OPTIMIZATION OF RESIDENCE TIME IN CONSTRUCTED FREE WATER SURFACE WETLANDS THROUGH BATHYMETRIC DESIGN

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INTRODUCTION

Storm water runoff from urbanized watersheds can potentially contain numerous contaminants that reduce water quality. Pollutants commonly present in storm water include sediment, toxic substances, heavy metals, pathogens, oxygen-demanding material, nutrients, and debris. Contaminants can diminish water quality as well as hinder aquatic habitat in the water body receiving the storm water discharge (USEPA, 2000a).

Constructed free water surface (FWS) wetlands have become a more popular method of storm water treatment used by practitioners, due to the increasing need for ecological and economically feasible means of detaining and treating urban storm water runoff. Constructed (and natural) wetlands behave similarly to the physiochemical and biological reactors used for treating wastewater, and are thus governed by the same physical laws and parameters as mechanical reactors. A principal parameter used in establishing the treatment effectiveness of reactors is the residence time. The mean residence time, or detention time, for a reactor is the average amount of time the material being treated spends in the reactor. Because the processes that are occurring within a wetland are all a function of time, maximizing the residence time will ultimately improve the treatment. The simplest method of increasing detention time is by increasing the wetland volume. However, space and cost limitations indicate that research focused on finding ways to improve and increase residence time of wetlands is warranted.

The objective of this work was to establish relationships between wetland bathymetry and hydraulic detention time using a model that solves the two dimensional hydrodynamic (St. Venant) shallow water flow equations. Simulation results were used to develop design guidelines for maximizing wetland hydraulic residence time, and thus storm water treatment, through specifically designed bottom topography.

Design guidelines for the physical features of the wetlands are currently qualitative, and based primarily on aesthetic and ecological purposes (e.g., Schueler, 1992). The research described herein utilizes and builds on the research and experience presented by previous researchers and focuses on maximizing HDT with variations in topography within the storm water wetlands.

METHODS

Our research was completed in two stages. Preliminary simulations first were made using generated topographies to simulate the effects of various topographic features. Simple rectangular wetlands were simulated in order to focus on the basic topographic features influencing HDT. The results from these simulations were then used to develop design procedures. The developed procedures were used to design a storm water treatment wetland that will be built on the University of Idaho campus in the near future.

The numerical model used in this work solves the 2-D hydrodynamic equations using a modified MacCormack, explicit finite difference scheme. The model was originally developed to solve the 2-D hydrodynamic equations for simulating overland flow with microtopography and interactive infiltration (Fiedler, 2000). The model allows for spatial variation in topography, infiltration and surface friction over the domain. However, for the purpose of this research only the effects of topographic features were examined. Uniform flow resistance was assumed, calculated using the Darcy-Weisbach equation. For laminar flow there is a linear relationship between friction factor (f) and Reynold's number R_e (Woolhiser, 1975) which is written

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

The resistance parameter, K_o, ranges from 30 to 120 for bare sand, from 1,000 to 4,000 for sparse vegetation, and from 3,000 to 10,000 for short grass prairies (Woolhiser, 1975). A K_o value of 8000 was used for all simulations. A sensitivity analysis of the assumed K_o was also performed to show the relative impact that this value has on the overall results. The analysis showed that HDT is linearly correlated to K_o for K_o values from 2,000 to 14,000.

Simulation results were analyzed to determine relationships between HDT, wetland morphology, physical characteristics of the topography, plan area of the wetland, and hydraulic loading rates. Hydraulic detention time 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. Submergence of the features was measured from the trough of the feature vertically to the water surface as illustrated in Figure 1.

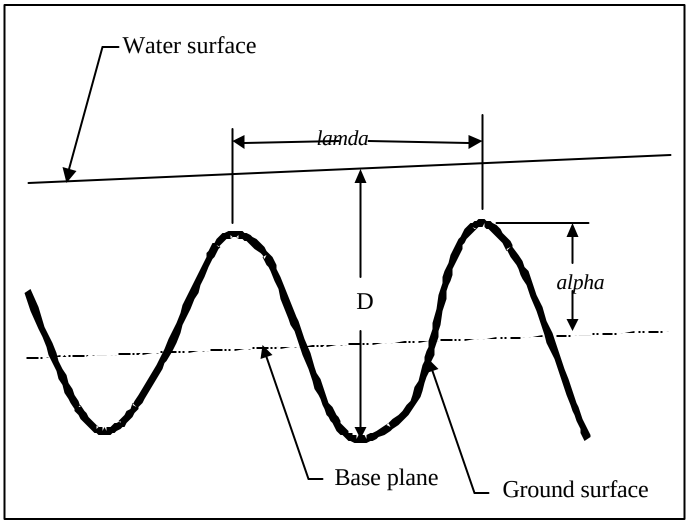

Figure 1. Definition sketch for submergence ratio calculations.

A mean wetland submergence was defined as the arithmetic average depth of water measured at the troughs of the dominant vertical topographic features. This depth measurement was taken near the peak of the passing flood wave. In order to compare the degree of short-circuiting occurring within the wetlands, a measurable parameter, designated the Submergence Ratio (S_r) was developed. The submergence ratio is defined as

$$S_r = D / 2 * a \qquad (2)$$

This parameter effectively describes the degree of short-circuiting occurring within wetlands. A ratio greater than 1.0 represents initiation of short-circuiting. Wetlands with a ratio less than 1.0 are not dominated by short-circuiting. For wetlands with no topographic features (i.e., $a = 0$) the ratio was assumed to be equal to 2. This value was assumed because HDT was found to be independent of S_r for S_r values greater than 2.0 (i.e., short-circuiting dominates) and thus did not affect the overall conclusions being made from the results.

The first step in the research was to develop a conceptual model of the topographic features that might influence HDT. Many natural wetlands exhibit a very sinuous meandering shape creating areas of shallow flow combined with deep slow moving pools. However, many constructed wetlands result in more uniform flow, in part due to ease of construction. Simulations thus encompassed this spectrum, with topographies ranging from a wide, smooth, uniform depth wetland, to a tortuous meandering wetland with a diverse bathymetry, as well as randomly shaped bathymetries containing islands and pools. All of the wetlands had the same plan area and overall slope from inlet to outlet crest. Each bathymetry contained the same forebay necessary for maintenance and sediment removal at the inlet of the wetland, and a micro-pool at the outlet, typical of constructed wetlands (Schueler, 1992) and (USEPA, 2000(b)). The forebay and micro-pool were added to insure the same inflow distribution, as well as out flow control characteristics for all of the wetlands modeled.

Engineering hydrology, i.e., determination of the magnitude and timing of storm water runoff, will be fundamental in any treatment wetland design. In the case study, a portion of the University of Idaho (UI) campus contributes runoff to the planned wetland. The contributing watershed area is approximately 45.7 hectares. The land use consists of about 8.1 hectares of forest, with the remaining area being a mixture of buildings, paved, and unpaved parking lots, and lawn.

Schueler (1992) developed guidelines for the plan area of constructed storm water 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 improved efficiency up to L:W ratios of 4; above which the rate of improvement begins to diminish. Using these guidelines, a 29-meter wide by 169-meter long wetland (0.405 hectare) formed the basis of the preliminary simulations, resulting in a wetland-to-watershed ratio of 1.07%. Excluding the forebay and outlet zones, the portion of the wetland that was modified between simulations had a L:W ratio of 4.0.

Wetland hydraulic function was simulated with the model of Fiedler (2000) on a one meter by one meter grid. For wetlands with many wet-dry interfaces (highly variable topography) the grid resolution was reduced to 0.5 meters by 0.5 meters to obtain a good mass balance.

The wetlands were designed with features and geometries present in constructed wetlands and in naturally occurring wetlands, with a broad-crested weir for the outlet works. The effects of including or excluding various features from a design were quantified through the beneficial increase of HDT and elimination of stagnation zones within the wetland. Simulations were initialized with each wetland in a “just full” condition (level pool at the elevation of the crest of the outlet weir). Specific details of the wetland morphologies analyzed and results of the comparisons are presented in Table 1.

Table 1. Summary of preliminary simulations.

Wetland Name	Description of Topography	Purpose of Simulation	Results
1	Flat bottom, no topography	Base case used for comparison.	NA
2	Three islands emerging from flat bottom.	Compared to Wetland 6 and Wetland 7 to determine the effects of disconnected deep pools and island location.	See below.
3	Meandering, baffled wetland with all baffles the same height. Six flow direction reversals.	Compared to Wetland 4 to determine the effect of increased number of baffles.	See below.
4	Meandering baffled wetland with all baffles the same height, slightly taller than Wetland 3. Nine flow direction reversals.	Compared to Wetland 3 to determine the effect of increased number of baffles.	Increased number of baffles increases flow path length and improves HDT.
5	Meandering baffled wetland with varying baffle height. All baffles inundated under level pool conditions. Three flow direction reversals.	Determine the effects of baffles being inundated during low flow conditions.	Baffles that are completely inundated allow short-circuiting and have minimized effect on HDT.
6	Same islands as Wetland 2, with disconnected deep pools between islands.	Compared to Wetland 2 to determine the effects of disconnected deep pools.	Disconnected deep pools cause no direct improvement of HDT.

7	Deep pool added near inlet, and large island added near outlet of the wetland.	Compared to Wetland 2 to determine the influence of island location, near inlet versus outlet.	No preference for island location.
8	Single diamond shaped island. 63 meters of shoreline at level pool conditions.	Compared to Wetland 9 to determine the influence of increased shoreline.	See below.
9	Single island, random shape. 70.5 meters of shoreline at level pool conditions.	Compared to Wetland 8 to determine the influence of increased shoreline.	Increased shoreline creates small increase in HDT.
10	Twelve islands with varying vertical scales and interstitial deep pools.	Compared to Wetland 11 to determine the influence of multiple vertical scale topography.	See below.
11	Five islands with single vertical scale and interstitial deep pools.	Compared to Wetland 10 to determine the influence of multiple scale topography.	Multiple scale island topography improves HDT.
12	Same topography as Wetland 4, however every third baffle height was increased by 5 cm.	Compared to wetland 4 to determine the influence of multiple vertical scale topography.	Multiple scale baffles drastically improve HDT versus single scale baffles.

RESULTS AND DISCUSSION

The first three preliminary rectangular wetland simulations revealed that topography has minimal impact on HDT for 2-year or higher return period floods for the size of the wetlands in question. For a wetland to watershed ratio of 1%, the flood hydrographs for the 10-year and 25-year return period events caused wetland water levels to completely inundate any physically realistic bottom topography (S_r ranged from 0.89 to 2.17). Variations in HDT due to changes in topography for these floods were insignificant.

Analysis of the HDT from these three preliminary runs did reveal that the HDT from the low flow, 142 Liter/second (L/sec) peak case to the 2-year flood (1700 L/sec peak) was 81% less for a 12-fold increase in flow rate. Subsequently, from the 2-year to the 10-year flood (3400 L/sec peak) only a 5.8% decrease in HDT occurred after doubling the flow rate. This observation indicated that further study of the effects of the topography at flow rates less than that of the 2-year flood was warranted. Large return period peak runoff events are a small portion of the total average annual volume of runoff. Thus, by increasing the treatment efficiency at low flows by lengthening HDT, and simultaneously making marginal gains in HDT for the moderate return period events, a larger volume of runoff water can be treated annually.

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

The relative increases in HDT due to topography are provided in Figure 2. As indicated by the HDT increase of Wetlands 4 and 12 in Figure 3; improvements in detention time can be maintained over a considerable range of low-flow rates. As the flood waves passed through the wetlands, the 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. The effects of overtopping features is a key result, and illustrates the importance of the amplitude of the features.

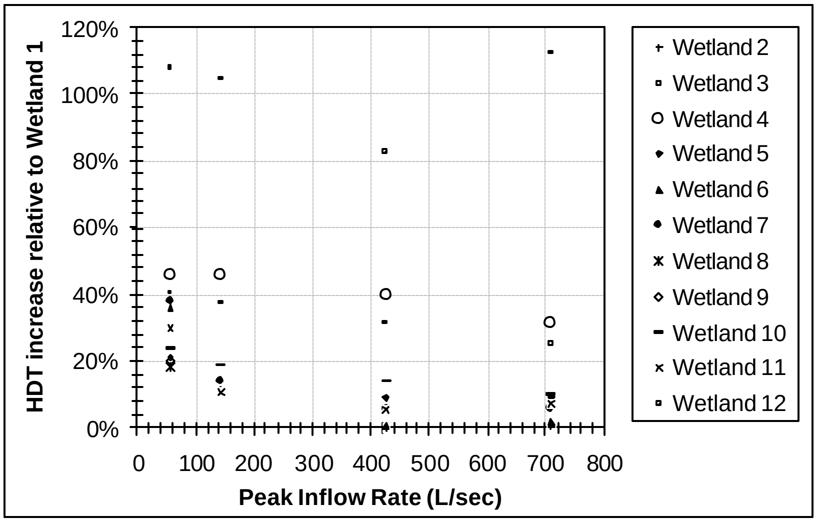

Figure 2. Hydraulic detention time increase relative to Wetland 1 versus peak inflow rate.

Baffles are seen to 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 in terms if HDT. The height of the baffles is their most important characteristic. The design height of the baffles is 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. Also, baffles should cover a range of vertical scales.

A value for S_r was established for each of the simulated wetlands for all four flow rates. 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 Figure3. Detention time decreases with increasing S_r. For values of S_r above about 2.0, HDT is independent of S_r.

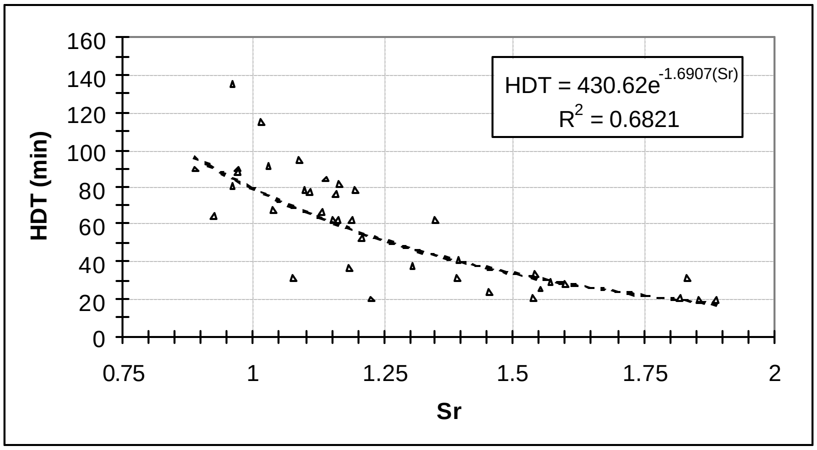

Figure 3. Short circuiting ratio versus hydraulic detention time.

From the preliminary simulation results, a procedure for designing the topography of the storm water wetlands was developed. This procedure incorporates many of the current elements and features being used in the design of storm water wetlands plus several new guidelines based on the simulation results presented in this paper. The purpose of the following section is to show how the concepts of our work are used in conjunction with the works of others to design a storm water treatment wetland; detailed explanations of standard procedures are not presented. The developed procedure is outlined below.

Step 1. Engineering Hydrology - This step involves the calculation of 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 are the 2-year, 10-year, and 25-year return period floods with a total storm duration equal to the time of concentration of the contributing watershed. Standard engineering hydrology principles are used in completing this step.

Step 2. Sizing the Wetland - The wetland can be sized by either of two methods; the first utilizes hydrologic considerations, and the second method is based on treatment considerations.

Method a - Schueler (1992) recommends that the volume of the wetland be based on "capturing" the 10% exceedence probability flood (i.e. 10-year return period) with rainfall duration equal to the time of concentration for the watershed. From previous work by Schueler (1992) the aerial extent of the watershed has been recommended as a minimum of 1% to 2% of the watershed contributing runoff to the wetland. Higher ratios may be used, however, evaporation and infiltration losses from the wetland will be increased due to the increased surface area. This recommendation is relatively site specific and was derived for the mid-Atlantic region near Washington, D.C.

Method b - This method is used when the detention time desired for the wetland is driven by the contaminants to be removed or reduced by the wetland. Storm water wetlands are used to biologically and chemically degrade nutrients, oxygen demanding material and hydrocarbons. Required detention times can be estimated by several methods. Common approaches are based on the assumption that wetlands behave as a first order PFR or series of CSTRs. When using our procedure, the wetland will more closely mimic plug flow conditions, where the length of the "reactor" varies with flow rate due to the multiple-scale topographic features.

Step 3. Establish Baffle Heights - The heights of the multiple scale baffles are calculated using an iterative procedure. In the first iteration, an estimate of the number of baffles to be used in the wetland is made. A rough estimate is first made by establishing a low-flow length to width ratio in the wetland of about 8:1. The high flow L:W ratio should be about 2:1.

The height of the lowest scale of topography is established first. This is done by assuming one-dimensional flow and applying Manning's equation to predict the depth at which the first set of features is over-topped at 8% of the 2-year flood peak flow rate. The channel geometry used when applying Manning's equation should be relatively simple, either a triangular or trapezoidal channel. Similarly, using 25% of the 2-year flood peak flow rate, the height of the second scale of topography is established. The highest scale of topography is determined by estimating the maximum pool elevation using standard hydrologic routing procedures for the largest design event. Note that the routing process is iterative and requires the simultaneous design of the wetland outlet works (weirs and/or orifices).

The stated percentages of the 2-year flood flow rate were chosen such that each scale of topography is approximately 1.5 times the height of the next lowest level of features. This value of 1.5 was chosen based on the results presented relative to the short-circuiting ratio. These results show that the baffle elements maintain control over the flow paths for water depths up to at most twice the height of the feature. Beyond this depth the features begin to behave similar to surface roughness elements.

Step 4. Calculate Number of Baffles - The number of baffles in the wetland is based on several different criteria, including those recommended by Schueler (1992). The first criterion is to create specific depth regions based on portions of the total wetland volume. Second, these depth regions should also be based on portions of the total aerial extent of the wetland. These criteria are recommendations, which are to be used as guidelines, not as strict rules. Site conditions as well as physical restrictions may dictate alterations of these recommendations. The criteria are given in Table 2.

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

	Forebay	**Micropool**	**Deepwater**	**Low Marsh**	**High Marsh**
Volume	10%	10%	10%	45%	25%
Area	5%	5%	5%	40%	45%

Low Marsh: 15 to 45 centimeters below normal pool
High Marsh: 0 to 15 centimeters below normal pool
Deep Water: 30 to 180 centimeters below normal pool

Normal pool is defined as the depth when the water surface is the same elevation as the weir outlet. As these baffles often will be constructed from on-site soils, their side slopes should not exceed about 15%. This will insure reasonably stable slope within the wetland and help to minimize erosion and soil loss.

If these recommendations are not met, then the estimated number of baffles within the wetland may need to be reevaluated, and the height of the baffles re-calculated as per Step 3. If these recommendations are met then move on to Step 5.

Step 5. Check Length to Width Ratios - An adequate flow path length for the various flood levels within the wetland must be ensured in order for the wetland volume to be utilized efficiently. The recommended L:W ratios are 8:1 for the low flow conditions (8% of the 2-year flood flow rate), and 2:1 for high-flow conditions, typically taken as the water level when the 25-year flood is routed through the wetland.

Step 6. Water Balance - 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 will be maintained in the wetland to support and maintain a healthy vegetative density in the low flow channel. The water balance should incorporate evaporation estimates and infiltration losses.

Step 7. Vegetation - 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 certain levels and time periods of inundation. Appropriate vegetation varies with geographic location. Using any elevation mapping software, water depth zones can be mapped throughout the wetland to insure that plant species are being planted in specific elevation zones to maximize their ecological success. Note that due to the strong role vegetation plays in frictional flow resistance, vegetation can also be chosen in part to maximize flow resistance. Additionally, 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.

CASE STUDY DESIGN

A constructed wetland is proposed to treat storm water runoff from the University of Idaho Campus in Moscow, Idaho. This site is used to demonstrate application of the above procedure. Physical constraints include existing parking lots, roads, and railroad tracks, and control the location and size of the wetland. Therefore, the geometry and topography of the wetland needed to be designed such that the space allotted for the wetland was used in the most efficient manner – not an uncommon occurrence. The presented design procedure was used to design the topography of the wetland to maximize hydraulic detention time and thus overall treatment efficiency. A digital elevation model (DEM) of the existing site was developed using site survey data. The DEM was then modified, creating a DEM of the wetland, in accordance with the presented design procedure. 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.

For the low flow conditions (8% of the 2-year flood peak), the height of the lowest scale of baffles was computed to be approximately 25 cm. The second scale of baffles was computed to be approximately 35 cm. The height of the highest level of features was calculated to be approximately 55 cm, using the results of routing the 25-year flood through the wetland. The number of baffles and layout configurations were determined such that the depth-volume and depth-area relationships were reasonably met, and side slopes of the baffles were maintained at less than 15%. The length-to-width ratio for the wetland was well over 8:1 for the low flow (8% of 2-year flood peak) case and over 2:1 for the high flow (25-year flood peak) case. A comparison wetland was also created having the same shape and volume as the designed wetland but with no internal topography. This wetland was used to show the relative improvement of using designed topography. The comparison wetland has the same outlet weir configuration and the same sediment forebay as the designed wetland topography. The ground topography of the designed wetland is illustrated in Figure 6. Inflow into the wetland is at the top of the figure and the outlet weir is located near the bottom left corner of each of the figures.

The designed wetland performed very well in all test case simulations. Figure 7 shows the distribution of water depths as the low flow (8% of the 2-year peak flow) case passed through the wetland. Figure 8 shows the distribution of water depths as the mid-level flow (25% of the 2-year peak flow) case passed through the wetland. As Figure 7 and Figure 8 show, the water depths over the lowest and second scale features were predicted to within one to two centimeters 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. This plot is illustrated in Figure 10. As the figure illustrates, even as both of the lowest levels of baffles are overtopped, they still maintain a considerable amount of control over the flow direction through the wetland whereby increasing HDT.

As was predicted by the preliminary simulations, the wetland with designed topography produced drastic increases in HDT over one with no bottom topography. For the low flow case (8% of the 2-year flood) the improvement was nearly 113% relative to the flat-bottomed wetland. The improvement was still maintained at 39% even at the 2-year flood flow rate. For the 25-year flood, HDT is typically fairly short and biological treatment likely would be minimal. However, some flood attenuation and thus limited physical removal of contaminants is still maintained by the wetland.

CONCLUSIONS

Previous design methodologies for constructed storm water wetlands did not explicitly account for the large effect that bottom topography has on hydraulic detention time. The results of this work show that a reasonably simple procedure can be used to design the internal bottom topography of storm water wetlands and markedly increase detention time. Creating baffled wetlands with multiple vertical scales of topography create a bottom configuration that utilizes the wetland volume more efficiently. Baffles increase the flow path length through the wetland, increasing detention time. Creating multiple vertical scales for these baffles allow them to be overtopped by increasing return period floods that require a larger cross-sectional flow area to maintain the same flow velocity. Overtopping reduces the flow path length, however the interaction with the next highest scale of topography still eliminates complete short-circuiting of the wetland. The proposed procedure will enable designers to minimize land use and increase treatment efficiency when designing storm water wetlands. Further, this paper has shown how the proposed design procedure is incorporated into a typical design process aimed at the overall comprehensive design of a storm water wetland system.

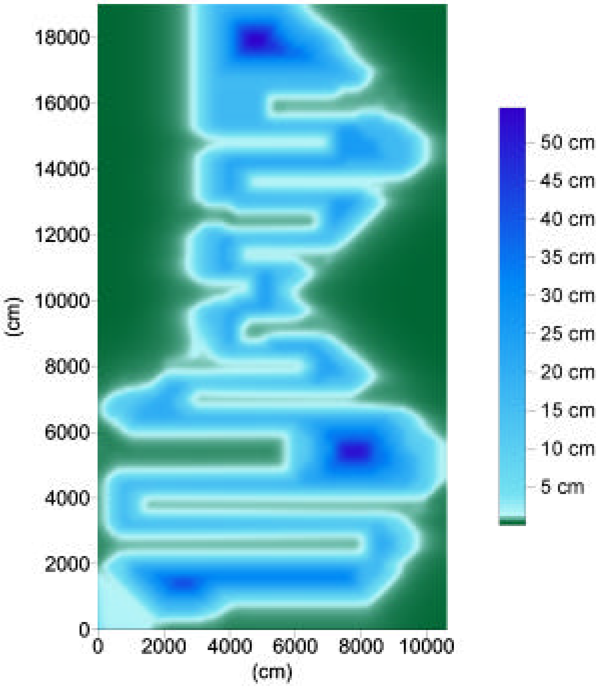

Figure 6. Case study wetland topography developed using the proposed procedure.

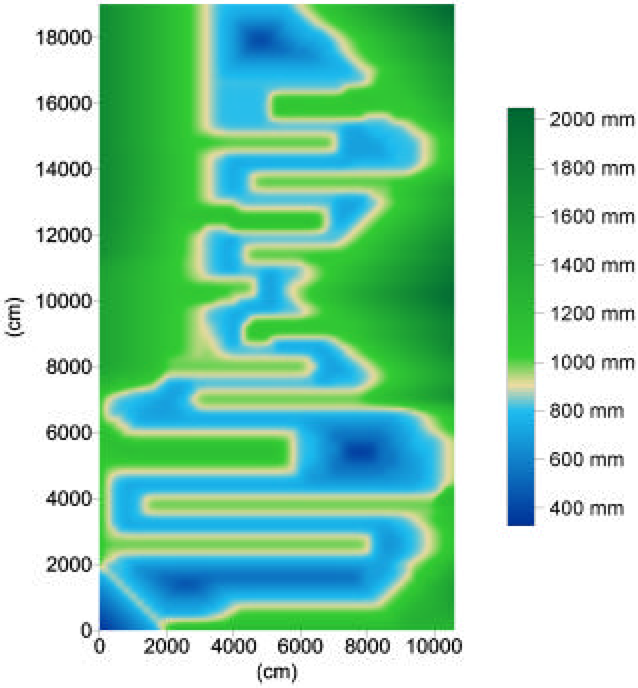

Figure7. Water depth distribution for 8% of 2-year flood peak (142 L/sec) case.

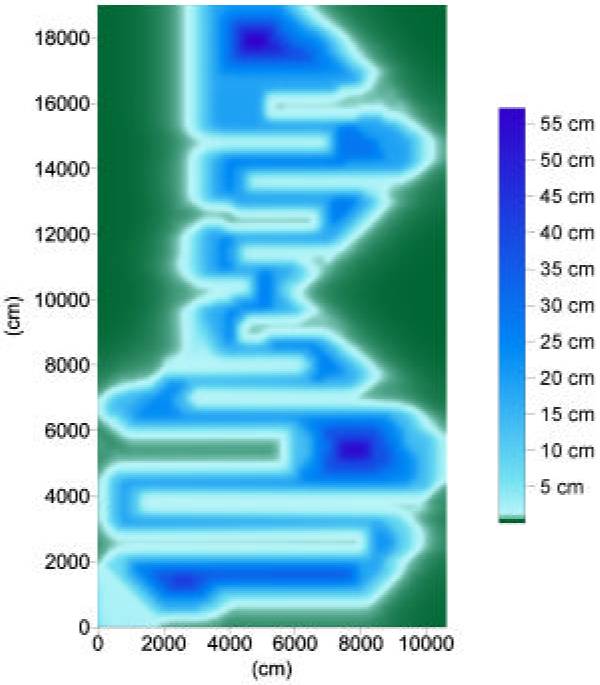

Figure 8. Water depth distribution for 25% of 2-year flood peak (426 L/sec) case.

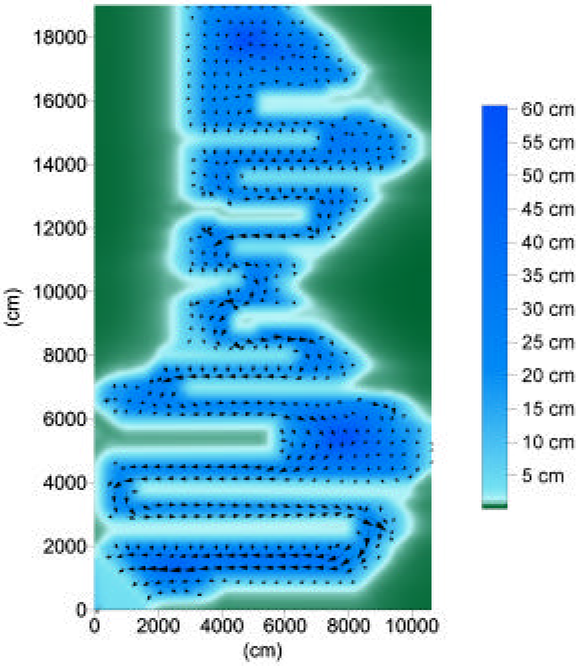

Figure 9. Depth averaged discharge vectors overlayed on water depth distribution for 25-year flood case.

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