

# Increasing Hydraulic Residence Time in Constructed Stormwater Treatment Wetlands with Designed Bottom Topography

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**ABSTRACT:** The treatment efficiency of wetlands depends primarily on the residence time of the polluted storm water (Walker, 1998). Because of this, increasing hydraulic residence times (HRTs) at various flow levels will increase the treatment efficiency of constructed wetlands. In this research, the effects of characteristic bottom topographic features that increase HRT were explored through the use of a two-dimensional hydrodynamic model. Based on numerical simulations of rectangular test wetlands, relationships were made between topographic features and their effects on HRT. Results from the simulations showed that creating baffled wetlands with multiple vertical-scale topography can markedly increase HRT, as is illustrated in a design example. When compared (using the hydrodynamic model) with a wetland having no bottom topography, the design example wetland increased HRT by 113% for the low-flow (142 L/sec) peak flood, and 39% for the 2-year flood event (1700 L/sec). *Water Environ. Res.*, **78**, 2514 (2006).

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## Introduction

Stormwater runoff from urbanized watersheds often contains contaminants that reduce water quality, including sediment, toxic substances, heavy metals, pathogens, oxygen-demanding material, nutrients, and debris. Contaminants can diminish water quality and degrade aquatic habitat in the water body receiving the stormwater discharge (U.S. EPA, 2000a); thus, stormwater runoff is frequently treated before allowing it into receiving water bodies.

Constructed free-water-surface wetlands have become a more popular method of stormwater treatment because of the increasing need for ecological and economically feasible means of detaining and treating stormwater runoff. Contaminated runoff entering wetlands is treated by physical, chemical, and biological processes. Wetlands also create wildlife habitat and provide a natural and aesthetically pleasing setting for the improvement of water quality.

Both constructed and natural wetlands behave similarly to the physiochemical and biological reactors used for treating polluted wastewater and are thus governed by the same physical laws and parameters as mechanical reactors. A principal parameter used in establishing the treatment efficiency of a reactor is residence time; this has been verified by many researchers (e.g., Kadlec and Knight, 1996; Martinez and Wise, 2003). The mean hydraulic residence time (HRT) for a reactor is the average amount of time the material being treated spends in the reactor. Because the physical, chemical, and biological wetland treatment processes are all a function of time, maximizing the

HRT will ultimately improve the treatment. The simplest method of increasing HRT is by increasing the wetland volume. However, space and cost limitations indicate that research focused on finding other ways to improve and increase HRT of wetlands is warranted.

Mean HRT is defined as the volume of water contained within the wetland divided by the volumetric flowrate out of the wetland at steady-state conditions. Most wetlands fail to achieve the theoretical mean HRT because of incomplete use of the wetland volume, leaving significant room for improvement (Persson et al., 1999). The incomplete use of wetland volume results from areas of stagnation or reduced mixing. The HRT in wetlands is influenced by several hydrologic variables, including flow resistance, rainfall on the wetland, evapotranspiration, infiltration, and topography (Hammer, 1989).

Relationships between the HRT of stormwater wetlands and bottom topography have not been directly addressed, to date. Stochastic relationships between storage volume, detention time, and long-term hydrologic effectiveness have been analyzed to determine the optimum storage volume based on the desired HRT and hydrologic efficiency (Wong and Somes, 1995). Existing design guidelines for the internal physical features of wetlands are primarily qualitative and based primarily on aesthetic and ecological purposes (e.g., Schueler, 1992). Ecological considerations for maximum and minimum hydraulic loading rate have been used to determine appropriate flows through wetlands to minimize erosion and damage to wetland vegetation resulting from excessive water velocities, and to ensure proper functioning during drought conditions. However, methods of maximizing HRT by specifying the geometry, and particularly bottom topography, of the wetland relative to specific hydraulic loading rates have yet to be developed.

While not directly addressed in this work, a portion of the hydraulic flow resistance present in wetlands is a result of emergent vegetation. The body of work related to the determination of frictional resistance in wetlands is quite extensive. Work has been done to quantify the resistance as being related primarily to the sum of fluid friction on individual plant stems rather than "channel or packed bed equations" (Kadlec, 1990). Analysis of a broad range of channels has shown that flow resistance in grassed channels may be as much as four orders of magnitude higher than that of typical open channels (Chen, 1976). Many of the equations relating frictional resistance have also been coupled with the effects of microtopography in overland flow (Woolhiser, 1975). Because of the wide range of variation, the effects of frictional resistance could be quite influential in determining HRT.

Topographic flow resistance related to wetland geometry has been analyzed in combination with vegetative resistance, in terms of hydraulic efficiency, as presented by Persson et al., (1999). This work defined hydraulic efficiency as the ratio of the actual detention time to the calculated detention time, as predicted by a plug-flow-reactor (PFR) model.

Because water passes through a wetland at various different speeds, the detention time of different “parcels” of water varies; thus, the residence time is truly a distribution. Several attempts have been made to predict residence time distributions for constructed wetlands (Werner and Kadlec, 2000). Werner and Kadlec (2000) have shown that a PFR model, coupled and interacting with multiple completely stirred tank reactor models along the PFR length, can produce reasonable residence time distributions. However, Werner et al. (2000) noted that this approach was generally inadequate, and there is, of yet, no way to relate bottom topography to reactor model parameters.

Somes et al. (1998) modeled five variations of vegetative resistance and wetland morphology on an existing constructed wetland near South Gippsland, Australia. The work established hydraulic efficiency based on complete use of the wetland volume and the degree of mixing within the wetland. The results show that increased vegetation and either a banded or low-flow channel-type bottom topography has a substantial effect on flow hydrodynamics and increases HRT (Somes et al., 1998). One difficulty with using vegetation to increase HRT and control flow hydrodynamics is that vegetation density varies with the hydrologic regime of the wetland (Persson et al., 1999) and with season; this is not a limitation of using topography to increase HRT.

Based on plan form alone, Persson et al. (1999) identified the following three geometric characteristics that increase hydraulic efficiency within a wetland: large length-to-width ratios, wide uniform depth with laterally uniform flow distribution at the inlet, and wide wetlands with transverse baffles creating a tortuous meandering flow path. These three characteristics were determined to be the most efficient; however, specifics, including number of flow direction changes, size, and amplitude of topographic features and wet areas relative to dry areas were not discussed.

Walker (1998) used a two-dimensional implicit finite difference program to model several rectangular stormwater storage ponds with varying length-to-width ratios and flat (horizontal) bottom topography. Using the results from the simulations, Walker (1998) used the model to predict the performance of an actual stormwater pond following some proposed structural changes to the interior of the pond. The results of the research and procedures described by Walker (1998) are simple and applicable to wetlands of any shape, provided they can be represented by a wetland with an equivalent rectangular shape. The research described herein uses and builds on the research and experience presented by these researchers and focuses on maximizing HRT with variations in topography within the stormwater wetlands.

The purpose of the presented work was to establish relationships between wetland topography and HRT and incorporate these relationships to design procedures. To do so, “synthetic” wetlands were created and numerically simulated with a model that solves the two-dimensional hydrodynamic (also called St. Venant) shallow water flow equations (Fiedler and Ramirez, 2000). Numerical simulation results were used to develop design guidelines aimed at maximizing wetland HRT, and thus stormwater treatment, through specifically designed bottom topography. A design example is included to illustrate the developed design approach.

## Methods

Our research was completed in two stages. First, exploratory simulations were made using numerous bottom topographies to model the general effects of various topographic features on HRT as related to influent flowrates and depth of submergence of wetland topographic features. Rectangular wetlands were modeled to focus on the effects of basic topographic features. One of the benefits of using a numerical model is that a large number of potential bottom topographies can be explored, which is not physically practical. The results from these exploratory simulations were then used to develop a simplified (i.e., not based in two-dimensional numerical modeling), yet comprehensive, design procedure that includes methods for specifying stormwater wetlands bottom topography. The developed procedure was then used to design an example stormwater treatment wetland, which will be built on the University of Idaho (Moscow, Idaho) campus. The new procedures developed by this research will help wetland designers specify geometries that optimize treatment efficiency with respect to bottom topography.

**Numerical Methods.** The numerical model used in this work solves the well-known depth-averaged Navier-Stokes equations for conservation of mass and momentum in two dimensions and has been shown to be fully capable of simulating discontinuous (both wet and dry areas) shallow flows over complex terrain (Fiedler, 1997; Fiedler and Ramirez, 2000). It uses a modified MacCormack explicit finite difference scheme on a structured computational mesh and uses the method of fractional steps, convective acceleration up-winding, and point-implicit treatment of the friction slope term. The scheme is second-order accurate and shock-capturing; thus, it is well-suited for simulating the quick response of small urban watersheds.

The model allows for spatial variation in topography, infiltration, and surface friction over the domain. However, this research is focused on the effects of bottom topography on HRT. Bottom topography is input in the form of a digital elevation model, where an elevation is provided at every computational node. A spatially uniform value of surface friction was assumed, and a sensitivity analysis of this parameter was performed. The infiltration component of the model was not used for this research.

Surface frictional resistance is computed using the Darcy-Weisbach equation. For laminar flow, there is a linear relationship between friction factor ( $f$ ) and Reynold's number ( $R_e$ ) related by the ground-surface-friction parameter ( $K_o$ ) (Woolhiser, 1975). The relationship is as follows:

$$f = K_o/R_e \quad (1)$$

The reported range of values of the resistance parameter  $K_o$  vary from 30 to 120 for bare sand, 1000 to 4000 for sparse vegetation, and 3000 to 10 000 for short grass prairies (Woolhiser, 1975). This range of values was originally developed for use in modeling hillslope overland flow, which is analogous to wetlands. An underlying assumption inherent in calculating the friction factor in this manner is the assumption of laminar flow conditions; in the turbulent flow regime,  $f$  becomes independent of  $R_e$ . Wetlands and overland flow are typically transitional, with characteristics of both laminar and turbulent flow. However, the assumption of laminar flow is typically used in modeling wetland hydrodynamics (Kadlec and Knight, 1996; Walker, 1998).

Values for friction parameters have been established by empirical relationships for vegetative resistance resulting from drag on individual emergent vegetation plant stems (Kadlec, 1990). The wide variability in frictional resistance observed in Kadlec's study

and limited data make it difficult to correlate values of  $f$  calculated in Kadlec's work to  $K_o$  values. Our analysis showed that the range of  $K_o$  values was similar for many vegetative ground covers.

Using the vegetative resistance values obtained by Kadlec (1990) as a general guideline, a  $K_o$  value of 8000 was used for all simulations. The variability of the distribution and abundance of the wetland vegetation because of seasonality is high and thus would be difficult to predict.

Simulation results were analyzed to determine relationships between HRT and bottom topography, plan area of the wetland, and hydraulic loading rates. The HRT was defined for this research as the time from when 50% ( $t_{50}$ ) of the inflow hydrograph volume had entered the wetland to the time when 50% ( $t_{50}$ ) of the outflow hydrograph volume had exited the wetland.

**Bottom Topography Characterization.** As a simple means of globally characterizing complex bottom topography, amplitude ( $\alpha$ ) of the features was computed relative to a base plane passed through the topography, as shown in Figure 1. The base plane was sloped, with approximately the same slope as that from inlet to outlet, passing through the mean midpoint elevation of the features.

Submergence of the features was measured from the trough of the feature vertically to the peak water surface elevation, as illustrated in Figure 1.

The areal mean wetland submergence was defined by the arithmetic average depth of water measured at the troughs of the dominant vertical topographic features. This value was determined at a time near the peak of the passing flood wave and thus is reported as the maximum for a given storm event that passes through the wetland. To compare the potential degree of short-circuiting occurring within wetlands, a measurable parameter, designated the submergence ratio ( $S_r$ ) was conceived. The submergence ratio is defined as follows:

$$S_r = D/2*\alpha \quad (2)$$

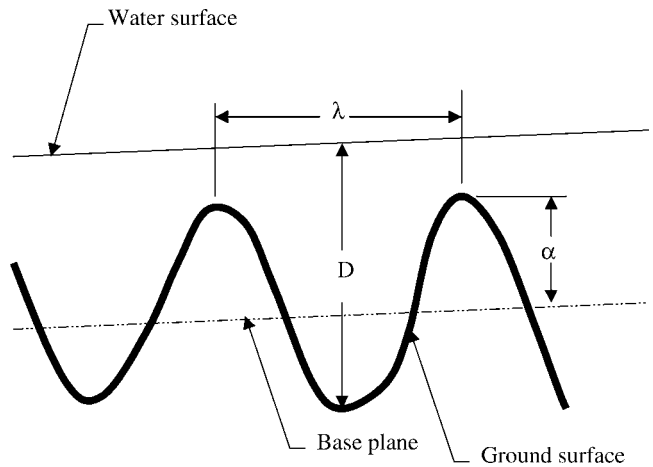
Where

$D$  = average depth, where the units are consistent with those used to define the wavelength ( $\alpha$ ).

This parameter effectively describes the degree of short-circuiting occurring within wetlands with respect to bottom topography. An  $S_r$  value greater than 1.0 represents incipient short-circuiting (i.e., topographic features begin to be overtopped). Wetlands with a ratio less than 1.0 are not dominated by short-circuiting. For wetlands with no topographic features (i.e.,  $\alpha = 0$ ), the ratio is assumed to be equal to 2, because HRT was found (described subsequently) to be independent of  $S_r$  for  $S_r$  values greater than 2 (i.e., short-circuiting dominates) and thus did not affect the overall conclusions being made from the results.

**Exploratory Simulations.** Simulation approaches are frequently used to model both natural and engineered systems when it is not feasible or practical to perform physical experiments. For this work, the described numerical model was used to explore the first-order effects of bottom topography on HRT. The results can be used to guide the design and construction of stormwater treatment wetlands; future research will use measurements made in built wetlands to refine the design procedure developed herein.

Several indirect and qualitative relationships were developed in the course of performing the numerous exploratory simulations. These qualitative relationships describe the effects of shape and location of island features, increased shoreline, deep pools, and scale of topography. We first developed a conceptual model of the topographic features that might influence HRT. Many natural

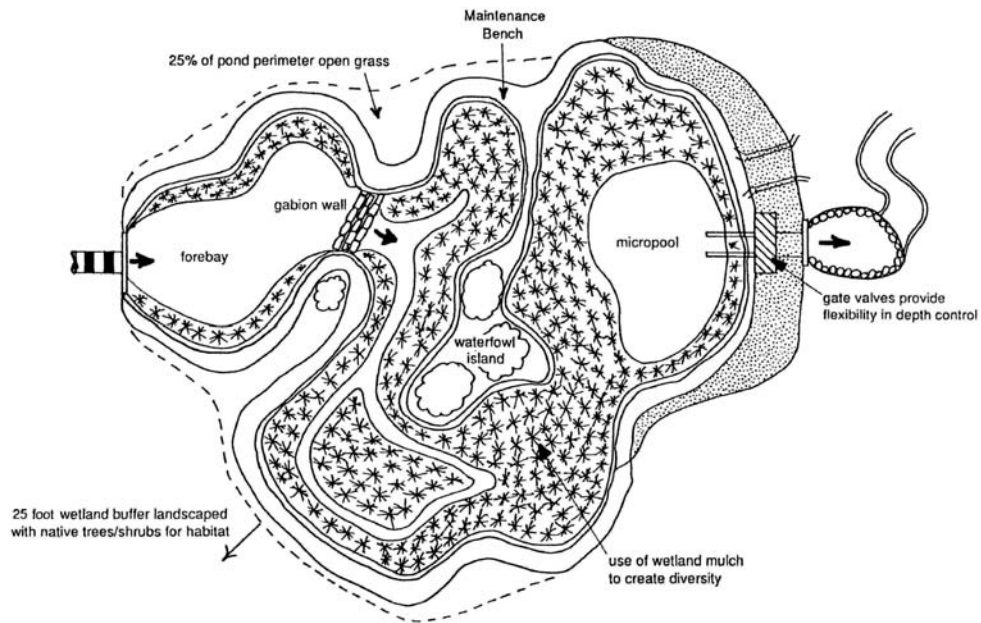


**Figure 1—Definition sketch for submergence ratio calculations.**

wetlands are characterized by extremely complex bottom topography, creating areas of shallow flow combined with deep, slow-moving pools. However, most constructed wetlands result in more uniform flow (in part, because of ease of construction). Thus, a broad spectrum of wetland topographies was simulated. This spectrum ranged from a wide, smooth, uniform-depth wetland to a tortuous meandering wetland with diverse topography, including select features that created islands and pools. While this broad spectrum was intended to span a wide range of potential constructed wetland configurations to develop new design procedures that explicitly incorporate bottom topography, we did not simulate every possible configuration.

To obtain comparable results, all of the exploratory wetlands had the same plan area and overall slope from inlet to outlet crest. Each geometry contained the same forebay necessary for maintenance and sediment removal at the inlet of the wetland and a micro-pool at the outlet, which is typical of constructed wetlands (Schueler, 1992; U.S. EPA, 2000b). Figure 2 illustrates the typical wetland features and configurations recommended by Schueler (1992). The forebay and micro-pool were added to ensure the same influent flow distribution and outflow control characteristics for all of the wetlands modeled.

Schueler (1992) developed guidelines for the plan area of constructed stormwater wetlands based on watershed area and the desired capture volume (90% of all rainfall events) for the wetland. Recommendations were also made for a minimum wetland-to-watershed-area ratio of 1 to 2% (Schueler, 1992). From the work of Walker (1998), wetlands with larger length-to-width ratios have drastically improved efficiency up to ratios of 4; above this, the rate of improvement begins to diminish. Using these existing guidelines and assuming a drainage area of 45.7 ha (identical to the design example described subsequently), a 29-m-wide × 169-m-long wetland (0.49 ha) formed the basis of the preliminary simulations, resulting in a wetland-to-watershed ratio of 1.07%. Note that this is the minimum ratio and that larger ratios will result in larger HRTs from a pure volumetric viewpoint; thus, this can be considered to be the critical case where designed bottom topography is most important. Excluding the forebay and outlet zones, the portion of the wetland that was modified between simulations had a length-to-width ratio of 4.0. The forebay (inlet) and outlet stilling pond represented approximately 30% of the overall length of the wetland



**Figure 2—Shallow marsh wetland system from Schueler (1992) (25 ft = 7.6 m).**

in the downslope direction. The wetlands were designed in this manner so that internal features could be modified without affecting the inlet and outlet hydraulics of the wetlands between simulations. Table 1 provides a summary of key topographic features from select exploratory simulations. Several of the simulated wetlands contained topographic elements that caused the flow path to become

**Table 1—Summary of exploratory simulations.**

Wetland	Description of topography
1	Flat bottom, no topography.
2	Three islands emerging from flat bottom.
3	Meandering, baffled wetland with all baffles the same height. Six flow direction reversals.
4	Meandering baffled wetland with all baffles the same height, slightly taller than wetland 3. Nine flow direction reversals.
5	Meandering baffled wetland with varying baffle height. All baffles inundated under level pool conditions. Three flow direction reversals.
6	Same islands as wetland 2, with disconnected deep pools between islands.
7	Deep pool added near inlet and large island added near outlet of the wetland.
8	Single diamond shaped island added near inlet. Approximately 63 m of shoreline at level pool conditions.
9	Single island, random shape added near inlet. Approximately 70.5 m of shoreline at level pool conditions.
10	Twelve islands with varying vertical scales and interstitial deep pools.
11	Five islands with single vertical scale and interstitial deep pools.
12	Same topography as wetland 4; however, every third baffle height was increased by 5 cm, slightly above the peak water surface elevation at this design flow.

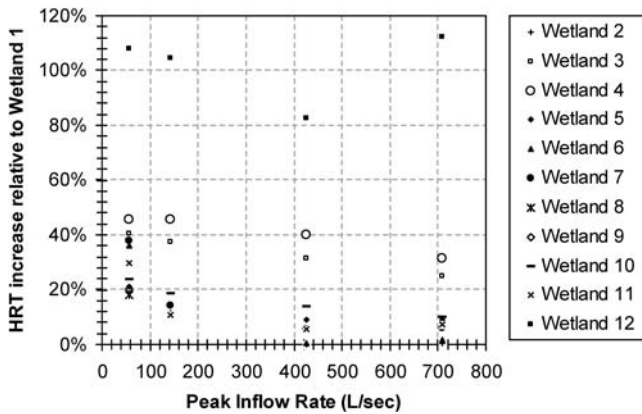
tortuous with multiple flow direction reversals. These elements essentially acted as “baffles” within the wetland. The baffles were generally arranged so that the end of one baffle overlaps, at least slightly, the end of the next baffle to cause a flow direction change and minimize the chance for short-circuiting.

The wetlands were modeled with the model of Fiedler and Ramirez (2000) (described previously) on a 1 m × 1 m grid. For wetlands with many wet-dry interfaces (highly variable topography), the grid resolution was reduced to 0.5 m × 0.5 m. A broad-crested weir with the same width as the wetland was specified for the outlet. Simulations were initialized with each wetland in a “just full” condition (water at the elevation of the crest of the outlet weir).

The key outcome from the preliminary results was the identification that wetlands containing multiple vertical scales of topography produced increased HRTs relative to single-scale topographies with comparable overall hydraulic volume. This hypothesis was tested in further simulations of a case-study wetland.

**Design Example.** The results of the exploratory simulations were used, in combination with currently accepted practices, to develop new design guidelines; the results and guidelines are presented subsequently. To illustrate how the developed design guidelines are used, they were applied to the design of the stormwater treatment wetland that is planned for construction on the University of Idaho campus.

A large portion of the University of Idaho campus contributes runoff to the planned wetland. The contributing watershed area is approximately 45.7 ha. The land use consists of approximately 8.1 ha of forest, with the remaining area being a mixture of buildings, paved, and unpaved parking lots, and lawn. The storm drains from the watershed currently discharge into a 335-m-long reach of Paradise Creek, where the creek is confined to a covered box-culvert. The University of Idaho plans to alter the course of Paradise Creek and reestablish a natural channel 200 to 300 m north of the current alignment close to the 1897 historic stream alignment. The realignment of Paradise Creek out of the box culvert would allow for the stormwater draining to the box-culvert to be



**Figure 3—Hydraulic residence time increase relative to wetland 1 versus peak inflow rate.**

pretreated by one or two wetland cells before discharge into Paradise Creek.

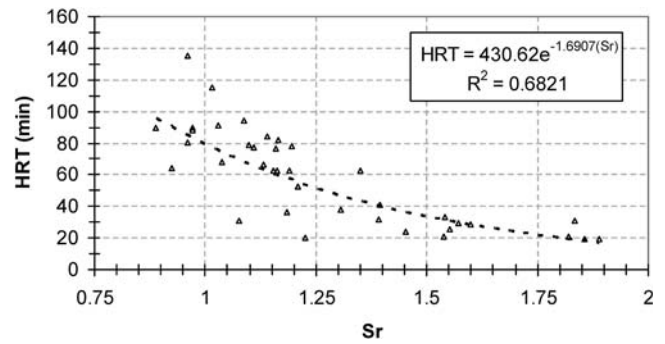
**Results and Discussion**

Exploratory simulations revealed that bottom topography has minimal effect on HRT for relatively large return period floods. For a minimum wetland-to-watershed ratio of approximately 1%, the flood hydrographs for the 10- and 25-year return period events caused wetland water levels to inundate most physically realistic bottom topography ( $S_r$  ranged from 0.89 to 2.17). Variations in HRT because of changes in bottom topography for these floods were insignificant. Consequently, subsequent exploratory simulations focused on the 2-year and smaller events. These low, but more frequent, flows contribute the bulk of the volume of stormwater. By increasing HRT and therefore treatment efficiency of low-flow events and making marginal gains in increasing HRT for moderate events, overall treatment of stormwater may be significantly improved. Additionally, for larger wetland-to-watershed-area ratios, designed bottom topography will improve HRT for larger events.

Simulations of numerous wetlands with differing topographies were made, including several minor variations to individual cases. Four different flowrates, all being near or below the 2-year flood, were simulated for each wetland with inflow hydrographs having peak flowrates of 57, 142, 426, and 710 L/sec. From these simulations, results were made relative (normalized) to the results obtained for wetland 1 (no topography; see Table 1).

The relative increases in HRT associated with the topographies described in Table 1 are provided in Figure 3. As indicated by these results, improvements in detention time can be maintained over a considerable range of low flowrates.

As the flood waves passed through the wetlands, those with multiple-scale topographic features were inundated to varying depths. Also, for the higher peak floods, some features became completely inundated and were overtopped, resulting in short-circuiting of the wetland. Note that wetland 12 performs better than wetland 4 because the baffle height was increased to an elevation greater than the peak-water-surface elevation. The effects of variable overtopping of multiscale topographic features on HRT is a key result and demonstrates the importance of the amplitude of the topographic features; as the lowest elevation features become inundated, the moderate elevation features begin to control flow directions; as these then become inundated, the highest elevation



**Figure 4—Short-circuiting ratio versus HRT.**

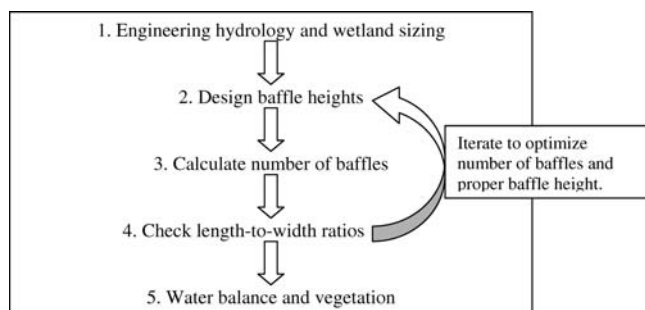
features control. Therefore, constructed wetlands should be designed with bottom topographies characterized by multiple elevations, rather than with more uniform topographic features.

Ultimately, one of the conclusions from this research is that more work is necessary to explore all of the ways that HRT is controlled by bottom topography. The focus of this research was on developing relationships and design procedures to create more effective constructed treatment wetlands. The following discussion summarizes the important findings of the exploratory simulations; note that many other exploratory simulations were made, and only key select results are presented.

The first individual topographic element shown to increase HRT is the addition of an island downstream of the sediment forebay. The island should be placed so that it essentially diverts the influent stream around itself. The island should be shaped to maximize the length of shoreline, while eliminating areas of stagnation. The total number of island features in a wetland must be balanced against the wetland volume. Each provides beneficial increases to HRT; however, the increase in HRT resulting from the volume gained by not including multiple islands typically outweighs the increases in HRT resulting from flow division created by the islands (an exception being the island located just past the sediment forebay). When multiple islands are used, adding a pool or “deeper” flow path can compensate for the volume of water displaced by the island feature. Islands should only be used in situations where topographic baffles are not able to be used because of intervening constraints, as baffles were generally found to be more effective.

Baffles direct the flow through the wetland creating an increased flow path length. Increasing the depth of flow between the baffle elements offsets the volume of the wetland lost by the addition of the baffles. The height of the baffles is their most important characteristic. Based on the previous discussion, there should be several distinct vertical scales to increase HRT over a range of flows; design specifications for multiscale baffles are presented in the following sections. The design heights of the baffles are influenced by several factors, including the return period of the flood being passed through the wetland and the amount of influence that the baffles have once they have been overtopped by the passing flood wave.

A value for  $S_r$  was established for each of the simulation wetlands for all four flowrates. The resulting data were fit with an exponential decay function. The resulting function, having an  $R^2$  value of 0.69, is a reasonable fit to the data, as shown in Figure 4. Detention time decreases with increasing  $S_r$ , as expected. For values of  $S_r$  higher than approximately 2.0, HRT is independent of  $S_r$ . This information is very useful, in a qualitative sense. However, attempts to correlate these observations for use in simplified design procedures applicable to generalized situations were not successful because of other



**Figure 5—Flow chart for stormwater wetland design procedure calculations.**

influencing factors, including inlet and outlet hydraulic controls and overall slope from inlet to outlet.

Based on the results of exploratory simulations, a procedure for designing the topography of the stormwater wetlands was created. This procedure incorporates many of the current elements and features being used in the design of stormwater wetlands plus specification of multiple-scale bottom topography. The following section describes how the concepts of our work are integrated with the works of others to design a stormwater treatment wetland; detailed explanations of standard procedures are not presented. The developed procedure is outlined in Figure 5.

**Step 1—Engineering Hydrology and Wetland Sizing.** This step involves calculating the magnitude and timing of the runoff to be treated by the wetland. The hydrographs synthesized in this step are needed for subsequent use in the procedure and are the 2-, 10-, and 25-year return period floods. Standard engineering hydrology principles are used.

The wetland can be sized (plan area and volume) by either of two methods. The first method uses hydrologic considerations and is based on recommendations from several previous researchers; these recommendations are general (e.g., wetland area equal to 1 to 2% of watershed area) and do not consider specific treatment limits. The second method for sizing is based on treatment considerations. This method is only used when a desired treatment performance is required by the design, and it requires estimates of reaction rate coefficients. Often, discharge regulations, such as requiring the peak outflow discharge to be equal to or less than predevelopment conditions, are not set for stormwater discharges for treatment purposes. The details of this step are not addressed in this paper; once the wetland size is determined, the following procedures are used increase HRT.

**Step 2—Establish Baffle Heights.** Baffle systems with multiple vertical scales were shown to be effective in increasing HRT over a range of flows in the exploratory simulations. Bottom topography characterized by three distinct heights balances design and construction complexity against effectiveness. In the first iteration, an estimate of the number of baffles to be used in the wetland is made, and it is refined based on subsequent steps. The first estimate is made by establishing a low-flow length-to-width ratio, using the length of the tortuous flow path created by the baffles and the width of that flow path (as opposed to the overall dimensions of the wetland), of approximately 8:1. The high-flow length-to-width ratio should be approximately 2:1, if possible. High flows inundate the majority of topographic features; thus, the 2:1 ratio applies to the overall wetland plan area.

The height of the lowest scale of topography is established first. This is done by assuming one-dimensional flow and applying

**Table 2—Depth recommendations based on percentages of treatment volume and aerial extent of treatment wetland (Schueler, 1992).**

	Forebay	Micropool	Deepwater <sup>a</sup>	Low marsh <sup>b</sup>	High marsh <sup>c</sup>
Volume	10%	10%	10%	45%	25%
Area	5%	5%	5%	40%	45%

<sup>a</sup> Deep water: 30 to 180 cm below normal pool<sup>d</sup>.

<sup>b</sup> Low marsh: 15 to 45 cm below normal pool<sup>d</sup>.

<sup>c</sup> High marsh: 0 to 15 cm below normal pool<sup>d</sup>.

<sup>d</sup> Normal pool is defined as the depth when the water surface is the same elevation as the weir outlet.

Manning's equation to predict the depth at which the first set of features is overtopped at a design flowrate equal to 8% of the 2-year flood peak flowrate. The cross-sectional channel shape can be assumed to be either a triangular or trapezoidal for this computation, as use of more complex shapes do not significantly affect the end result. The width of the low-flow channels is estimated based on the number of baffles required to obtain an 8:1 length-to-width ratio that will fit in the overall wetland area and limits on constructability (discussed subsequently). Preliminary low-scale topographic estimates are refined based on the results of steps 3 and 4.

Similarly, using a design flowrate equal to 25% of the 2-year flood peak flowrate, the height of the second scale of topography is established. A length-to-width ratio of 4:1 is used for computations, and channel top-widths are calculated assuming a trapezoidal cross-section with 15% side slopes. The bottom width of these channels includes the total width of the next lowest scale of topography.

The highest scale of topography is determined by estimating the maximum pool elevation using standard hydrologic routing procedures for the largest design event to be handled by the wetland. The flood routing process itself is also iterative, requiring simultaneous design of the wetland outlet works (weirs and/or orifices).

The stated percentages of the 2-year flood flowrate used for determining the low- and mid-scale topographic feature heights cause each scale of topography to be approximately 1.5 times the height of the next lowest level of features. As shown in the exploratory simulations, as  $S_r$  approaches a value of 2, bottom topography has less control over flow paths. By choosing flows that approximately correspond to an  $S_r$  value of 1.5, the designer is assured that the bottom topography exerts fairly continuous control over flow paths over a range of discharges. While both the values of 1.5 and the 2-year design discharge are somewhat arbitrary and wetland designers may find other values and design flows that increase HRT, we found these to be reasonable.

**Step 3—Calculate Number of Baffles.** Currently, wetland bottom topography is based on several different criteria, including those recommended by Schueler (1992). The first existing criterion is to create specific depth regions based on portions of the total wetland volume. These depth regions should also be based on portions of the total areal extent of the wetland. These criteria are recommendations to be used as guidelines, not as strict rules. Site conditions and physical restrictions may dictate alterations of these recommendations. The existing criteria are given in Table 2. As bottom topography is specified by the procedure presented in this paper, the designer must check the criteria presented in Table 2.

As baffles often will be constructed from on-site soils, their side slopes should not exceed approximately 15%. This will ensure

a reasonably stable slope within the wetland and help to minimize erosion and soil loss and minimize the possibility of the baffles being washed out by higher return period flood waves. Practical consideration to the design of the baffles is necessary. The tallest baffle (highest level of topography) should be designed so that the top width of the baffle is wide enough to be used for access with maintenance equipment. It is critical that baffles be arranged so that the end of one baffle overlaps, at least slightly, the end of the next baffle to cause a flow direction change and minimize the chance for short-circuiting; the overlap need not be large, as momentum effects will force the water to flow past the baffle ends. Also, the baffles should be approximately uniformly distributed in plan throughout the wetland.

An interesting discovery made during the exploratory simulations was that, if too many baffles were added, low hydraulic conveyance resulted, and all of the baffles became overtopped by the passing flood wave, thus creating short-circuiting. Thus, the method suggested for determining the number baffles is to calculate the channel cross-sections, as defined by the baffles necessary to pass the design flows for each flow condition. The cross-section geometries are determined using Manning's equation and the baffle heights calculated in step 2. The cross-sections are then used to estimate how many baffles can be arranged in the wetland area by positioning cross-sections in the wetland to create distinct flow channels for each of the design discharges, while maintaining flow-direction changes, ubiquitous constructed wetland features (i.e., a sediment forebay), limits on allowable slopes, and adequate top-widths of the highest-scale features as required for maintenance. This step is creative in nature, and the number of potential configurations is essentially limitless.

As with any design, this procedure is iterative. If the recommendations in Table 2 are not met after creating bottom topography, then the estimated number of baffles within the wetland may need to be reevaluated, and the height of the baffles recalculated as per step 2. If the Table 2 recommendations are met, then move on to Step 4.

**Step 4—Check Length-to-Width Ratios.** An adequate flow path length for the various flood levels within the wetland must be ensured for the wetland volume to be used efficiently. The recommended length-to-width ratios are 8:1 for the low-flow conditions (8% of the 2-year flood flowrate), 4:1 for the midlevel conditions (25% of the 2-year flood flowrate), and 2:1 for high-flow conditions, typically taken as the water level when the 25-year flood is routed through the wetland. This means that the wetland should be designed so that the highest level of topography (tallest baffle) should only be overtopped by floods with greater than a 25-year return period. The layout and baffle configuration should be adjusted so that each of these guidelines is met within reason.

**Step 5—Water Balance and Vegetation.** The final step is to calculate the dry weather hydrologic water balance for the wetland. The water balance should show that an adequate depth of water can be maintained in the wetland to support and maintain healthy wetland vegetation in the low-flow channel. The water balance should incorporate evapotranspiration and infiltration losses.

By designing the topography within the wetland in relation to specific water levels, the plant species to be used in the wetland can be specifically related to topographic elevation and time periods of inundation. Appropriate wetland vegetation, of course, also varies with geographic location. Water depth zones can be mapped throughout the wetland to ensure that plant species are planted in specific elevation zones to maximize their ecological success. Note that, because of the strong role vegetation plays in frictional flow resistance, vegetation can also be chosen, in part, to maximize flow resistance and increase HRT. While this research focused on the

effects of bottom topography rather than frictional flow resistance, a sensitivity analysis of the assumed  $K_o$  was also performed to show the relative effect that this value has on the overall results. The analysis showed that HRT is linearly correlated to  $K_o$ , for  $K_o$  values from 2000 to 14 000. Additional research on frictional resistance parameterization appropriate for high-resolution two-dimensional modeling and specification of plant species to maximize HRT in constructed wetlands with complex bottom topography appears warranted. Finally, certain types of vegetation are known to be more effective in treating a given contaminant; this will also play a role in the selection of vegetation.

### Design Example

Stormwater runoff from the University of Idaho Campus in Moscow, Idaho, is proposed to be treated with a constructed wetland. This project was used as a design example to illustrate application of the above procedure to a real situation. Physical site constraints include existing parking lots, roads, and railroad tracks, and control the location and size of the wetland. Because of the site restrictions, the geometry and topography of the wetland needed to be specified so that the space allotted for the wetland was used in the most efficient manner, which is not an uncommon occurrence. The developed procedure was used to design the bottom topography of the wetland to maximize HRT and thus overall treatment efficiency.

The wetland cells will be located at the outlet of the 335-m-long box-culvert that passes through the center of the University of Idaho campus. Stormwater discharging from the 17 storm drains that empty into the culvert will be treated by the wetland before emptying into the main channel of Paradise Creek. While no water quality data currently exist, stormwater is expected to contain contaminants typical of runoff from a developed, landscaped area, including sediment and nutrients, which are contaminants of concern in Paradise Creek. The bulk volume of the wetland was sized to capture the 10-year flood, and the wetland-area-to-watershed-area ratio was approximately 2.6%; this area just fits into the available space. A digital elevation model (DEM) of the existing site was developed using site survey data. The DEM of the site is illustrated in Figure 6. Note that site characteristics primarily dictate the widths of the wetland inlet and outlet.

The DEM was then modified, creating a DEM of the wetland, in accordance with the presented design procedure. The wetland DEM was used as input to the hydrodynamic model, the results of which were used to compute HRT.

For the low-flow conditions (142 L/sec, 8% of the 2-year flood peak), the height of the lowest scale of baffles was computed to be approximately 25 cm using a Manning's  $n$  of 0.1 and a trapezoidal-shaped channel. The second scale of baffles was computed to be approximately 35 cm, at a design flowrate of 426 L/sec (25% of the 2-year flood peak). The height of the highest level of features was calculated to be approximately 55 cm, using the results of routing the 25-year flood (value) through the wetland. The number of baffles and layout configurations were determined in an iterative manner so that the depth-volume and depth-area relationships were reasonably met, and side slopes of the baffles were maintained at less than 15%. Figure 7 illustrates the bottom topography of the designed wetland.

The length-to-width ratio for the designed wetland was well over 8:1 (approximately 50:1) for the low-flow (8% of 2-year flood peak) case and over 2:1 for the high-flow (25-year flood peak) case. For comparative purposes, a wetland with the same shape and volume as the designed wetland, but with no internal topography, was created. The comparison wetland has the same outlet weir

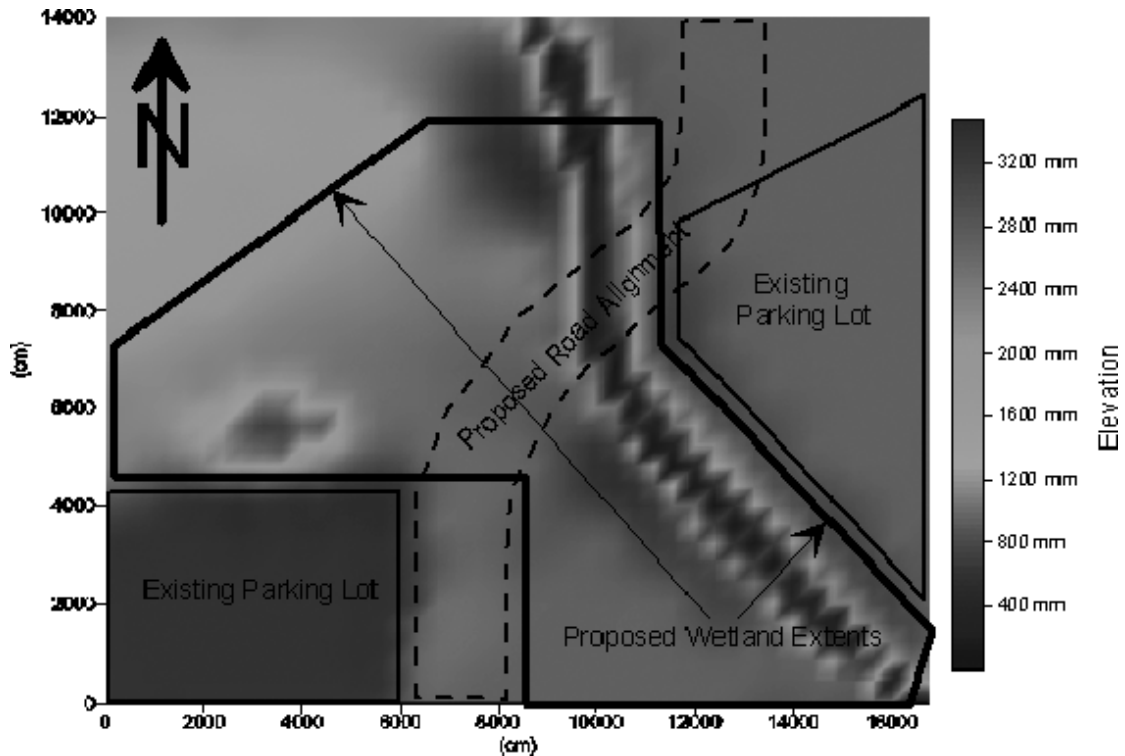


Figure 6—Design example wetland site map and digital elevation model.

configuration and sediment forebay as the wetland with designed bottom topography (Figure 8); however, the internal topographic features have been removed and replaced with a flat bottom while maintaining reasonable side slopes at the wetland boundaries. Inflow into the wetlands is at the top of the Figures 7 and 8, and the

outlet weir is located near the bottom left corner. The inlet and outlet configurations were designed to coincide with the physical space constraints presented at the site resulting from adjacent parking areas, inlet box-culvert, and downstream stream channel.

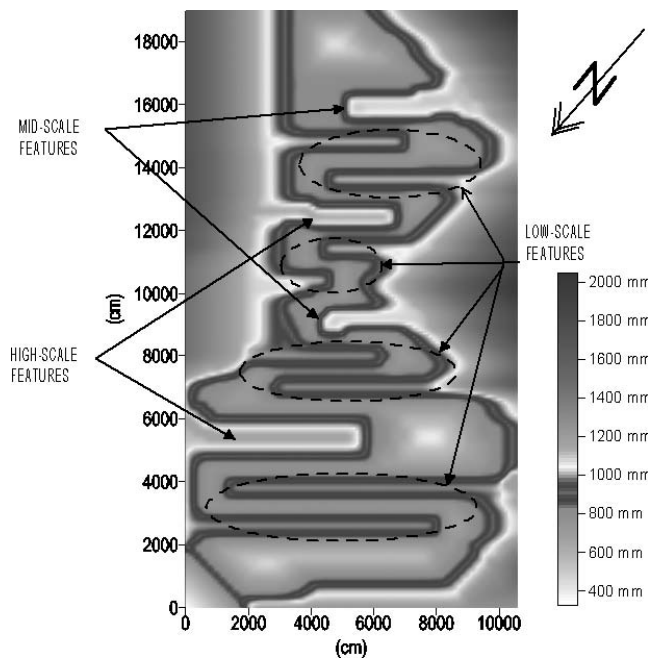


Figure 7—Design example wetland topography (ground surface elevations) developed using the proposed design procedure. Outlet weir elevation = 900 mm.

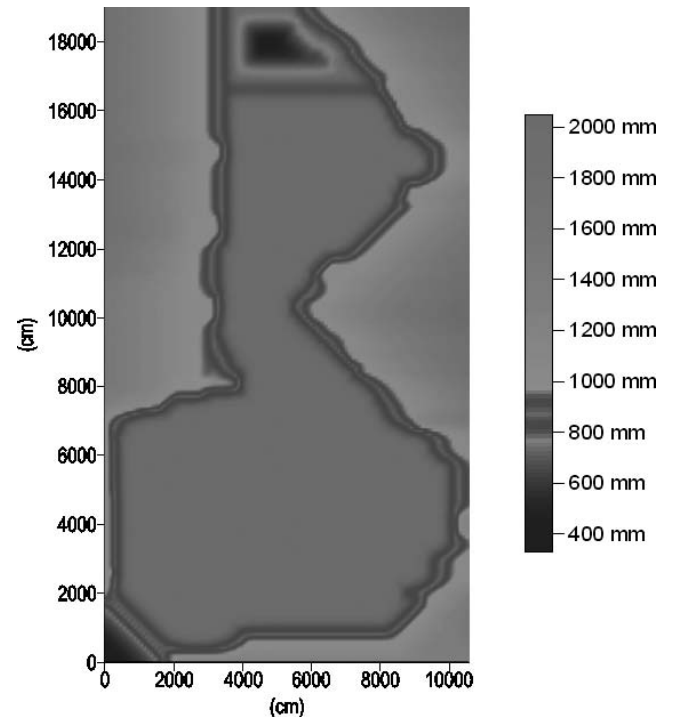
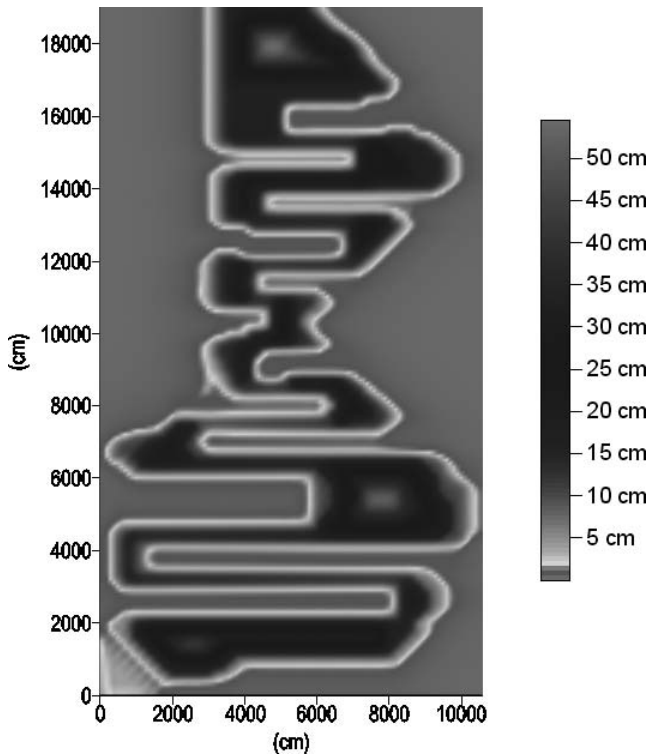


Figure 8—Flat-bottom comparison wetland, ground surface elevations. Outlet weir elevation = 900 mm.



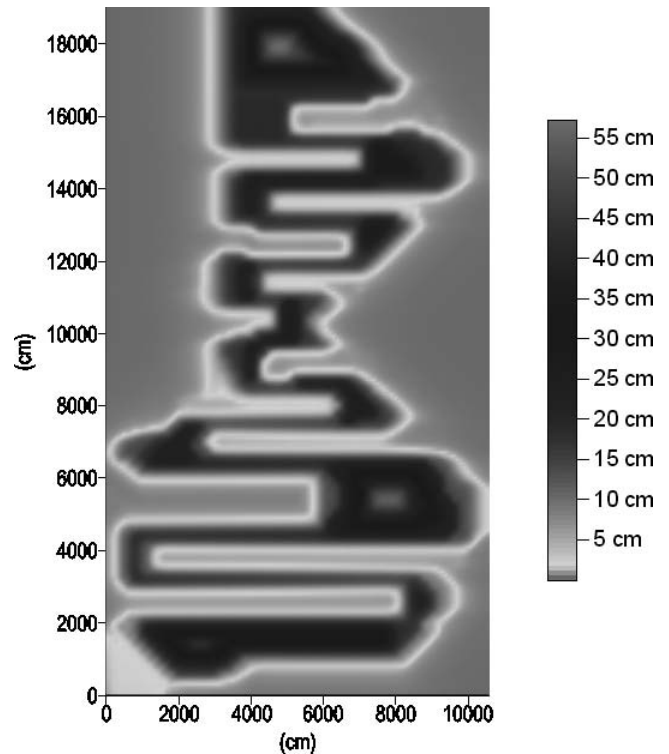
**Figure 9—Water depth distribution for 8% of 2-year flood peak (142 L/sec) case.**

Compared with the flat-bottomed wetland, the designed wetland performed very well in all simulations. Figure 9 shows the distribution of water depths as the low-flow (8% of the 2-year peak flow) case passed through the wetland. Figure 10 shows the distribution of water depths as the mid-level-flow (25% of the 2-year peak flow) case passed through the wetland. As Figures 9 and 10 show, the water depths over the lowest- and second-scale features were predicted to be within 1 to 2 cm for both cases. To illustrate the control that the topography has over the flow direction, even as the features are overtopped, a plot showing water depth distributions and depth averaged discharge vectors was generated as the 25-year flood wave passed through the wetland (Figure 11). Note that, in some areas, flow direction is opposite the expected flow direction, as a result of very shallow water depths. These areas have flow depths of less than 1 cm and are essentially stagnant. As Figure 11 illustrates, as both of the lowest levels of baffles are overtopped, they maintain a considerable amount of control over the flow direction (up to an  $S_f$  value of approximately 2).

The wetland with designed topography produced drastic increases in HRT over one without designed bottom topography. For the low-flow case, the improvement was approximately 113% relative and was approximately 39% at the full 2-year flood flowrate. For the 25-year runoff event, HRT is typically short, regardless of bottom topography, and treatment likely would be minimal. However, some flood attenuation and physical removal of contaminants is still maintained by the wetland.

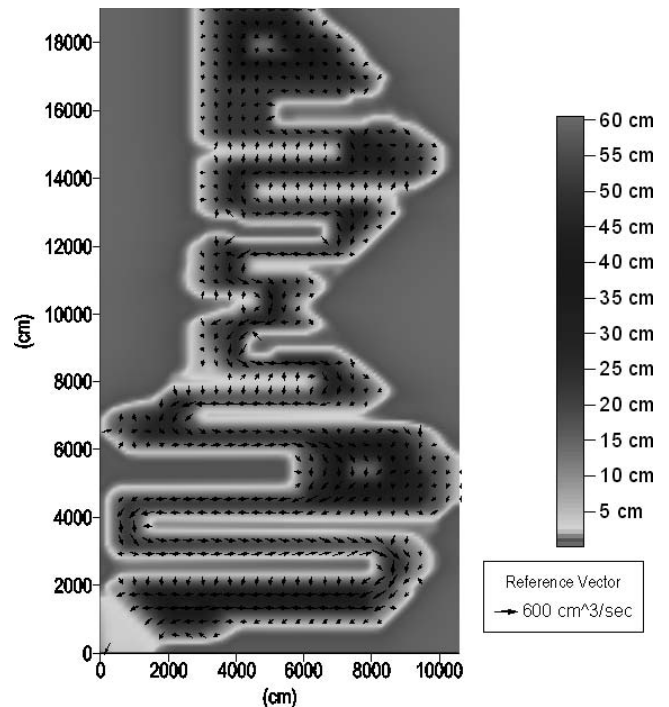
**Conclusions**

Current design methods for constructed stormwater wetlands do not explicitly account for the large effect that bottom topography has on HRT. The results of this work show that a reasonably simple



**Figure 10—Water depth distribution for 25% of 2-year flood peak (426 L/sec) case.**

procedure can be used to design the bottom topography of stormwater wetlands and markedly increase HRT. Creating baffled wetlands with *multiple vertical scales* of topography create conditions that cause the wetland volume to be used more efficiently.



**Figure 11—Depth-averaged discharge vectors overlaid on water depth distribution for 25-year flood case.**

Baffles increase the flow path length through the wetland and thus increase detention time. Multiple vertical scales of baffles cause them to be overtopped by differing return period floods, thus increasing HRT over a range of events. While overtopping reduces the flow path length, the interaction with the next highest scale of topography still eliminates complete short-circuiting of the wetland until the very highest design event. The presented procedure will enable designers to minimize land use and increase treatment efficiency (via increasing HRT) when designing stormwater treatment wetlands.

While this work has shown the importance of bottom topography on HRT and used simulation results to develop an improved constructed wetland design procedure, it is by no means comprehensive. It is possible, for example, that future work will show that other topographic factors, such as discrete islands in select locations, meander frequency, and the relative placement of baffles, will further improve HRT. The procedures developed through numerical simulations should be refined with measurements from actual wetlands; we hope to build the wetland described in the design example and publish monitoring results and procedure modifications in a subsequent paper. Preliminary work shows that flow resistance has a strong effect on HRT; thus, future research on the effects of various types of vegetation should be performed. Finally, the results of this and future work should be integrated to develop a comprehensive, quantitative design procedure that simultaneously considers bottom topography, hydraulics, hydrology, and vegetation.

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