed identical; thus the hydraulic retention time would be identical.

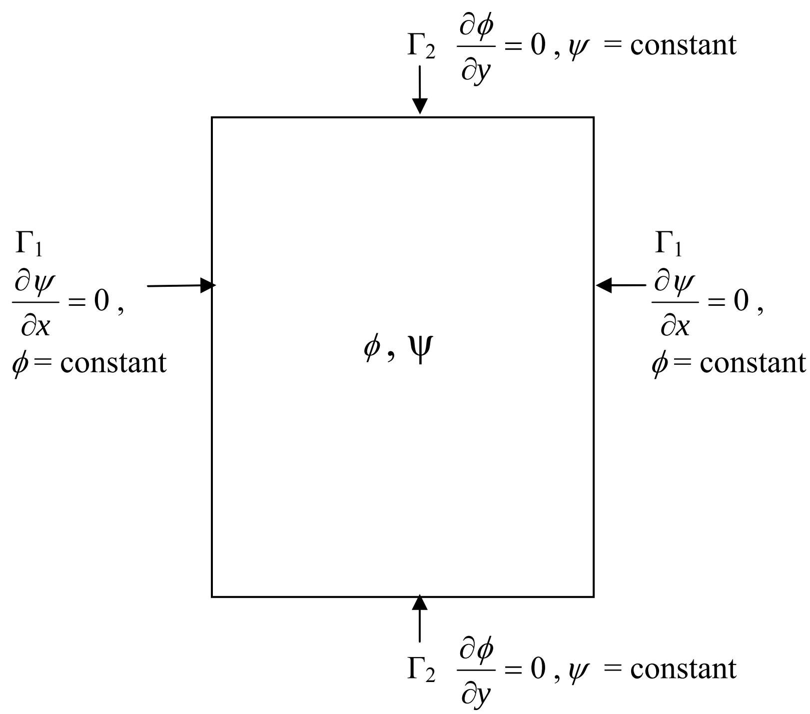


Figure 5. 1 Rectangular Domain of the Basin Model

Figure 5.1 depicts a rectangular computation domain used to model the basin hydraulics. The figure indicates that interior values of ϕ and ψ are to be computed, and depicts the two types of boundary conditions. Where boundary condition are constants, the constants (ϕ, ψ, dϕ , dψ) are not necessarily the same numerical values. The velocity potential is the solution to

$$\frac{\partial}{\partial x}(\frac{\partial \phi}{\partial x}) + \frac{\partial}{\partial y}(\frac{\partial \phi}{\partial y}) = 0 \ .$$

The stream function is the solution to

$$\frac{\partial}{\partial x}(\frac{\partial \psi}{\partial x}) + \frac{\partial}{\partial y}(\frac{\partial \psi}{\partial y}) = 0 \ .$$

Boundary conditions in the velocity-potential space are either zero-flux (no-flow) or constant value. The boundary conditions in stream-function space are the compliment of the velocity-potential boundary conditions. Thus, a zero-flux condition in velocity-potential space becomes a constant value in stream-function space, while a constant value in velocity-potential space will be a zero-gradient in stream-function space. Table 5.1 lists the types of boundary conditions in each space – the conditions must be complimentary for a meaningful solution.

Table 5. 1 Boundary Conditions for Velocity-Potential and Stream-Function

Velocity-Potential Boundary	Stream-Function Boundary
$\phi = const.$ on Γ_1	$\frac{\partial \psi}{\partial x} or \frac{\partial \psi}{\partial y} = 0$ on Γ_1
$\frac{\partial \phi}{\partial x} or \frac{\partial \phi}{\partial y} = 0$ on Γ_2	$\psi = const.$ on Γ_2

In the basin models the basin walls are treated as zero-gradient potential boundaries (and specified stream function boundaries), while the inlet and outlet are specified potential boundaries (and zero gradient stream function boundaries). Internal walls (baffles) are treated as zero-gradient potential boundaries, and specified stream function boundaries.

Once the velocity-potential field is computed, its gradient provides the flow velocities at a point in space. The flow velocities are obtained from

$$u(x, y) = \frac{\partial \phi}{\partial x} \Big|_{(x,y)} \quad ,$$

$$v(x, y) = \frac{\partial \phi}{\partial y} \Big|_{(x,y)} \quad .$$

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. The equations of particle motion are $X(t+\Delta t) = X(t) + \Delta t \cdot u(x,y)$,

$Y(t+\Delta t) = Y(t) + \Delta t \cdot v(x,y)$.

The tracking of the particles is somewhat tedious and time consuming, but it provides a tool to approximate basin behavior. Figure 5.2 illustrates the concept with the basin 2 configuration. The initial ensemble is released at time zero.

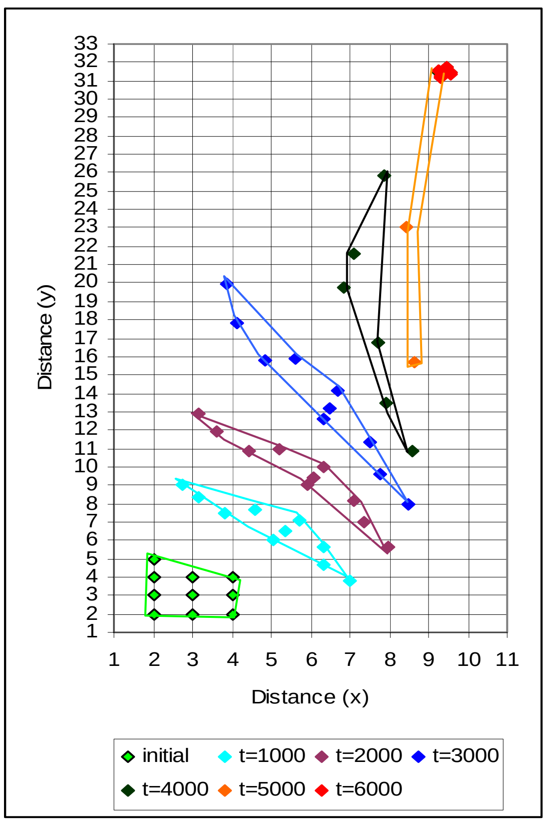


Figure 5. 2 Ideal Tracer Simulation by Ensemble of Particles

As time elapses the ensemble moves towards the outlet. In this illustration the ensemble is represented by a handful of markers. As the markers reach the outlet, the elapsed time for each particles arrival is recorded and the set of times for the ensemble is the tracer arrival time distribution. 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.

The actual computations are implemented in two purpose-written FORTRAN programs. One is a LaPlace solver with internal baffles that implements a Jacobi iteration routine to solve the difference equations to the two PDEs; the second is the particle tracking code implemented by Cleveland (1991) adapted from Kinzelbach's (1987) program. The concept of combining hydraulic computations with particle tracking models has been used in a variety of studies such as Kinzelbach and Herzer (1983), Wang and others (1996), and Cleveland and Garmon (1997).

5.3 Proposed Travel Path Ratio and Geometrical L/W Ratio Criteria

5.3.1 Stormwater Quality (SWQ) Ponds without Baffle

As is shown in Figure 5.3, ponds without baffles will never get values of the TPR greater than 1.0 because the distance TP (travel path) will always be less than A (length) and B (width) distances together. Therefore, ponds designed without a baffle must comply with the following TPR and geometrical L/W values:

- TPR > 0.5
- Geometrical L/W ratio ≥ 2.0

With these preset values we can guarantee that short circuiting is avoided, and the pond will perform well. Figure 5.3 illustrates the least distance (TP) that a particle would have to follow to exit the ponds.

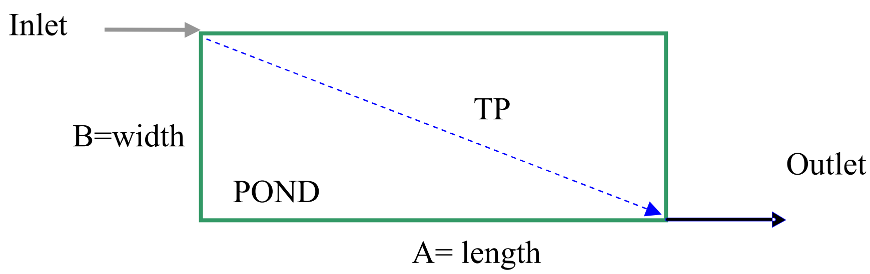


Figure 5. 3 Travel Path Illustration for a Stormwater Quality Pond without Baffle

Notice from figure 5.3 that the inlet is located at the farthest point from the outlet, and yet the TPR value will not be greater than 1.0 and this is explained as follows:

- TP < (A+B)
- TPR = TP/(A+B)
- TPR < 1.0

5.3.2 Stormwater Quality Ponds with Baffles

If the pond has at least one baffle, and assuming that the inlet and outlet are located on opposite sides of the baffle to maximize the travel path distance, the TP distance is measured along the most likely path that the water would follow to exit the pond, taking into account the baffle obstruction. The proposed new distance for the travel path “TP” is shown in Figure 5.4. Therefore, the TP can be approximated as the hypotenuses of the triangles formed with the baffle and the inlet and outlet points.

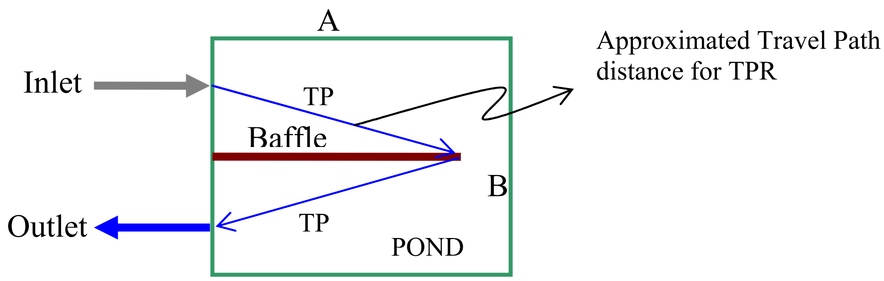


Figure 5. 4 Travel Path for a Stormwater Quality Pond with 1 Baffle and a L/W=1.0

Therefore, the TPR can get values greater than 1.0 when the geometrical L/W ratio is greater than 2.0. Even though the geometrical L/W ratio criterion is not met (L/W > 2.0) for the pond shown in Figure 5.4, the pond still performs well. For the particular case where the L/W is equal to 1.0 and the pond has one baffle, the travel path distance "TP" will be calculated as follows:

For A/B = 1, and assuming A= B =1

$$\text{TP} \approx 2 * \sqrt{(0.75)^2 + (0.25)^2} \approx 1.6,$$

$$\text{TPR} = \frac{TP}{A+B} = \frac{1.6}{1+1} = 0.8 \ .$$

In ponds with multiple baffles the TPR values exceed unity depending on baffle configuration.

5.4 Basin Design Evaluation with Ideal Flow Modeling

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 5.5 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.

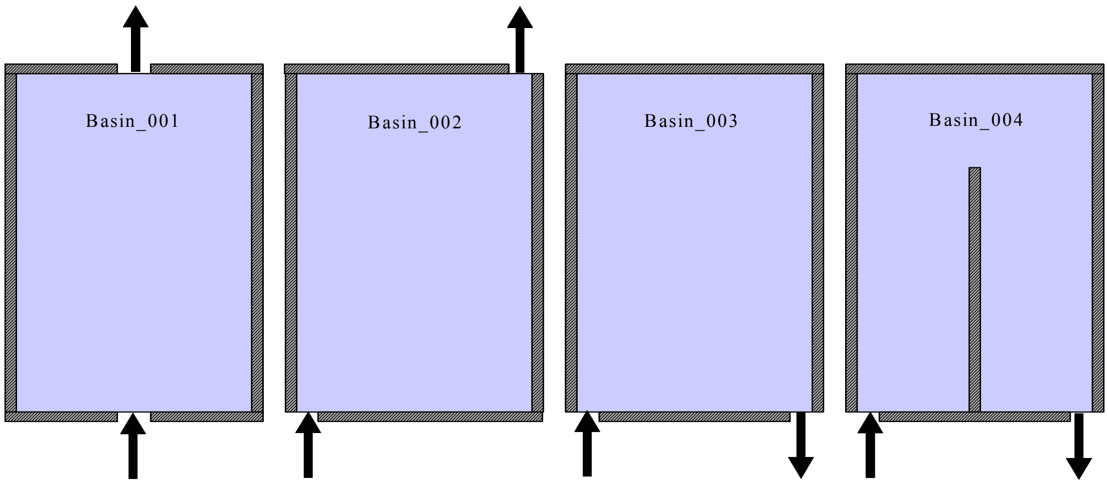


Figure 5. 5 Four Basin Configurations with the Same Geometric Length/Width Ratio

A computer program was constructed that solves the LaPlace equation on a rectangular region.

5.4.1 Basin 1

Figure 5.6 is a flow-net overlain on the velocity potential surface map for basin 1. The image is looking up-stream from the outlet. 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.

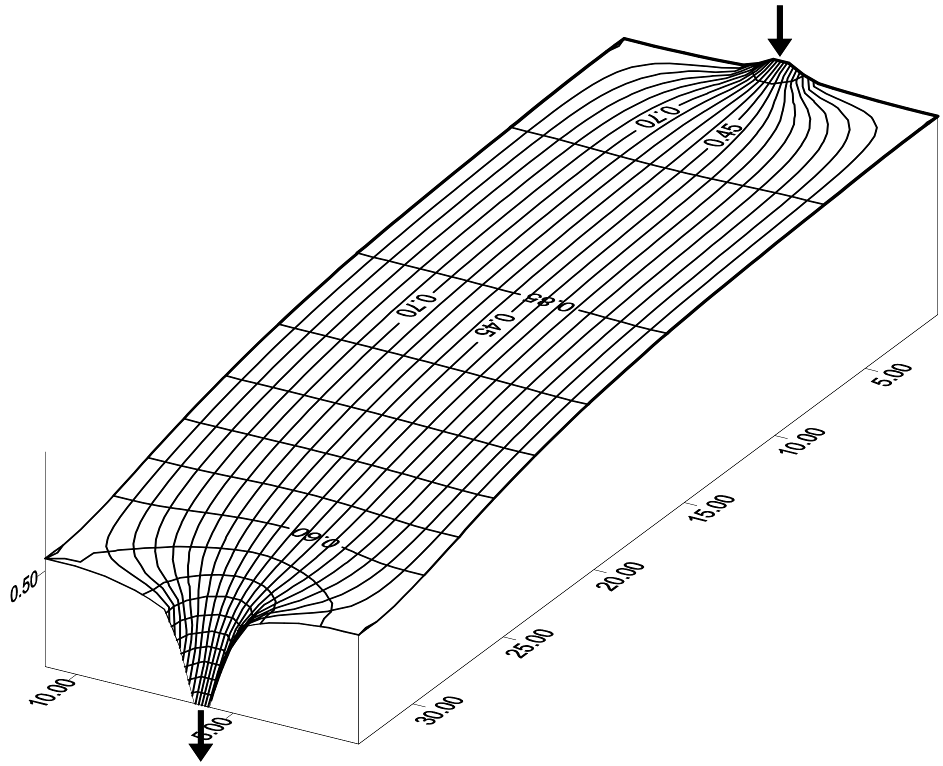


Figure 5. 6 Basin 1 Flow-Net on Potential Surface

Figure 5.7 is a plot of the cumulative tracer arrival time for an ensemble for tracer particles released near the inlet. The mean arrival 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.

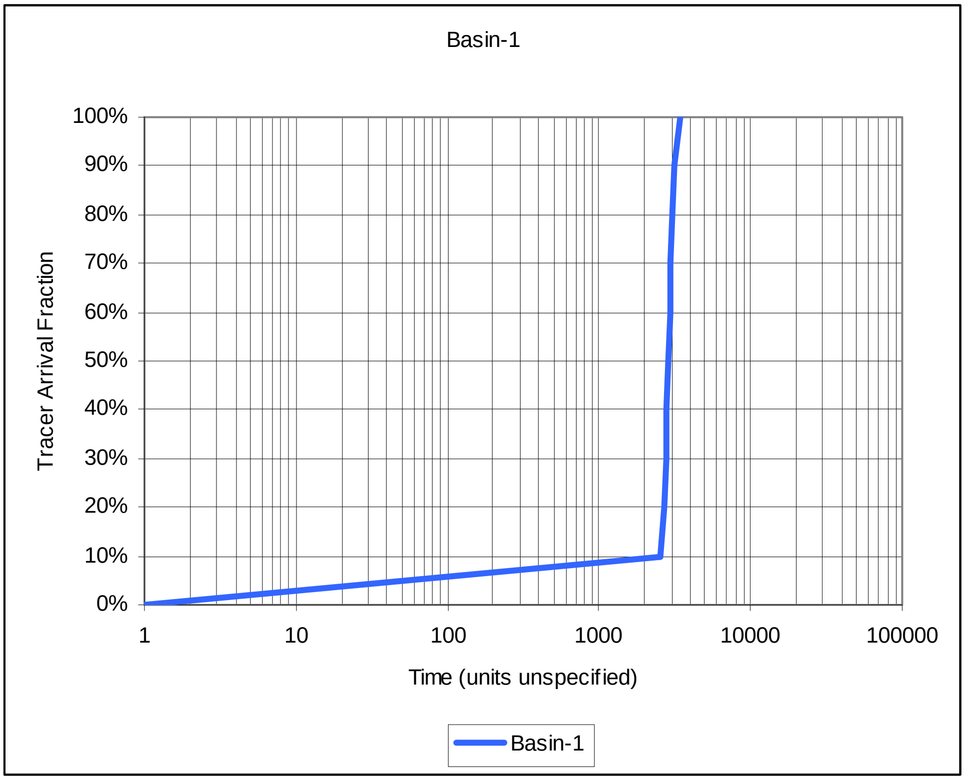


Figure 5. 7 Tracer Cumulative Arrival Time Diagram for Basin Model # 1

5.4.2 Basin 2

Figure 5.8 is a flow-net overlain on the velocity potential surface map for basin 2. The image is looking up-stream from the outlet. 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 flow-path ratio for this basin is 0.79 and would satisfy this selection criterion in our study.

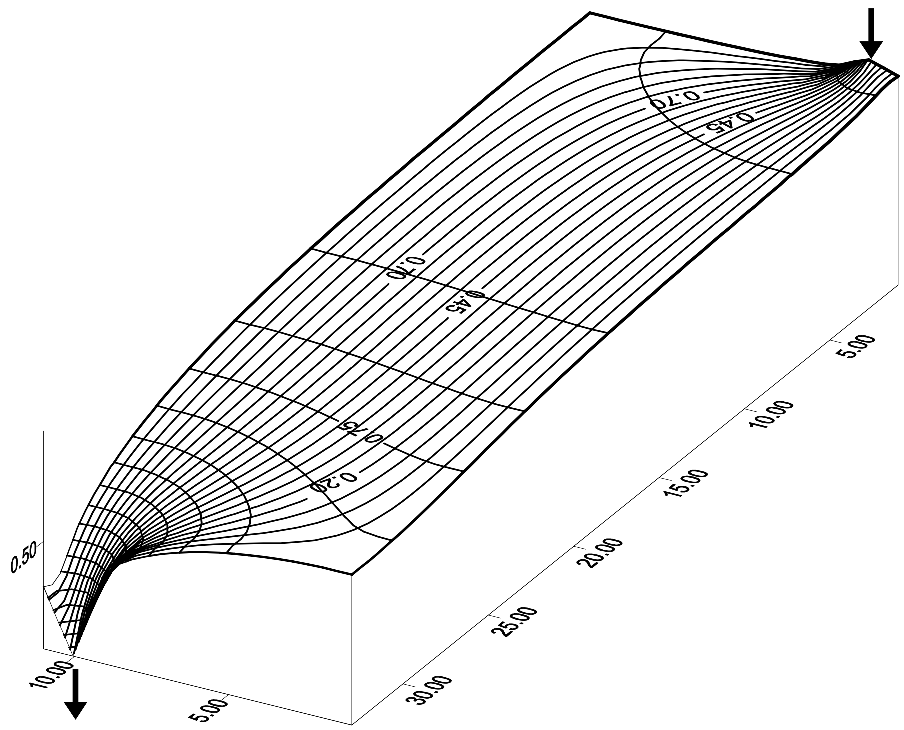


Figure 5. 8 Basin 2 Flow-Net on Potential Surface

Figure 5.9 is a plot of the cumulative tracer arrival time for an ensemble for tracer particles released near the inlet. The mean arrival time is 4332 time units, and the standard deviation normalized by the mean is 0.16.

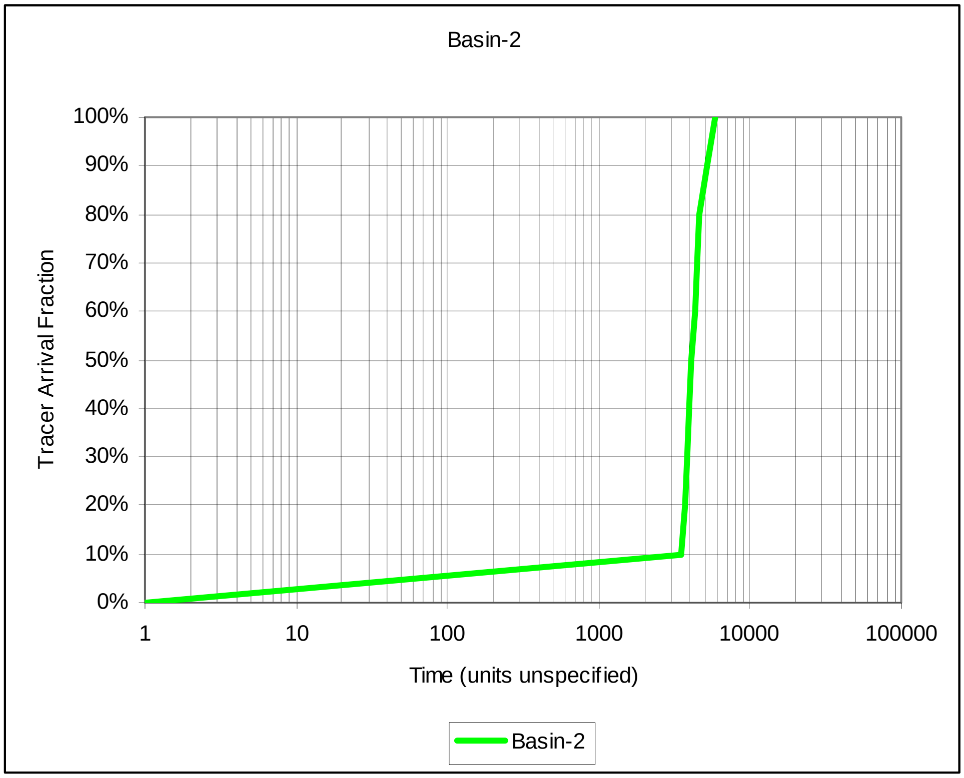


Figure 5. 9 Tracer Cumulative Arrival Time Diagram

This basin configuration is also common in both the Harris County and City of Houston jurisdictions; and meets suggested geometric design criteria in the Harris County guidance manual. In terms of predicted transit time across the basin, this configuration would be expected to perform somewhat better than basin 1.

5.4.3 Basin 3

Figure 5.10 is a flow-net overlain on the velocity potential surface map for basin 3. The image is looking up-stream from the outlet. Basin 3 is intended as an example of a poorly configured basin, although some examples of 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 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.

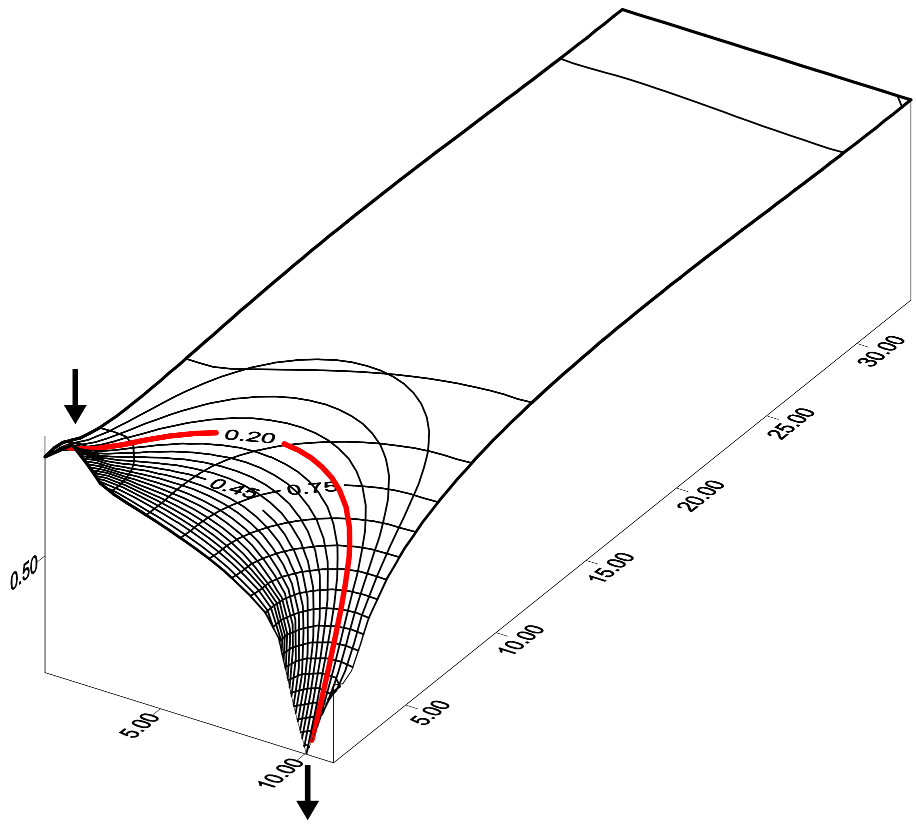


Figure 5. 10 Basin 3 Flow-Net on Potential Surface

The flow-path ratio for this basin is 0.25 and would fail the selection criterion in our study. Figure 5.11 is a plot of the cumulative tracer arrival time for an ensemble for tracer particles released near the inlet. The mean arrival time is 137 time units, and the standard deviation normalized by the mean is 0.34.

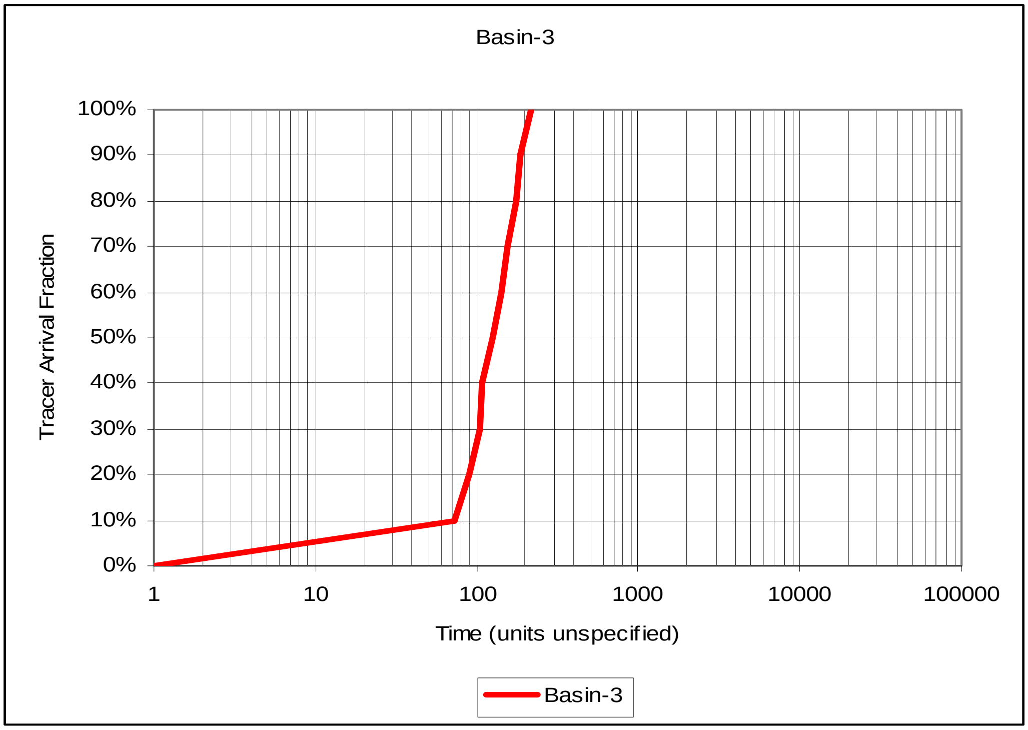


Figure 5. 11 Tracer Cumulative Arrival Time Diagram

This basin configuration is not common in the Harris County and City of Houston jurisdictions; and while it meets suggested geometric design criteria in the Harris County guidance manual it does not meet the criterion related to "minimization of short-circuiting." In terms of predicted transit time across the basin, this configuration would be expected to the poorest of any of the hypothetical basins.

5.4.4 Basin 4

Figure 5.12 is a flow-net overlain on the velocity potential surface map for basin 4. The image is looking up-stream from the outlet. 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.

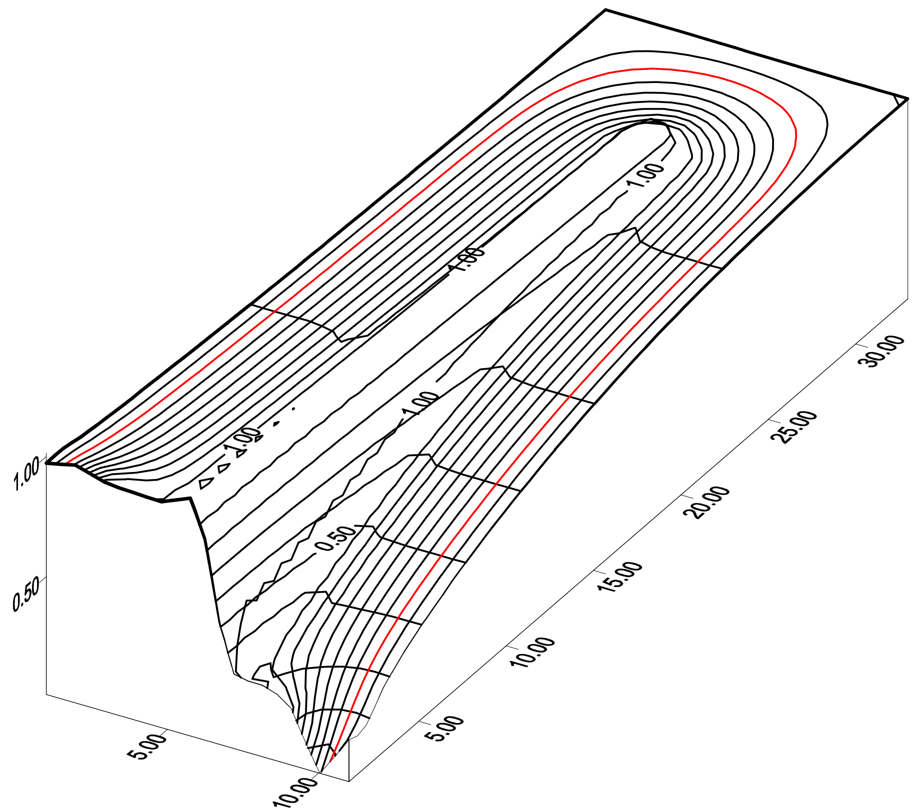


Figure 5. 12 Basin 1 Flow-Net on Potential Surface

The travel-path ratio for this basin is 1.5 and would satisfy this selection criterion in our study.

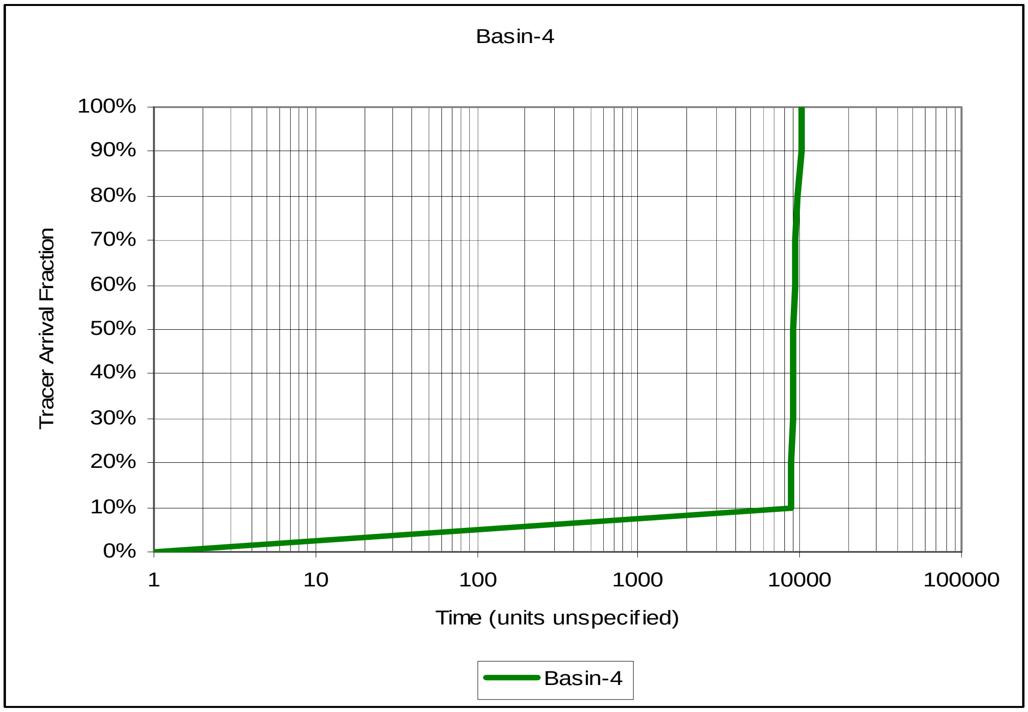


Figure 5. 13 Tracer Cumulative Arrival Time Diagram

Figure 5.13 is a plot of the cumulative tracer arrival time for an ensemble for tracer particles released near the inlet. The mean arrival time is 9369 time units, and the standard deviation normalized by the mean is 0.05.

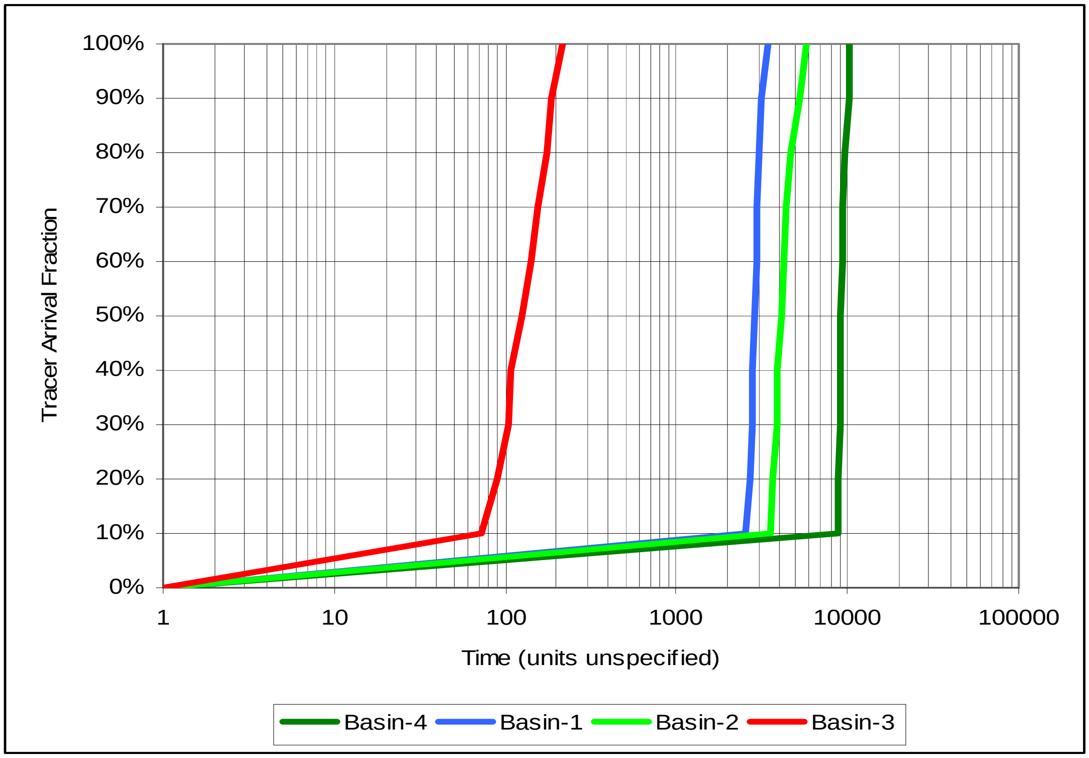


Figure 5. 14 Tracer Cumulative Arrival Time Diagram for the 4 Study Basins

Figure 5.14 is a plot of the tracer arrival plots on the same axis for the 4 basins. It is noteworthy that the time axis is logarithmic and that the worst performing basin in terms of traverse time is over one order of magnitude lower in traverse (and hence detention) 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.

5.5 Ideal Flow Modeling for Different Design Types of Actual SWQ Ponds

The previous section illustrated the modeling concept on generic ponds; in this section actual geometries in the permit database are examined.

The programs simulate the ideal (inviscid) flow, and therefore the following assumptions are imbedded in the simulations:

- Neglect flow resistance within the pond (inviscid fluid).
- Neglect dispersion of the particles (ideal tracers, advection only).
- No internal sources or sinks of the fluid.
- The particles “are placed” when the pond is completely full.
- 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 TPR parameter was an add-hoc criterion implemented to identify short circuiting potential and select the “best designed” ponds within the Harris County and The City of Houston permits files. Therefore, some of the most relevant pond designs found on these files are evaluated using ideal flow modeling and particle tracking programs. 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 that are assumed simulated in this thesis 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 design parameters like the length and width, 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 are so important for stormwater quality pond design.

In order to maintain the same base area of all the ponds, the model grids were created with different number and values of ΔX and ΔY, which provides different cell count while maintaining the same area.

5.6 Ideal Flow Simulation Results

The simulation of 15 different designs of stormwater quality and detention ponds is presented in table 5.2.

Table 5. 2 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				

In Table 5.2 the ponds are arranged by increasing particles residence times. The table shows that design types from ID 1 to 5 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 residence time's less than 2500 time units do not provide good pond performance.

Furthermore there is a relative large increase in the residence time when the TPR is greater than 0.5 (it nearly doubles in this set of permits).

5.7 Stormwater Quality Ponds Analysis

The remainder of this section presents the ponds that were simulated in this thesis.

<u>5.7.1 Permit Number 2003-0070</u>

Figure 5.15 is an image of the engineering drawing for the pond in permit 2003-0070. The pond has a L/W ration of 2.0 and a TPR value of 1.07. These values suggest that the pond meets the criteria.

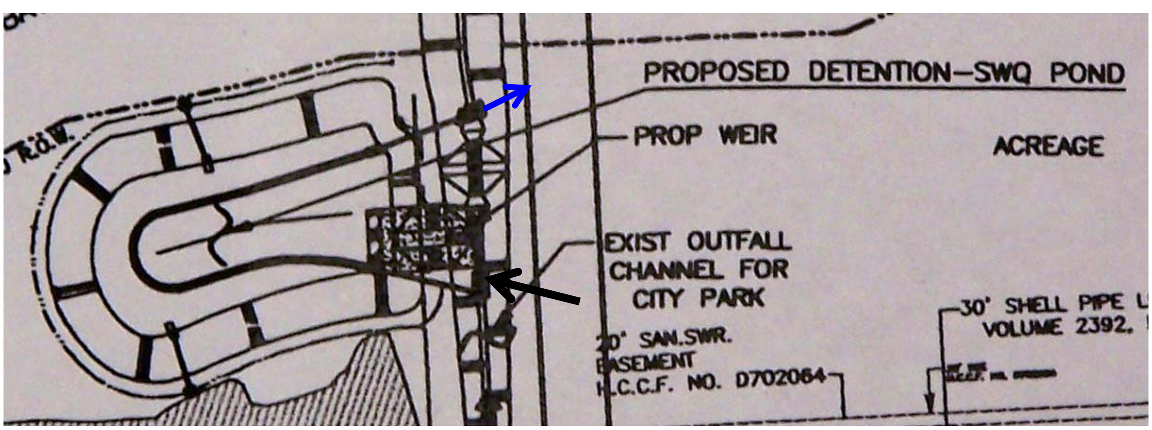


Figure 5. 15 Engineering Drawing for Permit 2003-0070 from COH

Figure 5.16 is a 3D rendering of the velocity potential with the flownet superimposed on the image. This pond design clearly has better performance than the same design without the baffle. The area designated for the pond is utilized efficiently while maintaining a good performance.

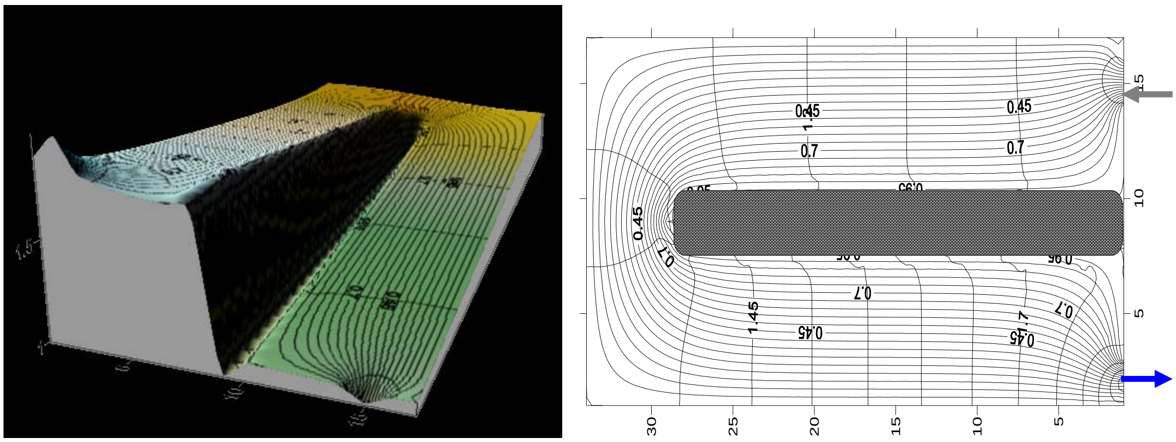


Figure 5. 16 Permit 2003-0070 (COH) Stormwater Quality Pond

Figure 5.16 also shows the computed flownet for the pond displayed in plan view. Here the stream lines show that the particulates would have to travel around the baffle to exit the pond increasing their residence and therefore increasing removal by settling.

The average residence time from the particle tracking program is 4597 time units, which is 7 times the residence time of the same pond design without the baffle. It is worth notice that the travel path has been practically duplicated, while the residence time is increased 7 times.

<u>5.7.2 Permit Number 2003-0070 without Baffle.</u>

The pond in permit 2003-0070 but without the baffle is presented in this section. One can observe that even though the geometrical L/W ratio is maintained (L/W =2.0), the TPR value is reduced to 0.33 and the pond will short circuit. In this case, the utility of the TPR parameter criterion is to indicate short circuiting. Figure 5.17 is a 3D rendering of the velocity potential with the flownet superimposed on the image. Figure 5.15 also shows the computed flownet for the pond displayed. There is a clear waste of the pond volume and the pond becomes just a detention pond and not a stormwater quality pond.

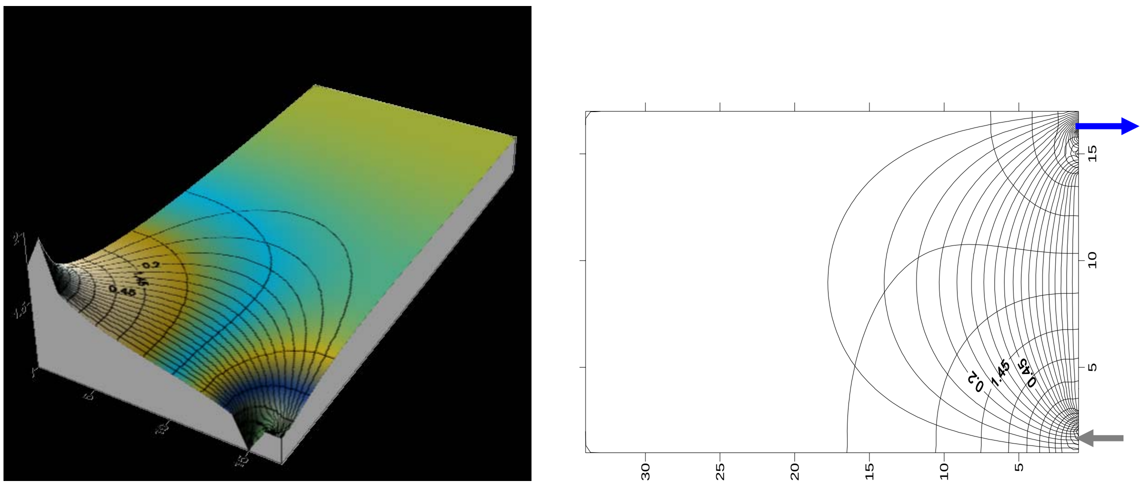


Figure 5. 17 Permit 2003-0070 (COH) Stormwater Quality Pond without Baffle.

The average residence time from the particle tracking program is 651 time units. Observe how the residence time was reduced from 4597 (for the pond with baffle) to 651 (for the pond without baffle) time units, showing the baffle improvement. Particles exit the pond almost immediately compared with other satisfactory designs. The stream lines use less than the 50% of the pond volume available due to the short circuiting obtained.

5.7.3 Permit Number 8-279-9

Figure 5.18 is an image of the engineering drawing for the pond in permit 8-279-9. The pond has a L/W ration of 1.6, and a TPR value of 0.42. These values suggest that the pond will short circuit.

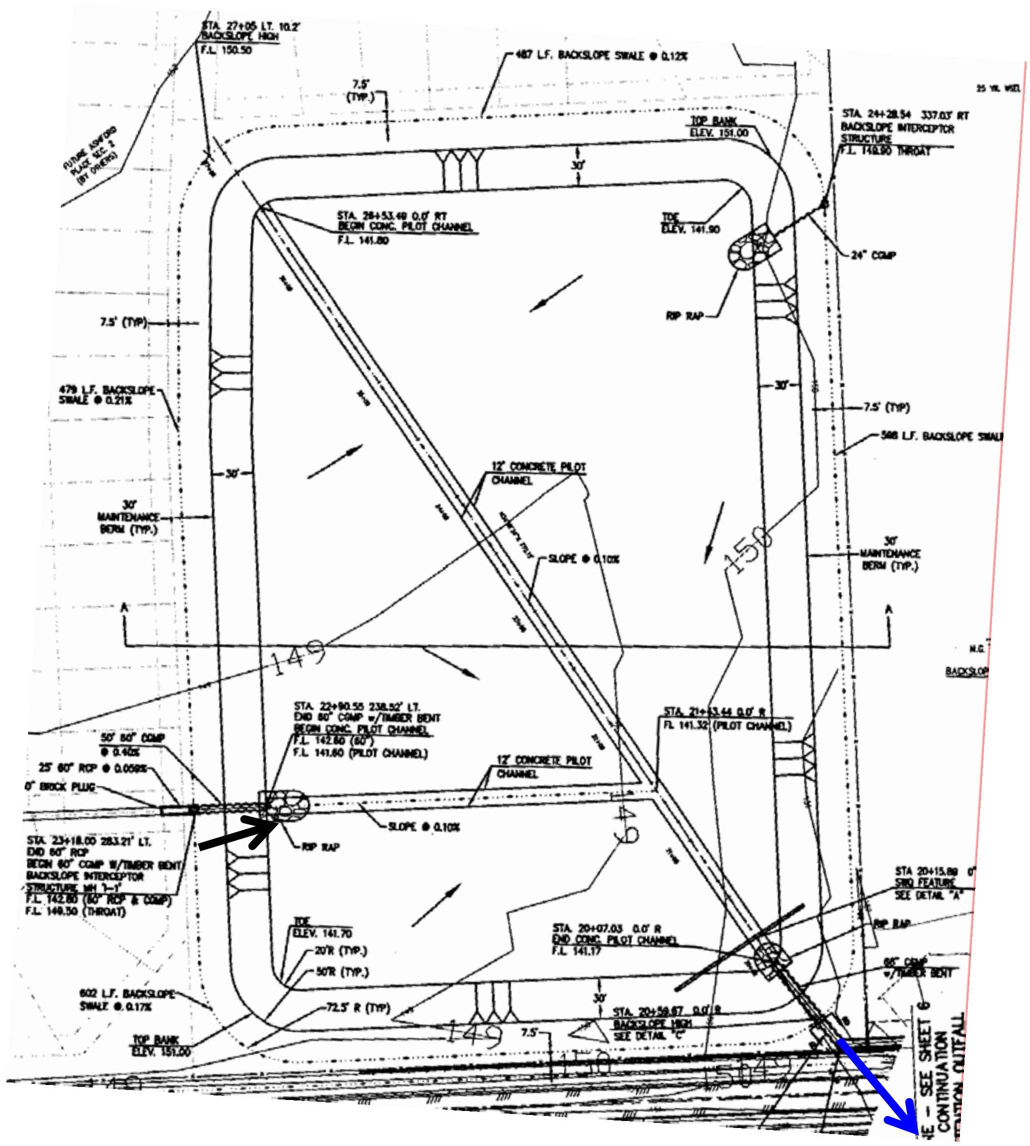


Figure 5. 18 Engineering Drawing for Permit 8-279-9 (Harris County) SWQ Pond

Figure 5.19 is a 3D rendering of the velocity potential with flownet superimposed on the image. Approximately 50% of the pond is wasted for pollutant removal. Particulates will move towards the outlet as soon as they enter the pond. The TPR parameter is identifying short-circuiting and this pond does not comply with the proposed criteria for stormwater quality pond design.

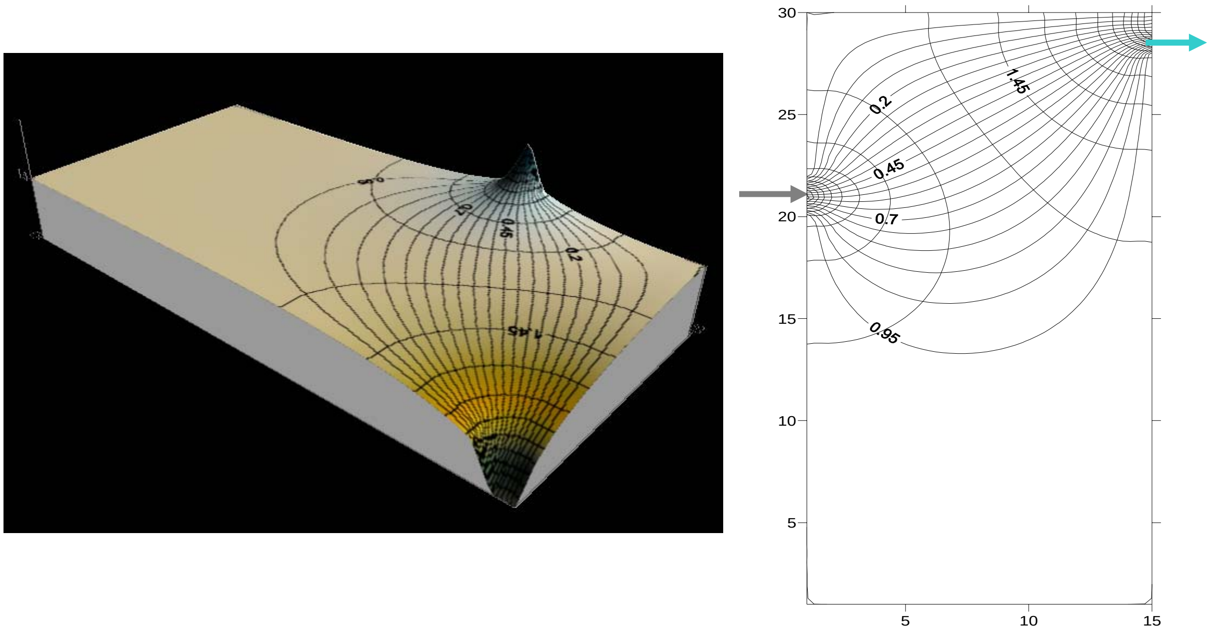


Figure 5. 19 Three-Dimensional View of Permit 8-279-9 SWQ Pond

Figure 5.19 also shows the computed flownet for the pond displayed in plan view. This is a clear combination of a poor design, where not only the length of the pond is wasted but the geometrical L/W ratio is small as well. The average residence time from the particle tracking program is 600 time units.

Observe in the plan view on Figure 5.19 that approximately 70% of the particulates will travel along the third part 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 only useful for detention purposes.

5.7.4 Permit Number 2005-0080

Figure 5.20 is an image of the engineering drawing for the pond in permit 2005-0080 from COH. The pond has a L/W ration of 21.0, and a TPR value of 0.48. These values suggest that the pond will short circuit.

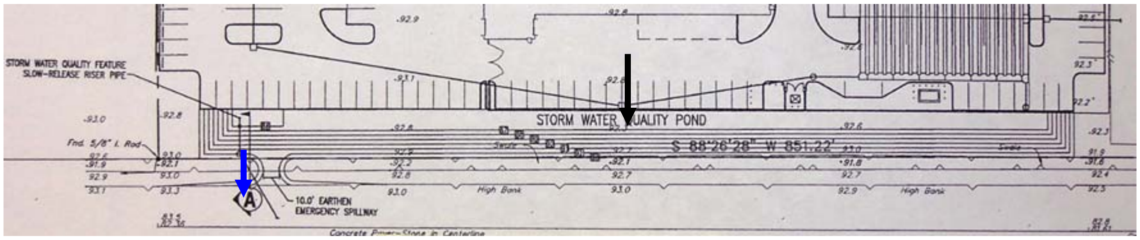


Figure 5. 20 Engineering Drawing for Permit 2005-0080 (COH) SWQ Pond

Figure 5.21 is a 3D rendering of the velocity potential with the flownet superimposed on the image. This is a very long and skinny pond and the L/W ration is very good. However, the TPR is only 0.48 due to the inlet position in the middle of the pond which generates short circuiting.

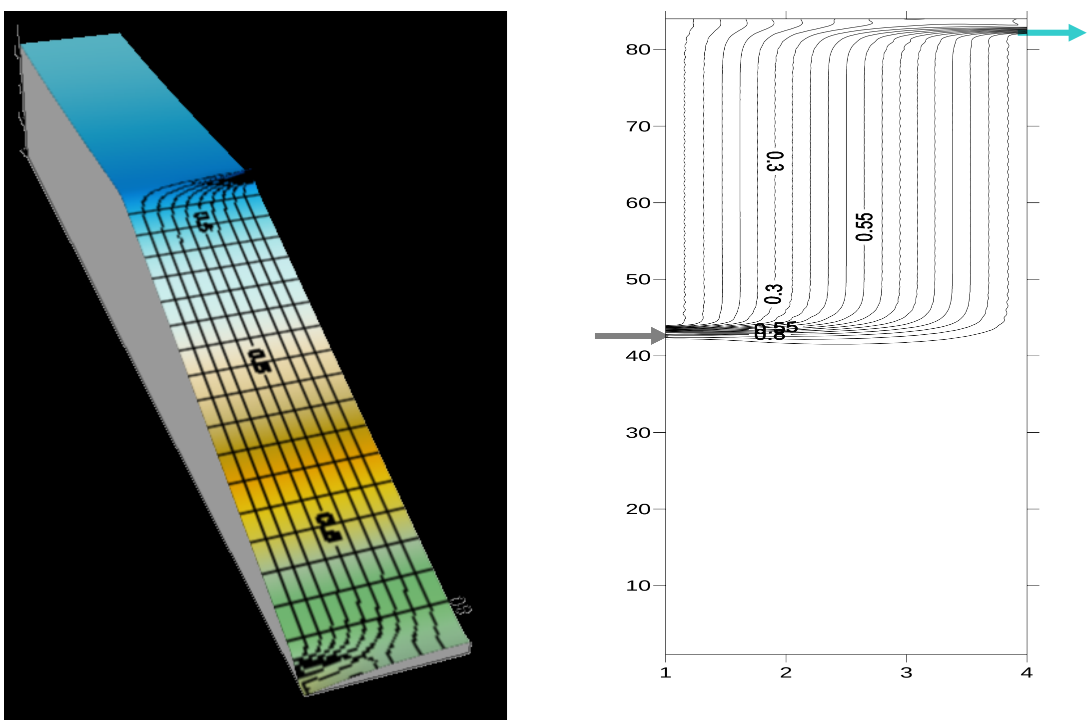


Figure 5. 21 Three Dimensional View and Flow-Net of Permit 2005-0080 SWQ Pond

Figure 5.21 also shows the computed flownet for the pond displayed in plan view. Again, half of the pond is being wasted for pollutant removal. The average residence time from the particle tracking program is 1172 time units.   In order to become a good and acceptable design, the inlet must be relocated to the opposite side of the pond. Good stormwater quality pond design should always try to maximize the travel path of the particles inside the pond. The X axes scales in Figure 5.21 were intentionally increased to be able to show the pond shape and flow net.

5.7.5 Permit Number 2003-0117

Figure 5.22 is an image of engineering drawing for the pond in permit 2003-0117. The pond has a L/W ration of 1.0, and a TPR value of 0.5. These values suggest that the pond will short circuit. This pond design would not pass either the actual regulatory agencies requirements found in the literature review, nor the requirements proposed in the present work.

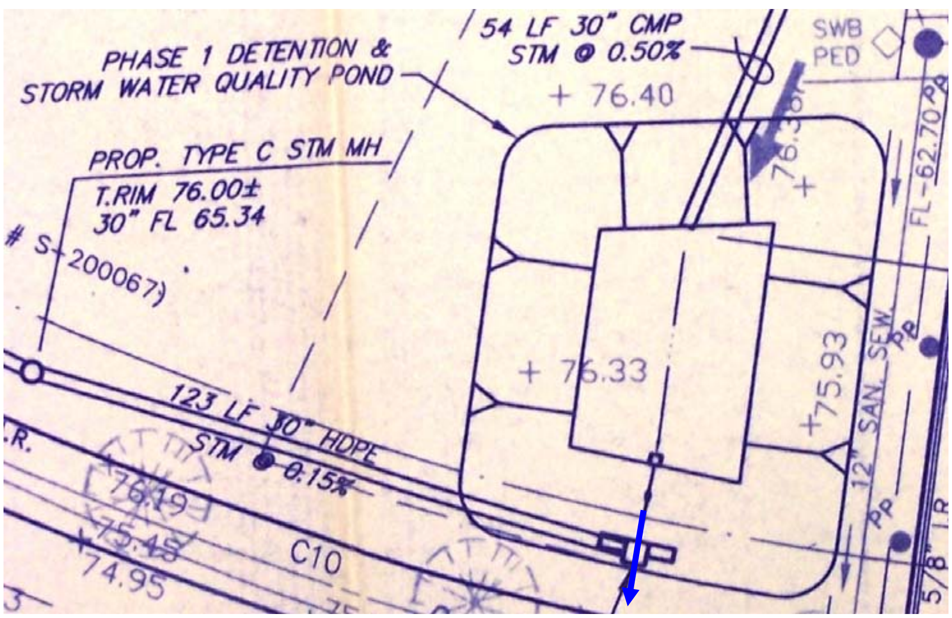


Figure 5. 22 Engineering Drawing for Permit 2003-0117 SWQ (COH) Pond

Figure 5.23 is a 3D rendering of the velocity potential with the flownet superimposed on the image. Figure 5.23 also shows the computed flownet for the pond displayed in plan-view. The TPR value is on the limit of acceptability indicating that the inlet/outlet positions are satisfactory but the L/W ratio is too low. This design can be improved by installing a baffle on the pond.

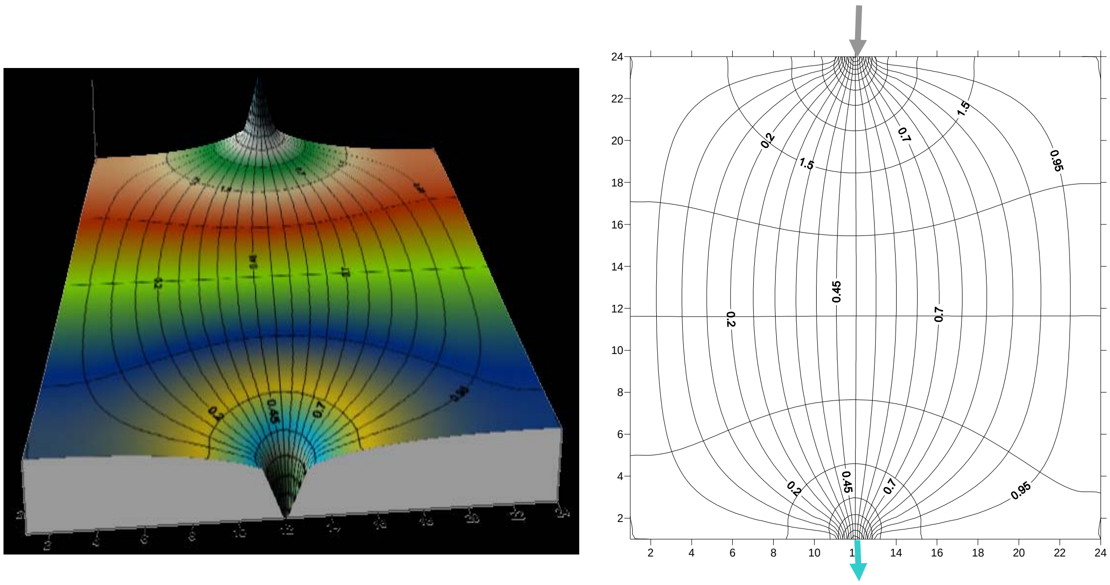


Figure 5. 23 Three-Dimensional View of Permit 2003-0117 SWQ Pond

The average residence time from the particle tracking program is 2413 time units. Even though the residence time is higher than the previous designs, where short circuiting is occurring, it is still less than the minimum established on this thesis (2500 time units).

5.7.6 Tennessee Design Criteria for Stormwater Quality Pond

Figure 5.24 is a 3D rendering of the velocity potential with the flownet superimposed on the image. This pond was built up following the minimum design criteria suggested by the Tennessee Department of Environmental and Conservation, and there is not a permit issued to this design. The pond has a geometric L/W ration of 1.7 and a TPR value of 0.74. The TPR value suggests that short circuiting is not occurring but the L/W ration of the pond is not high enough to provide good performance.

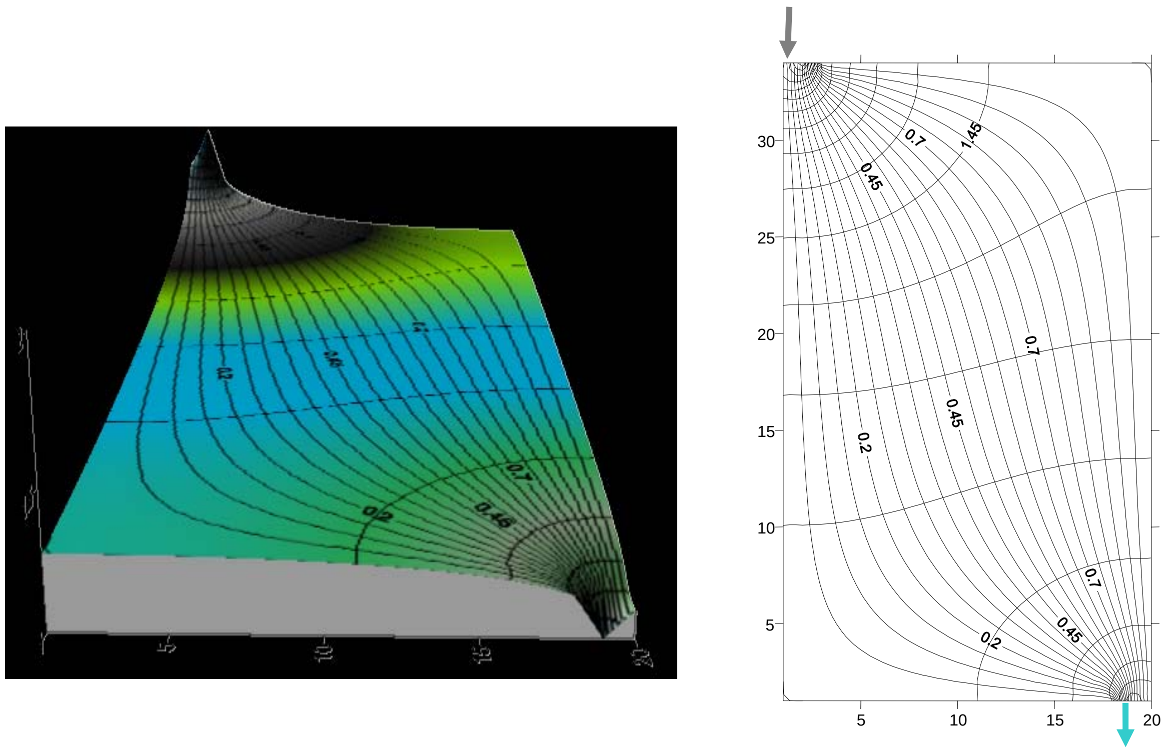


Figure 5. 24 Tennessee and Other States Design Criteria for SWQ Pond

This pond design was made up using the actual minimum criteria used by the Tennessee state and the inlet and outlet positions were located at the farthest point one to the other. The idea is to compare both the criteria proposed in this thesis and the criteria used by other regulatory agencies in different states.

As it was explained in the literature review, in Tennessee, as well as in California, Virginia, New Jersey, The City of Aurora (Illinois), The City of Woodland (California), and City of Golden (Colorado), the length of the pond is defined as the straight distance between the inlet and the outlet of the pond. The minimum L*/W[1] ratio required by the Tennessee Department of Environmental and Conservation and the other regulatory agencies mentioned above, is 2.0, except for the state of California which is 1.5 and the state of Connecticut with a L*/W of 3.0.

[1] L* is the straight distance from the inlet to the outlet of the pond.

The L*/W ratio of 2.0 gives a TPR value of 0.74 and a geometrical L/W ratio of 1.7. In this case the TPR criterion is passed but the L/W is not. Although it is close to the minimum specified, the L*/W= 2.0 criterion would not be enough, and another design implementation should be applied in order to improve the pond design.

The average residence time from the particle tracking program is 2493 time units. It is notice worth that the residence time is close to the minimum established in this thesis of 2500 time units, and another kind of study may be required to analyze this design. So based on the present work and taking in count that the efficiency of a stormwater quality pond should be always maximized, this kind of design does not comply with the present work requirements and is not recommended.

5.7.7 Permit Number 8-108-2

Figure 5.25 is an image of the engineering drawing for the pond in permit 8-108-2 from Harris County. The pond has a L/W ration of 3.0, and a TPR value of 0.67. These values suggest that the pond meets the criteria.

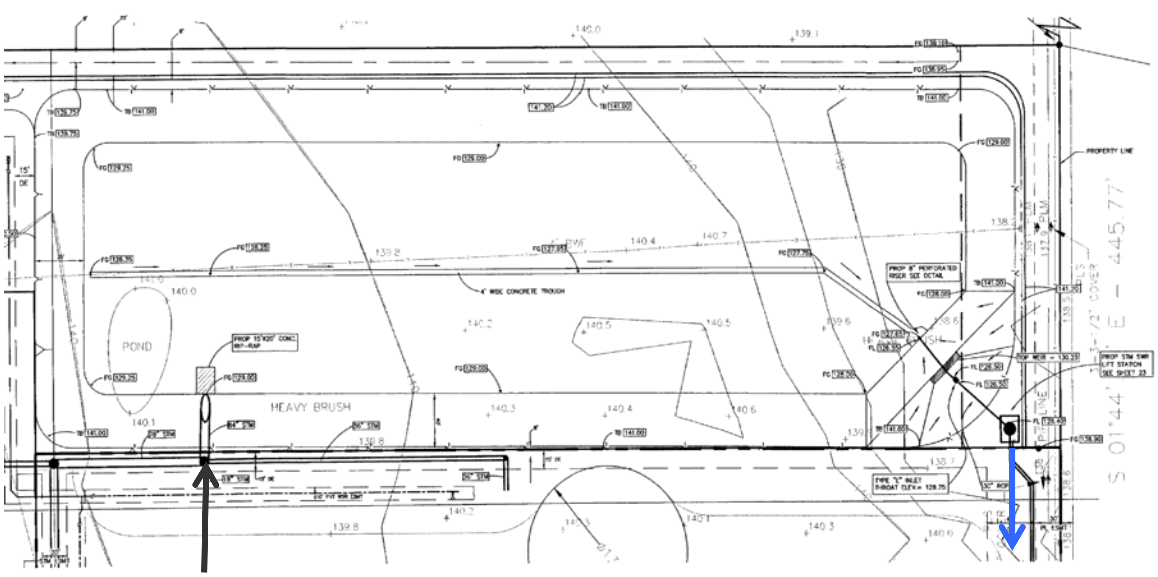


Figure 5. 25 Engineering Drawing for Permit 8-108-2 SWQ (Harris County) Pond

Figure 5.26 is a 3D rendering of the velocity potential with the flownet superimposed on the image. This pond was selected to be analyzed because it complies with the minimum proposed design criteria. The TPR value is less than other L/W ratio of 3.0 ponds because the inlet is not located at the farthest point from the outlet. However, the TPR value is greater than 0.5 and the pond meets the requirements. This is also observed on the residence time.

Figure 5.26 also shows the computed flownet for the pond displayed in plan-view.

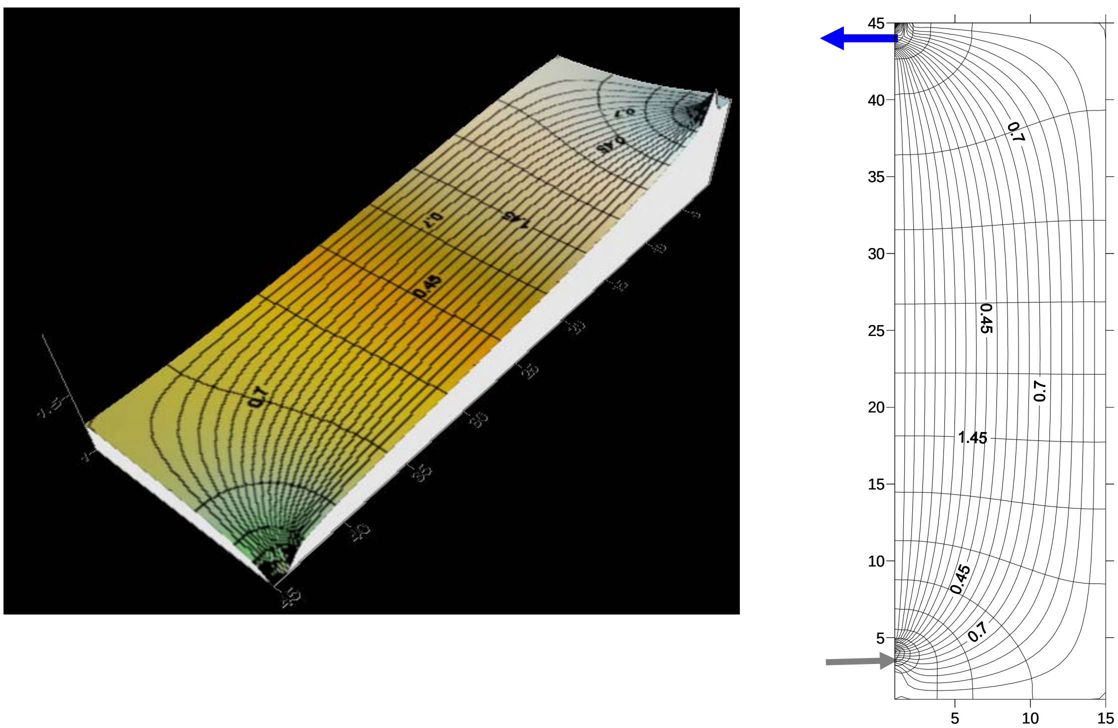


Figure 5. 26 Elevation View and Flow-Net for Permit 8-108-2 SWQ Pond

The average residence time from the particle tracking program is 2558 time units. This value is greater than the minimum established and therefore enough time is provided to the particulates to settle and get removed from the stormwater.

5.7.8 Permit Number 8-061-7

Figure 5.27 is an image of the engineering drawing for the pond in permit 8-061-7. The pond has a L/W ration of 2.5, and a TPR value of 0.79. These values suggest that the pond meets the criteria. Inlet is located at opposite corner of the outlet maximizing the travel path for the particulates.

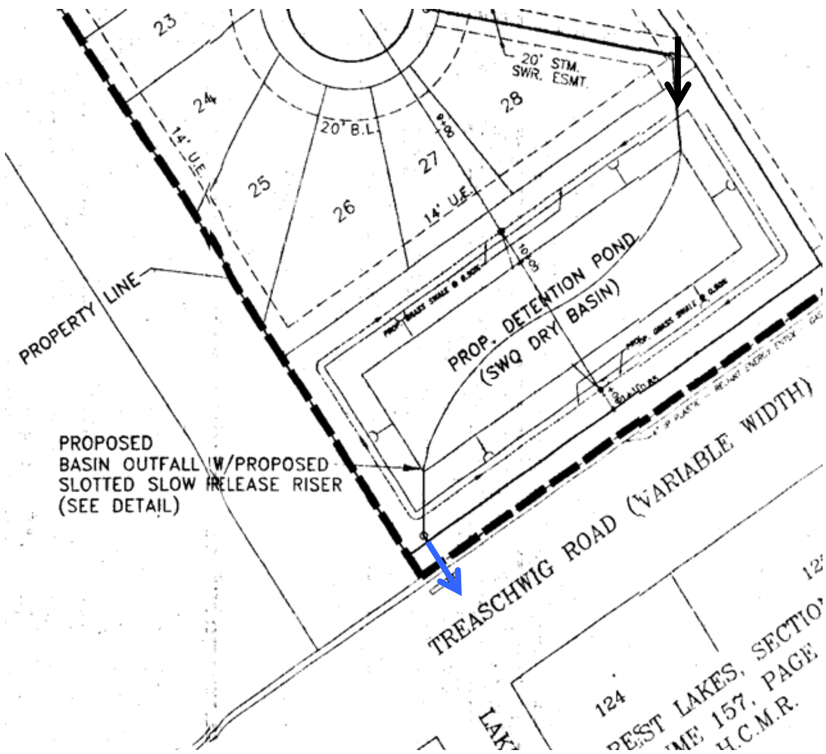


Figure 5. 27 Engineering Drawing for Permit 8-061-7 (Harris County) SWQ Pond

Figure 5.28 is a 3D rendering of the velocity potential with the flownet superimposed on the image. This pond was chosen to be analyzed because is one of the two ponds selected for sampling and monitoring by Carter & Burgess for the EPA project on which this research was based. Figure 5.28 also shows the computed flownet for the pond displayed in plan-view.

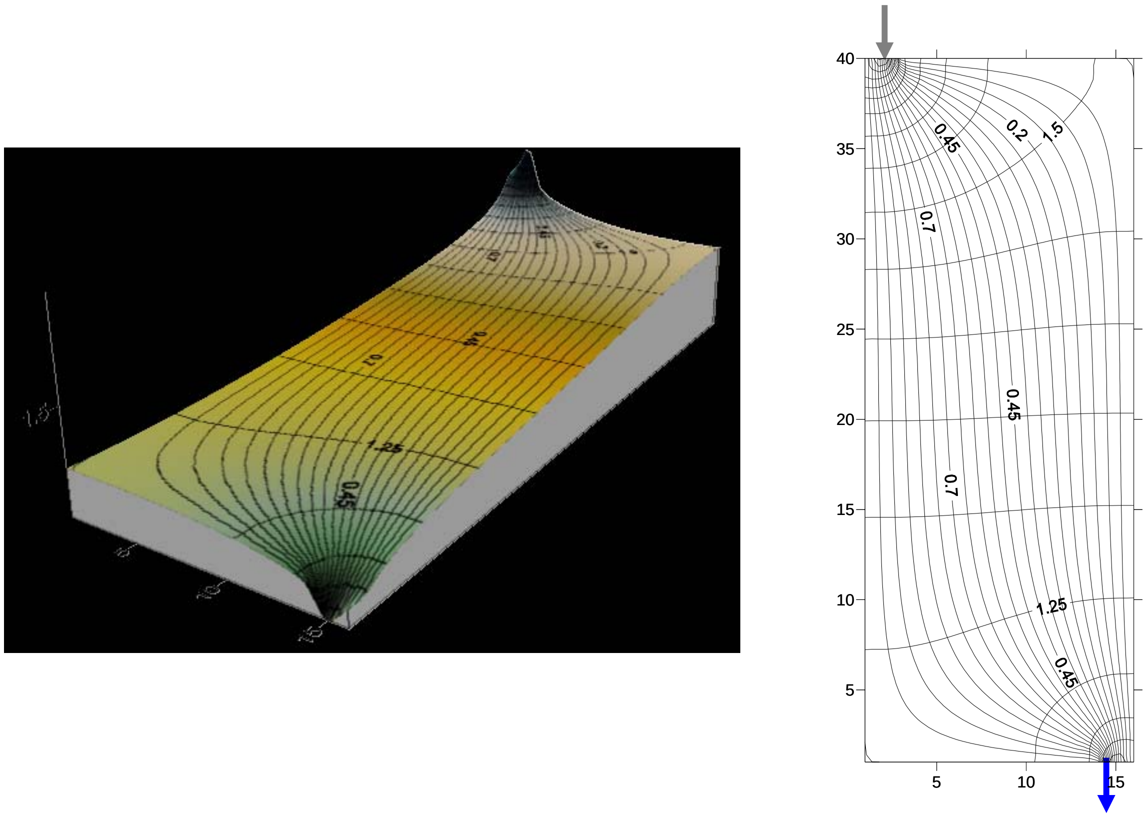


Figure 5. 28 Elevation View and Flow-Net for Permit 8-061-7 SWQ Pond

The average residence time from the particle tracking program is 2860 time units. This is clearly a good pond design, with a residence time above the minimum established, and is supported by the TPR and the L/W ratio.

<u>5.7.9 Permit Number 8-077-0</u>

Figure 5.29 is an image of the engineering drawing for the pond in permit 8-077-0. The pond has a L/W ration of 3.0, and a TPR value of 0.70. These values suggest that the pond meets the criteria.

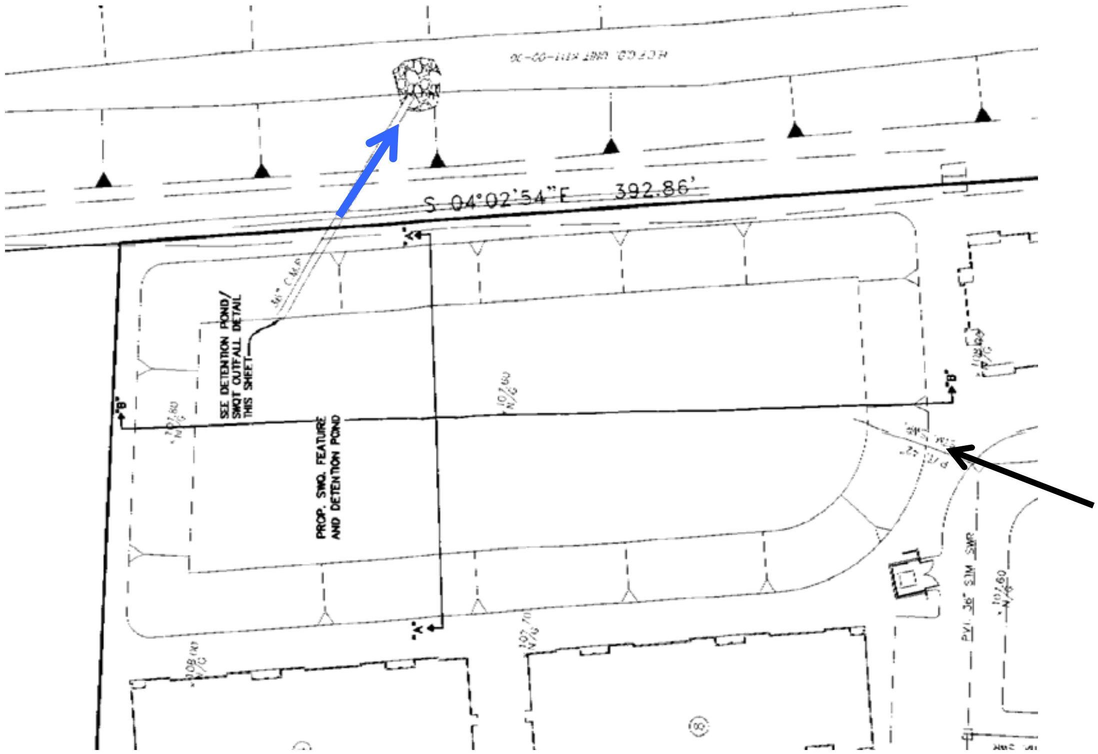


Figure 5. 29 Engineering Drawing for Permit 8-077-0 (Harris County) SWQ Pond

Figure 5.30 is a 3D rendering of the velocity potential with the flownet superimposed on the image. This pond is the second pond chosen by Carter & Burgess for sampling and monitoring in the EPA project. Figure 5.30 also shows the computed flow-net for the pond displayed in plan-view.

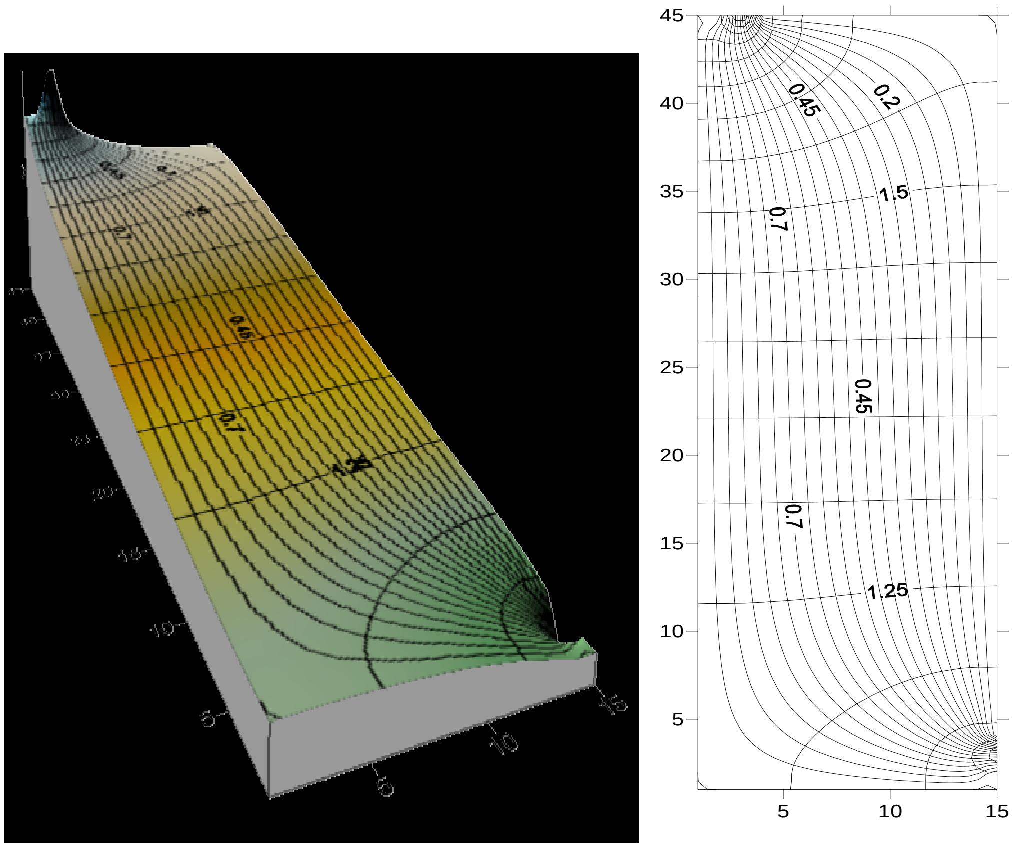


Figure 5. 30 Three-Dimensional View of Permit 8-077-0 SWQ Pond

Observe that pond in permit 8-077-0 is also a very well designed pond and meets the criteria proposed in this thesis. The average residence time from the particle tracking program is 3046 time units.

5.7.10 Connecticut Design Criteria for Stormwater Quality Pond

Connecticut is the only state, from the other states and cities studied, that has a conservative (and similar to the present work), criteria design. This pond was built up following the minimum design criteria suggested by Connecticut, and there is not a permit issued to this design. The pond has L/W ration of 2.82 and a TPR value of 0.78. Figure 5.31 is a 3D rendering of the velocity potential with the flownet superimposed on the image. Figure 5.31 also shows the computed flownet displayed in plan-view. Once again the TPR parameter indicates that short-circuiting is avoided. However, this design mixes the geometrical L/W ratio with the short circuiting criterion, and eventually can lead to misunderstandings, depending on every person's point of view. Therefore, using the TPR parameter and the geometrical L/W ratio, short circuiting can be better identified and prevented.

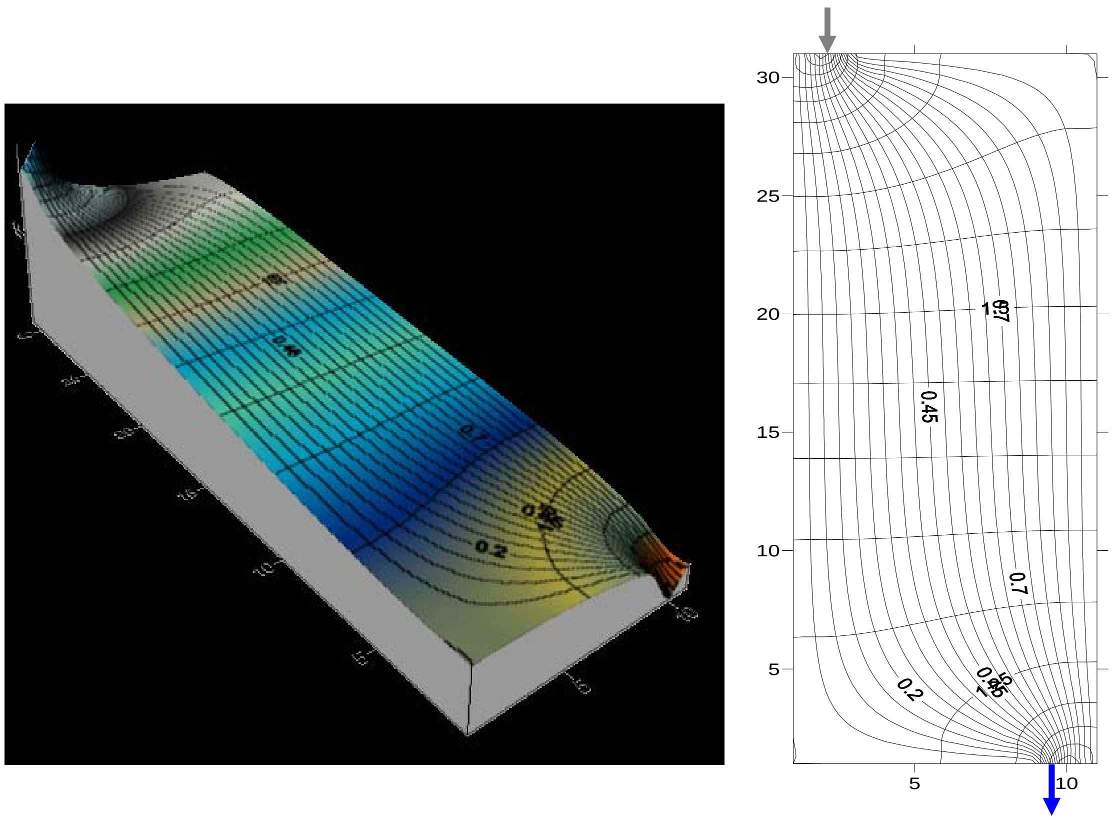


Figure 5. 31 Connecticut Design Criteria SWQ Pond

The average residence time from the particle tracking program is 2950 time units, verifying that enough time is provided to the particulates for settling and removed from stormwater.

5.7.11 Permit Number 8-169-8

Figure 5.32 is an image of the engineering drawing for the pond in permit 8-169-8. The pond has a geometrical L/W ration of 3.0, and a TPR value of 0.75. These values suggest that the pond meets the criteria.

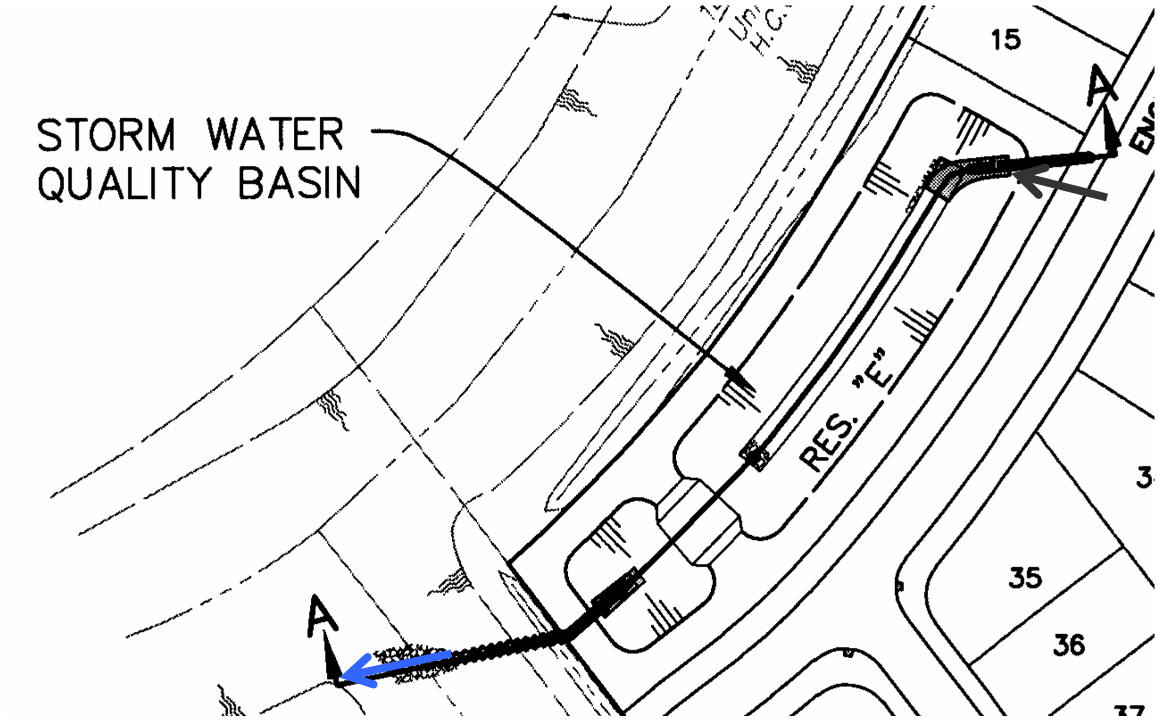


Figure 5. 32 Engineering Drawing for Permit 8-169-8 (Harris County) SWQ Pond

Figure 5.33 is a 3D rendering of the velocity potential with the flownet superimposed on the image. This pond was initially selected and recommended for sampling and monitoring in the EPA project. Monitoring equipment was installed, but due to vandalism another pond had to be selected (pond 8-061-7). Figure 5.33 also shows the computed flownet for the pond displayed in plan-view. Particles ideally move from the high potential to the lower potential following the stream lines illustrated in the Figure 5.33.

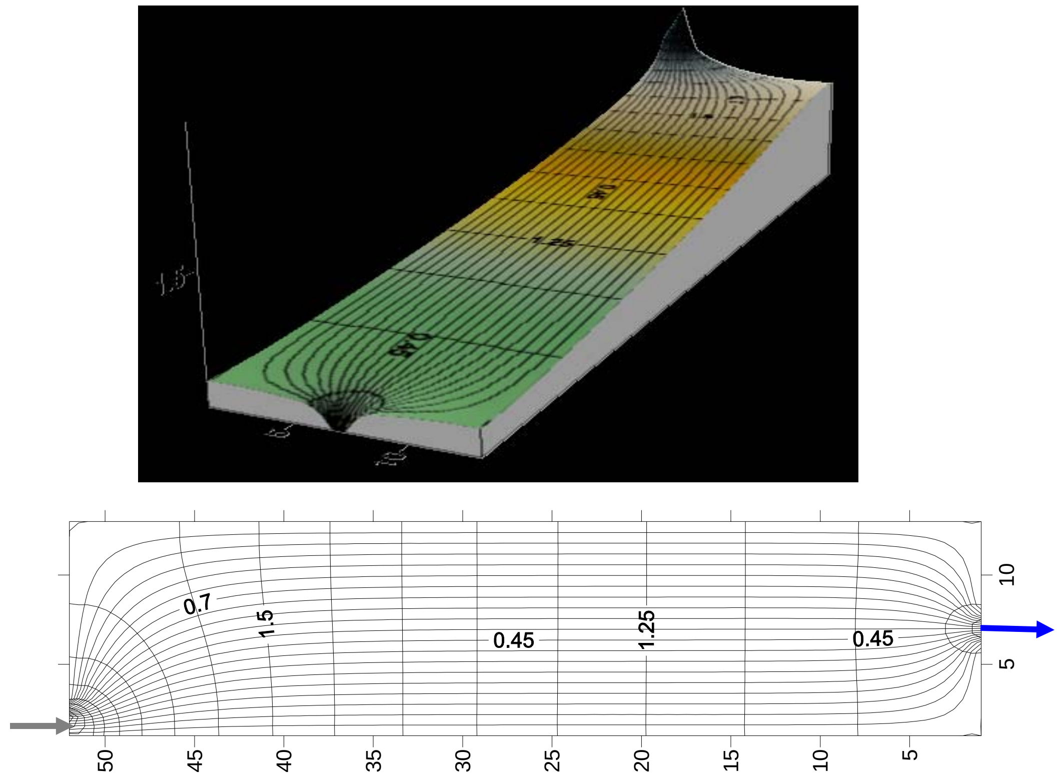


Figure 5. 33 Three-Dimensional View of the Flow-Net in Permit 8-169-8 SWQ Pond

The average residence time from the particle tracking program is 3411 time units. This is a very good design where the volume of the pond is utilized completely.

5.7.12 Permit Number 2004-0040

Figure 5.34 is an image of the engineering drawing for the pond in permit 2004-0040 from the City of Houston files. The pond has a L/W ration of 11.0, and a TPR value of 0.92. These values suggest that the pond meets the criteria.

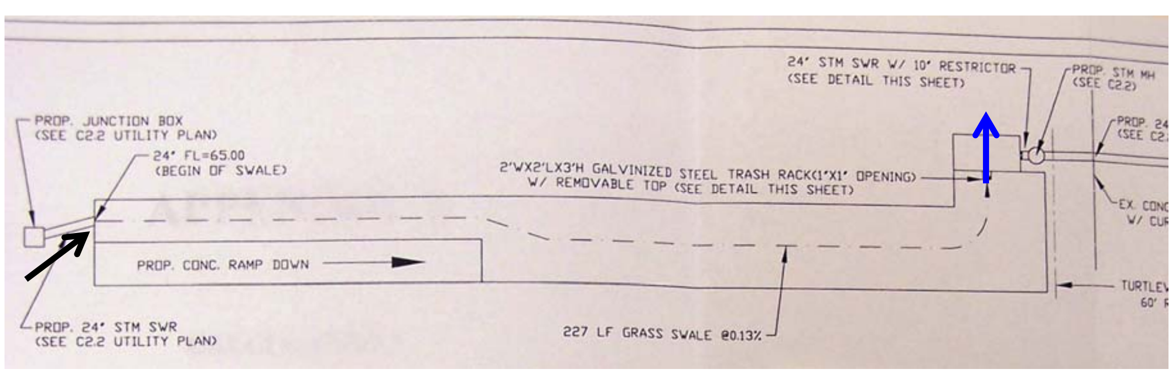


Figure 5. 34 Engineering Drawing for Permit 2004-0040 (COH) SWQ Pond

Figure 5.35 is a 3D rendering of the velocity potential with the flownet superimposed on the image. Figure 5.35 also shows the computed flownet for the pond displayed in plan-view. Observe that the whole pond is used for the pollutant removal because the inlet and outlet locations make the particulates travel along the complete length of the pond. TPR value is indicating that short circuiting is avoided and the pond will perform well.

Since it is a very long design, the pond performance is improved. However, it is a quite long type of basin and sometimes land developers are not willing to build this kind of ponds because of the lack of land. Therefore, a long and narrow pond may not be a feasible option, where the land is utilized as much as possible.

There are other design options that would help to obtain the same performance in a different shape or pond design type. However a moat-type layout where a pond nearly surrounds a subdivision can achieve the long-narrow behavior if the stormwater is collected and conveyed into one end of the moat. Nevertheless the piping costs involved would likely select against such a design. Permit 8-262-4 in the next section is one example of this option.

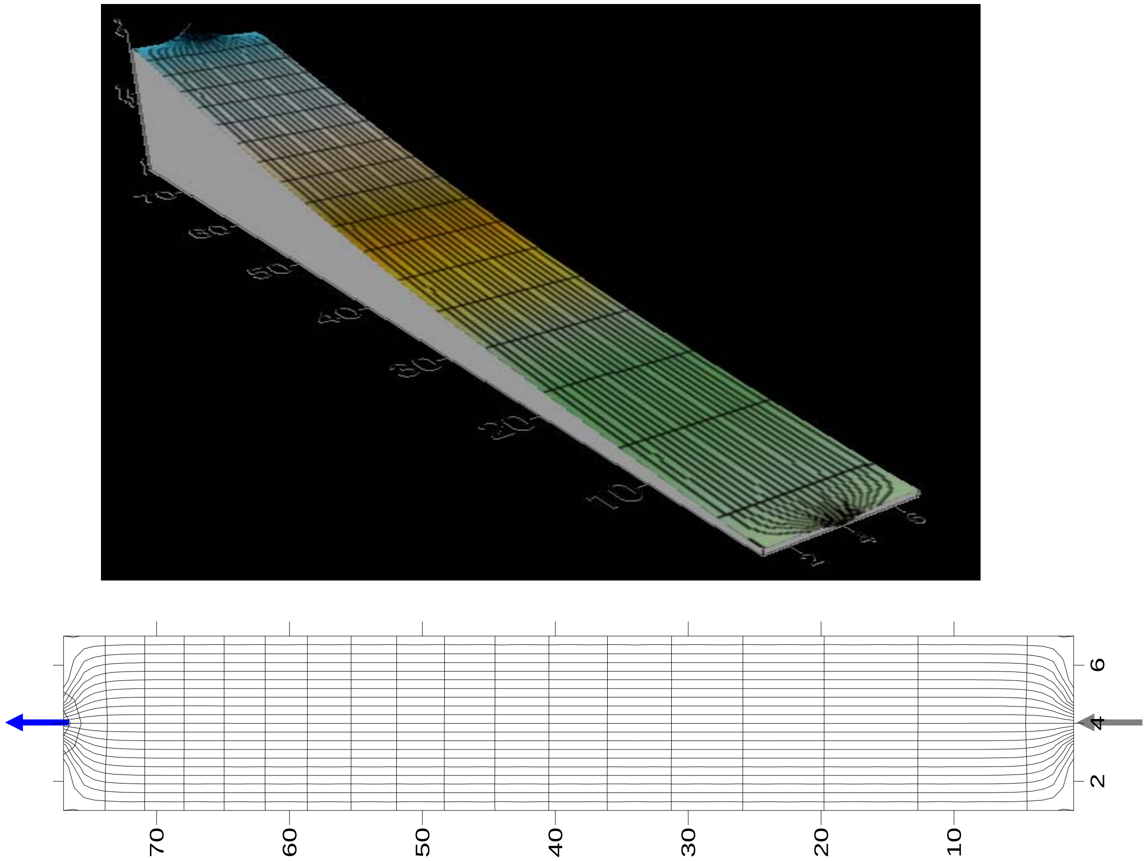


Figure 5. 35 Elevation View of Permit 2004-0040 SWQ Pond

The average residence time from the particle tracking program is 6863 units. This residence time value was expected to be very high compared with the minimum established of 2500 time units because of the high L/W ratio.

<u>5.7.13 Permit Number 8-262-4</u>

Figure 5.36 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 ration can be less than 2.0 and good performance is achieved.

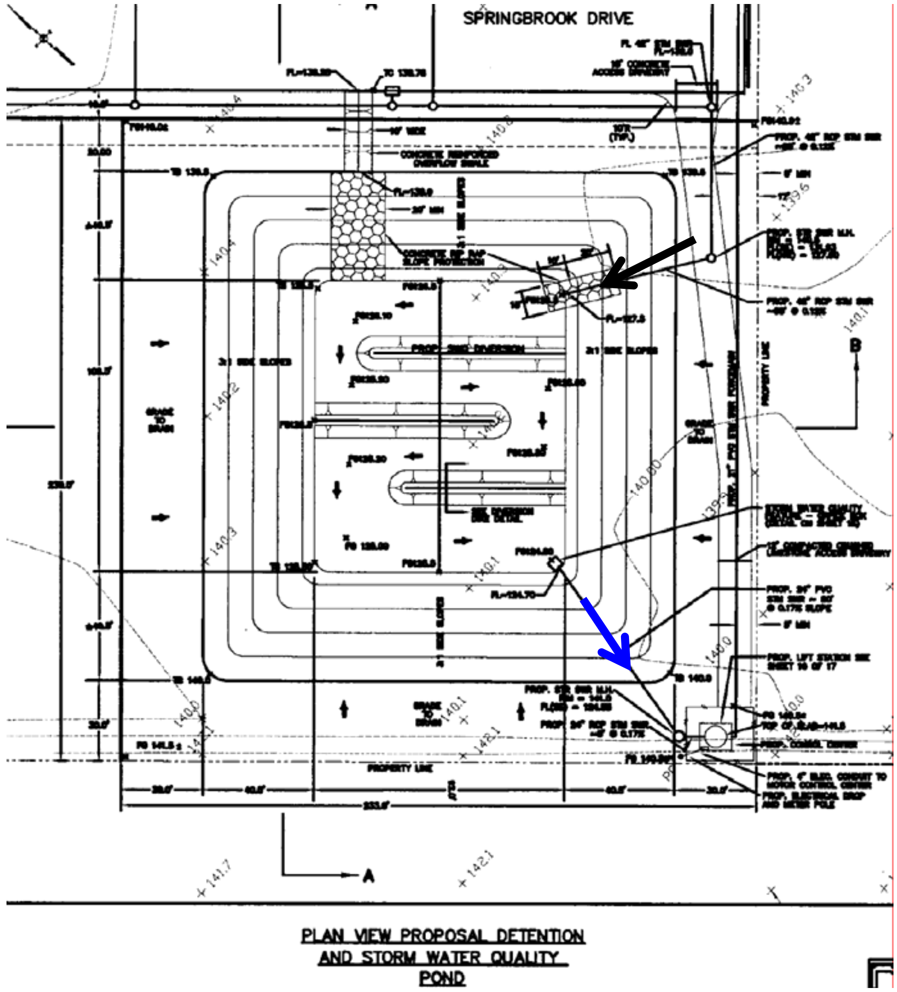


Figure 5. 36 Engineering Drawing for Permit 8-262-4 (Harris County) SWQ Pond

Figure 5.37 is a 3D rendering of the velocity potential with the flownet superimposed on the image. The three baffles installed in the pond increase the travel path of the particles which is reflected in the TPR value. Figure 5.37 also shows the computed flownet for the pond displayed in plan-view.

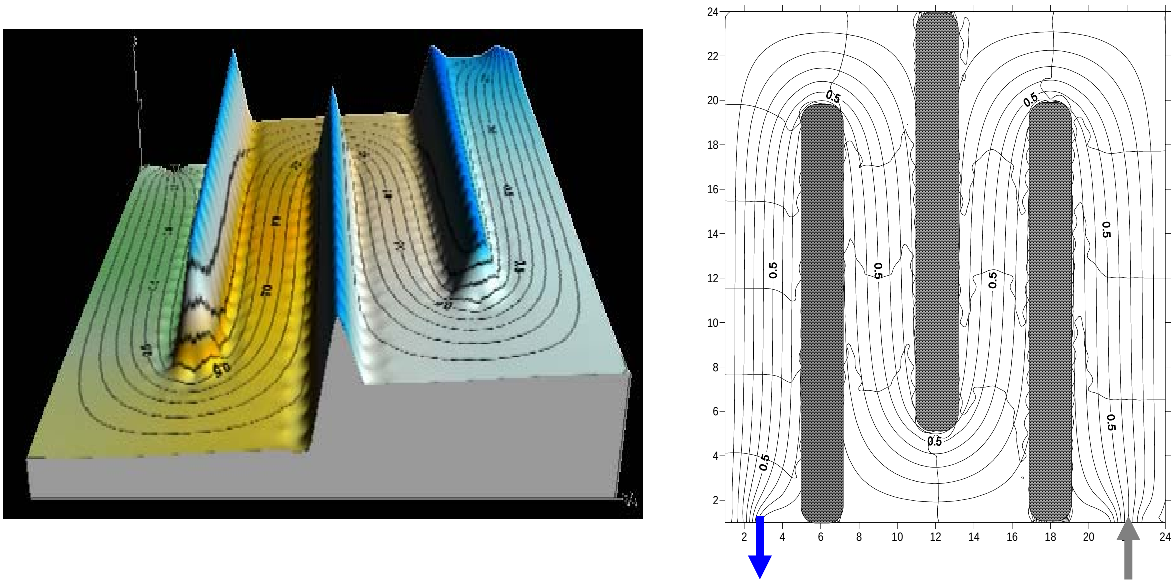


Figure 5. 37 Three-Dimensional Flow-Net of Permit 8-262-4 SWQ Pond

The average residence time of this pond is 7357 time units, which is an excellent design of a stormwater quality pond where the maximum advantage is taken from the pond area, and a good pollutant removal is achieved. This pond would perform as three ponds in series while the square shape is still maintained.

5.8 Baffle Design Analysis

Based on the fact that baffle installation improves the pond performance, and allow taking advantage of the pond area, ponds with 1 and 2 baffles were also simulated and analyzed to show the baffle design improvement. Figure 5.38 shows the cumulative residence time for ponds with 1, 2 and 3 baffles. The pond without baffles is the same design as the pond used in permit 2003-0117 with geometrical L/W ratio of 1.0, a TPR value of 0.5 and an average residence time of 2413 time units. The residence time of the pond without baffles is less than the minimum established of 2500 time units, indicating that the pond does not provide enough residence time to the particles. This can also be confirmed by looking at the TPR value of only 0.5.

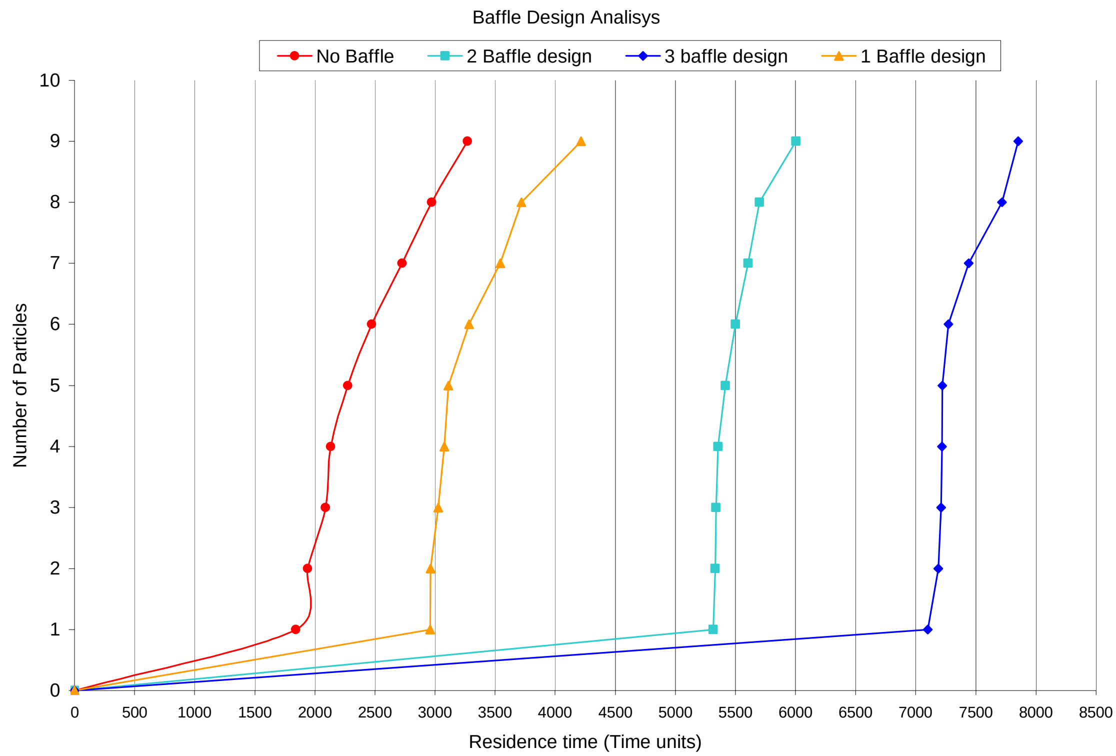


Figure 5. 38 Cumulative Residence Time for Baffle Pond Design

The pond design with 1 baffle increase the average residence time of the pond from 2413 to 3322 time units, which is 1.4 times the average residence time without baffle. If another baffle is installed, the residence time is increased 2.3 times the average residence time of the pond without baffle, and the TPR value is increased from 0.5 to 1.3. The same analysis can be applied to the basin with three baffles (pond in permit 8-262-4), but in this case the residence time is increased 3 times of the residence time of the pond without baffles as well as the TPR value which is increased from 0.5 to 1.5.

5.9 General Analysis of Cumulative Residence Time of the Pond Designs Studied

The residence time of all the design types studied are showed in Figure 5.39.

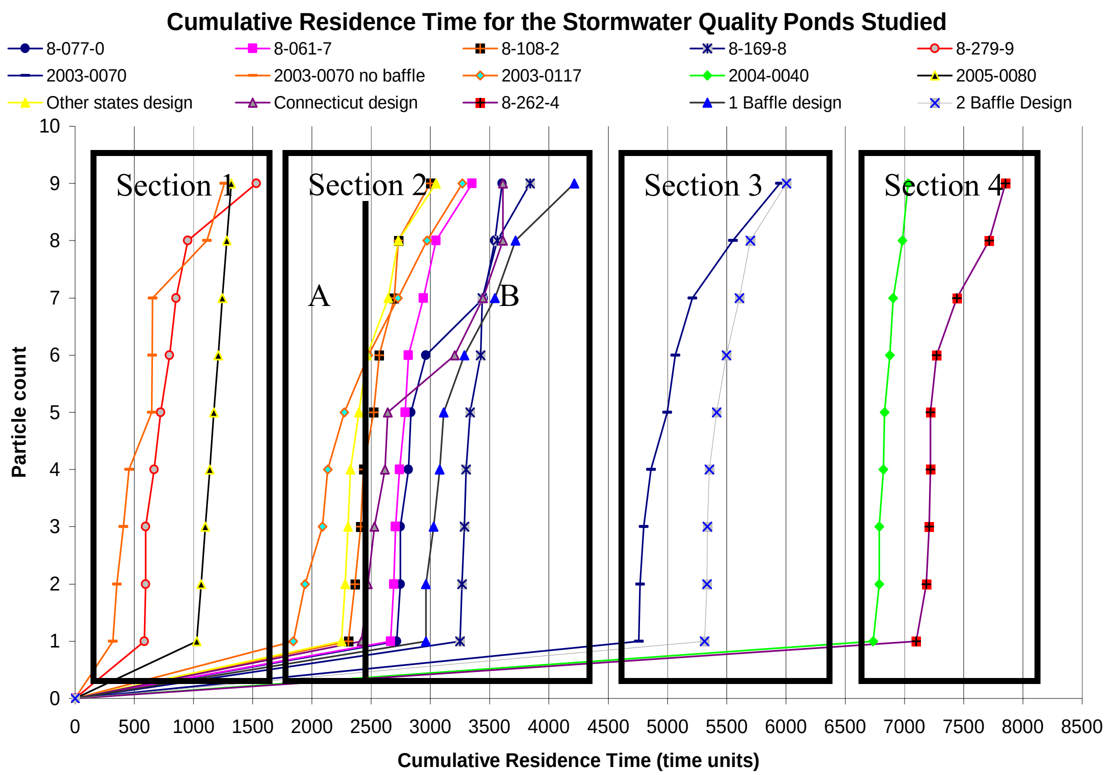


Figure 5. 39 Cumulative Residence Time for the Pond Designs Studied

From Figure 5.39, four sections can be identified. These four sections clearly 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.

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.

Since section two contains the minimum residence time established, this section is divided in two parts (Part A and B in Figure 5.39). The part A of section 2 is formed by permit 2003-0117 and the other states design types. These ponds provide better residence time than the ponds in the first section, but are still under the minimum residence time established. Also, the design types of these ponds do not pass the design criteria proposed in the present work for stormwater quality pond design. On the other hand, part B in section 2 contains the ponds in permits 8-108-2, the Connecticut state design type, permit 8-061-7, 8-077-0, 1 baffle design, and permit 8-169-8. All these designs comply with the proposed criteria for stormwater quality pond design, their average residence time is greater than 2500 time units, and are common design types found in the Harris County and The City of Houston permit files.

Section three in figure 5.39, contains permits 2003-0070 and the 2 baffle design type. The residence time achieved in this kind of design is clearly greater than the other common pond designs, which is explained by the baffle utilization.

Section four contains permits 8-262-4 and 2004-0040. These design types achieve a very high residence time compared with the other common designs found. Permit 8-262-4 provides a very long travel path due to the three baffles installed, and permit 2004-0040 provides also a long travel path due to the long shape of the pond. The pond in permit 2004-0040 provides the same effect as a squared pond with baffles like permit 8-262-4 pond.

5.10 Baffle Design Comments

One of the issues that might lead to the baffle design, when designing a storm water quality and detention basin, is to take advantage of the area designated for the detention pond, and at the same time obtain good pollutant removal efficiency. Some basic design recommendations should be taken in count when a baffle pond is designed in order to take advantage of the baffle. The baffle design provides an obstacle to the particles that travel inside the pond, with longer time and increase the chances to be settled and removed. If there weren't a baffle in a 1.0 geometrical L/W ratio pond, short circuiting would be the most probably issue for an engineer.

5.11 Recommendations for Stormwater Quality Ponds

The proposed recommendations that are believed to be important when designing a stormwater quality detention pond are the following:

- The inlet must be located at the farthest point from the outlet, and baffle design could be used to increase this distance.
- The pond has to have a geometrical L/W ratio greater than 2.0 and a TPR parameter value greater than 0.5.
- If there is more than one inlet, they should be connected together before entering the pond: using pipes, swales or channels.
- If the inlets are not joined together before the pond, they should enter the pond at the same place and on the farthest location from the outlet.
- More than one inlet ponds must not have the inlets at separate points.

5.12 Recommendation for Stormwater Quality Ponds with Baffles

When the pond has a baffle the TP distance increases making the TPR parameter greater than 0.5. In this case, the geometrical L/W ratio loses the relevance and the pond design might be accepted just with the TPR criterion. Later on, this case will be demonstrated using the ideal flow modeling. The following are the recommendation for baffle pond design:

- Baffles should maximize the travel path of the particles inside the pond.
- There can be more than 1 baffle depending on the requirements.
- Ponds with geometrical L/W ratio less than 2.0 must install at least one baffle to comply with the short circuiting criteria and provide good performance.
- If the pond has a geometrical L/W ratio equal or greater than 2.0, and the TPR is less than 0.5, installing a baffle could solve the short circuiting problem.
- The baffle should be between 75 to 90 percent of the length of the pond in order to provide good travel path increase and avoid short circuiting.
- The baffles should be high enough to treat the water coming from a 2 year storm event.
- Baffles should be constructed as strong as possible to avoid erosion from the water flow and an eventual deterioration of the pond performance.

CHAPTER 6 CONCLUSIONS

The conclusions of this thesis are presented as follows:

- Based on these ideal studies it was concluded that the flow-path ratio criterion used in the site selection procedure (TPR > 0.5), is a valid indicator of short-circuiting when used along with the length to width ratio criterion, ($L/W \geq 2.0$).
- The TPR parameter identified short-circuiting in 100 % of the cases.
- The use of baffles improves the pond removal potential.
- Long shaped ponds have similar performance of ponds with baffles.
- Higher residence times increases the pollutant removal efficiency.
- Even though the simulation programs have limitations; since they assume ideality, the residence time calculated provided good criteria when short circuiting is occurring.
- Other states mix the concept of length to width ratio with short-circuiting. By implementing the new TPR parameter, both concepts are separated to provide a better pond design and improve the stormwater quality to protect the environment.
- The implementation of the TPR will improve the stormwater quality pond design.
- Two databases that contain selected data from permitted BMPs in Harris County and the City of Houston were created and analyzed to select two dry detention ponds for water quality sampling to evaluate BMP performance.
- Harris County and the City of Houston have similar types of systems permitted.
- Wet/Dry basins are the most common type in the Harris County jurisdiction, with nearly three-quarters of the permits issued in Harris County being this type of BMP.
- The City of Houston permits issued are nearly equally divided between Wet/Dry basins and Oil-Grit separators.

- The City of Houston and Harris County have a small number of grassy-swales and vegetative buffer strips permitted.
- 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. (North of 29.80; West of 95.40).
- There is some coverage of BMPs in the southwest part of the county with relatively sparse coverage elsewhere. Of these 35 square miles of drainage area, about 25 square miles are served by some kind of pond-type BMP.

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APPENDIX I HARRIS COUNTY PERMITS DATABASE

APPENDIX II CITY OF HOUSTON PERMITS DATABASE

APPENDIX III La Place SOLVER SOURCE CODE

APPENDIX IV PARTICLE TRACKING PROGRAM SOURCE CODE