INVESTIGATION OF THE APPLICATION OF OPEN CHANNEL FLOW CONCEPTS IN SUPPORT OF WETLAND RESERVOIR ROUTING

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by

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The undersigned, appointed by the dean of the Graduate School,

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INVESTIGATION OF THE APPLICATION OF OPEN CHANNEL FLOW CONCEPTS IN SUPPORT OF WETLAND RESERVOIR ROUTING

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candidate for the degree of Master of Science

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INVESTIGATION OF THE APPLICATION OF OPEN CHANNEL FLOW CONCEPTS IN SUPPORT OF WETLAND RESERVOIR ROUTING

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ABSTRACT

The value of a wetland is represented in how much a society would value or put an importance to every function of the wetland. Understanding the hydraulics of wetlands is essential to help in the protection of natural wetlands and improving the design of constructed ones. The focus of this thesis is to investigate the means to structure hydraulic considerations in a study of the temporal and spatial occurrence of water in a wetland system. Flow, velocity, bed roughness and vegetation, size, shape, and depth are all important aspects of studying or designing any wetland. Measuring exactly how much water is being discharged from a wetland is quite difficult and for precise measurement, rating curves must be developed. Velocity of flow in open channels can be calculated by several empirical equations, such as Manning's Equation. By defining the storage capacity of a reservoir, or river, routing was performed while the outflow rate was less than the inflow rate. Results from the study focused on hydraulic concepts such as open channel sheet flow, hydraulically long channels, reservoir routing, wetland storage relationships, and water depth vs. distance profiles. A key finding was that depending upon size and elevation, water may flow from a downstream wetland to an upstream one. The higher the tailwater is, the less distance was needed for equilibrium to be reached. Additionally, a diagram was developed to illustrate step-by-step structure of the hydraulic calculations needed when modeling wetland systems.

Chapter 1: Introduction

1.1 Introduction

Understanding the hydraulics of wetlands is essential to helping in the protection of natural wetlands and in improving the design of constructed ones. Limited research has focused on the study of natural wetland hydraulics. Hydrological studies are more common because the hydrology and the dynamic nature of water flow in wetlands are directly impacted by the vegetation from the accumulation of organics, and the cycle of nutrients (Gosselink and Turner 1978). As the wetland hydrology has become better understood, new issue of wetland hydraulics. The U.S. Army Corps of Engineers (USACE) requires the evaluation of wetland modifications because the response of a wetland to hydrologic and hydraulic changes can affect not only the hydrological characteristics of a wetlands but also its functions.

Different types of wetlands can be associated with different hydrological and hydraulic processes. Factors such as climate, geology, and physiography also play role hydrological and hydraulic processes. For example, inflows and outflows from the overbank and channel will control the residence time which may range from hours to days. On the other hand, the value of roughness of the bed slope represented by Manning's friction coefficient will affect the lost energy of flow (Walton R. et al., 1995).

1.2 What is a Wetland?

Definitions of wetlands can vary based on the management level (i.e., federal or state) different classifications, and the various regulations that govern usage. The U.S. Fish and Wildlife Service (USFWS) adapted a technical definition of wetlands comprised of three main components. The first component, hydrology, describes the degree of saturation of the soil. The second component, vegetation, is related to the types of plants that are growing in the wetland. The third component, soils, is related to oxygen concentration in the root zone (Cowardin et al. 1979; Tiner, 1991). In this sense, "Wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water. For the purposes of this classification wetlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes; (2) the substrate is predominantly un-drained hydric soil; and (3) the substrate is non-soil and is saturated with water or covered by shallow water at some time during the growing season of each year. (Cowardin et al. 1979)."

The USACE and the Environmental Protection Agency (EPA) jointly define wetlands as: "Those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas. (USACE, 1987)."

Various states in the U.S. also define wetlands in different ways. For example, in Missouri, according to the State Wetlands Information Tool (SWIFT), "Wetlands are areas inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. (SWIFT, 2015)."

1.3 Function and Value

There is a profound difference between the function and the value of a wetland. The function of a wetland is characterized by water quality, aesthetics, aquatic life, storage of floodwater, and biological productivity. However, the value of a wetland represents how much a society values the importance of each function of the wetland. For example, a value of a wetland could be evaluated by the estimated reduced costs of damage by a wetland acting as floodwater reservoir.

Water storage is a key function of wetlands as they can act to slow the water's velocity. One small wetland might not be able to store large quantities of water. However, a network of small wetlands could accomplish this function. In the case of water treatment and filtration, wetlands function to slow the velocity of the water allowing sufficient time for the sedimentation process to occur (EPA, 2001).

1.4 Regulation of Wetlands

1.4.1 Clean Water Act

In 1972, the U.S Congress passed the Clean Water Act (CWA) under which wetlands and some of the activities they support are regulated. For instance, Section 404 of the CWA regulates the discharge of dredged or fill materials into wetlands. In 1977, an amendment expanded Section 404 into a significant program that includes exemption categories, the option of delegation of the 404 program to states, and enforcement powers.

1.4.2 Types of Permits

A general permit is a nationwide or regional permit that regulates activities that have a common basis and a limited adverse environmental effect. This kind of permit can be described as blanket approval because it apply nationwide. If a land owner wants to undertake an activity under a general permit he/she must notify the USACE before the beginning of the activity in the wetland. In some cases there is no need to even notify the USACE.

An individual permit is required when an activity has non-limited effects on the environment. An individual permit requires a study, and is issued on a case-by-case basis. Certain conditions must apply to an activity in order to obtain an individual permit (Turner and Gannon), such as:

1. The applicant must first show that all available alternatives to the proposed impact have been considered, and that no practicable alternative exists which would have less adverse impact on the aquatic ecosystem.

2. No discharge can be permitted if it would violate other applicable laws.

3. The discharge cannot cause or contribute to significant degradation of wetlands by adversely impacting wildlife, ecosystem integrity, recreation, aesthetics, or economic values.

1.4.3 Section 404 Exemptions

There are some exemptions from Section 404 requirements, which correspond to activities that are related to "farming, ranching, and forestry. Examples are: maintenance (not construction) of drainage ditches, construction and maintenance of irrigation ditches, construction and maintenance of farm or stock ponds, construction and maintenance of farm or forest roads (in accordance with best management practices), and maintenance of dams, dikes, and levees. These discharges are exempt from the 404 permitting requirements if they do not convert a wetland to an upland area through the discharge of dredged or fill material (Turner and Gannon)."

1.5 Project Focus

The focus of this thesis is to investigate hydraulic considerations in a study of the temporal and spatial occurrence of water in a wetland system. Certain hydraulic concepts are examined in this thesis such as weir flow, open channel sheet flow, open channel shallow concentrated flow, hydraulically long channels, reservoir routing, seasonal changes in Manning's roughness coefficient, and hydraulic gradients.

1.6 Research Objectives

The key objectives of this study are to:

1. identify hydraulic concepts that need to be evaluated in a wetlands system analysis,
2. identify the Geographic Information System (GIS) calculations that must be developed as part of the overall wetlands system analysis, and
3. devise an overall structure to organize all of the calculations that must be performed.

1.7 Thesis Structure

The thesis is organized into five chapters. Chapter 1 provides an introduction along with definitions of wetland function and value, the project focus, and objectives. Chapter 2 presents the literature review. Chapter 3 presents the applied methodology, the flow chart structure, and concepts that were used in the sample calculations. Chapter 4 presents the results and the discussion. Chapter 5 presents the key conclusions and recommendations.

Chapter 2: Literature Review

2.1 Introduction

Wetlands in Missouri are as diverse as their benefits. There are several benefits of wetlands, these benefits may be: "economic, environmental, social, flood water retention, water quality improvement, sediment retention, wildlife habitat, and recreational.
(Water Resources Center, 2013)." Vast areas of wetlands have been destroyed by draining or filling since settlements started in this country and the remaining wetlands are mostly in public or private hands. There is an urgent need to restore wetlands and further study their functions and ecosystems (Water Resources Center, 2013).

Almost 50% of plant species and 25% of migratory birds in Missouri are related to wetlands during their life cycle. Many endangered and rare plant and animal species (up to 200) live in wetlands as their main habitat. Wetlands in Missouri provide a primary environment for more than 43 amphibian species to breed and develop (Leahy, 2010). Differences in the nature of wetlands are due, and not limited to, topography, climate, soil, water chemistry, hydrology, and vegetation. Wetlands can form with no apparent connection to rivers or lakes or any other source of surface water, but wetlands must have a connection to groundwater. On the other hand, wetlands commonly form in flood plains and beside waterways (EPA, 2015). There are nine different types of wetlands seen in Missouri, and include marshes, shrub swamps, bottomland prairies, bottomland forests, swamps, sinkhole ponds, oxbow lakes and sloughs, riparian areas and groundwater seeps (Leahy, 2010).

2.2 Constructed Wetlands

Constructed wetlands are "engineered systems designed to simulate natural wetlands to exploit the water purification functional value for human use and benefits. Constructed wetlands consist of former upland environments that have been modified to create poorly drained soils and wetlands flora and fauna for the primary purpose of contaminant or pollutant removal from wastewaters or runoff (Hammer, 1992)". The main purpose of constructed wetlands is to improve water quality. What comes with improving the water quality is valuable wildlife habitat that enhances the efforts of protecting the environment. Because conventional wastewater treatment facilities require significant investments in construction and maintenance, constructed wetlands offer a viable alternative with regards to financial cost.

2.2.1 Constructed Wetlands Benefits

According to the Wetland Reserve Program, wetlands functions are classified into groups: (1) water quality, (2) landscape improvement, (3) wildlife habitat, and (4) recreational (Wetland Reserve Program, 1994). The water quality function is related to wastewater treatment as wastewater flows slowly through the wetland and pollutants settle out due to gravity. In addition, microorganisms attached to vegetation roots improve the efficiency of the wastewater treatment process. Regarding the development of habitats for wildlife and aquatic life, constructed wetlands provide suitable life conditions through food and a protective environment.

2.2.2 Constructed Wetlands Advantages and Disadvantages

The advantages of constructed wetlands are that they are simple to design, construct, and maintain. Also, the capital and operation costs are low. In addition, they provide highly efficient and reliable wastewater treatment under fluctuating hydraulic and contaminant loading rates. The disadvantages of constructed wetlands according to the United Nations Environment Program (UNDP) are that they have high land area requirements. Also, they require preliminary treatment as constructed wetlands normally are not used to treat raw wastewaters. In addition, they need a longer (compared to a conventional system) retention time, and they may cause problems with pests (UNDP, 1997).

2.3 Wetland Hydraulics

A wetland receives water through several inputs including precipitation, runoff, groundwater discharge, overbank flow, and tidal flow. A wetland discharges water through several outputs including evaporation, transpiration, channels, tidal flow, and recharge of groundwater. The time during which a wetland holds water is considered as temporary storage. The segments where water is held include channel, overbank, basin, and groundwater storage location (Walton R. et al., 1995).

2.3.1 Hydraulic Aspects of Wetland Design

The study of wetland creation and restoration is relatively new and practical experience with wetland restoration is still being collected. The understanding of hydraulic properties plays an important role in the restoration and creation process, but is not well integrated outside of treatment wetlands. Velocity of flow, wave action, vegetation and bed roughness, size, shape, and depth are all of critical aspects of characterizing a wetland.

Velocity of flow: Conveyance and energy grade line are what determine the velocity of water in a wetland. The greater the land slope, the greater the slope of the energy grade line, and thus the velocity of flow. Vegetation and soil roughness also affect the velocity (AASHTO, 2005).

Bed Roughness: The rougher the bed, the greater the flow resistance will be. Different types of vegetation and bed conditions have promoted scientists to develop large tables of Manning and Chezy coefficients related to various vegetation types.

In 1786, Antoine Chezy first proposed the relationship between the squared velocity and the product of the hydraulic radius and the slope of the channel via a constant that is known as the Chezy coefficient (ASCE Task Force Committee, 1963), Chezy equation is shown in 2.1.

$$v = c\ (RS)^{0.5} \tag{2.1}$$

In 1889, Manning (1889) developed his equation as shown in equation 2.2.

$$v = \frac{R^{2/3} S^{\,0.5}}{n} \tag{2.2}$$

In both equations, v is the cross-sectional averaged velocity (length per time), c is the Chezy roughness, R is the hydraulic radius (length), S is the friction slope (length per length), and n is the Manning's roughness coefficient.

The design of vegetated channels has been performed using relationship curves between Manning's coefficient (n) and the product of velocity and hydraulic radius of the channel (UxR) (Morris and Wiggert, 1963). As shown in Figure 2.1. Curve A represents a very high value of retardance (a grass height of greater than 30"), curve B represents a high value of retardance (a range of grass height of 11" to 24"), and curve C represrnts for a moderate value of retardance (a range of grass height of 6" to 10") (Morris and Wiggert, 1963). What can be noticed from Figure 2.1 is that Manning's n reaches a constant value as UxR reaches a value between 10 and 20.

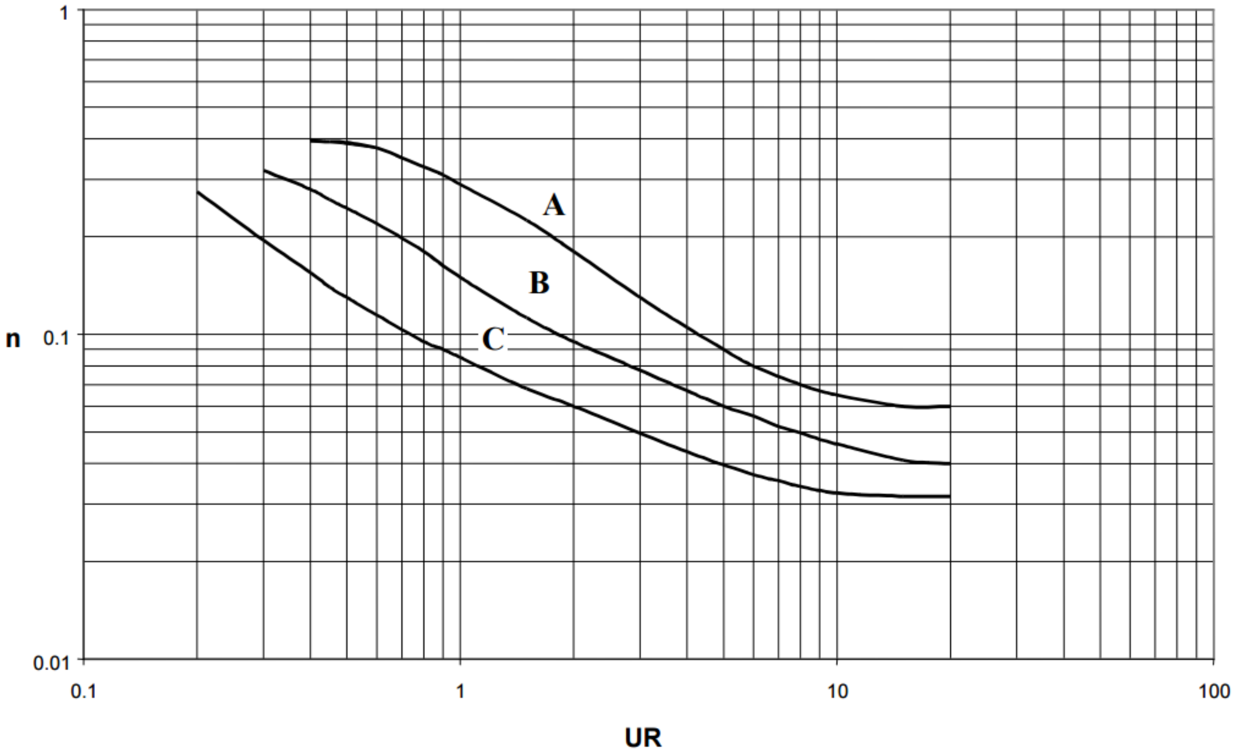


Figure 2.1 Relationship between Manning's n and UxR for varying grass heights.

Size, shape, and depth: Erosion and deposition (caused by wind and water flow) and other geomorphic forces determine the size, shape and depth of natural wetlands. That means that these properties are changing in a gradual pace unless major events happen such as a flood (AASHTO, 2005).

2.3.2 Hydraulic Loading Rate

The hydraulic loading rate (HLR) is defined as the distribution of flow over the wetland surface area. Equation 2.3 define the HLR (Kadlec and Wallace, 2009):

$$q = \frac{Q}{A} \tag{2.3}$$

where q is the HLR, (distance per time) A is the wetland area (wetted land area) (area squared), and Q is the water flow rate (volume/time).

However, this does not mean that the water is physically uniform over the surface area of the wetland. The main components of a water budget for a wetland flow that impacted the HLR are shown in Figure 2.2 (Kadlec and Wallace, 2009):

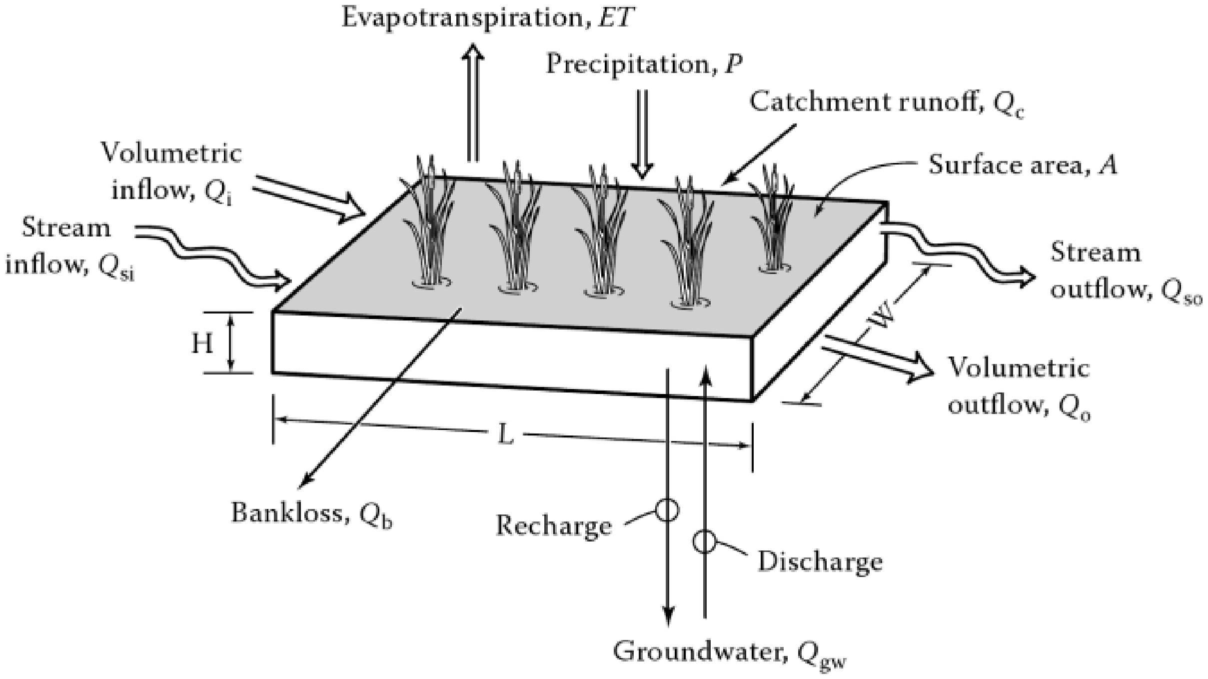


Figure 2.2 Components of the wetland water budget (Kadlec and Knight, 1996).

2.3.3 Hydraulic Retention Time

The nominal Hydraulic Retention Time (HRT) is defined as the ratio of the wetland water volume to the average flow rate. While water is contained within the pore space of wetland soils, for surface flow type constructed wetlands, a simplifying assumption is made to ignore the porosity of the soils is HRT calculations.

The HRT represents the ratio between the part of the wetland water volume that could be used and the average flow rate of the wetland. Because the usable wetland water volume depends on the porosity of the soil, this porosity should be included when calculating the HRT as in Equation 2.4 (Miller, 2007):

$$t = (V\varepsilon)/Q \tag{2.4}$$

where t is the retention time (time), V is the wetland volume ignoring vegetation (length cubed), ε is the porosity of the soil, and Q is the average flow rate (volume/time).

2.3.4 Hydraulic Gradient in a Free Water Surface Constructed Wetland

In constructed wetlands that are used for wastewater treatment, it is important to assess the head loss in the energy line from the inlet to the outlet of the wetland to make sure that the design is able to deal with all possible flows without the formation of backwater. It is assumed that Manning's Equation can be used to calculate the head loss for the free water surface (EPA, 1999).

2.4 Wetland Storage Characteristics

Geology plays an important role in generating storage, where the elevation of the water table (as in Figure 2.3) is a function of the porosity and type of the soil, the surface topography, and types and level of vegetation over the wetland (Welsch et al., 1995). One of the functions of wetlands, especially flood wetlands, is to temporarily store flood waters and runoff. It was mentioned earlier that wetlands behave as natural sponge nature of storing water. In addition, they behave as natural reservoirs in containing the water from surface runoff. Over time, the water in wetlands starts to seep into the underlying soil (Vermont Department of Environmental Conservation, 2014).

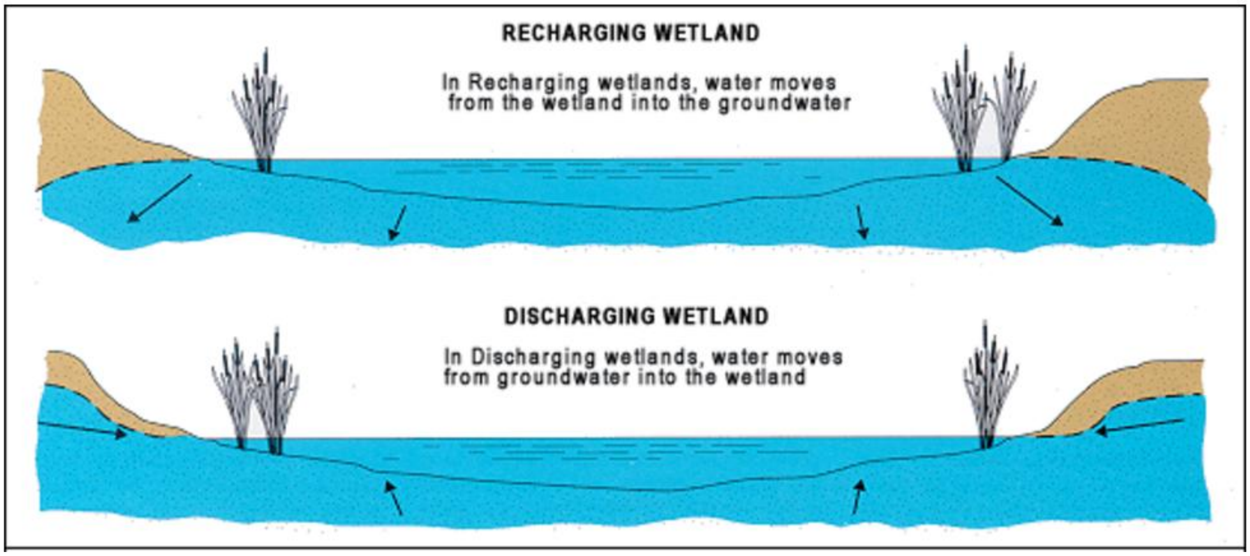


Figure 2.3 Fluctuating water tables can cause wetlands to shift back and forth from discharging to recharging.

A stage-storage curve produces the water volume in a wetland for any given elevation. Equation 2.5 shows the derivation of the curve (Kadlec and Wallace, 2009):

$$A = \frac{dV}{dh} \tag{2.5}$$

where A is the wetland area (length squared), h is the wetland depth (length), and V is the water volume (length cubed).

2.5 Wetland Discharge Characteristics

Measuring exactly how much water is being discharged from a wetland at any given time is quite difficult. Therefore, rating curves are developed to establish the stage discharge relationship for a particular reach or at a gauging station.

The y can be derived using a current meter at a series of different water levels (MedWet, 2016) and result in a curve such as Figure 2.4.

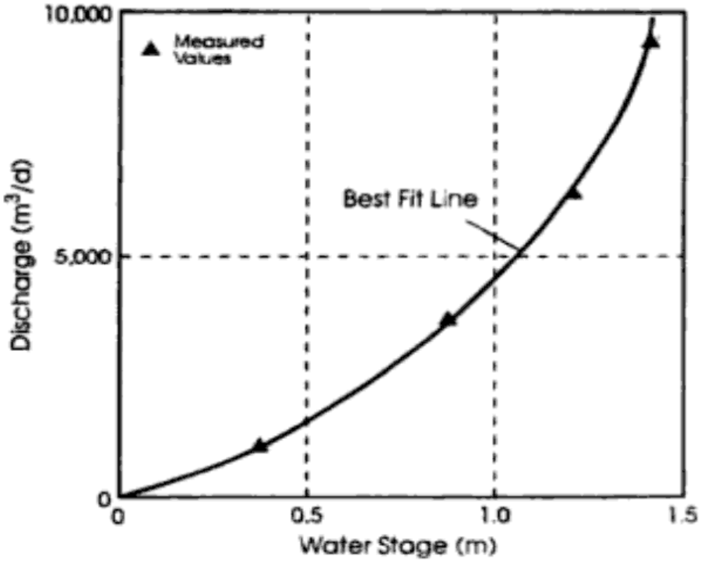


Figure 2.4 Empirical stage-discharge curve for constructed wetland.

2.5.1 Discharge Characterization - Sharp-Crested Weirs

In suppressed weirs, water flows over a length that is the entire width of the channel, as shown in Figure 2.5. Weirs may also exist in the contracted figuration with a shorter length. Equation 2.9 below is the Kindsvater-Carter equation that describe the flow rate over suppressed, partially contracted and fully contracted weirs taking into consideration a discharge coefficient:

$$Q = \frac{2}{3} C_e L_e (2g)^{1/2} H_e^{3/2} \tag{2.9}$$

where Q is the flow rate discharge over the weir (m^3/s), e is a subscript denoting "effective", C is the effective coefficient of discharge ($m^{1/2}/s$), L is the length of the weir crest (m), H is the head measured above the weir crest (m), and g is the gravitational acceleration (m/s^2).

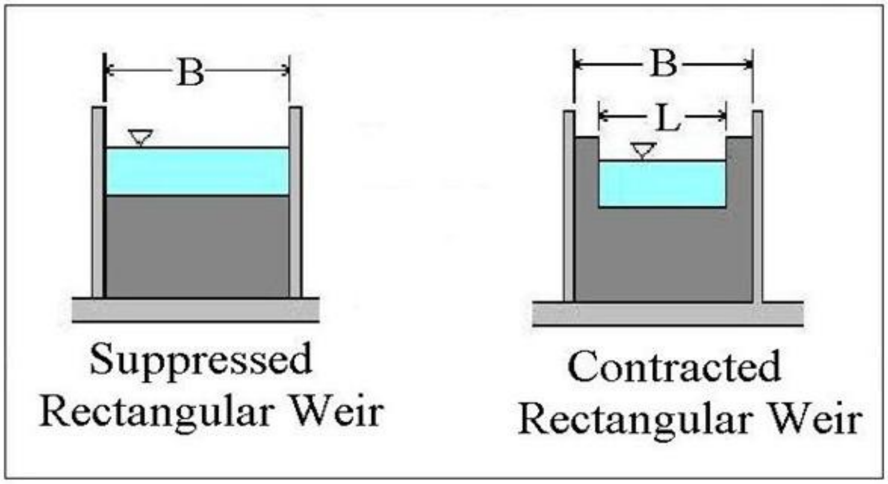


Figure 2.5 Cross sectional view of suppressed and contracted rectangular weirs.

The effective length of the weir crest is $L_e = L + k_b$, where k_b is a correction factor to obtain effective weir length, the value of k_b can be obtained from Figure 2.6 below. The effective head above the weir is $H_e = H + k_h$ where k_h a correction factor having a value of 0.0009144 (m).

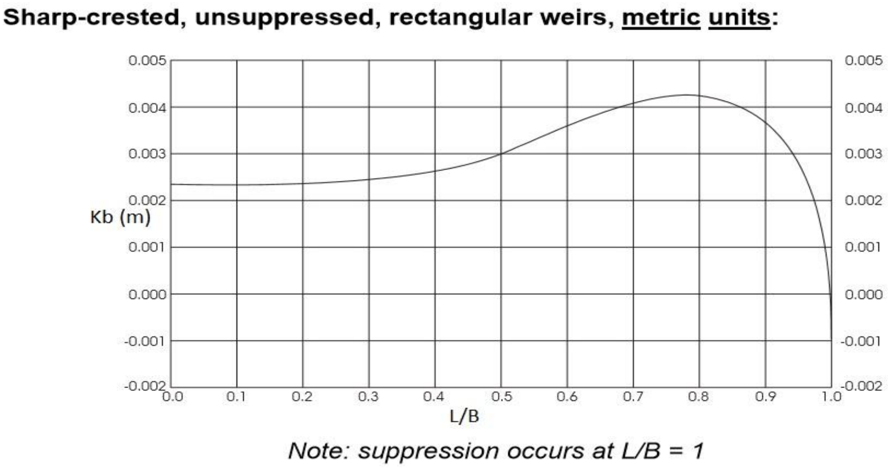
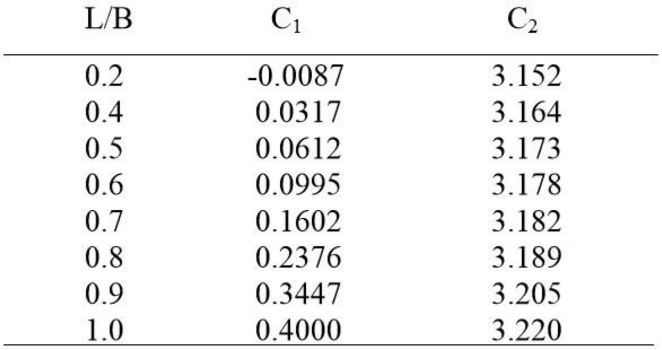


Figure 2.6 Correction factor (k_b) curve for sharp-contracted rectangular weirs.

To calculate the value of the discharge coefficient C_e, Equation 2.10 is used (Bengtson, 2011):

$$C_e = C_1 \left(\frac{H}{P}\right) + C_2 \qquad (2.10)$$

where C_1 and C_2 are functions of L/B as shown in Figure 2.7 below, and P is the vertical distance to the weir crest from the approach pool invert (m), and B is the total width of the weir (m).



L/B	C_1	C_2
0.2	-0.0087	3.152
0.4	0.0317	3.164
0.5	0.0612	3.173
0.6	0.0995	3.178
0.7	0.1602	3.182
0.8	0.2376	3.189
0.9	0.3447	3.205
1.0	0.4000	3.220

Figure 2.7 C1 and C2 discharge coefficient values for sharp-unsuppressed rectangular weirs.

2.5.2 Discharge Characterization - Broad-Crested Weirs

For a weir to be considered broad crested, the height of the water above the weir crest must not be greater than two times the width of the crest of weir. A typical broad crested weir is shown in Figure 2.8. A flow with this type of weir may be described as in Equation 2.11 (CodeCogs, 2012):

$$Q = 1.7\, C_e\, L\, H^{3/2} \tag{2.11}$$

where Q is the flow rate discharge over the weir (m^3/s), C_e is the effective coefficient of discharge, L is the length of the weir crest (m), H is the head measured above the weir crest (m).

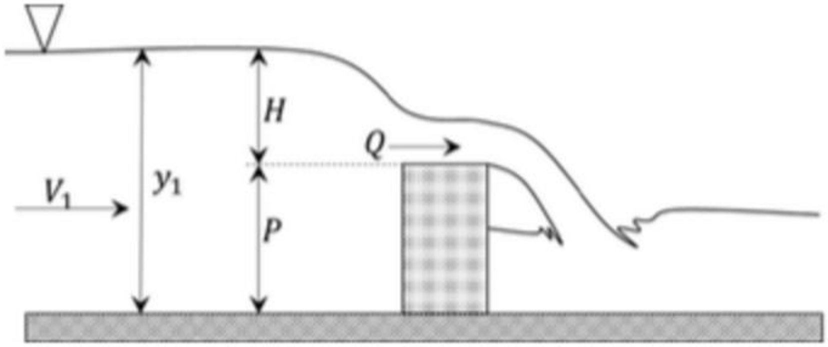


Figure 2.8 Cross sectional view of a broad crested weir.

2.5.3 Discharge Characterization - Spillways

Typically a spillway would have three zones that can be distinguished as: the crest, the face and the toe as shown in Figure 2.9. The equation need to calculate the discharge over a spillway assumes that the top of the spillway operates as a weir. However, an exact equation cannot be derived, so the case may be considered as a sharp crested weir flow (Tuan, 2003). Therefore, Equations 2.9 and 2.10 apply as well, with the appropriate discharge coefficient.

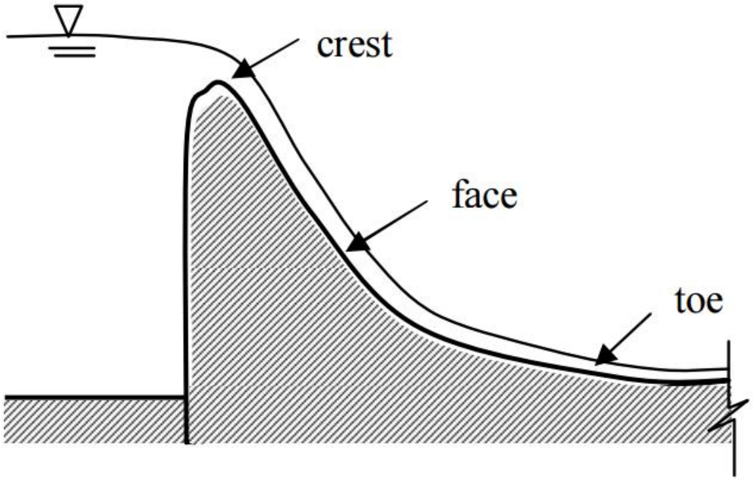


Figure 2.9 Cross sectional view of a spillway.

2.5.4 Discharge Characterization - Open Channel

Velocity in open channels can be calculated using several empirical equations. The one used most is Manning's Equation (Equation 2.2). Figure 2.10 depicts typical open channel side and cross section views where Equation 2.2 apply.

$$v = \frac{R^{2/3}S^{1/2}}{n} \tag{2.2}$$

From the continuity principle, the flow rate in the channel is equal to the velocity of the flow multiplied by the cross sectional area (A) of the channel as shown in Equation 2.12.

$$Q = \frac{AR^{2/3}S^{1/2}}{n} \tag{2.12}$$

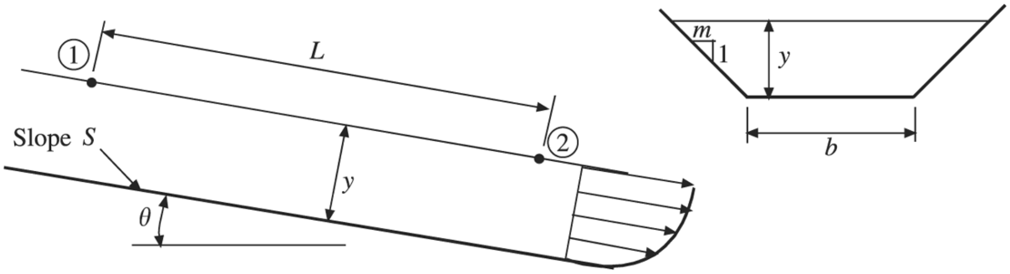


Figure 2.10 Side and cross sectional views of a typical open channel.

The equations for area, wetted parameter, top width, hydraulic radius, and hydraulic mean depth for different cross sections are shown in Figure 2.11.

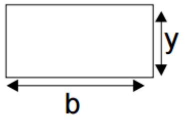
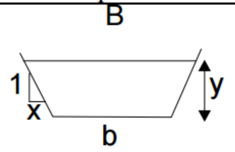
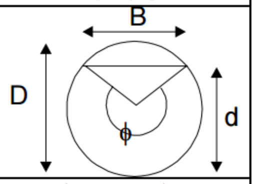
	Rectangle	Trapezoid	Circle
			
Area, A	by	$(b+xy)y$	$\frac{1}{8}(\phi-\sin\phi)D^2$
Wetted perimeter P	$b+2y$	$b+2y\sqrt{1+x^2}$	$\frac{1}{2}\phi D$
Top width B	b	$b+2xy$	$(\sin\phi/2)D$
Hydraulic radius R	$by/(b+2y)$	$\frac{(b+xy)y}{b+2y\sqrt{1+x^2}}$	$\frac{1}{4}\left(1-\frac{\sin\phi}{\phi}\right)D$
Hydraulic mean depth D_m	y	$\frac{(b+xy)y}{b+2xy}$	$\frac{1}{8}\left(\frac{\phi-\sin\phi}{\sin(1/2\phi)}\right)D$

Figure 2.11 Equations for physical characteristics for different cross sections.

The critical slope can be calculated from Manning's Equation. By solving for slope under the critical flow condition of minimum energy leads to Equation 2.13 (Sturm, 2001):

$$S_c = \frac{n^2Q^2}{{A_c}^2{R_c}^{\frac{4}{3}}} \qquad (2.13)$$

where S_c is the critical slope, A_c is the area of flow associated with critical depth, and R_c is the hydraulic radius associated with critical depth.

2.5.5 Discharge Characterization - Shallow Concentrated Flow

Shallow concentrated flow is defined as "flow collecting in swales, small rills, and gullies. It occurs after sheet flow but before open channel flow. There should be no well defined channels and native vegetation should be present in flow paths. Shallow concentrated flow generally has flow depths ranging from 0.1 to 0.5 feet (3 cm to 15 cm) (Roseke, 2013)."

The average landscape slope can be calculated from a topographic map. Slope in consideration with vegetation cover, can be used to calculate velocities, as in Figure 2.12. The travel time is calculated using Equation 2.14:

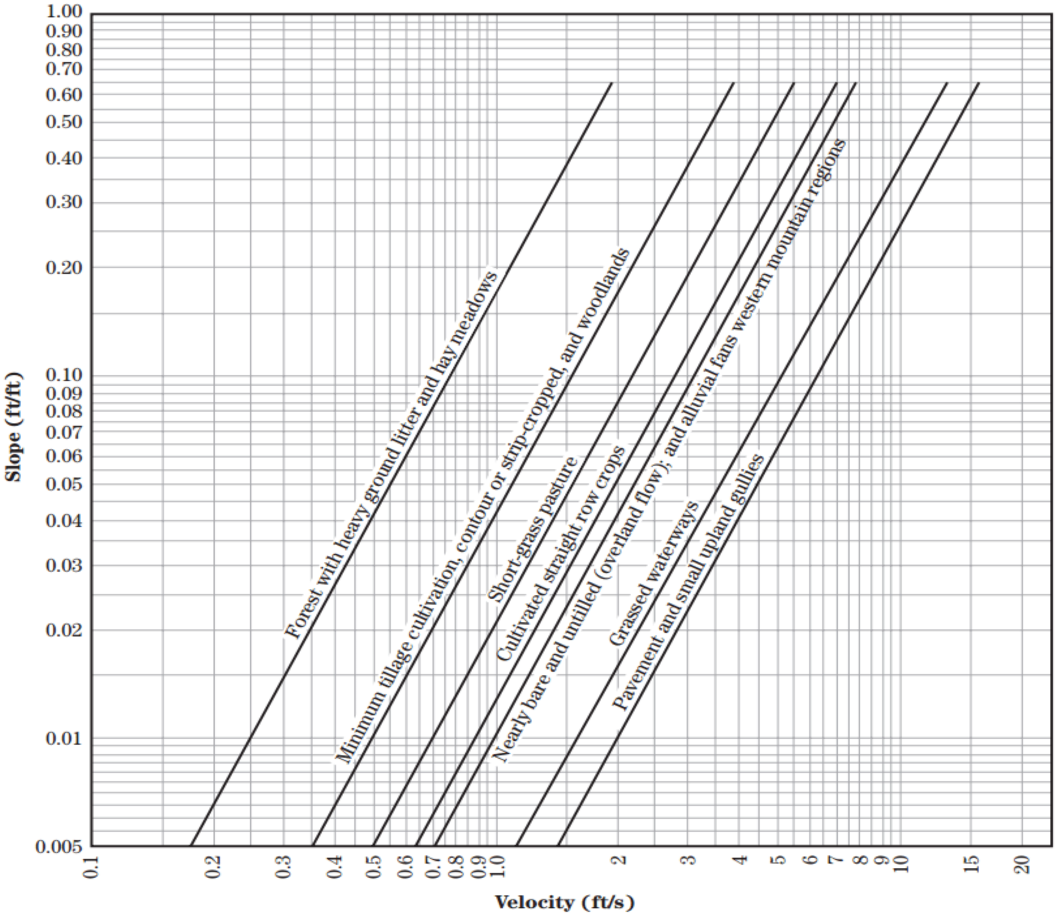


Figure 2.12 Average flow velocity diagram - shallow concentrated flow.

$$T = \frac{L}{3600V} \qquad (2.14)$$

where T is travel time (hrs), L is flow length (ft), and V is average velocity (ft/s).

2.6 Routing

"Reservoir routing involves the application of the continuity equation to a storage facility in which the storage volume for a particular geometry is a dependant only on the outflow.

(Smith, 2010)." It can also be used for the prediction of changes in the shape of the water along the river or channel and so is employed in designing channels and floodplains management strategies (Rafat et al., 2014).

2.6.1 Types of Routing

The basic concept of flood routing is the application of continuity to calculate the time base and the shape of the flood wave along a flow path. This concept is applied to both reservoirs and channels. By defining the storage capacity for the reservoir, or the channel or river, routing can be performed in irrespective of the relative values of inflow and outflow.

Storage in a reservoir occurs when the outflow is less than the inflow, which connects storage and outflow. For reservoir routing, equilibrium is reached when the inflow and outflow rates are equal, assuming that the water surface is level over the area of the reservoir. Then the highest depth, maximum spillway discharge, and the outflow hydrograph can be calculated for the reservoir (USSCS, 1989). After the equilibrium point has passed, water comes out of storage, and outflow is greater than inflow. Reservoir routing is much easier to perform than channel routing because storage-discharge relationships for pipes, weirs, and spillways are single-valued functions independent of inflow.

Channel routing is different from reservoir routing as the storage occurs within the channel reach rather than in a reservoir. Similar to a reservoir, the flow over the channel reach acts to reduce the peak of the flood hydrograph and extend its time base. This process continues from reach to reach . A second difference is that the water surface is not level, and will also vary along the channel with both the hydrograph and the channel characteristics. Thus, a progressive process is required to calculate water surface elevations all long a channel (USSCS, 1989).

2.7 Wetlands and GIS (Case Studies)

GIS is a useful and important tool in hydrology and to researchers in the scientific study and management of water resources. Hydrology is concerned with study of the motion of the Earth's waters through the hydrologic cycle, and the transport of constituents such as sediment and pollutants in the water as it flows. A GIS is focused on representing the landscape by means of spatially referenced data describing the character and shape of geographic features. Surface water is a geographic feature that is constantly in motion. Because the occurrence of water varies spatially and temporally throughout the hydrologic cycle, its study using GIS is essential (Maidment, 1996).

The use of GIS has increased given its ability to manage complex spatial data (Stanley et al., 2005). The most commonly used GIS data models are the vector and raster models. In the vector model, geographic features are represented as points, lines and polygons that are referenced according to their location on the Earth's surface given the application of some reference coordinate system (Garbrecht et al., 2001). Objects in the vector model can be subject to certain topological rules that describe the object's spatial relationship to other (i.e., neighboring) objects. This explicit and unambiguous definition of and linkage between objects makes vector structure attractive and allows for automated analysis and interpretation of spatial data in GIS environments (Meijerink, 1994).

The raster model represents a set of systematically spaced two-dimensional cells, where each cell is associated with a value representing the attribute being mapped. Each grid cell is referenced by a row and a column number, where corner cells are registered to geographic coordinates. In the raster model, a point is represented by a single grid cell, a line by a string of connected cells, and areas by a group of adjacent cells (Garbrecht et al., 2001).

Vector and raster structures have both advantages and disadvantages. Vector structures are well suited to represent networks, connected objects and features that are defined by discrete boundaries, while raster structure are best when the attributes they represent are continuously and smoothly varying in space (Garbrecht et al., 2001).

A GIS can be used to store, analyze and display spatially referenced environmental data (Nuckols et al., 2004). Geographically referenced data can be imported and topology can be generated among these features to construct a data layer. Tabular (attribute) data corresponding to features in the layer can also be associated with each data layer. Analytical functions within a GIS can be used to query and transform both topology and attribute data through linkages established within a database management system (Nuckols et al., 2004). A GIS provides the framework for making information usable for planners and decision makers with powerful analysis and visualization capabilities (Stanley et al., 2005).

Scientists have used multiband aerial photography as a means of identifying and monitoring vegetation types in wetland mitigation areas (Fitch et al., 2003). They found that using supervised classification on multi-temporal and multiband aerial images with a resolution of 1.0 meter, they were able to achieve approximately 80% accuracy in the identification of major plant communities. They did have difficulty in identifying species of Typha from aerial images because the vegetation forms a thin layer on the water surface. These and other thin vegetation canopies are difficult to identify because the signature of the ground or water below is often read instead. The researchers also experienced problems when a mixed plant community existed within a single pixel because the spectral signatures of plants composing that pixel could not be differentiated (Fitch et al., 2003). While Fitch et al. (2003) had success in identifying wetland vegetation in large known wetlands, it is difficult to say how successful vegetation identification would be for the purpose of wetland identification, especially with the inclusion of mixed land cover types in the image and the smaller size of many natural wetlands.

Maheu-Giroux (2005) used panchromatic and color aerial photographs to identify Phragmites australis, an invasive wetlands grass in Quebec, Canada. Phragmites australis is a facultative wetland plant (Reed, 1988) which means that 66-99% of the time it is found in wetlands (Mitsch and Gosselink, 2000) This plant is an excellent species to use in the identification of small wetlands using aerial photographs. Its mature height is over thirteen feet tall (USDA, 2006) and large stands can be easily identified.

Forested wetlands are difficult to identify from aerial photographs or satellite images because there is not much visual or spectral difference between a forested wetland and an upland forest canopy. Image classification using satellite data may be limited for this reason. Sader et al. (1995) compared the accuracy of using satellite image classification to identify forested wetlands at two locations in Maine: Orono and Acadia. They found the least accurate method of image classification to be unsupervised classification. They also found a tasseled-cap transformation that classified greenness, brightness and wetness to be more accurate than the unsupervised classification. The third method used was a “hybrid” classification. This method combined the unsupervised classification with supervised forest wetland training. Training areas were selected from aerial photographs and field visits. The hybrid classification was the most accurate of the three methods in identifying wetlands, but it was still limited in identifying forested wetlands.

Sader et al. (1995) also used a GIS rule-based model to predict likely locations of wetlands. Known forested wetlands were digitized and used as a basis for classification. The GIS model was dependant on four different layers that were each assigned a weight according to their importance. National Wetland Inventory information was assigned the highest weight. Soil data was used in the model and slope gradient was included in the model. Proximity to water was also a factor.

Butera (1983) compared medium resolution Landsat-1Multispectral Scanner (MSS) imagery with high resolution airborne MSS (7.6 m resolution). The Landsat-1 MSS appeared to over predict the total area of Roseau cane (Phragmites communis) in the Mississippi River delta. In mangrove wetlands of southwest Florida, Landsat-1 MSS achieved a higher overall classification accuracy, although an airborne multispectral scanner was able to distinguish three types of grassland marsh where Landsat-1 MSS could only identify a more general mixed wetland grasses cover type. This result suggests a tradeoff between discrimination detail and classification accuracy (Butera, 1983).

Jensen et al. (1986) used Landsat-1 MSS imagery to develop a regional map of wetlands in the Savannah River watershed. Similarly, large-scale Landsat-1 MSS wetland mapping efforts were conducted in the Great Dismal Swamp of Virginia and North Carolina (Gammon and Carter, 1976) and in northwestern Tennessee (Jones and Shahrokh, 1977).

Chapter 3: Materials and Methodology

3.1 Background

The methodology in this study focused on examining the hydraulic concepts occurring in two adjacent wetlands and the connection between them. Excel sheets were used to perform the calculations using hydraulic equations. The assessment of the movement of water between wetlands starting with assumed virtual dimensions for two wetlands with the corresponding volumes and times required to fill the wetlands due to a uniform rainfall event. GIS was used to describe the required shapes and volumes of the wetlands, as well as the channel connecting them. Additional Excel sheets were created to calculate water flow profiles and the changes in water depth with different values for slopes and Manning's n values.

The investigation in this study progresses through five stages, in the manner in which water on the landscape is tracked. The first stage is associated with determining the physical characteristics of wetlands including the elevations, dimensions and channel connecting wetlands. The water connection flow stage incorporated a uniform rainfall event to investigate the connection between wetlands, including discharges, flow depths, and the determination of hydraulically critical, mild, steep slopes as slope and Manning's n were varied. The third stage, included the calculations of the normal depth from excess precipitation flowing out of a wetland. The fourth stage is associated with the calculation of water profiles, including the calculation of the distance needed for the flow to reach equilibrium, using different sets of tailwater conditions, and different values of slope and manning's n. The fifth stage, the outlet flow, included calculations of total volume of merged wetlands, the time required to fill up the merged wetlands, and the direction of flow.

This investigation is based on several assumptions:

1. Two virtual wetlands are used with assumed characteristics, such as slope, Manning's n, and rectangular dimensions,

2. The rainfall intensity is uniform throughout an assumed storm and lasts long enough so that the two wetlands fill up and combine,

3. The water budget in this system excludes infiltration and evaporation, as the initial focus is only on the hydraulics of wetlands, and

4. The virtual wetlands are close enough together so that there can be a hydraulic connection between them.

3.2 Physical Characteristics of Wetlands

The first stage in this study was creating the physical characteristics of the two virtual wetlands. The size scale of the wetlands used in this study was small enough to replicate the important small wetlands in the landscape and to be able monitor discharge and flow depth.

The shape of the upstream wetland (higher) is a square and it is larger in volume than the downstream (lower) wetland. The wetland calculations were based on individual layers that started with the lowest layer with an area of 1 m2. Each additional layer increases the dimensions of the layer by 1 m for the width and the length. The upstream wetland is shown in Figure 3.1.

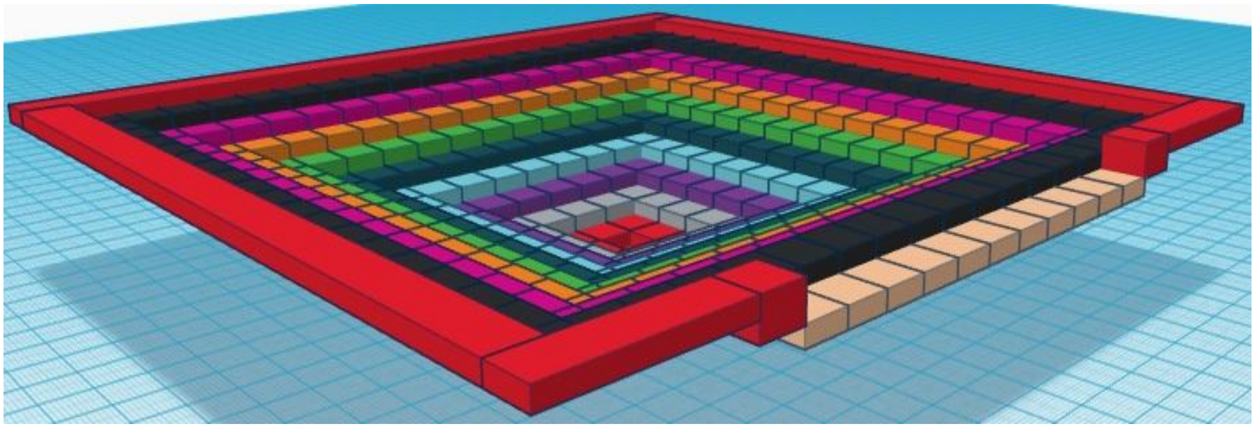


Figure 3.1 3D view of the virtual higher wetland's finite layers.

The overall volume of the downstream wetland is less than the upstream wetland in order to investigate what happens once the upper wetland fills with water. The downstream wetland also started with an area of 1 m^2 for the first layer and expanded to reach the total area similar to that of the upstream wetland. The downstream wetland shown in Figure 3.2.

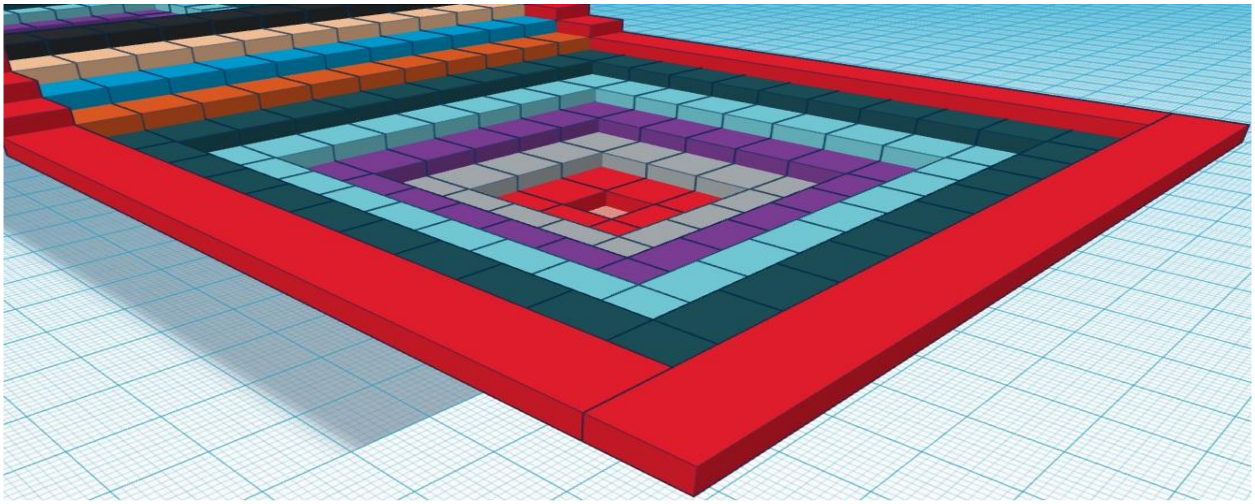


Figure 3.2 3D view of the virtual lower wetland's finite layers.

As might be expected with natural wetlands, there is very little difference in the bottom elevations of the two wetlands. The bottom of the higher wetland was set at 200.00 m and the bottom elevation of the lower wetland was set at 199.20 m. The elevation of the very top of the higher wetland was set at 200.30 m while the very top of the lower wetland was set at 199.95 m.

The relative dimensions and positions of the two wetlands are shown in Figure 3.3 and Figure 3.4. In both Figures 3.3 and 3.4 the vertical scale is expanded by factor of five in order to distinguish the topography.

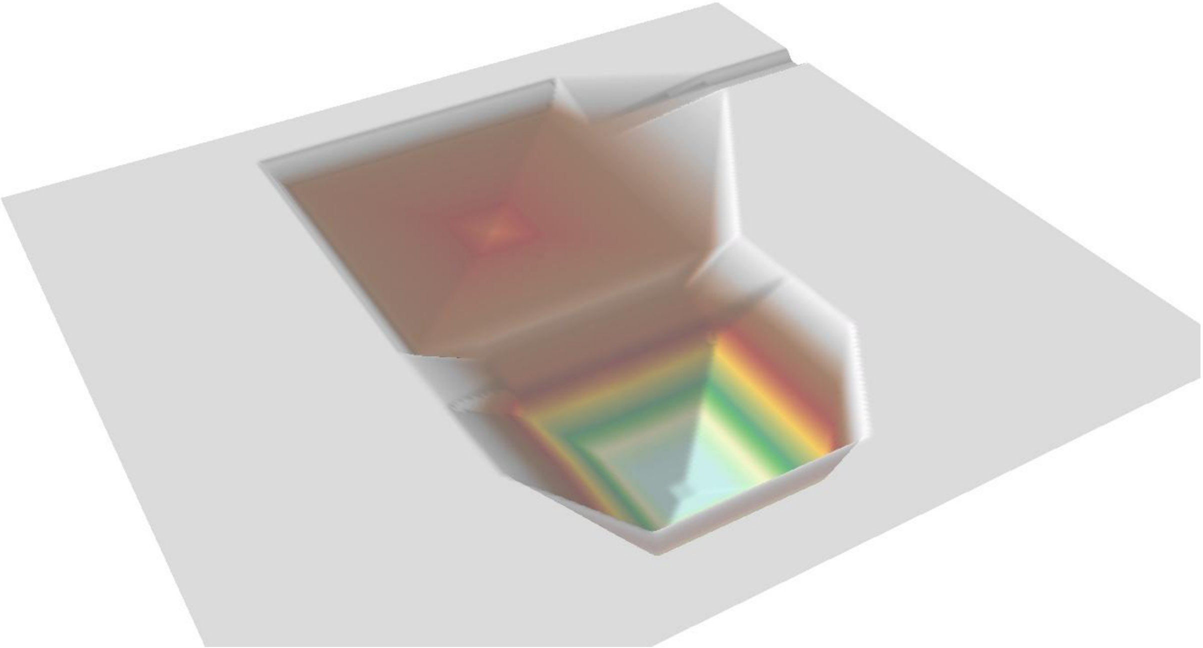


Figure 3.3 GIS 3D top view of the two wetlands.

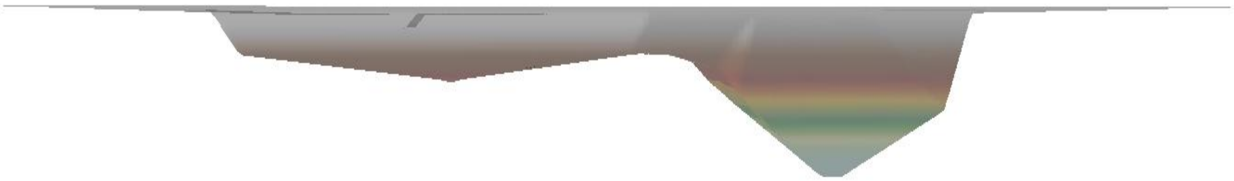


Figure 3.4 GIS side view of the wetlands.

3.3 Flow Connection

The channel connecting the two wetlands has a width of 11.0 m and a length of 4.0 m. The slope of this connection is 0.0875 and was used in the initial volume and storage calculations. Subsequent calculations maintained the original elevation-volume relationship but utilized a varying slope to identify changes in flow characteristics. This slope was changed to establish the critical, mild, and steep hydraulically slopes in order to draw the different water profiles over this channel connection. Changes in normal depth associated with changing slope and Manning's n were calculated. For the calculations, the channel connection was represented in two different ways. First, individual steps were used for area and volume for calculations purposes, as shown in Figure 3.5. Second, the steps were modeled into a ramp to represent changes in slope, as shown in Figure 3.6.

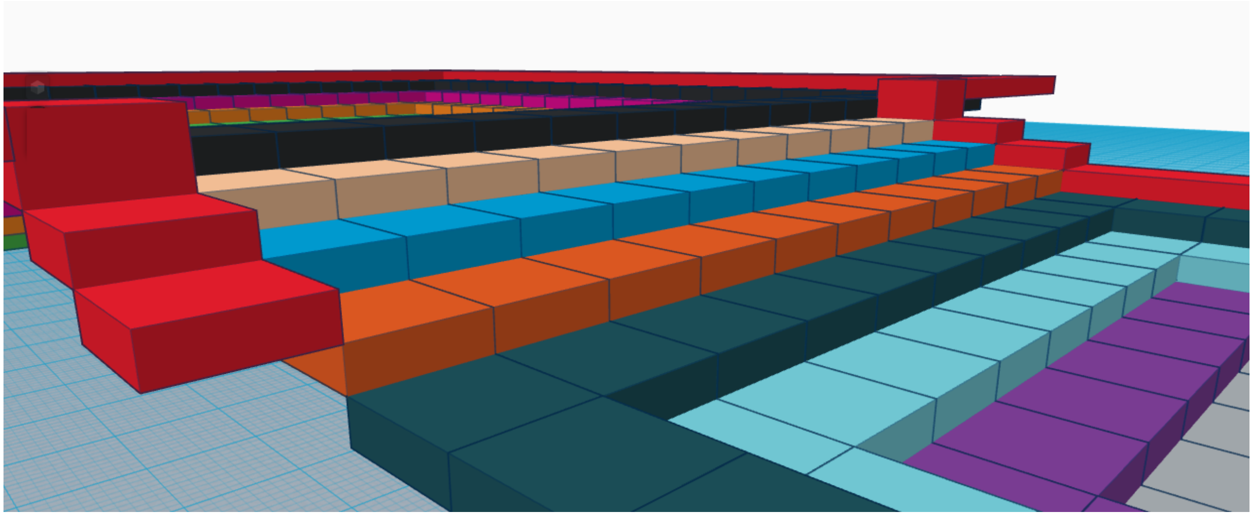


Figure 3.5 Channel connection as declining steps.

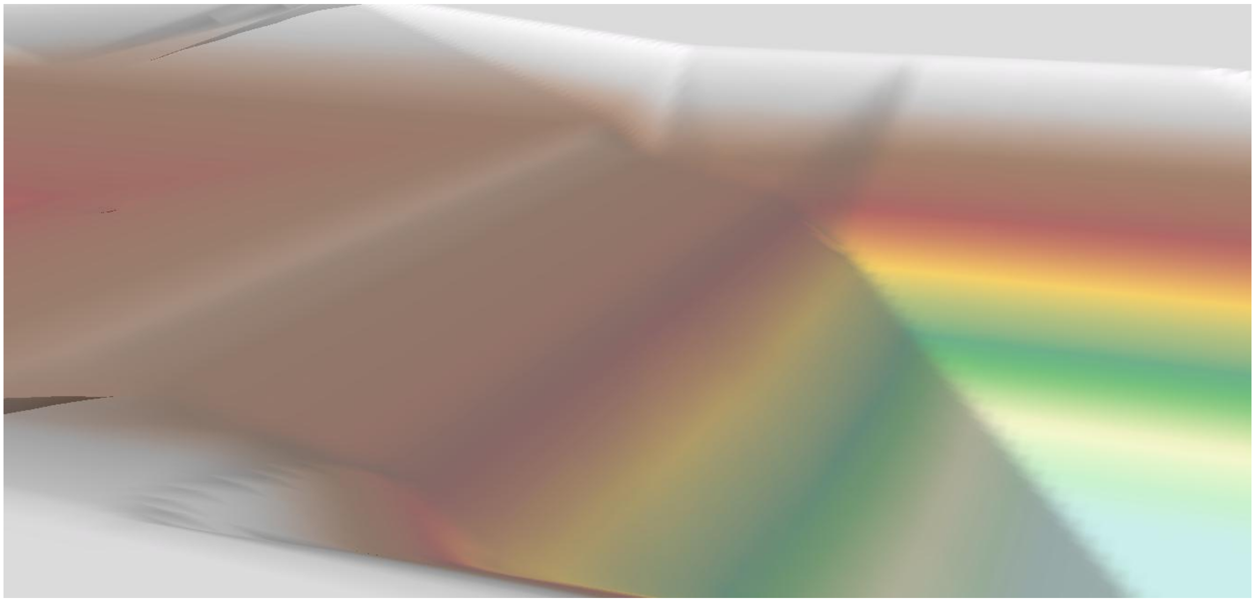


Figure 3.6 Channel connection ramp view.

3.4 Water Budget

The water source for the wetlands is assumed to be from rainfall only, so no groundwater discharge or sub-soil flow was considered. As per the assumptions, the rainfall event was at a uniform rate of 2.0 mm/min over both wetlands and steady over time, and lasted until the combined wetlands were full. The analysis examined how every layer in each wetland filled up with water and the how much time every layer took to be filled.

3.5 Water Profiles

Precipitation collecting in the lower wetland creates the tailwater for the flow between the two wetlands. The different tailwater conditions and the slope of the channel affect the depth of the flow and the distance needed for the flow to reach normal depth. Four different water profiles are possible that may be applicable to model slope conditions expected in wetlands.

1. The M2 curve, as shown in Figure 3.7, exists where the tailwater is equal to y_c, which causes a drawdown curve from the upstream uniform depth to the critical depth with a free outfall.

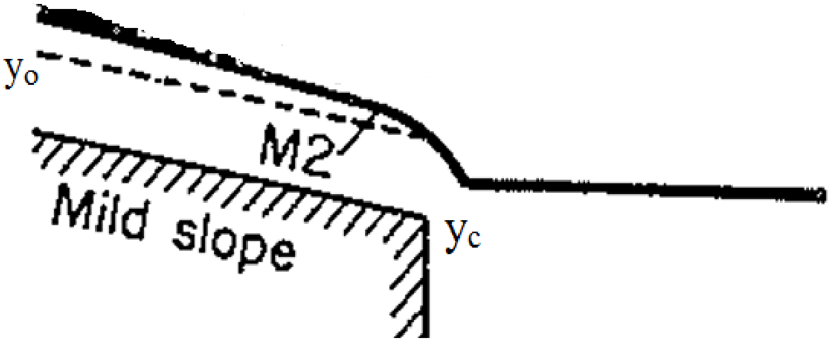


Figure 3.7 M2 profile where tailwater equals y_c (Chow, 1959).

2. The M2 curve, as shown in Figure 3.8, exists where the tailwater is greater than y_c but less than y_o. This again results in a drawdown cause from y_o to the tailwater. The distance required to reach y_o will be shorter than in the previous case due to the decreased change in depth that is required.

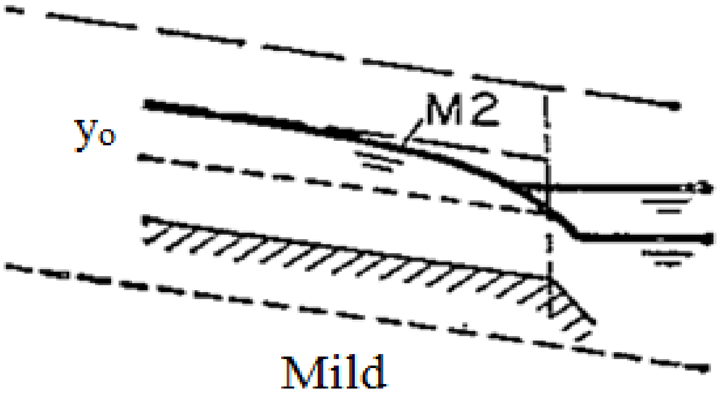


Figure 3.8 M2 profile where tailwater is higher than y_c but less than y_o (Chow, 1959).

3. The M1 curve, as shown in Figure 3.9, is generated when the tailwater is greater than y_o and a backwater curve from the tailwater to y_o is the result.

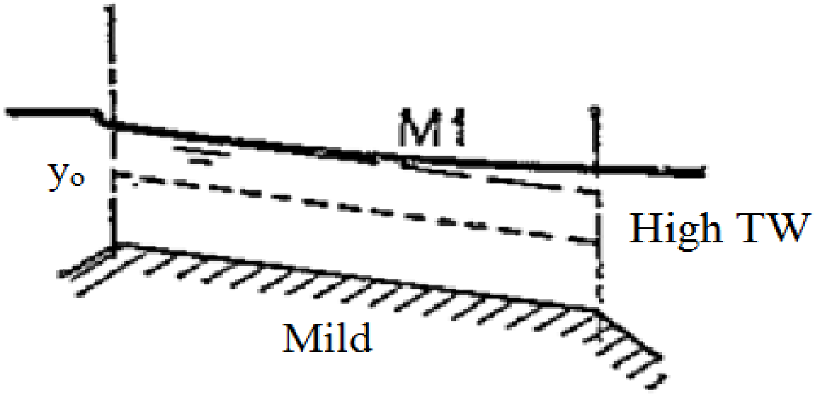


Figure 3.9 M1 profile where tailwater is higher than y_o (Chow, 1959).

4. The S1 curve as, shown in Figure 3.10, is possible when the connection between the two wetlands is hydraulically steep and the downstream wetland has a mild slope. Here, water flow at shallower y_o of the steep slope and them jumps to the deeper y_o of the downstream milder slope.

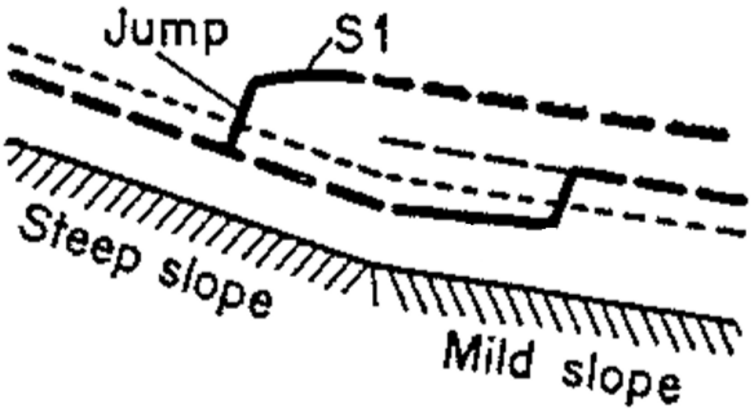


Figure 3.10 S1 profile where tailwater equals to y_c with steep slope (Chow, 1959).

3.6 Outlet Flow

The total volume of the two wetlands, including the connection channel between them, can be calculated based upon the creation of the virtual wetlands with a boundary ridge for the combined pond at an elevation 30 cm above the connection crest. The rainfall event continues until the total volume of the two wetlands is filled from precipitation and the discharge starts from the outlet. The outlet was proposed to be at the far side of the higher wetlands as shown in Figure 3.11, to make sure that the flow of direction above the connection channel will be reversed and go in the direction of lower wetland to the higher wetland. The outlet channel width was assumed to be 2.0 m.

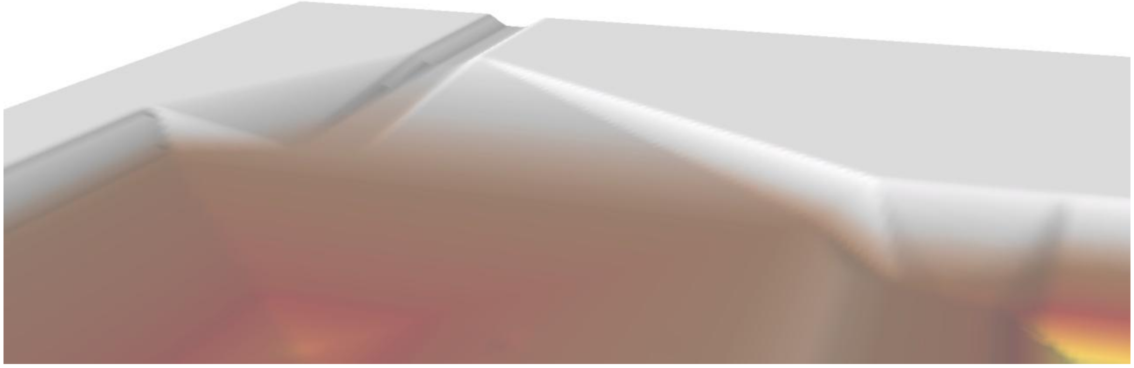


Figure 3.11 GIS 3D view of the outlet flow channel of the higher wetland.

Chapter 4: Results and Discussion

4.1 General

Conceptual results are produced based upon an examination of hydraulic requirements and conditions. Other results are produced using Excel by applying Manning's Equation, wetland storage relationships, water depth vs. distance profiles, and examining the sensitivity of flow depths and distances towards changes in channel bed slopes or Manning's friction coefficient.

4.2 Weir Selection

Several weir structures were considered to assess their applicability to wetland connections. Because the topography was virtual but built up to represent natural wetland topography, the connection must be simulated with the most realistic hydraulic structure that represents how natural wetlands act.

Sharp-crested weirs were considered, both contracted and suppressed, but the conditions required to describe flow using a weir that is a very small structure are not a available in the wetland systems. The sharp-crested weirs act as a control for the water flow, and the discharge over these weirs depends only on the weir characteristics without considering downstream conditions, which might be operative in that wetland.

Broad-crested weirs were considered but the configuration of the broad-crested weir is based on a hydraulically long obstacle in the path of the flow that changes the depth and the velocity of the flow between before and after the obstacle. The connection between the two wetlands in this study , and in wetlands in the field, do not constitute this hydraulic obstacle.

A spillway was considered but has the same limitations as a sharp crested weir. In addition, the configuration of a spillway requires a spillway or a drop off with the face and the toe whereas most wetlands are in relatively flat locations.

An open channel, described by Manning's Equation, can best represent the wetland connection, because field conditions can be considered to mimic those in a channel, including having a bed slope, a cross-section and vegetation that impact roughness.

4.3 Wetlands Dimensions and Volumes

The virtual wetlands that were studied here had assumed dimensions. Both wetlands were assumed to have the same squared shape but different in size and shape. Table 4.1 shows the summary of the dimensions, areas, and volumes of both wetlands.

From the bottom of the pond to the top, the area to each layer was increased by 1.0 m in length and 1.0 m in width. Each layer was assumed to be 3.0 cm for the higher wetland, and with ten layers, produced a total depth of 30 cm. For the lower wetland, each layer was 15 cm deep and arranged in six layers for a total depth of 90 cm. For both wetlands, the volume of each layer was calculated along with the cumulative volume was calculated. As Table 4.1 shows, the bottom elevation of the lower (but larger) wetland is 199.2 m above sea level with total volume of 42.9 m^3, and the bottom elevation of the higher (but smaller) wetland is 200 m with total volume of 39.9 m^3. The volume of the higher wetland was assumed to be larger than the lower one, in order to make sure that the higher wetland fills up first in order to flow to the lower one.

Table 4.1 Wetland dimensions, areas, and volumes.

Higher Wetland							
Layer	Elevation (m)	Length (m)	Width (m)	Area (m^2)	Depth of layer (m)	Volume of layer (m^3)	Cumulative volume of layer (m^3)
1	200.00	1	1	1	0.03	0.03	0.03
2	200.03	3	3	9	0.03	0.27	0.30
3	200.06	5	5	25	0.03	0.75	1.05
4	200.09	7	7	49	0.03	1.47	2.52
5	200.12	9	9	81	0.03	2.43	4.95
6	200.15	11	11	121	0.03	3.63	8.58
7	200.18	13	13	169	0.03	5.07	13.65
8	200.21	15	15	225	0.03	6.75	20.40
9	200.24	17	17	289	0.03	8.67	29.07
10	200.27	19	19	361	0.03	10.83	39.90
Lower Wetland							
Layer	Elevation (m)	Length (m)	Width (m)	Area (m^2)	Depth of layer (m)	Volume of layer (m^3)	Cumulative volume of layer (m^3)
1	199.95			1	0.15	0.15	0.15
2	199.80			9	0.15	1.35	1.50
3	199.65			25	0.15	3.75	5.25
4	199.50			49	0.15	7.35	12.60
5	199.35			81	0.15	12.15	24.75
6	199.20			121	0.15	18.15	42.90

4.4 Rainfall Accumulation and Wetlands Volumes (Reservoir Routing)

The 2.0 mm/min storm was long enough so that the higher wetland filled up and then the water started to discharge through the channel connection to the lower wetland which was concurrently receiving rainfall. As the storm continued, the water level in the lower wetland kept raising until the total volume was filled. With the water from both wetlands at the level of the connection crest, the wetlands merged and the water level continued to rise until it reached the outlet location.

Table A-1 in Appendix A shows the rainfall intensity and the times at which each layer in the higher wetland will be filled up.

4.5 Sheet Flow Discharge From Higher Wetland

Using Manning's Equation (2.12), discharge from the higher wetland over the channel connection and into the lower wetland can be calculated by:

$$Q = \frac{AR^{2/3}S^{1/2}}{n} \qquad (2.12)$$

As a sample of calculations, the value of Manning's n was set at 0.35, the bed slope was taken to be 0.005, and the channel width was 11 m. The calculated discharge vs. depth relationship is shown in Figure 4.1.

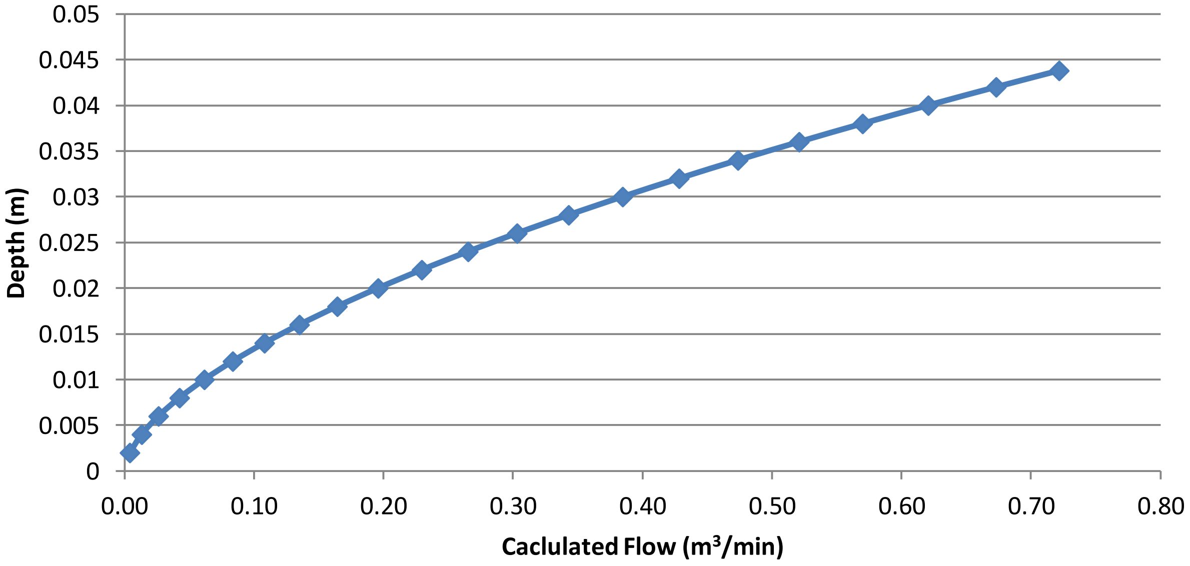


Figure 4.1 Calculated discharge values from higher wetland as a function of depth of flow.

The discharge from the higher wetland was assumed to start as sheet flow with small quantities that started at 0.00423 m^3/min over the 11 m of width. This value increases as the storm continues. As the discharge increases over time the flow changes from sheet flow into shallow concentrated flow and finally to full open channel flow. At a value of 0.722 m^3/min of discharge, equilibrium would be reached and the total volume of excess rainfall feeding the wetland would be discharged into the lower wetland. The normal depth at equilibrium is 0.0438 m (4.38 cm).

Table A-2 in Appendix A shows the rainfall intensity and the times at which each layer in the lower wetland will be filled up, and when the discharge from the higher wetland starts to fill up the lower wetland. After 56 minutes of the storm, the higher wetland will start to discharge into the lower one, which means that the lower wetland then received water from the rainfall over its surface area and from the discharge from the higher wetland. It took 97 minutes for both wetlands to fill up and the overall water surface to reach the crest.

As the storm continued, after 97 minutes, the water level from the lower wetland met the water level at the higher wetland. At this time both wetlands merged into one wetland with larger surface area to receive the rainfall. At a water depth of 5 cm above the crest, the merged total volume of the merged wetlands would be 25.75 m^3 and it would take an additional 25 minutes to completely fill it up if the rainfall continued. Table A-3 in Appendix A shows the rainfall intensity and the times at which both wetlands merge above the crest and act to form one larger wetland.

4.6 Critical Slope

The critical slope was calculated to identify the slope to be used in determining whether the channel connections were mild or steep. Using Equation 2.13 with an n value of 0.35, a discharge of 0.01203 m^3/sec, a width of 11 m, and a critical depth of 0.0049 m, the critical slope is 0.33, this means that any slope less than 0.33 is considered as hydraulically mild, and any slope higher than 0.33 is considered as hydraulically steep.

4.7 Water Profiles and Hydraulically Long Channel (Forward Flow or Backward Flow)

Two possibilities in this study was taken in consideration. The first one is that the higher wetland will fill up first which means that water will flow from the upstream location to the downstream location. In this case, the tailwater will keep increasing until the lower wetland fills up due to continuous rainfall and discharge from the higher wetland. The other possibility is that the lower wetland will fill up first which means that water will flow from the downstream wetland to the upstream one. Water in the higher wetland will keep raising from continuous rainfall and discharge from the lower wetland. At the point where water surfaces at both wetlands are the same, both wetlands merge into one wetland. Only forward flow calculations were performed in this study.

The water surface profiles demonstrated how the flow depth changes longitudinally. The profiles are classified based on the relationship between the actual water depth (y), the normal depth (y_o) and the critical depth (y_c). A flow profile is mild if $y_o > y_c$, and steep if $y_o < y_c$. Only mild profiles were drawn in this study.

The initial length of the channel connection was assumed to be 4 m, so different water profiles according to the different Manning's n values and different slopes were compared to this channel connection to see if it meets the requirements of being hydraulically a long channel or not, and what changes should be made to the length of the channel connection to allow enough length for the depth to increase from y_c to y_o.

4.7.1 Water Profiles with Different Slopes and Manning's n Values

Different water profiles were drawn for different values of slope and Manning's n. Every slope value impacted the normal depth of the flow: the steeper the slope, the shallower the normal depth for a fixed Manning's n. For Manning's n, the smaller the value, the shallower the normal depth for a fixed slope. Table 4.2 shows the normal depth when n is fixed for different slope values, and when slope is fixed for different n values.

Table 4.2 Normal depths associated with different slopes and Manning's n coefficients.

Fixed n = 0.35		Fixed S_o = 0.005	
S_o	y_o (m)	n	y_o (m)
0.0005	0.088	0.35	0.044
0.005	0.044	0.30	0.04
0.05	0.022	0.25	0.035
0.5	0.011	0.20	0.031

4.7.2 Mild Water Profiles

The distance needed for the depth of flow to transition from y_c to y_o, or from a high tailwater to y_o are calculated (from downstream to upstream) using the direct step method. Table 4.3 shows the distance (X) for the case of tailwater being a free outfall, if the tailwater is higher than y_c but less than y_o, and if the tailwater is higher than y_o.

Table 4.3 Distance (X) associated with different slopes and Manning's n coefficient.

Tailwater is a free outfall			
Fixed n = 0.35		Fixed S_o = 0.005	
S_o	X (m)	n	X (m)
0.0005	152.84	0.35	7.53
0.005	7.54	0.30	6.51
0.05	0.35	0.25	6.01
0.5	0.015	0.20	5.21
Tailwater is higher than y_c but less than y_o			
Fixed n = 0.35		Fixed S_o = 0.005	
S_o	X (m)	n	y_o (m)
0.0005	154.86	0.35	7.53
0.005	7.25	0.30	6.53
0.05	0.35	0.25	5.88
0.5	0.014	0.20	5.07
Tailwater is higher than y_o			
Fixed n = 0.35		Fixed S_o = 0.005	
S_o	X (m)	n	y_o (m)
0.0005	89.04	0.35	4.44
0.005	4.41	0.30	4.041
0.05	0.23	0.25	3.62
0.5	0.010	0.20	3.16

Profiles were first drawn for the situation where the tailwater equals y_c for different slopes and a fixed Manning's coefficient of 0.35. Figure 4.2 shows the mild water profile where the tailwater is a free fall. The negative distance means water depth increased from downstream to upstream. Full calculations for the direct step method for this water profile are in Table B-1 in Appendix B.

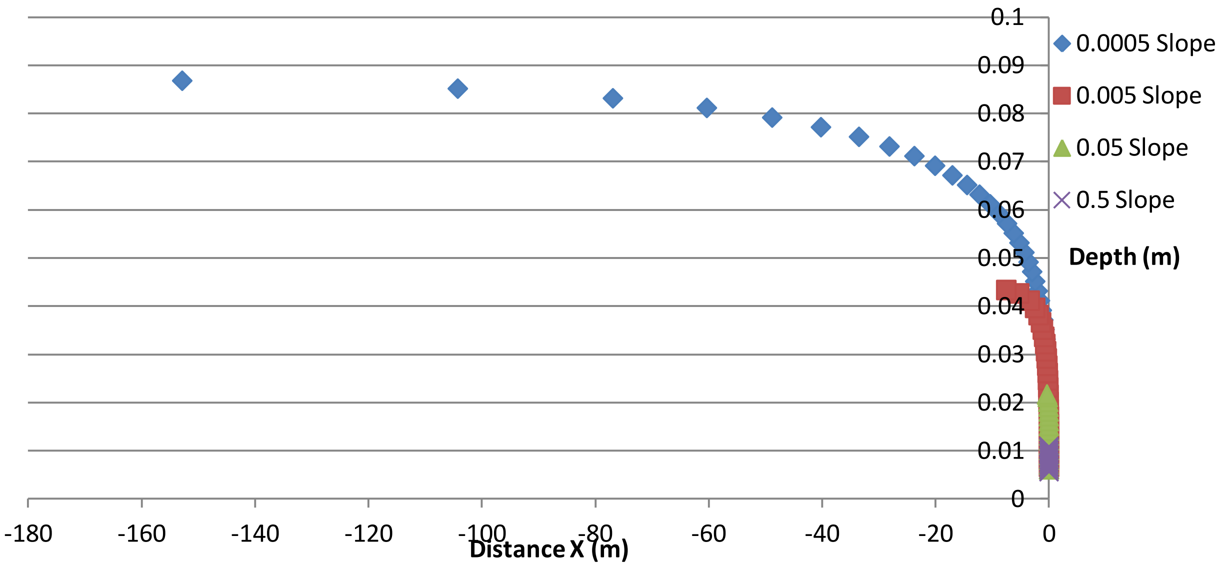


Figure 4.2 Mild water profile where tailwater is a free outfall for different slopes.

A second set of profiles was drawn for the situation where the tailwater equals y_c for different Manning's n values and a fixed slope of 0.005. Figure 4.3 shows the mild water profile where tailwater equals y_c. The negative distance means water depth increased from downstream to upstream. Full calculations for the direct step method for this water profile are in Table B-2 in Appendix B.

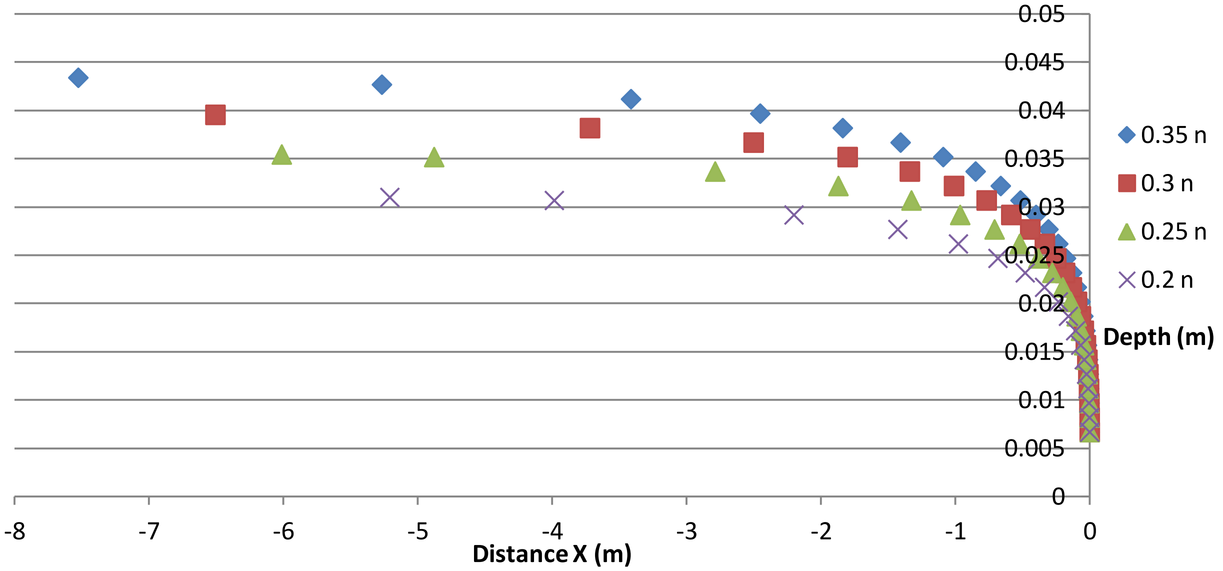


Figure 4.3 Mild water profile where tailwater is a free outfall for different Manning's n.

A third set of profiles was drawn for a situation where the tailwater is higher than y_c but less than y_o for different slopes and a fixed Manning's n value of 0.35. The water flowing from the higher wetland will meet a higher tailwater than y_c downstream. These profiles are shown in Figure 4.4. The negative distance means the water depth increased from downstream to upstream. Full calculations for the direct step method for this water profile are in Table B-3 in Appendix B.

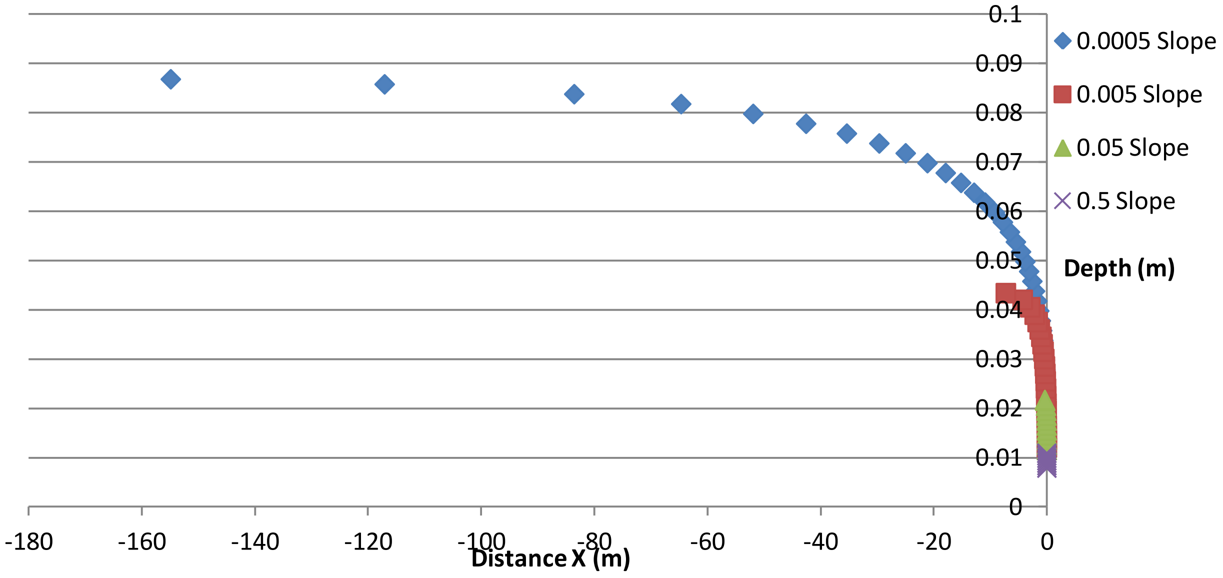


Figure 4.4 Mild water profile where tailwater is higher than y_c but less than y_o for different slopes.

The fourth set of profiles was drawn for the situation where the tailwater is higher than y_c but hless than y_o for different Manning's n values and fixed slope of 0.005. Figure 4.5 shows those profiles. The negative distance means water depth increased from downstream to upstream. Full calculations for the direct step method for this water profile are in Table B-4 in Appendix B.

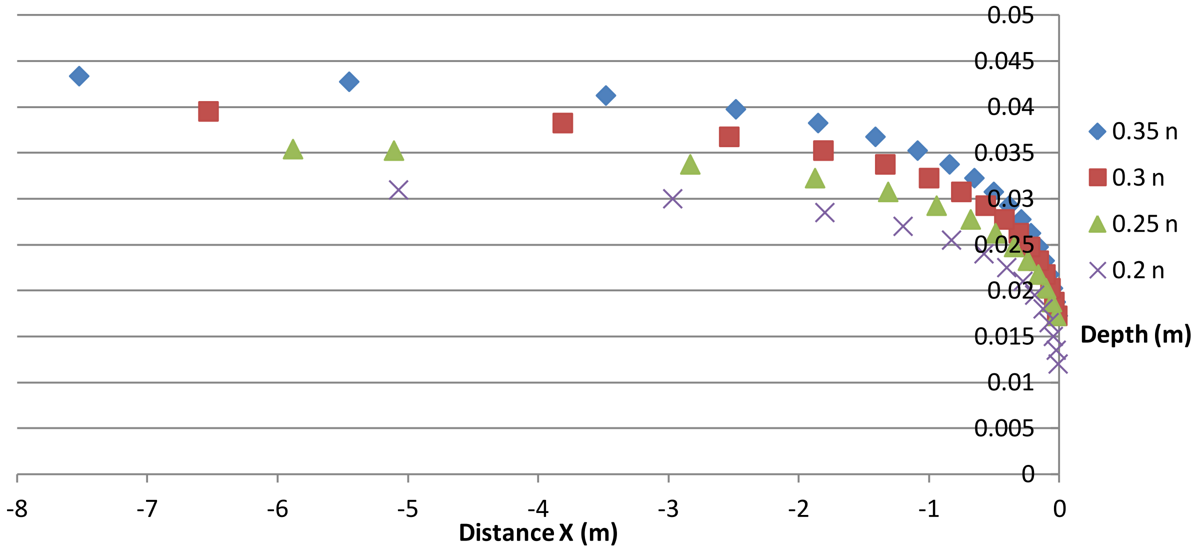


Figure 4.5 Mild water profile where tailwater is higher than y_c but less than y_o for different Manning's n values.

The fifth set of profiles was drawn for the situation where the tailwater is higher than y_o for different slopes and a fixed Manning's n value of 0.35. The backwater curve will decrease until it reaches y_o. Figure 4.6 shows these profiles. The negative distance means the water depth will decrease from downstream to upstream. Full calculations for the direct step method for this water profile are in Table B-5 in Appendix B.

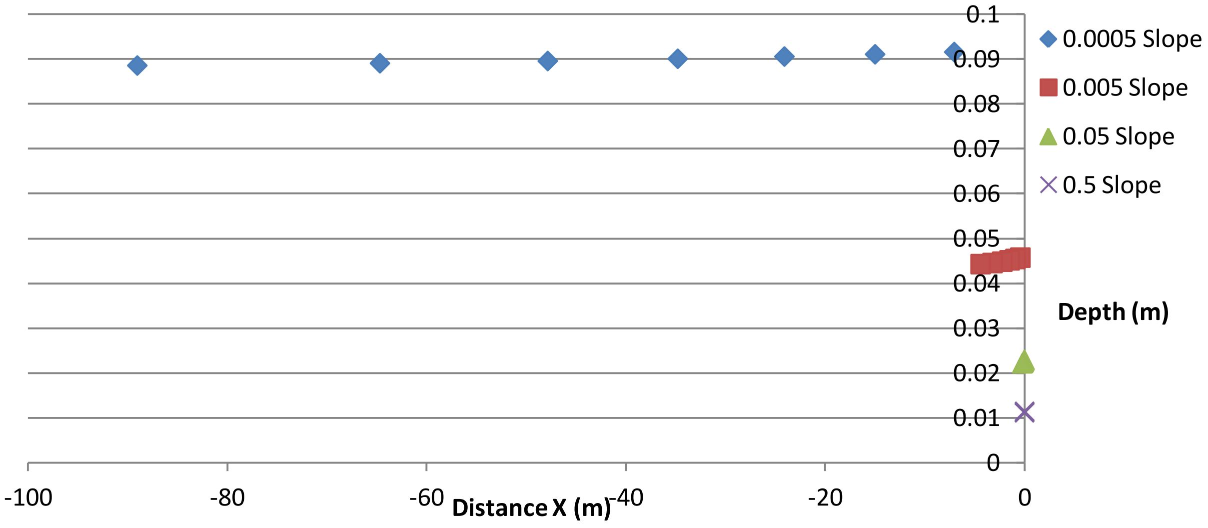


Figure 4.6 Mild water profile where tailwater is higher than y_o for different slopes.

The sixth and last set of profiles was drawn for the situation where the tailwater is higher than y_o for different Manning's n values and a fixed slope of 0.005. Figure 4.7 shows these profiles. The negative distance means the water depth will decrease from downstream to upstream. Full calculations for the direct step method for this water profile are in Table B-6 in Appendix B.

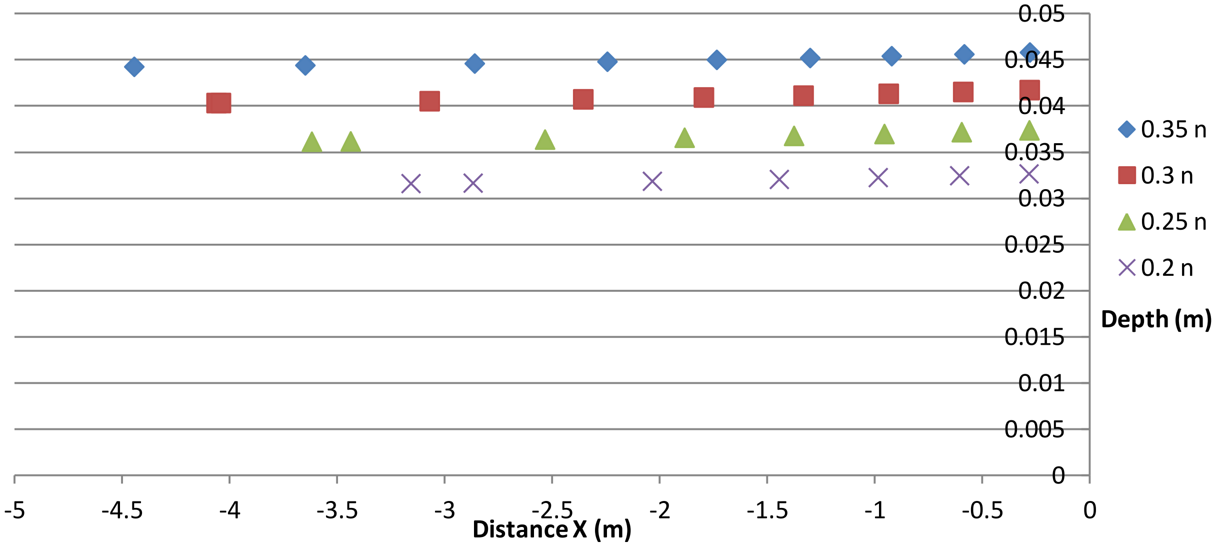


Figure 4.7 Mild water profile where tailwater is higher than y_o for different Manning's coefficient.

4.8 GIS Modeling Notes

These are some important issues addressed when representing a wetland system in a GIS.

1. One must recognizing the fact that depressions do exist in the environment and they must be refined as Earth's surface is not smooth as it appears in calculations. When dealing with GIS data like a DEM or LiDAR input, it is important to recognize where the significant depressions are and take them into consideration. This particularly important for isolated wetlands that may be small in aerial extent and/or smaller total volume.

2. In order to identify where the depressions actually exist and separating them from noise in a DEM or LiDAR, criteria must be sat up to differentiate between actual depressions and small insignificant noise.

3. An imaginary wall will be built up from the depth of water that will exist over the connection crest. This imaginary wall will create part of the elevation-storage characteristics that will exist above the weir crest, as water start to build up over the crest after one of the wetlands fills up.

4. A GIS must be used to assist in the determination of the bottom elevation of each of the wetlands in a flow system and track the water accumulation in that localized pond as rainfall continues.

5. When the rainfall stops, the spatial evapotranspiration and infiltration calculations must be initiated and the results tracked in a GIS.

4.9 Proposed Programming Calculations Structure

One output of this study is a diagram that illustrates a step-by-step calculation process that could be the spine of a software program to model the hydraulic concepts that were discussed in this study. As was mentioned earlier, the investigation in this study was based on five stages as detailed in Figure 4.8.

The first stage (indicated in pink) includes the physical characteristics of the wetlands system. Once the area of interest is determined and the needed DEM/LiDAR data obtained, the local minima for the system are found and the relative elevation of the wetland bottoms are determined. Additionally, the topography is analyzed to establish incremental and accumulating additions to surface area and volume. The imaginary wall can then be built at the crest between the two wetlands, enabling the development of the actual elevation-discharge relationship.

The second stage (shown in green), represents the processes that occur as the rainfall event accumulates in both wetlands simultaneously, and the question of which wetland will fill up first is asked. This assessment of available volume will determine the direction of the flow. (If the higher wetland fills up first this means a forward discharge will occur and water will flow from the higher wetland to the lower wetland. If the lower wetland fills up first this means a backward discharge will occur and water will flow from the lower wetland to the higher wetland). An ongoing question is whether the rainfall has stopped. While infiltration can be tracked during a precipitation event, the slow process of evapotranspiration means that it is not accounted for during precipitation.

The third stage (shown in blue), represents the channel connection that will only occur in the case of one of the wetlands filling up and starting to discharge into the other. The discharge value is calculated from the excess rainfall that will continue to feed the wetlands, and once the desired depth behind the imaginary wall is reached, an iterative process for the calculation of the normal depth over the channel connection is performed until equilibrium is reached and normal depth is found. The question of rainfall continuity is also asked at this stage because if rainfall stops then the hydraulics of the system will cease to be important and evapotranspiration will start to be tracked.

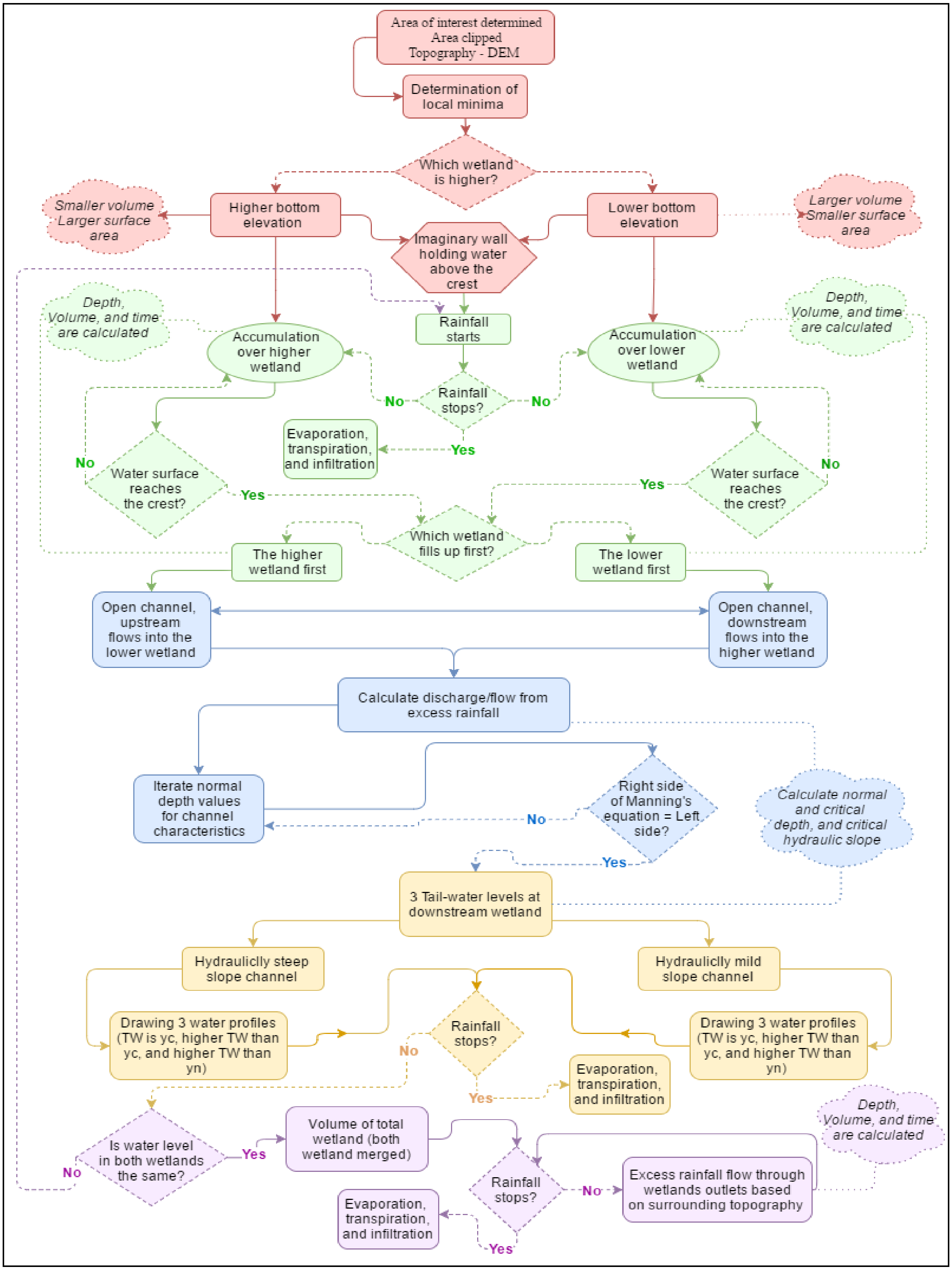


Figure 4.8 Proposed programming calculations structure.

The fourth stage (shown in yellow), is the calculation of water surface profiles and the determination of the distance needed over the channel connection for the water surface to be within 1% of y_o (either above or below). If the water surface is very close in the asymptotic approach to y_o, then the channel is considered to be hydraulically long. If a channel connection is not hydraulically long, the water surface at the crest will be above or below y_o, depending upon the tailwater condition. As with the third stage, once the precipitation stops, the calculations begin to track evapotranspiration.

The fifth, and final, stage (shown in purple), is the stage when the wetlands merge. This stage only occurs if the water level in both wetlands is the same and is above the crest. At this point the combined wetland will keep filling up only if the rainfall continues and depending on the surrounding topography, the outlet flow direction and rate could be determined. In case the rainfall stops, then again the evapotranspiration will be tracked.

For the more general case where more than two wetlands could be connected, the flow chart in Figure 4.9 describes the basic steps that would to be considered to understand the hydraulic connection between the wetlands.

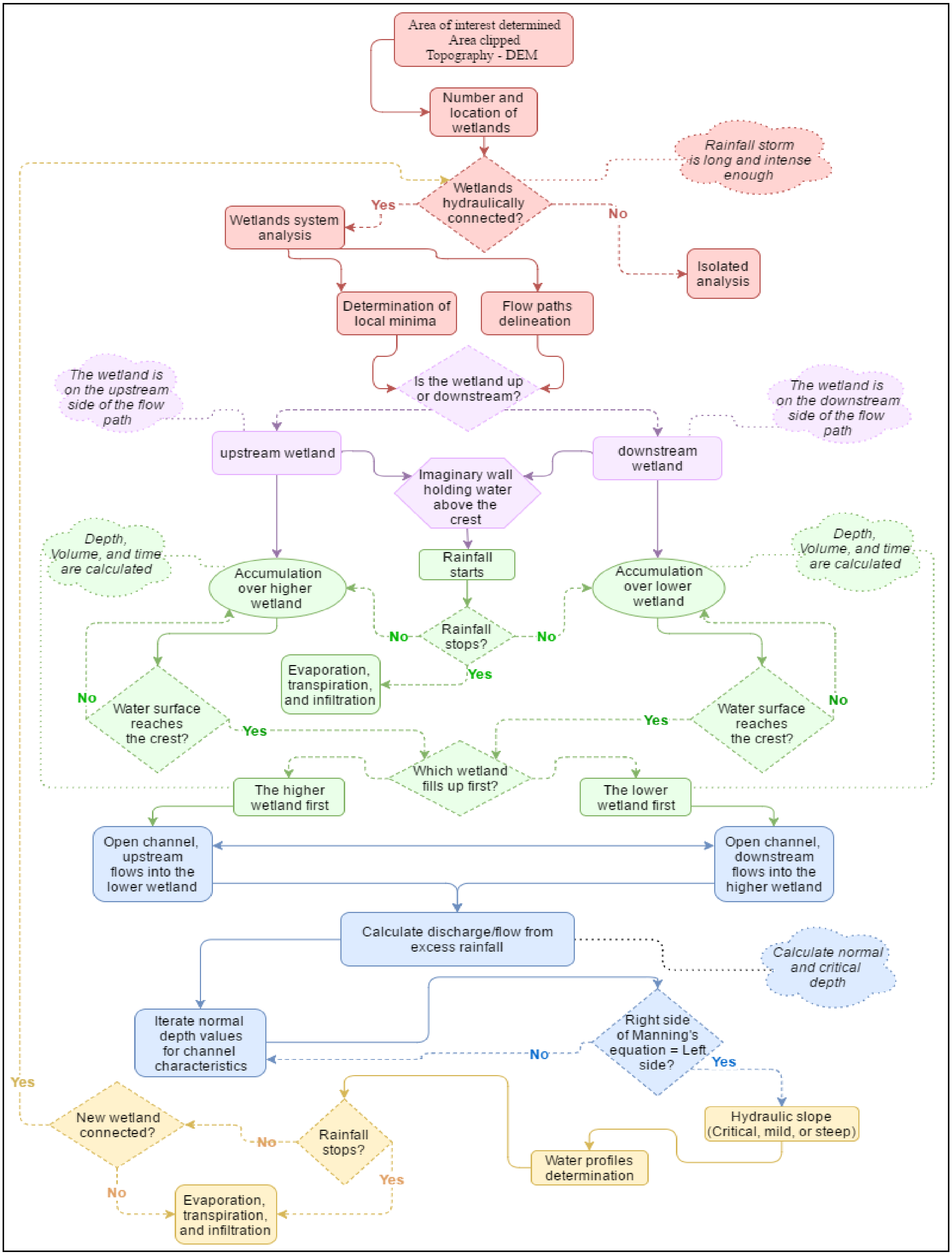


Figure 4.9 Proposed programming calculations structure for more than two wetlands.

Chapter 5: Conclusion

5.1 Conclusion

The results of this study show how important it is to consider wetland hydraulic concepts and not only on hydrology when studying wetlands. Important wetland characteristics such as discharge, depth, velocity, and equilibrium distance showed high sensitivity to different hydraulics parameters such as bed slope and Manning's coefficient.

The following are the main conclusions captured from this study:

1. The nearest representation of the connection between the two wetlands is open channel flow. Therefore, hydraulics of open channels were applied to a channel connection, and Manning's Equation was able to provide useful information regarding water surface elevations, even for small wetlands locations and with small flow rates.

2. The topographic configuration of wetlands plays a critical role into determining the direction, depth, and velocity of the flow between wetlands. In large wetland systems, the issues of rainfall uniformity and spatial distribution, could also impact the direction of initial flow between wetlands. Additionally, tailwater will also impact flow characteristics.

3. The physical characteristics of the channel connection between wetlands, specifically can impact the friction coefficient that can change during the year as vegetative cover changes can impact the determination of critical slope and whether a channel is hydraulically long.

4. The different water profiles drawn in this study showed how small changes in tailwater conditions will change the water surface behavior. As the flow from the higher wetland ended in

a free outfall, the water surface needed a longer distance to reach equilibrium and approach y_o. The higher the tailwater is the less distance was needed to reach equilibrium (i.e., to be hydraulically long), the distance dropped from 154 m to 89 m by changing the tailwater from a free outfall into a tailwater higher than y_o for the same slope and Manning's coefficient.

6. GIS is a useful tool for representing wetlands and conducting analysis to assess how a particular wetland or wetlands system performs in different landscapes. Local minima of wetlands system could be defined, and the noise in topography could be removed to secure more accurate calculations. In addition, the visual presentation of the GIS is important to understand the wetlands system as some of the flow conditions (i.e., the imaginary water wall) are not intuitively obvious.

7. The diagram of the hydraulic concepts calculations is considered as the seed of a modeling software that needs to be developed and has the potential to simulate different wetlands systems.

References

AASHTO (2005). Model Drainage Manual. Washington D.C: American Association of State Highway and Transportation Officials.

ASCE Task Force, "Friction Factors in Open Channels," Journal of the Hydraulics Division, ASCE, Vol 89, No. HY2, March 1963, pp. 97-143.

Bengtson, H. H. (2011). Sharp-Crested Weirs for Open Channel Flow Measurement. NC, Morrisville: PDH Enterprises, LLC.

Butera, M. (1983). Remote sensing of wetlands. Institute of Electrical and Electronics Engineers. Transactions on Geoscience and Remote Sensing. 3: 383-392.

Chow, V. T. (1959). Open Channel Hydraulics. New York City: McGraw-Hill.

CodeCogs. (2012, April 22). Discharge over different types of weirs. Retrieved March 17, 2016, from CodeCogs: http://www.codecogs.com/library/engineering/fluid_mechanics/weirs/discharge.php

Cowardin, L.M., Carter, Virginia, Golet, F.C., and LaRoe, E.T., 1979, Classification of wetlands and deepwater habitats of the United States: U.S. Fish and Wildlife Service Report FWS/OBS-79/31, 131 p.

Environmental Protection Agency. (1999). Constructed Wetlands Treatment of Municipal Wastewater Manual. Cincinnati, OH: National Risk Management Research Laboratory, Office of Research and Development, EPA.

Environmental Protection Agency. (2001, September). Functions and Values of Wetlands. Retrieved March 2016, from Water Home (Fact Sheet): https://owpubauthor.epa.gov/type/wetlands/upload/2006_08_11_wetlands_fun_val.pdf

Environmental Protection Agency. (2015, November). Section 404 of the Clean Water Act. Retrieved April 2016, from U.S. Environmental Protection Agency: https://www.epa.gov/cwa-404/section-404-clean-water-act-how-wetlands-are-defined-and-identified

Fitch, M. G., Anderson, J.E., Ridout, S.A., and Goodall, J.L. (2003). "Integrating of multiband imagery as a means of monitoring wetland resources for the Virginia Department of Transportation.". Virginia Transportation Research Council Report: 24.

Gammon, P., and Carter, V. (1976). Comparison of vegetation classes in the Great Dismal Swamp using two individual Landsat images and a temporal composite. Purdue Symposium on Machine Processing of Remotely Sensed Data, (pp. 3B-1).

Garbrecht, J., Ogden, F.L., Debarry, P.A., Maidment, A.R., (2001). GIS and Distributed Watershed Models. I: Data Coverages and Sources. . Journal of Hydrologic Engineering 6(6) , 506-514.

Gosselink, J.G., and Turner, R.E., 1978, The role of hydrology in freshwater wetland ecosystems, in Good, R.E., Whigham, D.F., and Simpson, R.L., eds., Freshwater wetlands--Ecological processes and management potential: New York, Academic Press, p. 63-78.

Hammer, D. (1992). Designing Constructed Wetlands Systems to Treat Agricultural Nonpoint Source Pollution. Ecological Engineering, 1:49-82.

Jensen, J.R., Hodgson, M.E., Christensen, E., Mackey, H.E., Tinney, L.R., and R. Sharitz. (1986). Remote sensing inland wetlands: a multispectral approach. Photogrammetric Engineering and Remote Sensing, 52:87-100.

Jones, N., and Shahrokh, I. F. (1977). Application of Landsat data to wetland study and land use classification in west Tennesee. the 11th International Symposium on Remote Sensing of Environment Volume I (pp. 609-613). Ann Arbor, MI: Environmental Research Institute of Michigan.

Kadlec, R. H., and Wallace, S. D. (2009). Treatment Wetlands Second Edition. Boca Raton, FL: CRC Press.

Kadlec, R., and Knight, R. (1996). Treatment Wetlands. First Edition. Boca Raton, FL: CRC Press.

Leahy, M. (2010). The Wetlands of Missouri. Retrieved January 2016, from Missouri Department of Conservation: http://mdc.mo.gov/node/9118

Maheu-Giroux, M. A. (2005). "Mapping the invasive species Phragmites australis in linear wetland corridors.". Aquatic Botany 83(4) 310-320.

Maidment, D. R. (1996). GIS and hydrologic modeling-an assessment of progress. Third International Conference on GIS and Environmental Modeling, (pp. 596 - 610). Santa Fe, New Mexico.

Manning, R. (1889). In “On the Flow of Water in Open Channels and Pipes.” Trans. (20, 161-166). Dublin, Ireland: Institute of Civil Engineers of Ireland.

MedWet. (2016). Wetland Terminology. Retrieved March 2016, from MedWet The Mediterrameam Wetlands Initiative: http://medwet.org/aboutwetlands/wetland-terminology/

Meijerink, A. M., (1994). "Introduction to the use of geographic information systems for practical hydrology". Publ. No. 23. Emschede, The Netherland: International Institute for Aerospace Survey and Earth Sciences.

Mierau, R., and Trimble, P. (1988). Hydrological Characteristics of the Kissimmee River Flood Plain, Boney Marsh Experimental Area. West Palm Beach, FL: South Florida Water Management District.

Miller, J. M. (2007). Constructed Wetlands Technology Assessment and Design Guidance. Pleasant Hill, Iowa: Iowa Department of Natural Resources.

Mitsch, W. J., and Gosselink, J. (2000). Wetlands. New York: John Wiley and Sons, Inc.

Morris, H., and Wiggert, J. (1963). Applied Hydraulics in Engineering (p. 489). New York: John Wiley and Sons.

Nuckols, Ward, M.H., Jarup, L. (2004). “Using geographic information systems for exposure assessment in environmental epidemiology studies”. Environ Health Perspective.

Rafat, M., Yazdi, M., Rafat, M., and Moghadam, E. (2014). Numerical Evaluation of Routing of Dam Reservoir to Discuss the Flood Plain. Journal of Current Research in Science, Vol. 2, No. 3, 350-354.

Reed, P. (1988). National list of plant species that occur in wetlands. Washington, D.C: United

States Fish and Wildlife Service, U.S. Dept. of the Interior, Research and Development.

Roseke, B. (2013, November). How to Calculate Shallow Concentrated Flow. Retrieved April 2016, from Culvert Design: http://culvertdesign.com/how-to-calculate-shallow-concentrated-flow/

Sader, S. A., Ahl, D., and Liou, W. S. (1995). Accuracy of Landsat-TM and GIS Rule-Based Methods for Forest Wetland Classification in Maine. Remote Sensing of the Environment 53(3) , 133-144.

Smith, A. A. (2010). Hydraulic Theory - Reservior Routing. Retrieved April 2016, from Alan a. Smith: http://www.alanasmith.com/theory-Reservoir-Routing.htm

Stanley, S., J. Brown, and S. Grigsby (2005). Protecting Aquatic Ecosystems: A Guide for Puget Sound Planners to Understand Watershed Processes. Olympia, WA: Washington State Department of Ecology. Publication #05-06-027.

Sturm, T. W. (2001). Open Channel Hydraulics. NCY, United States: McGraw-Hill.

State Wetlands Information Tool. (2015). Wetland State Resource Locator. Retrieved December 2015, from Environmental Compliance Assistance Platform: http://www.envcap.org/statetools/swift/swift2.cfm?st=MO

Tiner, R.W. 1991, The concept of a hydrophyte for wetland identification: BioScience, v. 41, no. 4, p. 236-247.

Tuan, A. L. (2003). Open Channel Hydraulics for Engineers. Delft: Delft University of

Technology.

Turner, M. H. and Gannon, R. (NCSU). Wetland protection. Retrieved from Watershed: http://www.water.ncsu.edu/watershedss/info/wetlands/protect.html#intro

United States Army Corps of Engineers Wetlands Delineation Manual. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station, 1987.

United States Department of Agriculture. (2006). Plants Database. Retrieved March 2016, from Natural Resources Conservation Service: http://plants.usda.gov/

United States Department of Agriculture, Soil Conservation Service. (1989). Hydrology Training Series Module 111 – Reservoir Flood Routing Study Guide.

Vermont Department of Environmental Conservation. Watershed Management Division (2014, April). Wetlands - Water Storage for Flood Water and Storm Runoff. Retrieved March 17, 2016. http://www.watershedmanagement.vt.gov/wetlands/htm/wl_func-storage.htm

Walton, R., Martin, T. H., Chapman, R. S., and Davis, J. E. (1995). Investigation of Wetlands Hydraulic and Hydrological Processes, Model Development, and Application. Washington, DC: U.S. Army Corps of Engineers.

Water Resources Center. (2013). Missouri Wetland Program Plan 2013 – 2018 . Jefferson City: Missouri Department of Natural Resources.

Welsch, D. J., Smart, D. L., Boyer, J. N., Minkin, P., Smith, H. C., McCandless, T. L. (1995, April). Hydrology - Forested Wetlands Functions, Benefits and the Use of Best Management Practices. Retrieved March 17, 2016, from United States Department of Agriculture Forest

Service: http://www.na.fs.fed.us/spfo/pubs/n_resource/wetlands/wetlands4_hydrology.htm

Wetland Reserve Program. (1994). Methods for evaluating wetland functions, WRP Technical note WG-EV-2.2. Wetland Reserve Program.

Appendices

Appendix A

Table A-1. Rainfall intensity and time needed for each layer in the higher wetland to fill up.

Layer	Elevation (m)	Area (m^2)	Depth of layer (m)	Volume of layer (m^3)	Cumtv. volume of layer (m^3)	Time (min)	Rainfall (mm/min)	Volume (m^3/min)	Cumtv. volume (m^3)
1	200.00	1	0.03	0.03	0.03	-	-	-	-
2	200.03	9	0.03	0.27	0.3	1	2	0.722	0.722
3	200.06	25	0.03	0.75	1.05	2	2	0.722	1.444
						3	2	0.722	2.166
						4	2	0.722	2.888
4	200.09	49	0.03	1.47	2.52	5	2	0.722	3.61
						6	2	0.722	4.332
5	200.12	81	0.03	2.43	4.95	7	2	0.722	5.054
						8	2	0.722	5.776
						9	2	0.722	6.498
						10	2	0.722	7.22
						11	2	0.722	7.942
6	200.15	121	0.03	3.63	8.58	12	2	0.722	8.664
						13	2	0.722	9.386
						14	2	0.722	10.108
						15	2	0.722	10.83
						16	2	0.722	11.552
						17	2	0.722	12.274
		-	-			18	2	0.722	12.996
7	200.18	169	0.03	5.07	13.65	19	2	0.722	13.718
						20	2	0.722	14.44
						21	2	0.722	15.162
		-	-			22	2	0.722	15.884
		-	-			23	2	0.722	16.606
		-	-			24	2	0.722	17.328
		-	-			25	2	0.722	18.05
		-	-			26	2	0.722	18.772

		-	-			27	2	0.722	19.494
		-	-			28	2	0.722	20.216
8	200.21	225	0.03	6.75	20.4	29	2	0.722	20.938
						30	2	0.722	21.66
		-	-			31	2	0.722	22.382
		-	-			32	2	0.722	23.104
		-	-			33	2	0.722	23.826
		-	-			34	2	0.722	24.548
		-	-			35	2	0.722	25.27
		-	-			36	2	0.722	25.992
		-	-			37	2	0.722	26.714
		-	-			38	2	0.722	27.436
		-	-			39	2	0.722	28.158
						40	2	0.722	28.88
9	200.24	289	0.03	8.67	29.07	41	2	0.722	29.602
						42	2	0.722	30.324
		-	-			43	2	0.722	31.046
		-	-			44	2	0.722	31.768
		-	-			45	2	0.722	32.49
		-	-			46	2	0.722	33.212
		-	-			47	2	0.722	33.934
		-	-			48	2	0.722	34.656
		-	-			49	2	0.722	35.378
						50	2	0.722	36.1
		-	-			51	2	0.722	36.822
		-	-			52	2	0.722	37.544
		-	-			53	2	0.722	38.266
		-	-			54	2	0.722	38.988
		-	-			55	2	0.722	39.71
10	200.27	361	0.03	10.83	39.9	56	2	0.722	40.432

Table A-2. Rainfall intensity and time needed for each layer in the lower wetland to fill up.

Layer	Elevation (m)	Area (m^2)	Depth of layer (m)	Volume of layer (m^3)	Cumtv. volume of layer (m^3)	Time (min)	Rainfall (mm/min)	Volume (m^3/min)	Cumtv. volume (m^3)
1	199.95	1	0.15	0.15	0.15	-	-	-	-
						1	2	0.242	0.242

						2	2	0.242	0.484
						3	2	0.242	0.726
						4	2	0.242	0.968
						5	2	0.242	1.21
						6	2	0.242	1.452
2	199.80	9	0.15	1.35	1.5	7	2	0.242	1.694
						8	2	0.242	1.936
						9	2	0.242	2.178
						10	2	0.242	2.42
						11	2	0.242	2.662
						12	2	0.242	2.904
						13	2	0.242	3.146
						14	2	0.242	3.388
						15	2	0.242	3.63
						16	2	0.242	3.872
						17	2	0.242	4.114
						18	2	0.242	4.356
						19	2	0.242	4.598
						20	2	0.242	4.84
						21	2	0.242	5.082
3	199.65	25	0.15	3.75	5.25	22	2	0.242	5.324
						23	2	0.242	5.566
						24	2	0.242	5.808
						25	2	0.242	6.05
						26	2	0.242	6.292
						27	2	0.242	6.534
						28	2	0.242	6.776
						29	2	0.242	7.018
						30	2	0.242	7.26
						31	2	0.242	7.502
						32	2	0.242	7.744
						33	2	0.242	7.986
						34	2	0.242	8.228
						35	2	0.242	8.47
						36	2	0.242	8.712
						37	2	0.242	8.954
						38	2	0.242	9.196
						39	2	0.242	9.438
						40	2	0.242	9.68
						41	2	0.242	9.922

						42	2	0.242	10.164
						43	2	0.242	10.406
						44	2	0.242	10.648
						45	2	0.242	10.89
						46	2	0.242	11.132
						47	2	0.242	11.374
						48	2	0.242	11.616
						49	2	0.242	11.858
						50	2	0.242	12.1
						51	2	0.242	12.342
						52	2	0.242	12.584
4	199.50	49	0.15	7.35	12.6	53	2	0.242	12.826
						54	2	0.242	13.068
						55	2	0.242	13.31
			Flow from the other wetland	Volume (m^3/min)	Cumtv. Volume (m^3/min)	56	2	0.242	13.552
				0.004	0.004	57	2	0.242	13.80
				0.013	0.018	58	2	0.242	14.05
				0.026	0.044	59	2	0.242	14.32
				0.043	0.087	60	2	0.242	14.61
				0.062	0.149	61	2	0.242	14.91
				0.084	0.232	62	2	0.242	15.24
				0.108	0.341	63	2	0.242	15.59
				0.135	0.476	64	2	0.242	15.96
				0.164	0.640	65	2	0.242	16.37
				0.196	0.836	66	2	0.242	16.81
				0.230	1.066	67	2	0.242	17.28
				0.265	1.331	68	2	0.242	17.79
				0.303	1.635	69	2	0.242	18.33
				0.343	1.978	70	2	0.242	18.92
				0.385	2.363	71	2	0.242	19.54
				0.428	2.791	72	2	0.242	20.22
				0.474	3.265	73	2	0.242	20.93
				0.521	3.786	74	2	0.242	21.69
				0.570	4.356	75	2	0.242	22.51
				0.621	4.977	76	2	0.242	23.37
5	199.35	81	0.15	0.673	5.650	77	2	0.242	24.28
				0.722	6.372	78	2	0.242	25.25

				0.722	7.094	79	2	0.242	26.21
				0.722	7.816	80	2	0.242	27.18
				0.722	8.538	81	2	0.242	28.14
				0.722	9.259	82	2	0.242	29.10
				0.722	9.981	83	2	0.242	30.07
				0.722	10.703	84	2	0.242	31.03
				0.722	11.425	85	2	0.242	32.00
				0.722	12.147	86	2	0.242	32.96
				0.722	12.869	87	2	0.242	33.92
				0.722	13.591	88	2	0.242	34.89
				0.722	14.312	89	2	0.242	35.85
				0.722	15.034	90	2	0.242	36.81
				0.722	15.756	91	2	0.242	37.78
				0.722	16.478	92	2	0.242	38.74
				0.722	17.200	93	2	0.242	39.71
				0.722	17.922	94	2	0.242	40.67
				0.722	18.644	95	2	0.242	41.63
				0.722	19.366	96	2	0.242	42.60
6	199.20	121	0.15	0.722	20.087	97	2	0.242	43.56

Table A-3. Rainfall intensity and the time at which both wetlands merge above the crest and act as one large wetland.

Layer	Elevation (m)	Area (m^2)	Depth of layer (m)	Volume of layer (m^3)	Cumtv. volume of layer (m^3)	Time (min)	Rainfall (mm/min)	Volume (m^3/min)	Cumtv. volume (m^3)
						98	2	1.03	1.03
						99	2	1.03	2.06
						100	2	1.03	3.09
						101	2	1.03	4.12
						102	2	1.03	5.15
						103	2	1.03	6.18
						104	2	1.03	7.21
						105	2	1.03	8.24
						106	2	1.03	9.27
						107	2	1.03	10.3

						108	2	1.03	11.33
						109	2	1.03	12.36
						110	2	1.03	13.39
						111	2	1.03	14.42
						112	2	1.03	15.45
						113	2	1.03	16.48
						114	2	1.03	17.51
						115	2	1.03	18.54
						116	2	1.03	19.57
						117	2	1.03	20.6
						118	2	1.03	21.63
						119	2	1.03	22.66
						120	2	1.03	23.69
						121	2	1.03	24.72
1	200.30	515	0.05	25.75	25.75	122	2	1.03	25.75

Appendix B

Table B-1. Direct step method for calculating water surface profiles for a trapezoidal channel on a mild slope with a free outfall, while varying slope.

Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m				
0.01203	0.08766	0.0049	0.0005	11	0.35	0.01				
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.005145	0.0566	11.0103	0.00514	0.2126	0.0074	6.2392				
0.007145	0.0786	11.0143	0.00714	0.1531	0.0083	2.0891	4.164151	0.0009	-0.0002	-0.0002
0.009145	0.1006	11.0183	0.00913	0.1196	0.0099	0.9181	1.503575	0.0015	-0.0010	-0.0012
0.011145	0.1226	11.0223	0.01112	0.0981	0.0116	0.4751	0.696589	0.0018	-0.0025	-0.0038
0.013145	0.1446	11.0263	0.01311	0.0832	0.0135	0.2742	0.374636	0.0019	-0.0050	-0.0087
0.015145	0.1666	11.0303	0.0151	0.0722	0.0154	0.1711	0.222638	0.0019	-0.0086	-0.0174
0.017145	0.1886	11.0343	0.01709	0.0638	0.0174	0.1132	0.142148	0.0019	-0.0137	-0.0311
0.019145	0.2106	11.0383	0.01908	0.0571	0.0193	0.0784	0.095806	0.0020	-0.0206	-0.0516
0.021145	0.2326	11.0423	0.02106	0.0517	0.0213	0.0563	0.067367	0.0020	-0.0295	-0.0811
0.023145	0.2546	11.0463	0.02305	0.0473	0.0233	0.0417	0.049011	0.0020	-0.0408	-0.1218
0.025145	0.2766	11.0503	0.02503	0.0435	0.0252	0.0316	0.036671	0.0020	-0.0548	-0.1767
0.027145	0.2986	11.0543	0.02701	0.0403	0.0272	0.0245	0.028089	0.0020	-0.0720	-0.2487
0.029145	0.3206	11.0583	0.02899	0.0375	0.0292	0.0194	0.021949	0.0020	-0.0927	-0.3414
0.031145	0.3426	11.0623	0.03097	0.0351	0.0312	0.0155	0.017447	0.0020	-0.1175	-0.4589
0.033145	0.3646	11.0663	0.03295	0.0330	0.0332	0.0126	0.014077	0.0020	-0.1468	-0.6056
0.035145	0.3866	11.0703	0.03492	0.0311	0.0352	0.0104	0.011508	0.0020	-0.1811	-0.7868
0.037145	0.4086	11.0743	0.0369	0.0294	0.0372	0.0086	0.009518	0.0020	-0.2212	-1.0080
0.039145	0.4306	11.0783	0.03887	0.0279	0.0392	0.0073	0.007953	0.0020	-0.2678	-1.2757
0.041145	0.4526	11.0823	0.04084	0.0266	0.0412	0.0062	0.006707	0.0020	-0.3216	-1.5973
0.043145	0.4746	11.0863	0.04281	0.0253	0.0432	0.0053	0.005704	0.0020	-0.3837	-1.9810
0.045145	0.4966	11.0903	0.04478	0.0242	0.0452	0.0045	0.004888	0.0020	-0.4552	-2.4362
0.047145	0.5186	11.0943	0.04675	0.0232	0.0472	0.0039	0.004217	0.0020	-0.5373	-2.9735
0.049145	0.5406	11.0983	0.04871	0.0223	0.0492	0.0034	0.003662	0.0020	-0.6318	-3.6054
0.051145	0.5626	11.1023	0.05068	0.0214	0.0512	0.0030	0.003198	0.0020	-0.7406	-4.3459
0.053145	0.5846	11.1063	0.05264	0.0206	0.0532	0.0026	0.002808	0.0020	-0.8658	-5.2118
0.055145	0.6066	11.1103	0.0546	0.0198	0.0552	0.0023	0.002478	0.0020	-1.0106	-6.2224
0.057145	0.6286	11.1143	0.05656	0.0191	0.0572	0.0021	0.002196	0.0020	-1.1784	-7.4008
0.059145	0.6506	11.1183	0.05852	0.0185	0.0592	0.0018	0.001955	0.0020	-1.3739	-8.7746
0.061145	0.6726	11.1223	0.06048	0.0179	0.0612	0.0017	0.001747	0.0020	-1.6029	-10.3776
0.063145	0.6946	11.1263	0.06243	0.0173	0.0632	0.0015	0.001567	0.0020	-1.8733	-12.2509

0.065145	0.7166	11.1303	0.06439	0.0168	0.0652	0.0013	0.001411	0.0020	-2.1954	-14.4463
0.067145	0.7386	11.1343	0.06634	0.0163	0.0672	0.0012	0.001274	0.0020	-2.5835	-17.0298
0.069145	0.7606	11.1383	0.06829	0.0158	0.0692	0.0011	0.001154	0.0020	-3.0577	-20.0875
0.071145	0.7826	11.1423	0.07024	0.0154	0.0712	0.0010	0.001048	0.0020	-3.6471	-23.7346
0.073145	0.8046	11.1463	0.07219	0.0150	0.0732	0.0009	0.000955	0.0020	-4.3961	-28.1307
0.075145	0.8267	11.1503	0.07414	0.0146	0.0752	0.0008	0.000872	0.0020	-5.3753	-33.5060
0.077145	0.8487	11.1543	0.07608	0.0142	0.0772	0.0008	0.000798	0.0020	-6.7038	-40.2098
0.079145	0.8707	11.1583	0.07803	0.0138	0.0792	0.0007	0.000732	0.0020	-8.6012	-48.8110
0.081145	0.8927	11.1623	0.07997	0.0135	0.0812	0.0006	0.000674	0.0020	-11.5200	-60.3309
0.083145	0.9147	11.1663	0.08191	0.0132	0.0832	0.0006	0.000621	0.0020	-16.5662	-76.8972
0.085145	0.9367	11.1703	0.08385	0.0128	0.0852	0.0006	0.000573	0.0020	-27.3487	-104.2459
0.0867834	0.9547	11.1736	0.08544	0.0126	0.0868	0.0005	0.000534	0.0016	-48.5912	-152.8370
Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m				
0.01203	0.0438	0.0049	0.005	11	0.35	0.01				
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	Se	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.005145	0.0566	11.01029	0.00514	0.2126	0.0074	6.2392				
0.006645	0.0731	11.01329	0.006637	0.1646	0.0080	2.6603	4.449748	0.0006	-0.0001	-0.0001
0.008145	0.0896	11.01629	0.008133	0.1343	0.0091	1.3503	2.005266	0.0010	-0.0005	-0.0006
0.009645	0.1061	11.01929	0.009628	0.1134	0.0103	0.7689	1.059597	0.0012	-0.0012	-0.0018
0.011145	0.1226	11.02229	0.011123	0.0981	0.0116	0.4751	0.621999	0.0013	-0.0022	-0.0040
0.012645	0.1391	11.02529	0.012616	0.0865	0.0130	0.3120	0.393535	0.0014	-0.0036	-0.0076
0.014145	0.1556	11.02829	0.014109	0.0773	0.0144	0.2148	0.263385	0.0014	-0.0055	-0.0131
0.015645	0.1721	11.03129	0.015601	0.0699	0.0159	0.1536	0.184169	0.0014	-0.0081	-0.0211
0.017145	0.1886	11.03429	0.017092	0.0638	0.0174	0.1132	0.133379	0.0015	-0.0114	-0.0325
0.018645	0.2051	11.03729	0.018582	0.0587	0.0188	0.0856	0.099416	0.0015	-0.0155	-0.0480
0.020145	0.2216	11.04029	0.020072	0.0543	0.0203	0.0662	0.075905	0.0015	-0.0208	-0.0688
0.021645	0.2381	11.04329	0.021561	0.0505	0.0218	0.0521	0.059148	0.0015	-0.0273	-0.0962
0.023145	0.2546	11.04629	0.023048	0.0473	0.0233	0.0417	0.046904	0.0015	-0.0354	-0.1316
0.024645	0.2711	11.04929	0.024536	0.0444	0.0247	0.0338	0.037764	0.0015	-0.0454	-0.1770
0.026145	0.2876	11.05229	0.026022	0.0418	0.0262	0.0278	0.030814	0.0015	-0.0577	-0.2346
0.027645	0.3041	11.05529	0.027507	0.0396	0.0277	0.0231	0.025441	0.0015	-0.0729	-0.3075
0.029145	0.3206	11.05829	0.028992	0.0375	0.0292	0.0194	0.021226	0.0015	-0.0920	-0.3995
0.030645	0.3371	11.06129	0.030476	0.0357	0.0307	0.0164	0.017877	0.0015	-0.1160	-0.5155
0.032145	0.3536	11.06429	0.031959	0.0340	0.0322	0.0140	0.015184	0.0015	-0.1467	-0.6622
0.033645	0.3701	11.06729	0.033441	0.0325	0.0337	0.0120	0.012996	0.0015	-0.1869	-0.8491
0.035145	0.3866	11.07029	0.034923	0.0311	0.0352	0.0104	0.011202	0.0015	-0.2411	-1.0903
0.036645	0.4031	11.07329	0.036404	0.0298	0.0367	0.0090	0.009717	0.0015	-0.3172	-1.4074
0.038145	0.4196	11.07629	0.037884	0.0287	0.0382	0.0079	0.008478	0.0015	-0.4303	-1.8377
0.039645	0.4361	11.07929	0.039363	0.0276	0.0397	0.0070	0.007437	0.0015	-0.6141	-2.4518

0.041145	0.4526	11.08229	0.040841	0.0266	0.0412	0.0062	0.006557	0.0015	-0.9615	-3.4133
0.042645	0.4691	11.08529	0.042319	0.0256	0.0427	0.0055	0.005808	0.0015	-1.8537	-5.2670
0.043362	0.4770	11.08673	0.043024	0.0252	0.0434	0.0052	0.005315	0.0007	-2.2695	-7.5365
Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m				
0.01203	0.0219	0.0049	0.05	11	0.35	0.01				
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.005145	0.0566	11.0103	0.00514	0.2126	0.0074	6.2392				
0.006145	0.0676	11.0123	0.00614	0.1780	0.0078	3.4523	4.845795	0.0003	-0.0001	-0.0001
0.007145	0.0786	11.0143	0.00714	0.1531	0.0083	2.0891	2.770701	0.0006	-0.0002	-0.0003
0.008145	0.0896	11.0163	0.00813	0.1343	0.0091	1.3503	1.719670	0.0007	-0.0004	-0.0007
0.009145	0.1006	11.0183	0.00913	0.1196	0.0099	0.9181	1.134187	0.0008	-0.0007	-0.0015
0.010145	0.1116	11.0203	0.01013	0.1078	0.0107	0.6498	0.783933	0.0009	-0.0012	-0.0026
0.011145	0.1226	11.0223	0.01112	0.0981	0.0116	0.4751	0.562430	0.0009	-0.0018	-0.0044
0.012145	0.1336	11.0243	0.01212	0.0900	0.0126	0.3568	0.415968	0.0009	-0.0025	-0.0069
0.013145	0.1446	11.0263	0.01311	0.0832	0.0135	0.2742	0.315518	0.0009	-0.0035	-0.0104
0.014145	0.1556	11.0283	0.01411	0.0773	0.0144	0.2148	0.244486	0.0010	-0.0049	-0.0153
0.015145	0.1666	11.0303	0.0151	0.0722	0.0154	0.1711	0.192938	0.0010	-0.0067	-0.0221
0.016145	0.1776	11.0323	0.0161	0.0677	0.0164	0.1383	0.154686	0.0010	-0.0092	-0.0313
0.017145	0.1886	11.0343	0.01709	0.0638	0.0174	0.1132	0.125744	0.0010	-0.0129	-0.0442
0.018145	0.1996	11.0363	0.01809	0.0603	0.0183	0.0937	0.103471	0.0010	-0.0183	-0.0625
0.019145	0.2106	11.0383	0.01908	0.0571	0.0193	0.0784	0.086071	0.0010	-0.0272	-0.0897
0.020145	0.2216	11.0403	0.02007	0.0543	0.0203	0.0662	0.072295	0.0010	-0.0441	-0.1338
0.021145	0.2326	11.0423	0.02106	0.0517	0.0213	0.0563	0.061255	0.0010	-0.0876	-0.2214
0.021681	0.2385	11.0434	0.0216	0.0504	0.0218	0.0518	0.054076	0.0005	-0.1299	-0.3513
Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m				
0.01203	0.01097	0.0049	0.5	11	0.35	0.01				
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.005145	0.0566	11.01029	0.00514	0.2126	0.0074	6.2392				
0.005645	0.0621	11.01129	0.005639	0.1937	0.0076	4.5806	5.409921	0.0001	0.0000	0.0000
0.006145	0.0676	11.01229	0.006138	0.1780	0.0078	3.4523	4.016471	0.0002	-0.0001	-0.0001
0.006645	0.0731	11.01329	0.006637	0.1646	0.0080	2.6603	3.056298	0.0003	-0.0001	-0.0002
0.007145	0.0786	11.01429	0.007136	0.1531	0.0083	2.0891	2.374654	0.0003	-0.0002	-0.0004
0.007645	0.0841	11.01529	0.007634	0.1431	0.0087	1.6676	1.878315	0.0003	-0.0003	-0.0006
0.008145	0.0896	11.01629	0.008133	0.1343	0.0091	1.3503	1.508927	0.0004	-0.0004	-0.0010
0.008645	0.0951	11.01729	0.008632	0.1265	0.0095	1.1072	1.228746	0.0004	-0.0005	-0.0015
0.009145	0.1006	11.01829	0.00913	0.1196	0.0099	0.9181	1.012651	0.0004	-0.0008	-0.0023
0.009645	0.1061	11.01929	0.009628	0.1134	0.0103	0.7689	0.843502	0.0004	-0.0012	-0.0036
0.010145	0.1116	11.02029	0.010126	0.1078	0.0107	0.6498	0.709343	0.0004	-0.0021	-0.0057

0.010645	0.1171	11.02129	0.010625	0.1027	0.0112	0.5536	0.601670	0.0004	-0.0044	-0.0100
0.01086	0.1195	11.02172	0.010839	0.1007	0.0114	0.5178	0.535708	0.0002	-0.0054	-0.0155

Table B-2. Direct step method for calculating water surface profiles for a trapezoidal channel on a mild slope with a free outfall, while varying Manning's roughness coefficient.

Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m				
0.01203	0.0438	0.0049	0.005	11	0.35	0.01				
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.005145	0.0566	11.0103	0.00514	0.2126	0.0074	6.2392				
0.006645	0.0731	11.0133	0.00664	0.1646	0.0080	2.6603	4.449748	0.0006	-0.0001	-0.0001
0.008145	0.0896	11.0163	0.00813	0.1343	0.0091	1.3503	2.005266	0.0010	-0.0005	-0.0006
0.009645	0.1061	11.0193	0.00963	0.1134	0.0103	0.7689	1.059597	0.0012	-0.0012	-0.0018
0.011145	0.1226	11.0223	0.01112	0.0981	0.0116	0.4751	0.621999	0.0013	-0.0022	-0.0040
0.012645	0.1391	11.0253	0.01262	0.0865	0.0130	0.3120	0.393535	0.0014	-0.0036	-0.0076
0.014145	0.1556	11.0283	0.01411	0.0773	0.0144	0.2148	0.263385	0.0014	-0.0055	-0.0131
0.015645	0.1721	11.0313	0.0156	0.0699	0.0159	0.1536	0.184169	0.0014	-0.0081	-0.0211
0.017145	0.1886	11.0343	0.01709	0.0638	0.0174	0.1132	0.133379	0.0015	-0.0114	-0.0325
0.018645	0.2051	11.0373	0.01858	0.0587	0.0188	0.0856	0.099416	0.0015	-0.0155	-0.0480
0.020145	0.2216	11.0403	0.02007	0.0543	0.0203	0.0662	0.075905	0.0015	-0.0208	-0.0688
0.021645	0.2381	11.0433	0.02156	0.0505	0.0218	0.0521	0.059148	0.0015	-0.0273	-0.0962
0.023145	0.2546	11.0463	0.02305	0.0473	0.0233	0.0417	0.046904	0.0015	-0.0354	-0.1316
0.024645	0.2711	11.0493	0.02454	0.0444	0.0247	0.0338	0.037764	0.0015	-0.0454	-0.1770
0.026145	0.2876	11.0523	0.02602	0.0418	0.0262	0.0278	0.030814	0.0015	-0.0577	-0.2346
0.027645	0.3041	11.0553	0.02751	0.0396	0.0277	0.0231	0.025441	0.0015	-0.0729	-0.3075
0.029145	0.3206	11.0583	0.02899	0.0375	0.0292	0.0194	0.021226	0.0015	-0.0920	-0.3995
0.030645	0.3371	11.0613	0.03048	0.0357	0.0307	0.0164	0.017877	0.0015	-0.1160	-0.5155
0.032145	0.3536	11.0643	0.03196	0.0340	0.0322	0.0140	0.015184	0.0015	-0.1467	-0.6622
0.033645	0.3701	11.0673	0.03344	0.0325	0.0337	0.0120	0.012996	0.0015	-0.1869	-0.8491
0.035145	0.3866	11.0703	0.03492	0.0311	0.0352	0.0104	0.011202	0.0015	-0.2411	-1.0903
0.036645	0.4031	11.0733	0.0364	0.0298	0.0367	0.0090	0.009717	0.0015	-0.3172	-1.4074
0.038145	0.4196	11.0763	0.03788	0.0287	0.0382	0.0079	0.008478	0.0015	-0.4303	-1.8377
0.039645	0.4361	11.0793	0.03936	0.0276	0.0397	0.0070	0.007437	0.0015	-0.6141	-2.4518
0.041145	0.4526	11.0823	0.04084	0.0266	0.0412	0.0062	0.006557	0.0015	-0.9615	-3.4133
0.042645	0.4691	11.0853	0.04232	0.0256	0.0427	0.0055	0.005808	0.0015	-1.8537	-5.2670
0.04336	0.4770	11.0867	0.04302	0.0252	0.0434	0.0052	0.005316	0.0007	-2.2591	-7.5262
Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m				
0.01203	0.039917	0.0049	0.005	11	0.3	0.01				

y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.005145	0.0566	11.01029	0.00514	0.2126	0.0074	4.5839				
0.006645	0.0731	11.01329	0.006637	0.1646	0.0080	1.9545	3.269202	0.0006	-0.0002	-0.0002
0.008145	0.0896	11.01629	0.008133	0.1343	0.0091	0.9920	1.473257	0.0010	-0.0007	-0.0009
0.009645	0.1061	11.01929	0.009628	0.1134	0.0103	0.5649	0.778479	0.0012	-0.0016	-0.0025
0.011145	0.1226	11.02229	0.011123	0.0981	0.0116	0.3490	0.456979	0.0013	-0.0030	-0.0054
0.012645	0.1391	11.02529	0.012616	0.0865	0.0130	0.2292	0.289128	0.0014	-0.0049	-0.0103
0.014145	0.1556	11.02829	0.014109	0.0773	0.0144	0.1578	0.193508	0.0014	-0.0076	-0.0179
0.015645	0.1721	11.03129	0.015601	0.0699	0.0159	0.1128	0.135308	0.0014	-0.0111	-0.0290
0.017145	0.1886	11.03429	0.017092	0.0638	0.0174	0.0832	0.097993	0.0015	-0.0157	-0.0446
0.018645	0.2051	11.03729	0.018582	0.0587	0.0188	0.0629	0.073041	0.0015	-0.0216	-0.0662
0.020145	0.2216	11.04029	0.020072	0.0543	0.0203	0.0486	0.055767	0.0015	-0.0291	-0.0953
0.021645	0.2381	11.04329	0.021561	0.0505	0.0218	0.0383	0.043455	0.0015	-0.0385	-0.1338
0.023145	0.2546	11.04629	0.023048	0.0473	0.0233	0.0306	0.034460	0.0015	-0.0504	-0.1841
0.024645	0.2711	11.04929	0.024536	0.0444	0.0247	0.0249	0.027745	0.0015	-0.0654	-0.2495
0.026145	0.2876	11.05229	0.026022	0.0418	0.0262	0.0204	0.022639	0.0015	-0.0844	-0.3339
0.027645	0.3041	11.05529	0.027507	0.0396	0.0277	0.0170	0.018691	0.0015	-0.1089	-0.4428
0.029145	0.3206	11.05829	0.028992	0.0375	0.0292	0.0142	0.015595	0.0015	-0.1408	-0.5836
0.030645	0.3371	11.06129	0.030476	0.0357	0.0307	0.0120	0.013134	0.0015	-0.1836	-0.7672
0.032145	0.3536	11.06429	0.031959	0.0340	0.0322	0.0103	0.011156	0.0015	-0.2427	-1.0099
0.033645	0.3701	11.06729	0.033441	0.0325	0.0337	0.0088	0.009548	0.0015	-0.3287	-1.3385
0.035145	0.3866	11.07029	0.034923	0.0311	0.0352	0.0076	0.008230	0.0015	-0.4630	-1.8016
0.036645	0.4031	11.07329	0.036404	0.0298	0.0367	0.0066	0.007139	0.0015	-0.6995	-2.5011
0.038145	0.4196	11.07629	0.037884	0.0287	0.0382	0.0058	0.006229	0.0015	-1.2178	-3.7189
0.039518	0.4347	11.07904	0.039238	0.0277	0.0396	0.0052	0.005492	0.0014	-2.7871	-6.5060
Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m				
0.01203	0.03577	0.0049	0.005	11	0.25	0.01				
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.005145	0.0566	11.0103	0.00514	0.2126	0.0074	3.1833				
0.006645	0.0731	11.0133	0.00664	0.1646	0.0080	1.3573	2.270279	0.0006	-0.0003	-0.0003
0.008145	0.0896	11.0163	0.00813	0.1343	0.0091	0.6889	1.023095	0.0010	-0.0010	-0.0013
0.009645	0.1061	11.0193	0.00963	0.1134	0.0103	0.3923	0.540611	0.0012	-0.0023	-0.0036
0.011145	0.1226	11.0223	0.01112	0.0981	0.0116	0.2424	0.317346	0.0013	-0.0043	-0.0079
0.012645	0.1391	11.0253	0.01262	0.0865	0.0130	0.1592	0.200783	0.0014	-0.0071	-0.0150
0.014145	0.1556	11.0283	0.01411	0.0773	0.0144	0.1096	0.134380	0.0014	-0.0110	-0.0260
0.015645	0.1721	11.0313	0.0156	0.0699	0.0159	0.0783	0.093964	0.0014	-0.0162	-0.0422
0.017145	0.1886	11.0343	0.01709	0.0638	0.0174	0.0578	0.068050	0.0015	-0.0231	-0.0653

0.018645	0.2051	11.0373	0.01858	0.0587	0.0188	0.0437	0.050723	0.0015	-0.0321	-0.0974
0.020145	0.2216	11.0403	0.02007	0.0543	0.0203	0.0338	0.038727	0.0015	-0.0437	-0.1412
0.021645	0.2381	11.0433	0.02156	0.0505	0.0218	0.0266	0.030177	0.0015	-0.0588	-0.1999
0.023145	0.2546	11.0463	0.02305	0.0473	0.0233	0.0213	0.023931	0.0015	-0.0784	-0.2783
0.024645	0.2711	11.0493	0.02454	0.0444	0.0247	0.0173	0.019268	0.0015	-0.1042	-0.3825
0.026145	0.2876	11.0523	0.02602	0.0418	0.0262	0.0142	0.015721	0.0015	-0.1389	-0.5214
0.027645	0.3041	11.0553	0.02751	0.0396	0.0277	0.0118	0.012980	0.0015	-0.1868	-0.7082
0.029145	0.3206	11.0583	0.02899	0.0375	0.0292	0.0099	0.010830	0.0015	-0.2559	-0.9641
0.030645	0.3371	11.0613	0.03048	0.0357	0.0307	0.0084	0.009121	0.0015	-0.3623	-1.3264
0.032145	0.3536	11.0643	0.03196	0.0340	0.0322	0.0071	0.007747	0.0015	-0.5439	-1.8704
0.033645	0.3701	11.0673	0.03344	0.0325	0.0337	0.0061	0.006631	0.0015	-0.9167	-2.7871
0.035145	0.3866	11.0703	0.03492	0.0311	0.0352	0.0053	0.005715	0.0015	-2.0913	-4.8783
0.035413	0.3896	11.0708	0.03519	0.0309	0.0355	0.0052	0.005235	0.0003	-1.1339	-6.0122
Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m				
0.01203	0.031278	0.0049	0.005	11	0.2	0.01				
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.005145	0.0566	11.01029	0.00514	0.2126	0.0074	2.0373				
0.006645	0.0731	11.01329	0.006637	0.1646	0.0080	0.8687	1.452979	0.0006	-0.0004	-0.0004
0.008145	0.0896	11.01629	0.008133	0.1343	0.0091	0.4409	0.654781	0.0010	-0.0016	-0.0020
0.009645	0.1061	11.01929	0.009628	0.1134	0.0103	0.2511	0.345991	0.0012	-0.0036	-0.0056
0.011145	0.1226	11.02229	0.011123	0.0981	0.0116	0.1551	0.203102	0.0013	-0.0067	-0.0124
0.012645	0.1391	11.02529	0.012616	0.0865	0.0130	0.1019	0.128501	0.0014	-0.0113	-0.0236
0.014145	0.1556	11.02829	0.014109	0.0773	0.0144	0.0701	0.086003	0.0014	-0.0176	-0.0412
0.015645	0.1721	11.03129	0.015601	0.0699	0.0159	0.0501	0.060137	0.0014	-0.0262	-0.0674
0.017145	0.1886	11.03429	0.017092	0.0638	0.0174	0.0370	0.043552	0.0015	-0.0378	-0.1052
0.018645	0.2051	11.03729	0.018582	0.0587	0.0188	0.0280	0.032463	0.0015	-0.0535	-0.1587
0.020145	0.2216	11.04029	0.020072	0.0543	0.0203	0.0216	0.024785	0.0015	-0.0745	-0.2332
0.021645	0.2381	11.04329	0.021561	0.0505	0.0218	0.0170	0.019313	0.0015	-0.1034	-0.3366
0.023145	0.2546	11.04629	0.023048	0.0473	0.0233	0.0136	0.015316	0.0015	-0.1438	-0.4804
0.024645	0.2711	11.04929	0.024536	0.0444	0.0247	0.0110	0.012331	0.0015	-0.2028	-0.6832
0.026145	0.2876	11.05229	0.026022	0.0418	0.0262	0.0091	0.010062	0.0015	-0.2941	-0.9773
0.027645	0.3041	11.05529	0.027507	0.0396	0.0277	0.0075	0.008307	0.0015	-0.4507	-1.4281
0.029145	0.3206	11.05829	0.028992	0.0375	0.0292	0.0063	0.006931	0.0015	-0.7727	-2.2007
0.030645	0.3371	11.06129	0.030476	0.0357	0.0307	0.0054	0.005837	0.0015	-1.7833	-3.9841
0.030965	0.3406	11.06193	0.030793	0.0353	0.0310	0.0052	0.005260	0.0003	-1.2241	-5.2081

Table B-3. Direct step method for calculating water surface profiles for a trapezoidal channel on a mild slope with a tailwater greater than critical depth but less than normal depth, while varying slope.

Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m		TW (m)		
0.01203	0.08766	0.0049	0.0005	11	0.35	0.01		0.015		
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.01575	0.1733	11.0315	0.01571	0.0694	0.0160	0.1502				
0.01775	0.1953	11.0355	0.01769	0.0616	0.0179	0.1009	0.125516	0.0019	-0.0156	-0.0156
0.01975	0.2173	11.0395	0.01968	0.0554	0.0199	0.0707	0.085778	0.0020	-0.0230	-0.0386
0.02175	0.2393	11.0435	0.02166	0.0503	0.0219	0.0513	0.060986	0.0020	-0.0326	-0.0712
0.02375	0.2613	11.0475	0.02365	0.0460	0.0239	0.0383	0.044772	0.0020	-0.0447	-0.1159
0.02575	0.2833	11.0515	0.02563	0.0425	0.0258	0.0292	0.033752	0.0020	-0.0597	-0.1756
0.02775	0.3053	11.0555	0.02761	0.0394	0.0278	0.0228	0.026018	0.0020	-0.0779	-0.2535
0.02975	0.3273	11.0595	0.02959	0.0368	0.0298	0.0181	0.020442	0.0020	-0.0998	-0.3532
0.03175	0.3493	11.0635	0.03157	0.0344	0.0318	0.0146	0.016326	0.0020	-0.1258	-0.4791
0.03375	0.3713	11.0675	0.03355	0.0324	0.0338	0.0119	0.013228	0.0020	-0.1566	-0.6357
0.03575	0.3933	11.0715	0.03552	0.0306	0.0358	0.0098	0.010853	0.0020	-0.1926	-0.8283
0.03775	0.4153	11.0755	0.03749	0.0290	0.0378	0.0082	0.009005	0.0020	-0.2346	-1.0629
0.03975	0.4373	11.0795	0.03947	0.0275	0.0398	0.0069	0.007546	0.0020	-0.2832	-1.3461
0.04175	0.4593	11.0835	0.04144	0.0262	0.0418	0.0059	0.006381	0.0020	-0.3395	-1.6856
0.04375	0.4813	11.0875	0.04341	0.0250	0.0438	0.0050	0.005440	0.0020	-0.4043	-2.0898
0.04575	0.5033	11.0915	0.04537	0.0239	0.0458	0.0043	0.004671	0.0020	-0.4788	-2.5686
0.04775	0.5253	11.0955	0.04734	0.0229	0.0478	0.0038	0.004038	0.0020	-0.5646	-3.1332
0.04975	0.5473	11.0995	0.04931	0.0220	0.0498	0.0033	0.003513	0.0020	-0.6631	-3.7963
0.05175	0.5693	11.1035	0.05127	0.0211	0.0518	0.0029	0.003073	0.0020	-0.7766	-4.5729
0.05375	0.5913	11.1075	0.05323	0.0203	0.0538	0.0025	0.002702	0.0020	-0.9074	-5.4803
0.05575	0.6133	11.1115	0.05519	0.0196	0.0558	0.0022	0.002388	0.0020	-1.0587	-6.5391
0.05775	0.6353	11.1155	0.05715	0.0189	0.0578	0.0020	0.002119	0.0020	-1.2344	-7.7734
0.05975	0.6573	11.1195	0.05911	0.0183	0.0598	0.0018	0.001889	0.0020	-1.4393	-9.2127
0.06175	0.6793	11.1235	0.06107	0.0177	0.0618	0.0016	0.001690	0.0020	-1.6799	-10.8927
0.06375	0.7013	11.1275	0.06302	0.0172	0.0638	0.0014	0.001517	0.0020	-1.9647	-12.8574
0.06575	0.7233	11.1315	0.06498	0.0166	0.0658	0.0013	0.001367	0.0020	-2.3051	-15.1625
0.06775	0.7453	11.1355	0.06693	0.0161	0.0678	0.0012	0.001236	0.0020	-2.7167	-17.8792
0.06975	0.7673	11.1395	0.06888	0.0157	0.0698	0.0011	0.001120	0.0020	-3.2221	-21.1014
0.07175	0.7893	11.1435	0.07083	0.0152	0.0718	0.0010	0.001019	0.0020	-3.8543	-24.9556
0.07375	0.8113	11.1475	0.07278	0.0148	0.0738	0.0009	0.000929	0.0020	-4.6638	-29.6195

0.07575	0.8333	11.1515	0.07473	0.0144	0.0758	0.0008	0.000849	0.0020	-5.7329	-35.3523
0.07775	0.8553	11.1555	0.07667	0.0141	0.0778	0.0007	0.000778	0.0020	-7.2035	-42.5558
0.07975	0.8773	11.1595	0.07862	0.0137	0.0798	0.0007	0.000714	0.0020	-9.3450	-51.9008
0.08175	0.8993	11.1635	0.08056	0.0134	0.0818	0.0006	0.000657	0.0020	-12.7377	-64.6384
0.08375	0.9213	11.1675	0.0825	0.0131	0.0838	0.0006	0.000606	0.0020	-18.9032	-83.5416
0.08575	0.9433	11.1715	0.08444	0.0128	0.0858	0.0005	0.000560	0.0020	-33.5154	-117.0570
0.0867834	0.9547	11.1736	0.08544	0.0126	0.0868	0.0005	0.000527	0.0010	-37.8060	-154.8630
Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m		TW (m)		
0.01203	0.0438	0.0049	0.005	11	0.35	0.01		0.01		
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.0105	0.1155	11.021	0.01048	0.1042	0.0111	0.5794				
0.012	0.1320	11.024	0.011974	0.0911	0.0124	0.3714	0.475427	0.0014	-0.0029	-0.0029
0.0135	0.1485	11.027	0.013467	0.0810	0.0138	0.2509	0.311158	0.0014	-0.0046	-0.0075
0.015	0.1650	11.03	0.014959	0.0729	0.0153	0.1767	0.213781	0.0014	-0.0069	-0.0144
0.0165	0.1815	11.033	0.016451	0.0663	0.0167	0.1286	0.152640	0.0015	-0.0098	-0.0242
0.018	0.1980	11.036	0.017942	0.0608	0.0182	0.0963	0.112448	0.0015	-0.0136	-0.0379
0.0195	0.2145	11.039	0.019431	0.0561	0.0197	0.0738	0.085014	0.0015	-0.0184	-0.0563
0.021	0.2310	11.042	0.020921	0.0521	0.0211	0.0576	0.065693	0.0015	-0.0244	-0.0806
0.0225	0.2475	11.045	0.022409	0.0486	0.0226	0.0458	0.051720	0.0015	-0.0317	-0.1123
0.024	0.2640	11.048	0.023896	0.0456	0.0241	0.0370	0.041381	0.0015	-0.0408	-0.1532
0.0255	0.2805	11.051	0.025383	0.0429	0.0256	0.0302	0.033579	0.0015	-0.0521	-0.2052
0.027	0.2970	11.054	0.026869	0.0405	0.0271	0.0250	0.027588	0.0015	-0.0660	-0.2712
0.0285	0.3135	11.057	0.028354	0.0384	0.0286	0.0209	0.022917	0.0015	-0.0832	-0.3544
0.03	0.3300	11.06	0.029838	0.0365	0.0301	0.0176	0.019226	0.0015	-0.1049	-0.4594
0.0315	0.3465	11.063	0.031322	0.0347	0.0316	0.0150	0.016272	0.0015	-0.1325	-0.5919
0.033	0.3630	11.066	0.032804	0.0331	0.0331	0.0128	0.013883	0.0015	-0.1682	-0.7601
0.0345	0.3795	11.069	0.034286	0.0317	0.0346	0.0111	0.011931	0.0015	-0.2157	-0.9759
0.036	0.3960	11.072	0.035767	0.0304	0.0360	0.0096	0.010322	0.0015	-0.2811	-1.2569
0.0375	0.4125	11.075	0.037247	0.0292	0.0375	0.0084	0.008984	0.0015	-0.3756	-1.6325
0.039	0.4290	11.078	0.038727	0.0280	0.0390	0.0074	0.007863	0.0015	-0.5227	-2.1552
0.0405	0.4455	11.081	0.040205	0.0270	0.0405	0.0065	0.006918	0.0015	-0.7805	-2.9357
0.042	0.4620	11.084	0.041683	0.0260	0.0420	0.0057	0.006116	0.0015	-1.3422	-4.2780
0.043362	0.4770	11.08673	0.043024	0.0252	0.0434	0.0052	0.005457	0.0014	-2.9734	-7.2513
Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m		TW (m)		
0.01203	0.0219	0.0049	0.05	11	0.35	0.01		0.01		
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.0105	0.1155	11.021	0.01048	0.1042	0.0111	0.5794				

0.0115	0.1265	11.023	0.01148	0.0951	0.0120	0.4280	0.503707	0.0009	-0.0020	-0.0020
0.0125	0.1375	11.025	0.01247	0.0875	0.0129	0.3242	0.376087	0.0009	-0.0028	-0.0049
0.0135	0.1485	11.027	0.01347	0.0810	0.0138	0.2509	0.287551	0.0009	-0.0040	-0.0088
0.0145	0.1595	11.029	0.01446	0.0754	0.0148	0.1978	0.224336	0.0010	-0.0055	-0.0143
0.0155	0.1705	11.031	0.01546	0.0706	0.0158	0.1584	0.178078	0.0010	-0.0075	-0.0218
0.0165	0.1815	11.033	0.01645	0.0663	0.0167	0.1286	0.143504	0.0010	-0.0104	-0.0322
0.0175	0.1925	11.035	0.01744	0.0625	0.0177	0.1057	0.117181	0.0010	-0.0145	-0.0467
0.0185	0.2035	11.037	0.01844	0.0591	0.0187	0.0879	0.096811	0.0010	-0.0209	-0.0676
0.0195	0.2145	11.039	0.01943	0.0561	0.0197	0.0738	0.080818	0.0010	-0.0319	-0.0995
0.0205	0.2255	11.041	0.02042	0.0533	0.0206	0.0624	0.068100	0.0010	-0.0544	-0.1539
0.0215	0.2365	11.043	0.02142	0.0509	0.0216	0.0533	0.057868	0.0010	-0.1254	-0.2793
0.021681	0.2385	11.0434	0.0216	0.0504	0.0218	0.0518	0.052558	0.0002	-0.0699	-0.3493
Q (m^3/s)	y$_o$ (m)	y$_c$ (m)	S$_o$	b (m)	n	m		TW (m)		
0.01203	0.01097	0.0049	0.5	11	0.35	0.01		0.007		
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S$_e$	S$_{ebar}$	Del E (m)	Del X (m)	Sum X (m)
0.00735	0.0809	11.0147	0.00734	0.1488	0.0085	1.9012				
0.00785	0.0864	11.0157	0.007839	0.1393	0.0088	1.5269	1.714015	0.0004	-0.0003	-0.0003
0.00835	0.0919	11.0167	0.008337	0.1310	0.0092	1.2430	1.384915	0.0004	-0.0004	-0.0007
0.00885	0.0974	11.0177	0.008836	0.1236	0.0096	1.0241	1.133514	0.0004	-0.0006	-0.0014
0.00935	0.1029	11.0187	0.009334	0.1170	0.0100	0.8527	0.938396	0.0004	-0.0010	-0.0023
0.00985	0.1084	11.0197	0.009832	0.1110	0.0105	0.7169	0.784812	0.0004	-0.0015	-0.0038
0.01035	0.1139	11.0207	0.010331	0.1057	0.0109	0.6079	0.662387	0.0004	-0.0027	-0.0066
0.01085	0.1194	11.0217	0.010829	0.1008	0.0114	0.5195	0.563688	0.0004	-0.0070	-0.0136
0.01086	0.1195	11.02172	0.010839	0.1007	0.0114	0.5178	0.518670	0.0000	-0.0005	-0.0141

Table B-4. Direct step method for calculating water surface profiles for a trapezoidal channel on a mild slope with a tailwater greater than critical depth but less than normal depth, while varying Manning's roughness coefficient.

Q (m^3/s)	y$_o$ (m)	y$_c$ (m)	S$_o$	b (m)	n	m		TW (m)		
0.01203	0.0438	0.0049	0.005	11	0.35	0.01		0.015		
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S$_e$	S$_{ebar}$	Del E (m)	Del X (m)	Sum X (m)
0.01575	0.1733	11.0315	0.01571	0.0694	0.0160	0.1502				
0.01725	0.1898	11.0345	0.0172	0.0634	0.0175	0.1109	0.130549	0.0015	-0.0116	-0.0116
0.01875	0.2063	11.0375	0.01869	0.0583	0.0189	0.0840	0.097485	0.0015	-0.0159	-0.0275

0.02025	0.2228	11.0405	0.02018	0.0540	0.0204	0.0650	0.074544	0.0015	-0.0212	-0.0487
0.02175	0.2393	11.0435	0.02166	0.0503	0.0219	0.0513	0.058164	0.0015	-0.0278	-0.0766
0.02325	0.2558	11.0465	0.02315	0.0470	0.0234	0.0411	0.046176	0.0015	-0.0360	-0.1126
0.02475	0.2723	11.0495	0.02464	0.0442	0.0248	0.0334	0.037215	0.0015	-0.0462	-0.1587
0.02625	0.2888	11.0525	0.02613	0.0417	0.0263	0.0274	0.030392	0.0015	-0.0586	-0.2174
0.02775	0.3053	11.0555	0.02761	0.0394	0.0278	0.0228	0.025112	0.0015	-0.0741	-0.2915
0.02925	0.3218	11.0585	0.0291	0.0374	0.0293	0.0191	0.020966	0.0015	-0.0935	-0.3850
0.03075	0.3383	11.0615	0.03058	0.0356	0.0308	0.0162	0.017669	0.0015	-0.1179	-0.5028
0.03225	0.3548	11.0645	0.03206	0.0339	0.0323	0.0138	0.015016	0.0015	-0.1492	-0.6520
0.03375	0.3713	11.0675	0.03355	0.0324	0.0338	0.0119	0.012859	0.0015	-0.1902	-0.8422
0.03525	0.3878	11.0705	0.03503	0.0310	0.0353	0.0103	0.011088	0.0015	-0.2456	-1.0879
0.03675	0.4043	11.0735	0.03651	0.0298	0.0368	0.0090	0.009623	0.0015	-0.3236	-1.4115
0.03825	0.4208	11.0765	0.03799	0.0286	0.0383	0.0078	0.008399	0.0015	-0.4402	-1.8517
0.03975	0.4373	11.0795	0.03947	0.0275	0.0398	0.0069	0.007371	0.0015	-0.6313	-2.4831
0.04125	0.4538	11.0825	0.04094	0.0265	0.0413	0.0061	0.006501	0.0015	-0.9977	-3.4807
0.04275	0.4703	11.0855	0.04242	0.0256	0.0428	0.0054	0.005760	0.0015	-1.9713	-5.4521
0.04336	0.4770	11.0867	0.04302	0.0252	0.0434	0.0052	0.005294	0.0006	-2.0731	-7.5252
Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m		TW (m)		
0.01203	0.039917	0.0049	0.005	11	0.3	0.01		0.015		
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.01575	0.1733	11.0315	0.015705	0.0694	0.0160	0.1103				
0.01725	0.1898	11.0345	0.017196	0.0634	0.0175	0.0815	0.095914	0.0015	-0.0160	-0.0160
0.01875	0.2063	11.0375	0.018687	0.0583	0.0189	0.0617	0.071621	0.0015	-0.0220	-0.0381
0.02025	0.2228	11.0405	0.020176	0.0540	0.0204	0.0478	0.054767	0.0015	-0.0296	-0.0677
0.02175	0.2393	11.0435	0.021665	0.0503	0.0219	0.0377	0.042732	0.0015	-0.0392	-0.1070
0.02325	0.2558	11.0465	0.023153	0.0470	0.0234	0.0302	0.033925	0.0015	-0.0513	-0.1583
0.02475	0.2723	11.0495	0.02464	0.0442	0.0248	0.0245	0.027342	0.0015	-0.0665	-0.2248
0.02625	0.2888	11.0525	0.026126	0.0417	0.0263	0.0202	0.022329	0.0015	-0.0859	-0.3107
0.02775	0.3053	11.0555	0.027611	0.0394	0.0278	0.0167	0.018450	0.0015	-0.1108	-0.4216
0.02925	0.3218	11.0585	0.029096	0.0374	0.0293	0.0141	0.015404	0.0015	-0.1434	-0.5650
0.03075	0.3383	11.0615	0.03058	0.0356	0.0308	0.0119	0.012981	0.0015	-0.1871	-0.7521
0.03225	0.3548	11.0645	0.032063	0.0339	0.0323	0.0102	0.011032	0.0015	-0.2477	-0.9998
0.03375	0.3713	11.0675	0.033545	0.0324	0.0338	0.0087	0.009447	0.0015	-0.3361	-1.3359
0.03525	0.3878	11.0705	0.035027	0.0310	0.0353	0.0076	0.008147	0.0015	-0.4753	-1.8112
0.03675	0.4043	11.0735	0.036507	0.0298	0.0368	0.0066	0.007070	0.0015	-0.7229	-2.5341
0.03825	0.4208	11.0765	0.037987	0.0286	0.0383	0.0058	0.006171	0.0015	-1.2780	-3.8121
0.039518	0.4347	11.07904	0.039238	0.0277	0.0396	0.0052	0.005465	0.0013	-2.7203	-6.5324
Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m		TW (m)		

0.01203	0.03577	0.0049	0.005	11	0.25	0.01		0.015		
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.01575	0.1733	11.0315	0.01571	0.0694	0.0160	0.0766				
0.01725	0.1898	11.0345	0.0172	0.0634	0.0175	0.0566	0.066607	0.0015	-0.0237	-0.0237
0.01875	0.2063	11.0375	0.01869	0.0583	0.0189	0.0429	0.049737	0.0015	-0.0328	-0.0565
0.02025	0.2228	11.0405	0.02018	0.0540	0.0204	0.0332	0.038033	0.0015	-0.0447	-0.1012
0.02175	0.2393	11.0435	0.02166	0.0503	0.0219	0.0262	0.029675	0.0015	-0.0600	-0.1612
0.02325	0.2558	11.0465	0.02315	0.0470	0.0234	0.0210	0.023559	0.0015	-0.0800	-0.2411
0.02475	0.2723	11.0495	0.02464	0.0442	0.0248	0.0170	0.018987	0.0015	-0.1063	-0.3474
0.02625	0.2888	11.0525	0.02613	0.0417	0.0263	0.0140	0.015506	0.0015	-0.1417	-0.4891
0.02775	0.3053	11.0555	0.02761	0.0394	0.0278	0.0116	0.012812	0.0015	-0.1908	-0.6799
0.02925	0.3218	11.0585	0.0291	0.0374	0.0293	0.0098	0.010697	0.0015	-0.2619	-0.9418
0.03075	0.3383	11.0615	0.03058	0.0356	0.0308	0.0083	0.009015	0.0015	-0.3719	-1.3138
0.03225	0.3548	11.0645	0.03206	0.0339	0.0323	0.0071	0.007661	0.0015	-0.5615	-1.8752
0.03375	0.3713	11.0675	0.03355	0.0324	0.0338	0.0061	0.006561	0.0015	-0.9579	-2.8331
0.03525	0.3878	11.0705	0.03503	0.0310	0.0353	0.0052	0.005657	0.0015	-2.2751	-5.1082
0.035413	0.3896	11.0708	0.03519	0.0309	0.0355	0.0052	0.005209	0.0002	-0.7752	-5.8834
Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m		TW (m)		
0.01203	0.031278	0.0049	0.005	11	0.2	0.01		0.01		
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.0105	0.1155	11.021	0.01048	0.1042	0.0111	0.1892				
0.012	0.1320	11.024	0.011974	0.0911	0.0124	0.1213	0.155241	0.0014	-0.0091	-0.0091
0.0135	0.1485	11.027	0.013467	0.0810	0.0138	0.0819	0.101603	0.0014	-0.0146	-0.0237
0.015	0.1650	11.03	0.014959	0.0729	0.0153	0.0577	0.069806	0.0014	-0.0222	-0.0459
0.0165	0.1815	11.033	0.016451	0.0663	0.0167	0.0420	0.049842	0.0015	-0.0324	-0.0783
0.018	0.1980	11.036	0.017942	0.0608	0.0182	0.0314	0.036718	0.0015	-0.0462	-0.1245
0.0195	0.2145	11.039	0.019431	0.0561	0.0197	0.0241	0.027760	0.0015	-0.0647	-0.1891
0.021	0.2310	11.042	0.020921	0.0521	0.0211	0.0188	0.021451	0.0015	-0.0898	-0.2790
0.0225	0.2475	11.045	0.022409	0.0486	0.0226	0.0150	0.016888	0.0015	-0.1247	-0.4037
0.024	0.2640	11.048	0.023896	0.0456	0.0241	0.0121	0.013512	0.0015	-0.1745	-0.5782
0.0255	0.2805	11.051	0.025383	0.0429	0.0256	0.0099	0.010965	0.0015	-0.2495	-0.8276
0.027	0.2970	11.054	0.026869	0.0405	0.0271	0.0082	0.009008	0.0015	-0.3717	-1.1993
0.0285	0.3135	11.057	0.028354	0.0384	0.0286	0.0068	0.007483	0.0015	-0.6006	-1.7999
0.03	0.3300	11.06	0.029838	0.0365	0.0301	0.0057	0.006278	0.0015	-1.1682	-2.9681
0.030965	0.3406	11.06193	0.030793	0.0353	0.0310	0.0052	0.005457	0.0010	-2.1048	-5.0729

Table B-5. Direct step method for calculating water surface profiles for a trapezoidal channel on a mild slope with a tailwater greater than normal depth, while varying slope.

Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m		TW (m)		
0.01203	0.08766	0.0049	0.0005	11	0.35	0.01		0.092043		
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.092043	1.0126	11.1841	0.09054	0.0119	0.0921	0.0004				
0.091543	1.0071	11.1831	0.09005	0.0119	0.0916	0.0004	0.000429	-0.0005	-7.0621	-7.0621
0.091043	1.0016	11.1821	0.08957	0.0120	0.0911	0.0004	0.000437	-0.0005	-7.9410	-15.0031
0.090543	0.9961	11.1811	0.08908	0.0121	0.0906	0.0004	0.000445	-0.0005	-9.1007	-24.1038
0.090043	0.9906	11.1801	0.0886	0.0121	0.0901	0.0005	0.000453	-0.0005	-10.7010	-34.8048
0.089543	0.9851	11.1791	0.08812	0.0122	0.0896	0.0005	0.000462	-0.0005	-13.0518	-47.8565
0.089043	0.9796	11.1781	0.08763	0.0123	0.0891	0.0005	0.000470	-0.0005	-16.8414	-64.6980
0.0885366	0.9740	11.1771	0.08714	0.0124	0.0885	0.0005	0.000479	-0.0005	-24.3469	-89.0449
Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m		TW (m)		
0.01203	0.0219	0.0049	0.05	11	0.35	0.01		0.022995		
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.022995	0.2530	11.046	0.0229	0.0476	0.0231	0.0426				
0.022895	0.2519	11.0458	0.0228	0.0478	0.0230	0.0432	0.042919	-0.0001	-0.0140	-0.0140
0.022795	0.2508	11.0456	0.0227	0.0480	0.0229	0.0439	0.043548	-0.0001	-0.0153	-0.0293
0.022695	0.2497	11.0454	0.0226	0.0482	0.0228	0.0445	0.044188	-0.0001	-0.0170	-0.0463
0.022595	0.2486	11.0452	0.0225	0.0484	0.0227	0.0452	0.044841	-0.0001	-0.0192	-0.0655
0.022495	0.2475	11.045	0.0224	0.0486	0.0226	0.0458	0.045506	-0.0001	-0.0220	-0.0875
0.022395	0.2464	11.0448	0.0223	0.0488	0.0225	0.0465	0.046184	-0.0001	-0.0259	-0.1135
0.022295	0.2452	11.0446	0.02221	0.0491	0.0224	0.0472	0.046876	-0.0001	-0.0317	-0.1451
0.022195	0.2441	11.0444	0.02211	0.0493	0.0223	0.0479	0.047581	-0.0001	-0.0409	-0.1860
0.022119	0.2433	11.0442	0.02203	0.0494	0.0222	0.0485	0.048212	-0.0001	-0.0420	-0.2280
Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m		TW (m)		
0.01203	0.0438	0.0049	0.005	11	0.35	0.01		0.04599		
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.04599	0.5059	11.09198	0.045611	0.0238	0.0460	0.0043				
0.04569	0.5026	11.09138	0.045315	0.0239	0.0457	0.0043	0.004297	-0.0003	-0.4263	-0.4263
0.04539	0.4993	11.09078	0.04502	0.0241	0.0454	0.0044	0.004392	-0.0003	-0.4927	-0.9190
0.04509	0.4960	11.09018	0.044725	0.0243	0.0451	0.0045	0.004489	-0.0003	-0.5868	-1.5058
0.04479	0.4927	11.08958	0.04443	0.0244	0.0448	0.0046	0.004590	-0.0003	-0.7304	-2.2362
0.04449	0.4894	11.08898	0.044135	0.0246	0.0445	0.0047	0.004693	-0.0003	-0.9761	-3.2123
0.044238	0.4866	11.08848	0.043887	0.0247	0.0443	0.0048	0.004791	-0.0003	-1.2023	-4.4146

Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m		TW (m)		
0.01203	0.01097	0.0049	0.5	11	0.35	0.01		0.011519		
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.011519	0.1267	11.02304	0.011495	0.0949	0.0120	0.4257				
0.011419	0.1256	11.02284	0.011395	0.0958	0.0119	0.4382	0.431960	-0.0001	-0.0014	-0.0014
0.011319	0.1245	11.02264	0.011295	0.0966	0.0118	0.4513	0.444747	-0.0001	-0.0017	-0.0030
0.011219	0.1234	11.02244	0.011196	0.0975	0.0117	0.4648	0.458030	-0.0001	-0.0022	-0.0052
0.011119	0.1223	11.02224	0.011096	0.0984	0.0116	0.4789	0.471833	-0.0001	-0.0032	-0.0084
0.01108	0.1219	11.02216	0.011058	0.0987	0.0116	0.4845	0.481672	0.0000	-0.0019	-0.0104

Table B-6. Direct step method for calculating water surface profiles for a trapezoidal channel on a mild slope with a tailwater greater than normal depth, while varying Manning's roughness coefficient.

Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m		TW (m)		
0.01203	0.0438	0.0049	0.005	11	0.35	0.01		0.045988		
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.045988	0.5059	11.092	0.04561	0.0238	0.0460	0.0043				
0.045788	0.5037	11.0916	0.04541	0.0239	0.0458	0.0043	0.004282	-0.0002	-0.2783	-0.2783
0.045588	0.5015	11.0912	0.04521	0.0240	0.0456	0.0044	0.004345	-0.0002	-0.3048	-0.5831
0.045388	0.4993	11.0908	0.04502	0.0241	0.0454	0.0044	0.004409	-0.0002	-0.3377	-0.9208
0.045188	0.4971	11.0904	0.04482	0.0242	0.0452	0.0045	0.004474	-0.0002	-0.3794	-1.3003
0.044988	0.4949	11.09	0.04462	0.0243	0.0450	0.0046	0.004540	-0.0002	-0.4341	-1.7343
0.044788	0.4927	11.0896	0.04443	0.0244	0.0448	0.0046	0.004607	-0.0002	-0.5088	-2.2431
0.044588	0.4905	11.0892	0.04423	0.0245	0.0446	0.0047	0.004676	-0.0002	-0.6170	-2.8601
0.044388	0.4883	11.0888	0.04403	0.0246	0.0444	0.0048	0.004747	-0.0002	-0.7879	-3.6480
0.044236	0.4866	11.0885	0.04388	0.0247	0.0443	0.0048	0.004809	-0.0002	-0.7957	-4.4437
Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m		TW (m)		
0.01203	0.039917	0.0049	0.005	11	0.3	0.01		0.015		
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.041913	0.4611	11.08383	0.041598	0.0261	0.0419	0.0043				
0.041713	0.4589	11.08343	0.041401	0.0262	0.0417	0.0043	0.004285	-0.0002	-0.2793	-0.2793
0.041513	0.4567	11.08303	0.041204	0.0263	0.0415	0.0044	0.004354	-0.0002	-0.3090	-0.5883
0.041313	0.4545	11.08263	0.041007	0.0265	0.0413	0.0045	0.004424	-0.0002	-0.3467	-0.9350
0.041113	0.4523	11.08223	0.04081	0.0266	0.0411	0.0045	0.004496	-0.0002	-0.3961	-1.3311
0.040913	0.4501	11.08183	0.040613	0.0267	0.0409	0.0046	0.004569	-0.0002	-0.4635	-1.7946

0.040713	0.4479	11.08143	0.040416	0.0269	0.0407	0.0047	0.004644	-0.0002	-0.5609	-2.3555
0.040513	0.4457	11.08103	0.040218	0.0270	0.0406	0.0048	0.004721	-0.0002	-0.7143	-3.0698
0.040313	0.4435	11.08063	0.040021	0.0271	0.0404	0.0048	0.004799	-0.0002	-0.9913	-4.0611
0.040317	0.4435	11.08064	0.040025	0.0271	0.0404	0.0048	0.004837	0.0000	0.0203	-4.0408
Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m		TW (m)		
0.01203	0.03577	0.0049	0.005	11	0.25	0.01		0.015		
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.037559	0.4132	11.0751	0.03731	0.0291	0.0376	0.0043				
0.037359	0.4110	11.0747	0.03711	0.0293	0.0374	0.0043	0.004289	-0.0002	-0.2806	-0.2806
0.037159	0.4088	11.0743	0.03691	0.0294	0.0372	0.0044	0.004366	-0.0002	-0.3147	-0.5953
0.036959	0.4066	11.0739	0.03671	0.0296	0.0370	0.0045	0.004445	-0.0002	-0.3593	-0.9546
0.036759	0.4044	11.0735	0.03652	0.0298	0.0368	0.0046	0.004525	-0.0002	-0.4204	-1.3751
0.036559	0.4022	11.0731	0.03632	0.0299	0.0366	0.0046	0.004608	-0.0002	-0.5090	-1.8841
0.036359	0.4000	11.0727	0.03612	0.0301	0.0364	0.0047	0.004693	-0.0002	-0.6491	-2.5332
0.036159	0.3978	11.0723	0.03592	0.0302	0.0362	0.0048	0.004779	-0.0002	-0.9037	-3.4369
0.036128	0.3974	11.0723	0.03589	0.0303	0.0362	0.0048	0.004830	0.0000	-0.1807	-3.6176
Q (m^3/s)	y_o (m)	y_c (m)	S_o	b (m)	n	m		TW (m)		
0.01203	0.031278	0.0049	0.005	11	0.2	0.01		0.01		
y (m)	A (m^2)	P (m)	R (m)	V (m/s)	E (m)	S_e	S_{ebar}	Del E (m)	Del X (m)	Sum X (m)
0.032842	0.3613	11.06569	0.032648	0.0333	0.0329	0.0043				
0.032642	0.3591	11.06529	0.03245	0.0335	0.0327	0.0043	0.004294	-0.0002	-0.2824	-0.2824
0.032442	0.3569	11.06489	0.032252	0.0337	0.0325	0.0044	0.004383	-0.0002	-0.3229	-0.6053
0.032242	0.3547	11.06449	0.032055	0.0339	0.0323	0.0045	0.004473	-0.0002	-0.3785	-0.9838
0.032042	0.3525	11.06409	0.031857	0.0341	0.0321	0.0046	0.004567	-0.0002	-0.4599	-1.4437
0.031842	0.3503	11.06369	0.031659	0.0343	0.0319	0.0047	0.004663	-0.0002	-0.5904	-2.0341
0.031642	0.3481	11.06329	0.031462	0.0346	0.0317	0.0048	0.004761	-0.0002	-0.8335	-2.8677
0.031591	0.3475	11.06318	0.031411	0.0346	0.0317	0.0048	0.004824	-0.0001	-0.2890	-3.1566