ABSTRACT

Title of Document: EVALUATION OF THE EFFECTS OF WETLAND RESTORATION DESIGN ON HYDRAULIC RESIDENCE TIME AND NUTRIENT RETENTION

Stephen Victor Strano, Master of Science, 2009

Directed By: Professor Gary K. Felton
Department of Biological Resources Engineering

Hydraulic residence time (HRT) is a critical factor that can be integrated into wetland restoration designs to promote nutrient retention, but HRT in the context of wetlands with storm-driven hydrology is not well understood. A model for nutrient retention optimization based on HRT was evaluated using three indicators of HRT and nutrient stocks in above-ground plant biomass. Results indicated that a commonly used indicator of HRT, the ratio of wetland to watershed area, may be insufficient, while nominal HRT provided an overestimate for wetlands receiving storm runoff. While there was little relationship between total nitrogen and HRT, results suggested that HRT may explain some variation in total phosphorus. Results also indicated that the studied wetland restorations were not designed to provide sufficient HRT to promote the retention of dissolved nutrients, and that staged outlets could be used to provide significant HRT's for a range of storm events.

EVALUATION OF THE EFFECTS OF WETLAND RESTORATION DESIGN ON HYDRAULIC RESIDENCE TIME AND NUTRIENT RETENTION

By

Stephen Victor Strano

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
M.S. Biological Resources Engineering
2009

Advisory Committee:
Professor Gary K. Felton, Chair
Professor Andrew H. Baldwin
Professor Adel Shirmohammadi

Acknowledgements

This research would not have been possible without the cooperation of the owners of the wetland study sites, and their interests in wetlands, water quality, and scientific endeavors. Staff located in the Kent and Queen Anne’s County Soil Conservation District offices provided support for site selection and gathering data on wetland designs. The support provided by David Doss and Ginger Murphy, former State Conservationists in Maryland, and Anne Lynn, State Resource Conservationist in Maryland, is greatly appreciated. Especially significant was the support of Bruce Nichols, biologist, friend, and former District Conservationist in Worcester County, Maryland, who not only provided encouragement for me to pursue a graduate degree, but introduced me to applied wetland restoration and demonstrated a great appreciation for wetland ecosystems. I would also like to acknowledge the support of my friends and family, and of course, my parents, who always provided encouragement and belief in my abilities.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AB – aboveground biomass

ANOVA – analysis of variance

ARC1 – antecedent runoff condition I

ARC2 – antecedent runoff condition II

ARC3 – antecedent runoff condition III

CI – constant intensity (storm)

CN – runoff curve number

C:N – carbon to nitrogen ratio

C:P – carbon to phosphorus ratio

CREP – Conservation Reserve Enhancement Program

CSTR – continuously-stirred tank reactor

DUH – dimensionless unit hydrograph

D_W – depth of wetland

DRP – dissolved reactive phosphorus

ES – emergency spillway

FWA – flow-weighted average

GIS – geographic information systems

GOF – goodness-of-fit (statistics)

GPS – global positioning system

HLR – hydraulic loading rate

hr – hour

HRT – hydraulic residence time

KS – Kolmogorov-Smirnov one-sample (test)

LIDAR – light detecting and ranging [remotely-sensed topographic data]

L_W – length of wetland

MES – Maryland Eastern Shore

MHRT – mean hydraulic residence time

NHRT – nominal hydraulic residence time

N:P – nitrogen to phosphorus ratio

NPSP – nonpoint source pollution

NRCS – U. S. Department of Agriculture, Natural Resources Conservation Service

PP – particulate phosphorus

RWW – ratio of wetland to watershed area

T – duration of flow

T2 – type II (storm)

T_c – time of concentration

TC – total carbon

TN – total nitrogen

TP – total phosphorus

TR20 – Technical Release 20: Computer Program for Project Formulation Hydrology

USGS – United States Geological Survey

V_R – volume of runoff entering the wetland

V_W – volume of the wetland

W_W – width of wetland

WWT – wastewater treatment wetlands

yr – year

Chapter 1: Introduction

There has been much study on nutrient retention and cycling in wetlands, with the greatest focus on nitrogen and phosphorus, the two main nutrients in animal waste and agricultural runoff, and which are of most concern for their roles in eutrophication. The dynamics of nutrient retention in constructed wastewater treatment wetlands (WWT) are relatively well understood. Indeed, whole volumes have been written on the use of wetlands for the treatment of wastewater (Hammer 1989, Kadlec and Knight 1996). The understanding of constructed wetlands benefits from the relative ease and certainty with which nutrient and hydraulic loads can be predicted from wastewater. Although many of the fundamental principles related to nutrient removal apply to wetlands in agricultural landscapes, the variability in both nutrient concentrations and hydraulic loadings from nonpoint source pollution (NPSP) (Kadlec 1999; Crumpton 2001; Jordan et al. 2003; Reinhardt et al. 2005) makes it much more difficult to develop criteria for wetland design. The lack of any comprehensive resource for designing wetlands to treat NPSP in agricultural landscapes is evidence of this.

A number of studies have attempted to elucidate the factors that determine nutrient retention in wetlands treating NPSP (Chescheir et al. 1991; Hammer 1992; Mitsch 1992; Kadlec and Hey 1994; Raisin and Mitchell 1995; Comin et al. 1997; Jordan et al. 2003; Raisin et al. 1997; Almendinger 1999; Spieles and Mitsch 2000; Casey and Klaine 2001; Crumpton 2001; Tweedy and Evans 2001; Fink and Mitsch 2004; Reinhardt et al. 2005). Some of these studies have provided guidance for optimizing nutrient retention from

NPSP in agricultural landscapes. Crumpton (2001) demonstrated the importance of site selection in designing wetland restorations. He determined that when sited appropriately, restored wetlands could remove approximately 35 percent of the annual nitrate load from agricultural watersheds in the corn belt, in contrast to only 4 percent when location was not explicitly considered.

Few models have been developed to provide design guidance for treating NPSP with constructed wetlands. Of the published models (Almendinger 1999; Dorge 1994; Crumpton 2001; Lee et al. 2002), only Crumpton's (2001) empirically-developed model has been put into practical use on a relatively large scale. Deterministic models have probably not been adopted for a number of reasons, such as a lack of applicability to real-world situations with multiple objectives, difficulty of use, lack of input data availability, incomplete model validation, and perhaps a lack of appropriate technology transfer. Cultural issues in the context of practitioners, such as using the easiest and most commonly accepted modeling tools, may also play a role. Most wetland restorations are designed for a variety of objectives, and the nutrient and hydrologic loads are highly variable. Although deterministic models may be appropriate for treatment of specific pollutants in controlled environments, the variability in restored wetlands may be better addressed with empirical models. Most applicable may be an empirical model for treating NPSP that focuses specifically on the variables that are easily controllable within the current cultural and technical context of wetland restoration being conducted by practitioners, such as the U.S. Department of Agriculture – Natural Resources Conservation Service (NRCS).

HYDROLOGIC AND HYDRAULIC DESIGN

One possible method of accounting for the high variability in NPSP is to develop an empirical model that incorporates the primary hydrologic mechanisms for nutrient retention – hydraulic loading rate and residence time – with evidence of nutrient retention in existing restored wetlands. Hydraulic residence time (HRT) is cited as one of the critical factors for nutrient retention in wetlands (Chescheir et al. 1991; Raisin and Mitchell 1995; Kadlec and Knight 1996; Cirmo and McDonnell 1997; Almendinger 1999; Mitsch and Gosselink 2000; Fisher and Acreman 2004; Reinhardt et al. 2005). HRT is important because it increases the amount of time for biogeochemical transformation, adsorption, and absorption of nutrients within the wetland. Increased HRT also promotes the settling of suspended sediments, which are an important transport vectors for phosphorus. In treatment wetlands, HRT is one of the primary variables used in determining the design specifications of the wetland. Nominal HRT can be calculated as (Kadlec and Knight 1996; Almendinger 1999; Reinhardt et al. 2005; Toet et al. 2005):

$$HRT = \frac{V_W}{V_R T^{-1}} = \frac{L_W \times W_W \times D_W}{V_R T^{-1}} \qquad (1)$$

where V_W = volume of the wetland

V_R = volume of runoff entering the wetland

T = duration of flow

L_W = length of wetland

W_W = width of wetland

D_W = depth of wetland

In a WWT, the factors that determine HRT can be controlled with relative precision. V_R can be easily estimated because it is typically the result of a standard process that occurs on a regular basis. In cases where flow variability exists, holding structures can be used to make V_R more consistent. For example, in a dairy operation, waste is often sent to a solids separator prior to treatment of the wastewater, after which the wastewater can be released at a controlled rate. Because V_R can be predetermined and kept relatively constant, a WWT can be sized to obtain an appropriate value of HRT for treatment. In sizing a WWT, the depth of runoff in the wetland can also be kept relatively constant, ensuring a high proportion of the runoff comes in contact with bioreactive surfaces.

In contrast to the WWT scenario, in watersheds where NPSP is being treated, V_R will vary considerably with storm event precipitation, seasonal climate changes, and drainage basin size, shape and land use. Theoretically, with long-term runoff data from a watershed, or predictive models of NPSP, wetlands could be sized to provide the appropriate HRT to treat NPSP for a majority of storm events. In reality, because land is a limited resource, it is not reasonable to expect to be able to construct wetlands of any size necessary for treatment. It follows that V_W is often controlled by factors other than what is needed for treatment: L_W and W_W are constrained by the area of land available for the wetland, and D_W by the need for shallow water levels in wetlands. Assuming wetland area has uncontrolled variability, HRT needs to be addressed using the knowledge of the variability in V_R and the limited flexibility in selecting D_W.

Technical Release 20 (TR-20) is a model that was designed to determine storm runoff volume, peak rate of discharge, and hydrographs for the design of stormwater management structures (USDA-SCS 1983), and has been adapted for use in agricultural watersheds. TR-20 estimates watershed runoff volume based on the Soil Conservation Service (SCS) method, and develops runoff hydrographs based on the SCS curvilinear unit hydrograph. The runoff hydrographs are routed through channels and structures to create hydrographs that represent outflow from the watershed. An in-depth description of the TR-20 model can be found in McCuen (1998). The inputs for TR-20 consist of the following:

- *Runoff curve number (CN)* – The watershed CN is determined by a weighted average of the CN for each land cover type (e.g., straight row crops with residue) and hydrologic soil group combination within the watershed. The CN is an empirically-derived value that represents a relationship between rainfall and runoff depth (Schwab et al. 1993). The highest value of CN, equal to 98, is applied to impervious surfaces, which have the highest rate of runoff.

- *Time of concentration* (T_C) – The T_C is the amount of time required for runoff to flow from the most remote point in a watershed to the outlet. The T_C is calculated based on flow path length, slope, surface cover type, and channel hydraulic characteristics, which are determined from field surveys and remotely sensed data (e.g. digital elevation models). The surface cover type and channel characteristics are used to calculate the flow velocity based on Manning's equation. The flow segments can be of three types: sheet, shallow concentrated, and channel. The times of travel for each segment are summed to obtain the T_C for the watershed. A detailed description of the calculation of T_C can be found in chapter 15 of the National Engineering Handbook, Part 630 (Kent 1972).

- *Storm reach* – A storm reach represents the channel routing for runoff when it becomes concentrated. If the concentrated runoff does not flow through a channel, then the storm reach identifies the structure or outlet where the runoff concentrates.

- *Structure rating* – The term “structure rating” in TR-20 is synonymous with the stage-storage-discharge rating. The structure rating is the relationship between the flow capacity (i.e., discharge) of the structure, the water surface elevation (i.e., stage), and the storage volume upstream of the structure. The structure rating is determined with knowledge of the physical and hydraulic characteristics of the structure and topography of the upstream area. This relationship determines the rate of outflow (i.e., discharge) relative to the inflow (runoff). The stage is the depth of water relative to the normal pool elevation (Figure 1). When the stage is above the normal pool elevation, there is a hydraulic head (H) associated with the outlet structure. Also when the stage is above the normal pool, there is an area into which runoff can be temporarily stored. Since both the discharge and storage vary with the stage, a stage-storage-discharge relationship exists for each wetland site. The stage-storage-discharge relationship (or structure rating) provides the basis for routing runoff through a structure in TR-20.

- *Storm analysis* – The storm analysis represents the type of storm event that is modeled, and is defined by rainfall intensity, rainfall distribution type, and antecedent runoff condition (ARC). The rainfall distribution type (e.g., type II) characterizes the pattern of a storm event. For example, a storm may begin and end with low intensity rainfall, and be at maximum intensity in the middle of the event. The ARC represents the soil moisture conditions when the storm event begins, and is categorized as either dry (ARC1), average (ARC2), or wet (ARC3). An ARC3 can be described as heavy rainfall or light rainfall with low temperatures within 5 d prior to a storm event (Schwab et al. 1993).

- *Dimensionless unit hydrograph (DUH)* – The DUH represents the relationship between the runoff discharge and the runoff duration, and is independent of peak runoff. A standard curvilinear DUH was developed by the SCS for small watersheds (Schwab et al. 1993), and is the most commonly used DUH. For some locations, a special DUH was developed, as is the case for the Delmarva Peninsula.

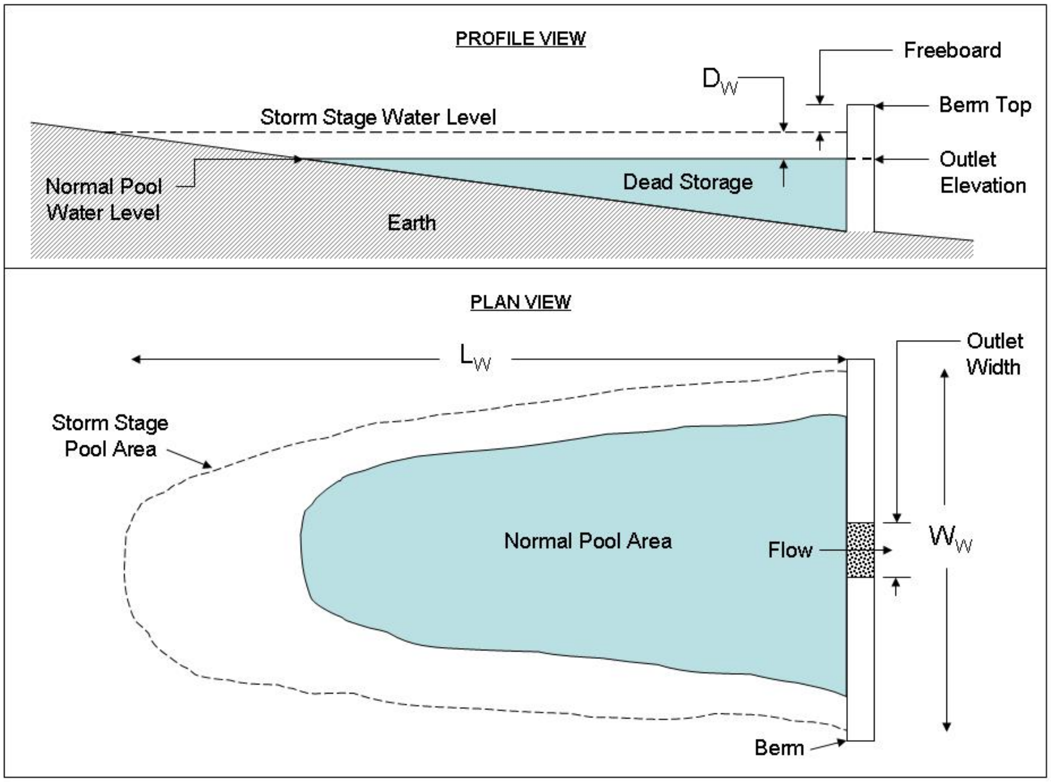


Figure 1. Profile and plan views of wetland at normal and storm stages. The normal pool area is the area that is covered by water when the water level in the wetland is at the outlet elevation. For a specific storm event, there will be a peak water elevation (i.e., storm stage water level) and pool area (i.e., storm stage pool area). D_W is the storage depth, assuming that the wetland is initially filled to the normal pool elevation. The area between the storm stage and normal pool in the profile view represents a cross-section of the storm storage volume. The flow is a function of the stage-storage relationship (i.e., outlet width, and storm stage level and area). Weir flow through the outlet is assumed in this figure.

In a simple watershed runoff scenario, a structure can be placed at the outlet of the watershed (Figure 2). TR-20 will calculate the peak flow upstream and downstream of the structure, taking into account the storage area above the structure. The difference between the peak flow upstream and downstream of the structure is a function of the storage area and the structure capacity. If the storage area (L_W x W_W) is constant, a smaller capacity structure will result in a higher storm stage for the same storm event (V_R). The difference in the outlet structure and storm stage elevations is the wetland storage depth (D_W), which, as demonstrated by Equation 1, is intricately linked to HRT (Figure 1).

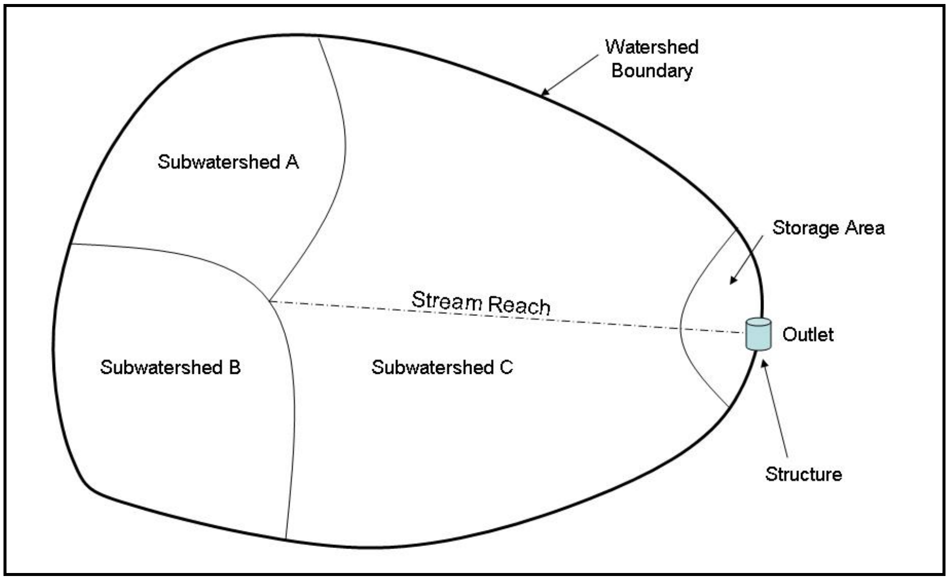
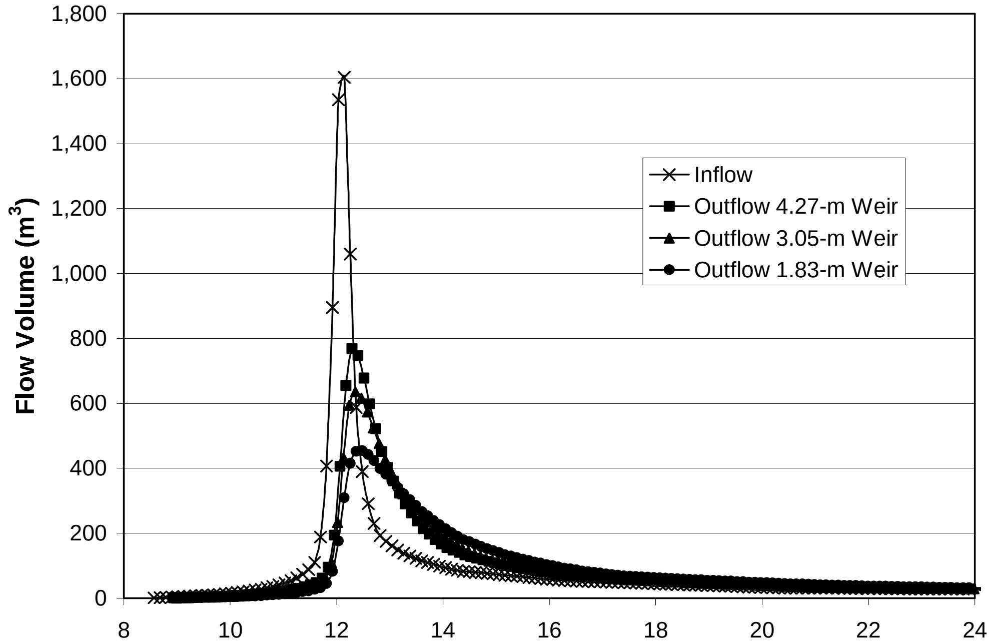


Figure 2. Schematic of watershed as modeled in TR-20. In this model, flow from subwatersheds A and B would be modeled as sheet and shallow concentrated flow, entering a stream channel at the upward end of the stream reach. Subwatershed C would be modeled as sheet and shallow concentrated flow going directly to the structure. TR-20 will report the peak flow upstream and downstream of the structure and outlet, which in this scenario are at the same location in the flow path.

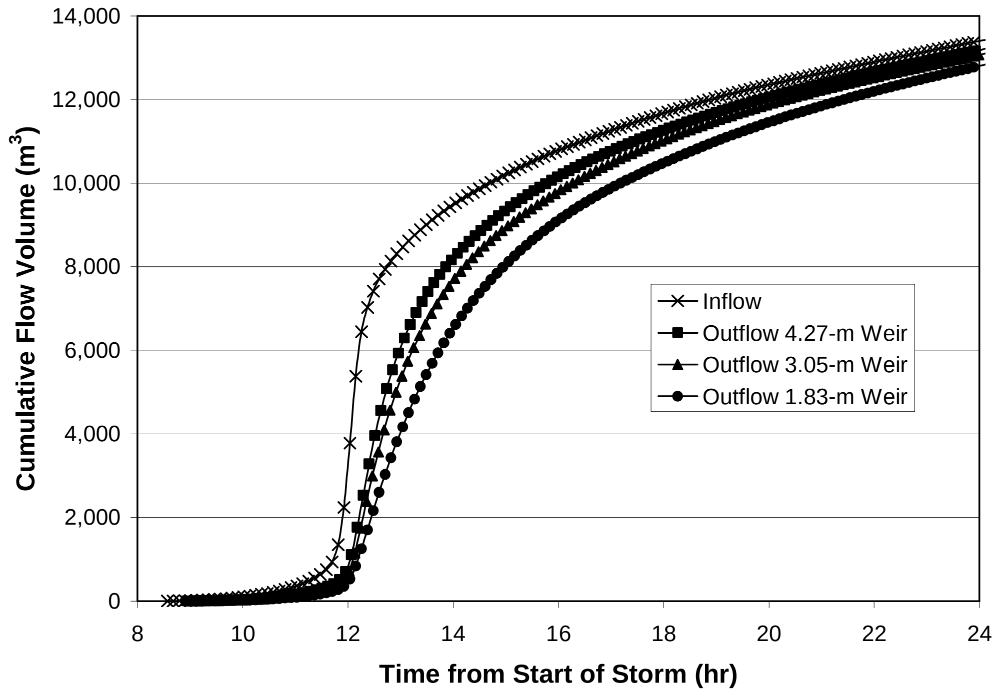
The relationship between D_W and HRT can be demonstrated by modeling a hypothetical wetland with TR-20. The data for Table 1 and Figures 3a and 3b was developed using TR-20 to model a hypothetical 0.8-ha (2.0 ac) wetland with a 20.2-ha (50 ac) watershed and three outlet size scenarios. Figure 3a demonstrates the attenuation of the peak storm flow entering the wetland. Figure 3b displays the increased time that the storm flow volume takes to exit the wetland as the outlet size decreases. As shown in Table 1, HRT and storm stage (D_W) increase as the outlet size decreases, with relatively small changes in storm stage resulting in significant changes in HRT. For example, for the 1-yr 24-hr storm event, a change from a 3.05-m (10 ft) to a 1.83-m (6 ft) wide outlet results in an increase in storm stage of only 2.2 cm (0.07 ft), but provides an increase in mean HRT of 0.8 hours.

Table 1. Storm stage and mean hydraulic residence time (MHRT) for 1-yr and 10-yr 24-hr storm events modeled with TR-20, based on the same model as used for Figures 3a and 3b. Relatively small increases in storm stage can result in significant increases in mean residence time for both storm events.

Weir Length (m)	**1-yr 24-hr Storm**		**10-yr 24-hr Storm**	
	Storm Stage (cm above normal pool)	MHRT (hr)	Storm Stage (cm above normal pool)	MHRT (hr)
4.27	18.6	0.9	43.0	0.8
3.05	20.1	1.3	47.2	1.1
1.83	22.3	2.1	53.6	1.7



(a)



(b)

Figure 3. 10-yr 24-hr storm inflow and outflow hydrographs for a hypothetical 0.8-ha wetland with a 20.2-ha watershed modeled with TR-20. Flow volumes represent the approximate volume entering and leaving the wetland for a constant time increment (Equation 11). The flows were modeled with three different outlet sizes (4.27-m, 3.05-m, and 1.83-m weirs). Notice in Figure 3a that the peak inflow is reduced significantly at the outlet, with the greatest reduction occurring with the smallest outlet. Figure 3b demonstrates the increase in retention time for the flow volume with decreasing outlet size.

A significant portion of the wetland restorations in agricultural areas are implemented with the assistance of the U. S. Department of Agriculture's Natural Resource Conservation Service (NRCS) and its partners, because NRCS is the lead technical agency for delivery of Farm Bill conservation programs. In providing this assistance, NRCS and partner staff regularly use TR-55 (USDA-SCS 1986), a simpler version of TR-20, to design wetland restorations. The Maryland NRCS conservation practice standard for wetland restoration requires that outlets are sized to provide 15 cm (0.5 ft) of freeboard (Figure 1) above the 10-yr 24-hr design storm water level, and that the berm height is no greater than 1.22 m (4.0 ft) (USDA-NRCS 2006). Based on my experience, for farm scale watersheds on the Maryland Eastern Shore (MES), the 10-yr 24-hr storm will typically produce water levels from 6 to 30 cm (0.2 to 1.0 ft) above the normal pool elevation for typical watershed to wetland size ratios. Often, outlets are designed to produce a storm stage of 15 cm (0.5 ft), which requires that berms are 30 cm (1.0 ft) above the design normal pool. In some cases, both primary and emergency spillways are used. The primary spillway is often a riser-type structure with boards that allow water level management. The primary spillway usually carries a small portion of the design storm flow, and because the emergency spillway is at a higher elevation than the primary spillway, the primary spillway controls the normal pool level.

This method of sizing outlets and berms is based on minimizing berm heights to reduce construction costs and meet the design criteria of the wetland restoration practice standard. As shown in Table 1, relatively small increases in storm stage can result in significant increases in HRT. During smaller, and more frequent storm events, outlet sizing can result in even more significant increases in HRT. This is demonstrated by the greater increase in HRT per unit change in storm stage for the 1-yr 24-hr storm versus the 10-yr 24-hr storm ($dHRT/dD_W$ of 20.0 versus 4.3), based on the data in Table 1. Thus, relatively subtle changes in design (i.e., berm height and outlet size) may provide significant water quality benefits. If guidance were available, designs could be improved to address nutrient retention. But the question that needs to be answered is, what increase in storm storage provides a change in HRT that significantly affects nutrient retention? One possible method to begin to answer this question is to compare modeled hydrologic and hydraulic variables with indicators of nutrient retention in existing restored wetlands.

PLANTS AS INDICATORS OF NUTRIENT RETENTION

Plants play an important role in nutrient retention and removal in wetlands. In a review, Fisher and Acreman (2004) identified vegetative processes as one of the most frequently reported significant factors for nutrient removal in wetlands. Studies have shown that plants can remove significant amounts of nutrients from water flowing into wetlands (Davis and van der Valk 1983; Howard-Williams 1985; Mitsch 1992; Comin et al. 1997; Silvan et al. 2004; Herr-Turoff and Zedler 2005). However, most studies have indicated that the many indirect effects of plants on nutrient retention are even more significant. Plants help to sustain nutrient retention by recycling nutrients. For example, Howard-Williams (1985) demonstrated that internal cycling in wetland plants can account for half the annual flux of N and P in *Phragmites australis*, as nutrients are exchanged between above and below-ground tissues. Plants promote the removal of nutrients from interstitial water by absorbing nutrients and making adsorption sites available (Davis and van der Valk 1983). Plants reduce flow velocities, which causes nutrient-laden sediments to accumulate in wetlands. The annual deposition of plant litter is one of the most important roles of plants in wetlands (Davis and van der Valk 1983). The carbon sequestered from the atmosphere and returned to the soil during the decay process is critical for microorganism production and consequent removal of N through denitrification. Plants also create aerobic zones in saturated soils when they release oxygen into the root zone (Hammer 1992; Brix 1997). The resulting association of aerobic and anaerobic zones facilitates the transformation of N compounds, including the process of denitrification (Reddy et al. 1989; Caffrey and Kemp 1992; Hammer 1992; Munch et al. 2005). Martin and Reddy (1997) showed that plants with high rates of evapotranspiration can affect the movement of NH_4-N and NO_3-N in the root zone, and consequently, promote denitrification. With plants playing such an important role in nutrient retention, cycling, and removal in wetlands, it follows that greater plant biomass production results in greater nutrient retention and removal (Davis and van der Valk 1983; Hammer 1992; Mitsch 1992; Silvan et al. 2004).

Wetland vegetation has also been shown to be impacted by elevated nutrient levels in wetland soils and surface waters. Many studies have found higher assimilation of N and P in plant tissue in nutrient-enriched environments (Craft and Richardson 1993; Greenway 1997; Miao and Sklar 1998; Craft et al. 2007; Kroger et al. 2007), which is often referred to as “luxury uptake”. Hence, plants are part of a biofeedback process in which they both support nutrient retention and respond to elevated levels of primary nutrients with increased absorption. It follows that increased levels of nutrients in plant tissues will be found in wetlands where conditions enhance nutrient availability and assimilation. Such conditions would include longer hydraulic residence times, especially when the majority of nutrient loading occurs during storm events.

The objective of this research was to evaluate the feasibility of a model for optimizing nutrient retention in restored wetlands based on the relationship between HRT and both plant biomass and standing nutrient stocks. Using HRT as the independent variable and plant biomass and nutrient standing stocks as the dependent variables, I expected the model to display a positive relationship. I also hypothesized that the relationship would display two inflection points, coinciding with the HRT at which nutrient retention begins to increase significantly, and the HRT at which nutrient retention becomes less significant (Figure 4). If this relationship held, the proposed model could be used to optimize nutrient retention by designing wetland restorations that have HRT's that approach the second inflection point. HRT would be designed for by adjustment of the controlling variables, which include watershed/runoff effects, storm stage, and outlet size and type.

The use of an empirical model provides the benefit of accounting for variability inherent in landscape level analyses (e.g. nutrient loadings, precipitation), variability due to landowner objectives, and variability due to ecological functions and limitations. Thus, the model would provide a set of criteria that are applicable to nontidal wetland restorations implemented on the MES. Moreover, the model could easily be adapted to other important agricultural regions because it does not require long-term data, and it makes use of NRCS conservation practice standards and widely accepted hydrologic and hydraulic modeling tools.

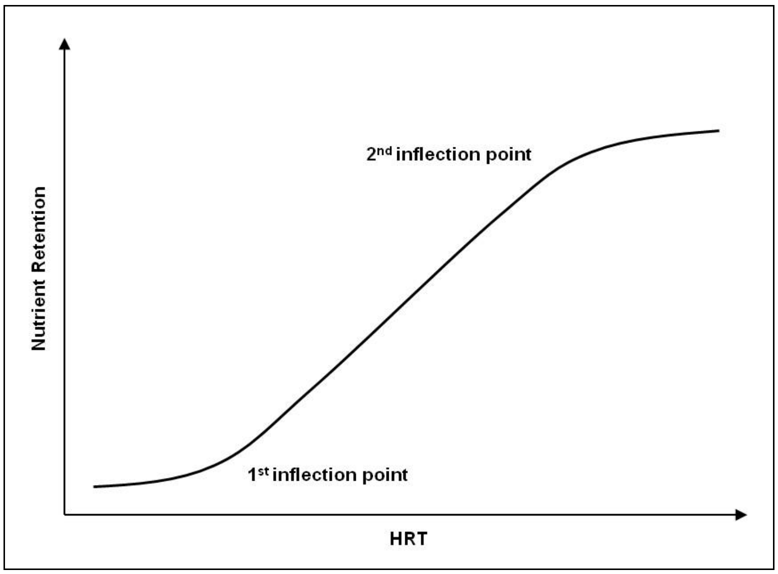


Figure 4. Graphical representation of hypothesized relationship between nutrient retention and HRT. The first inflection point is that at which increased HRT starts to show a significant increase in nutrient retention. The second inflection point is where increasing HRT begins to show diminished nutrient retention benefits, which occurs when the capacity of the wetland to achieve significantly greater biomass production and luxury uptake of nutrients has been reached.

Chapter 2: Review of Literature

The objective of my research was to evaluate a hypothetical model for nutrient retention in restored wetlands based on factors that could be employed in the design of wetland restorations. Following is a review of the literature for which models were developed to address the wetland design requirements to treat NPSP in agricultural watersheds. Where applicable, I discuss the practical application of the model. A general discussion of models for nutrient removal in wetlands can be found in *Chapter 1: Introduction*.

Almendinger (1999) developed a model to prioritize wetland restorations sites for water quality improvement for NPSP-affected areas in agricultural watersheds in Minnesota. Almendinger suggested combining the major variables in "function effectiveness" – hydraulic residence time, hydraulic flux, and wetland area, volume and average depth – into a single term (ε) that can provide an estimate of site potential. The term ε is reduced to a function of wetland area and the average annual flux of water through the wetland. The model lacks any indicators of water quality improvement, and presumably, for this reason, the author suggests the use of site monitoring to assess and enhance model effectiveness. A weakness of the model is the use of average annual flux for the hydraulic loading because NPSP is primarily event-driven (Raisin et al. 1997; Braskerud et al. 2000).

Dorge (1994) describes a deterministic model, MIKE 11 WET, for nitrogen removal and retention in wetlands from agricultural runoff. The model describes water flow and nitrogen cycling in the surface and root zone of freshwater temperate wetlands. Because the model is deterministic, it requires many assumptions, including constant saturation in the wetland soil, no nitrogen limitations for plant production, and a nitrogen cycle that is independent of P and carbon. The model also requires knowledge of local N loads, which would be difficult to develop for all potential wetland restorations. The model is useful for assessing the effectiveness of existing wetlands, rather than planned wetlands.

Lee et al. (2002) developed and evaluated a model (WETLAND) to enhance wetland design for NPSP control. WETLAND models both subsurface and free-water surface flow wetlands by simulating the hydrologic, nitrogen, carbon, dissolved oxygen, bacterial, vegetative, phosphorus, and sediment cycles. The model requires daily input values for hydrologic and nutrient parameters, which according to the authors, can be derived from measured data, NPSP models (e.g. ANSWERS), or calculation of daily runoff values using the SCS curve number method and nutrient runoff coefficients. The model was calibrated using a municipal wastewater treatment wetland, rather than a wetland that received NPSP. A model simulation provided results comparable to those reported in the literature, but the efficacy of the model has not been tested with real-world wetlands. The authors suggest that more rigorous testing is required for validation, and no follow-up validation of the model was found in the literature.

Crumpton (2001) applied a temperature-dependent first-order nitrate removal equation, which was developed for treatment wetlands and is described in Kadlec and Knight (1996), to a continuously-stirred tank reactor (CSTR) in-series mass balance model to simulate nitrate removal in two hypothetical restored wetlands in the corn belt of the U.S.A. In the first scenario, referred to as the *conventional* approach, the restored wetland intercepted 4 percent of the total drainage from the watershed. In the second scenario, referred to as the *watershed* approach, the wetland intercepted 50 percent of the total drainage. The difference between the *conventional* and *watershed* approaches was that the importance of wetland landscape position in relation to water quality was explicitly recognized in the latter. Therefore, in the *watershed* approach, the wetland was sited to have a larger wetland to watershed ratio (i.e. 50 percent) (Crumpton 2001). In both scenarios, the restored wetlands occupied 10 percent of a 2,550 ha watershed. Model coefficients were estimated from experimental and mesocosm wetland studies. Hydraulic loading rates (HLR) and temperature were estimated from measured values in a typical watershed. Results of the model indicated that the *conventional* approach would have little effect on nitrate concentrations, resulting in less than 4 percent removal of the annual nitrate load. In contrast, the model indicated the *watershed* approach would substantially reduce nitrate concentrations, resulting in removal of approximately 35 percent of the annual nitrate load. Unlike the previously described models, Crumpton's model has achieved practical application. The model forms the basis for the Iowa Conservation Reserve Enhancement Program (CREP) (Crumpton et al. 2006), which provides financial incentives for landowners to implement targeted wetland restoration. Technical eligibility criteria for the Iowa CREP is based upon the research findings of Crumpton (2001), and requires that: (1) Restored wetlands are located below a tile drainage system with a watershed that includes at least 200 ha of cropland; (2) The wetland area is between 0.5 and 2 percent of the drainage area; (3) At least 75 percent of the wetland pool is less than 0.9 m deep; and (4) The wetlands are designed to maintain drainage for upstream landowners. As of December 2006, 20 wetlands have been restored through the Iowa CREP, ranging in size from 1.4 to 7.5 ha, and intercepting drainage from watersheds ranging from 208 to 1,478 ha (Crumpton et al. 2006). Crumpton et al. (2006) conducted further analysis of predicted nitrate removal by wetlands using measurement data from 3 CREP sites and 12 experimental wetland sites in Ohio, Illinois, and Iowa. Results indicated that 94 percent of the variability in mass removal rates of nitrate could be explained by a model that considers HLR and flow-weighted average (FWA) nitrate concentration. Inherent in the wetland performance model is the variability in HLR and FWA nitrate concentrations, so site-specific values of HLR and FWA are needed for model reliability. Crumpton et al. (2006) used the wetland performance model in combination with a geographic information systems (GIS) model of nitrate loadings based on land-use, gage station, and climatic data, to determine the potential reduction of nitrate loads in the Upper Mississippi River and Ohio River basins. Results indicated that a 30 percent reduction in nitrate load to the basins could be expected if 210,000 to 450,000 ha of wetlands were constructed in the areas with the highest nitrate loads.

Although the Crumpton (2001) model may be appropriate for the corn belt region, landscape scale factors and the difference in predominant drainage practices (i.e., tile drainage versus surface drainage) limit the transferability of the model to the MES. On the large scale that the model was applied, and with tile drainage systems as the primary means of water conveyance, these watersheds are likely to be much less storm-driven than smaller watersheds with surface drainage. Consequently, the large tile-drained watersheds should produce less variability in HLR, which is an important factor for maximizing HRT (Jordan et al. 2003) in wetlands. This is implied by the fact that the wetland performance model is based on a nitrate removal equation that assumes plug flow, in which the nitrate-loaded water follows a linear pathway from inlet to outlet, maximizing contact time (i.e., residence time) with bioreactive surfaces. The difference between the large tile-drained watersheds and smaller surface-drained watersheds of the MES is somewhat akin to the data presented in Crumpton et al. (2006), where the Iowa CREP wetland with the lower nitrate removal rates had greater variability in nitrate concentrations, and the response to high flows was much more similar between inflow and outflow nitrate rates. Crumpton suggested that this may have been related to differences in soils, topography, and/or drainage systems, but further investigation had not been conducted. Presumably, these explanations are all related to hydrologic pathways, since soils, topography, and drainage systems can affect the path through which excess water travels. Heavy soils, steep topography, and surface drainage will tend to support surface runoff as compared to sandy soils, flat topography, and tile drainage, which will promote infiltration. Since water movement through soil is slower than flow across the surface, it can be assumed that the surface pathway will result in shorter concentration times, higher peak flows, greater flow variability, shorter residence times, and subsequently, lower nitrogen removal rates.

Jordan (2007) developed a nutrient removal model based on a limited review of existing published data on treatment of agricultural NPSP. The purpose of the model was to provide nutrient reduction efficiencies of wetland restorations for use in the Chesapeake

Bay Program watershed model. The model was based on the assumption that nutrient removal rates generally follow first-order kinetics, where the rate of removal is proportional to the concentration of the substance in the water, and is dependent on the amount of time the water is retained (i.e., retention time) in the wetland. The assumption was also made that retention time is proportional to the percentage of the catchment occupied by the wetland. Thus, assuming watershed discharge is similar for watersheds of equal size, a larger ratio of wetland area to watershed area would result in greater retention time. The model, based on these assumptions, follows:

$$\text{Removal} = 1 - e^{-kA}, \qquad (2)$$

where, removal = the proportion of the input removed by the wetland;

A = the proportion of the watershed occupied by the wetland; and

k = the rate constant, fitted from experimental data

Values of k were determined for total N and P removal by applying non-linear regression to annual removal data from 15 published articles. For total N, k = 7.90, with lower and upper 95 percent confidence intervals of 4.56 and 11.2. For total P, k = 16.4, with lower and upper 95 percent confidence intervals of 8.74 and 24.0. Plots based on these values can be seen in Figure 5.

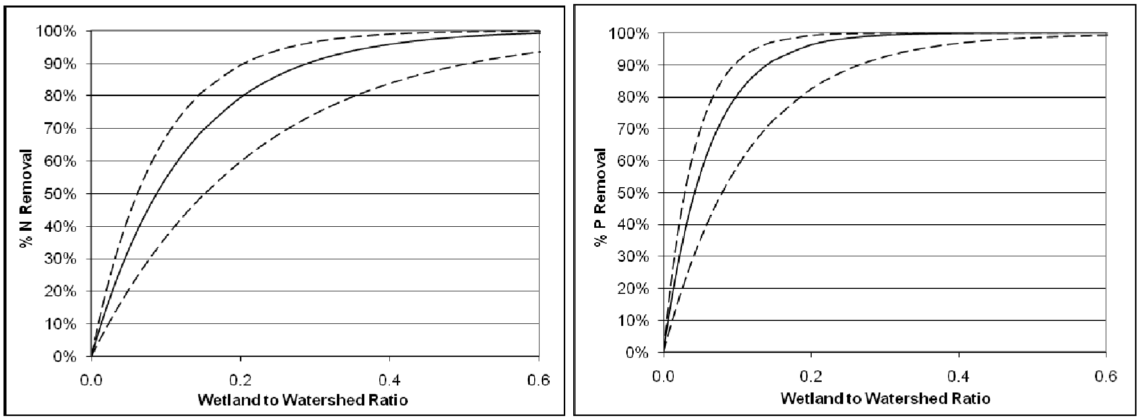


Figure 5. Total N (left) and P (right) removal as a function of the proportion of wetland to watershed, based on Jordan (2007), where removal = $1 - e^{-kA}$. Dashed lines represent lower and upper 95 percent confidence intervals.

Jordan cautions that wetland age, flow paths, flow variability, landscape, and wetland maintenance are all factors that can affect removal rates, but are not accounted for by the model. An issue with the model is that much of the data used to determine the k values comes from studies where wetlands were constructed specifically for treatment of NPSP, which could result in higher removal rates than would be attained in wetlands constructed for multiple objectives. Also, because all but one of the studies from which the model was extracted were conducted outside of the MES, the rate constants may not be applicable to the region.

The substitution of the ratio of wetland to watershed area (RWW) for retention time poses some significant problems. As noted by Jordan (2007), flow paths, flow variability, landscape, and wetland volume are all factors that can create significant variability in removal rates. In developing the model, Jordan omitted data where only negative removal rates had been reported, and used average data where a combination of positive and negative removal rates were reported from the same study. Negative removal rates are most likely a result of storm-driven flow variability. In Jordan et al. (2003), from which data was used for the model, total N and P removal was positive in the first year, but not significantly different from zero in the second year of the study. This was partly due to the wetter summer conditions in the second year, which resulted in higher wetland water levels, and subsequently, shorter residence times during runoff events. Jordan et al. (2003) demonstrated that retention times were much less over shorter time scales. For example, retention times calculated over the first and second years of the study were 19 and 12 d, respectively, while the retention time for the day with the highest loading rate was only 0.51 d. This demonstrates the importance of considering storm-based hydraulic loading in assessing nutrient removal in wetlands receiving unregulated inflows.

Chapter 3: Objectives

The primary objectives of this study were to:

1. Evaluate a hypothetical model for nutrient retention in restored wetlands based on plant nutrient stocks and HRT.

2. Evaluate the effects of typical wetland restoration design on HRT and nutrient retention in agricultural areas of the Maryland Eastern Shore.

3. Provide design recommendations for optimizing HRT within the existing framework for restoring wetlands in agricultural areas of the Maryland Eastern Shore.

Chapter 4: Materials and Methods

STUDY AREA

The MES is generally considered to be all the land in the State of Maryland that is east of the Chesapeake Bay. Part of the coastal plain physiographic province (Figure 6), the MES is relatively flat, and is an area of intensive commodity crop and poultry production. Agricultural field slopes range up to 10 percent in the northwest, and generally trend to 5 percent or less towards the southeast, where much of the land has slopes of less than 2 percent. Typical agricultural soils range from loamy sands to silty clay loams, and excessively drained to very poorly drained. Approximately 50 percent of the soils on the lower MES are hydric. The movement towards intensive grain crop production on the MES over the last 50 to 60 years has resulted in the establishment of a vast network of artificial drainage ditches and channelized streams to allow for enhanced crop production on former wetlands. Of the hydric soils that are farmed, the sandy loams tend to be more desirable, as indicated by their capability class under drained conditions (USDA-NRCS 2007). The fine-textured silty and clayey hydric soils, although often productive, can be difficult to work, and can cause stress to crops because of surface water ponding and low hydraulic conductivity. Although precipitation is fairly constant throughout the year, precipitation exceeds evapotranspiration in the winter and early spring prior to leaf-out. Much of the cropland in the lower portion of the MES has very high phosphorus levels due to decades of land application of poultry litter.

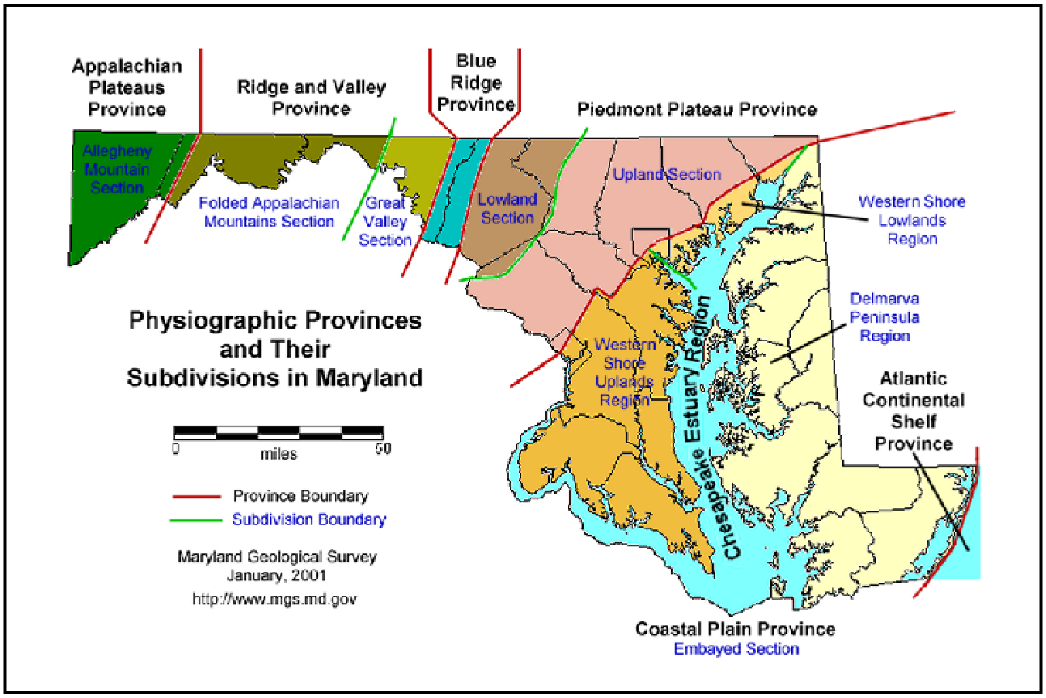


Figure 6. Physiographic provinces of Maryland (Maryland Geologic Survey 2001). The subdivision labeled *Delmarva Peninsula Region* is synonymous with the *Eastern Shore of Maryland.*

SITE SELECTION

Seven wetland restoration sites with characteristics typical of wetland restorations on the MES were selected for evaluation (Table 2). To ensure the potential for agriculturally-related NPSP to enter the wetland, selected sites had a watershed that included land in agricultural production. The watersheds of all the sites were relatively small (≤ 17 ha), and provided only emphemeral flows to the wetlands. To reduce variability related to soil nutrient concentrations prior to restoration, sites were limited to those that were in crop production within five years of the time of restoration. To reduce variability related to the initial development of wetland functions, selected sites had been restored for a minimum of three years. All sites were nontidal, located on hydric soils, and had similar soil map units with a soil texture of silt loam, except for one site with sandy loam soils.

Table 2. Characteristics of study sites.

	Restored Wetland				Watershed			RWW†	Buffer Width‡ (m)
Site	Size (ha)	Age (yr)	Mapped Soil	Soil Texture	Size (ha)	Percent Cropland	Weighted Curve Number		
CON	1.5	7	Hurlock	Sandy loam	15.3	80	76	0.09	20
GLP	0.4	11	Whitemarsh	Silt loam	10.5	96	78	0.04	5
GPT	0.1	5	Whitemarsh	Silt loam	4.5	48	68	0.03	60
SPF	5.8	7	Fallsington, Mattapex, Othello	Sandy loam, loam, silt loam	17.0	33	76	0.34	80
STN	1.4	9	Whitemarsh	Silt loam	5.7	66	72	0.24	5
STS	2.2	8	Carmichael, Kentuck	Loam, mucky silt loam	15.3	46	74	0.14	25
WDF	2.1	3	Carmichael, Othello, Whitemarsh	Silt loam	8.5	14	69	0.25	30

† RWW = ratio of wetland area to watershed area

‡ Buffer width measured along concentrated flow path from where it enters buffer to where it enters wetland. Flow paths shown in Appendix N.

DATA COLLECTION

Restoration project information for each site, including plans, topographic surveys, designs, and as-built surveys were collected from soil conservation district files. Designs were not available on one site (i.e. site CON), so elevation relationships between wetland and outlet were determined on-site and remotely, using light detecting and ranging (LIDAR) elevation data. Topographic surveys developed for the original site design and LIDAR elevation data were used to determine stage-storage relationships. Watershed information, including watershed size, land use, and flow path, were evaluated in the field, and remotely using geographic information systems (GIS), with supporting data such as LIDAR, topographic maps, aerial photography, and soil surveys.

Data on biomass was collected in ten 1-m^2 quadrats at each site, by the methods described below. Sampling locations were restricted to areas with emergent wetland vegetation. Prior to sampling, the size and shape of the wetland area containing emergent vegetation was estimated using GIS. An X-Y coordinate system was fitted to the wetland, and pairs of random numbers within the range of the X-Y coordinate system were developed for each site using Microsoft Excel. Starting at the beginning of the list, random X-Y coordinates were evaluated to determine if they fell within the estimated boundary of emergent wetland vegetation, and the process was continued until ten valid random locations were selected.

On-site, the origin of the coordinate system was estimated, and the random coordinates were paced out. A 1-m^2 frame made from ¾-in PVC pipe was dropped from head height over the vegetation. Stake flags were placed inside the frame at two opposite corners. Along the inner boundary of the frame, vegetation was determined as being “in” or “out” by where the stem emerged from the ground. Standing live and dead biomass was clipped at the ground and collected in labeled 30-gal trash bags. Using a laser level and survey rod, the elevation of the surface of the sample plot was measured relative to an on-site benchmark, such as a water control structure or other permanent type of structure. All samples were returned to an ambient indoor air-temperature storage location. Eventually, all biomass samples were transferred from plastic garbage bags to 30-gal paper lawn and leaf bags. The biomass samples were placed in environmental chambers, standing upright and open, at the University of Maryland College Park. Samples remained in the environmental chambers until they could be dried and prepared for analysis. Due to logistics, there was some variation in handling of samples amongst sites. See Appendix L for specific handling information.

Each biomass sample was weighed with the paper bag on a Toledo 500 g scale immediately prior to placement in the drying oven. Biomass samples were oven-dried at 55° C for a minimum of 7 d. The majority of samples were dried to a constant weight. However, some samples were weighed only once post-drying, after having been in the drying ovens for a period of 17 d. The dry sample weight was calculated by subtracting the empty dry bag weight from the weight of the final dry sample and bag. Dried biomass was ground in a No. 3 Wiley Mill with a 2 mm mesh screen. To ensure that a representative and well-mixed ground sample was obtained, biomass was pulled from various locations in the unground sample. The ground sample material was placed in labeled 1-gal Ziploc bags. If the amount of biomass was more than could fit in a 1-gal bag, the remainder of the sample was discarded. The mill, screen, and collection box was cleaned after each sample was ground. The paper sample bags were checked to ensure they were empty, and were weighed immediately after grinding.

Part of each sample was further ground in a coffee grinder to a particle size that was acceptable (1 mm or less) for carbon- hydrogen-nitrogen (C-H-N) analysis by combustion. To ensure a representative sample, three subsamples were pulled from different locations of each 1-gal bag using a stainless steel measuring cup. The subsample was placed into the coffee grinder and leveled off by lightly shaking the grinder. A piece of cardboard was placed on top of the material in the grinder to keep the material near the grinding blade in the base of the grinder cup. The lid was placed on the grinder and the grinder was activated for a minimum of 15 s. The lid and cardboard was removed, and the material was mixed gently with a knife blade and leveled out. The cardboard and lid were replaced and the material was ground again for another period of at least 15 s. The lid and cardboard were removed, and the sample was emptied into a stainless steel measuring cup. The fine-ground sample was removed from the measuring cup using a steel measuring spoon and placed into labeled Whirl-pak sample bags. Any remaining fine-ground material in the measuring cup was disposed of prior to pulling another subsample. After fine-grinding the three subsamples, all implements were thoroughly cleaned using a brush. The coffee grinder was run without a lid, facing down into the rotoclone dust collection system, to aide in removing residue. The fine-ground samples were stored, and the remaining 2-mm ground material was left in the 1-gal bags and stored. Tissue samples were analyzed for percent total carbon, hydrogen, and nitrogen by combustion (Campbell 1992) at the University of Maryland Soils Laboratory using a LECO CHN-2000. Tissue samples were analyzed for total phosphorus (TP) at the Penn State Analytical Laboratory by standard dry ash sample digestion and ICP spectrometer methods (Miller 1998). Nutrient standing stocks were determined by multiplying the percent of each nutrient by the dry weight of each biomass sample. Because plant tissue was analyzed for total nutrient content, the nutrient standing stocks were assumed to represent the total carbon (TC), total nitrogen (TN), and total phosphorus (TP) in the above-ground plant biomass.

HYDROLOGIC AND HYDRAULIC ANALYSIS

WinTR-20 Input

Standard input data for the hydrologic analysis, including land use details, flow paths, structures, and storm storage were gathered from the original engineering designs and final construction surveys, site visits, and GIS analysis of aerial photography, USGS- and LIDAR-based digital elevation models, and NRCS soil surveys. Hydrographs were developed for all sites using the WinTR-20 model (USDA-NRCS 2004a).

Runoff Curve Number

The weighted runoff curve number (CN) was calculated based on the SCS Runoff Curve Number method (USDA-SCS 1986), using the following equation:

$$CN = \sum (CN_{i,j} \times A_{i,j}) / \sum A_{i,j} \qquad (3)$$

where i = surface cover type

j = hydrologic soil group

$CN_{i,j}$ = the runoff curve number for the land in the watershed with surface cover type i and hydrologic soil group j

$A_{i,j}$ = area of watershed with surface cover type i and hydrologic soil group j (ha)

See Appendix A for CN calculation data.

Time of Concentration

The time of concentration (T_c) was calculated based on the SCS method (USDA-SCS 1986). Input data for determing T_c was derived from remote sensing with GIS using aerial photography and USGS- and LIDAR-based digital elevation models. The following equations were used to calculate T_c:

$$T_c = T_{t(SF)} + T_{t(SCF)} \quad (4)$$

where $T_{t(SF)}$ = the travel time for sheet flow (hr)

$T_{t(SCF)}$ = the travel time for shallow concentrated flow (hr)

$T_{t(SF)}$ was calculated based on the following equation:

$$T_{t(SF)} = (0.091 \text{ x } (nL)^{0.8}) / (P_2^{0.5} \text{ x } S^{0.4}) \quad (5)$$

where n = Manning’s roughness coefficient

L = flow length (m)

P_2 = 2-year, 24-hour rainfall (mm)

S = land slope (m/m)

using the following values:

n = 0.17 for cultivated land > 20% residue (USDA-NRCS 2004b)

n = 0.24 for dense grass cover (USDA-NRCS 2004b)

P_2 = 84 mm

$Tt_{(SCF)}$ was calculated based on the following equation:

$$T_{t(SCF)} = L / (V \text{ x } 3600) \quad (6)$$

where L = flow length (m)

V = average velocity (m/s), based on Manning's equation:

$$V = (r^{2/3} \times S^{1/2}) / n$$

where n = Manning's coefficient

r = hydraulic radius (m)

S = watercourse slope (m/m)

using the following values:

n = 0.05 (shallow concentrated flow on an unpaved surface) (USDA-NRCS 2004b)

r = 0.12 m (USDA-NRCS 2004b)

See Appendix B for T_c calculation data.

Stage-Storage-Discharge Ratings

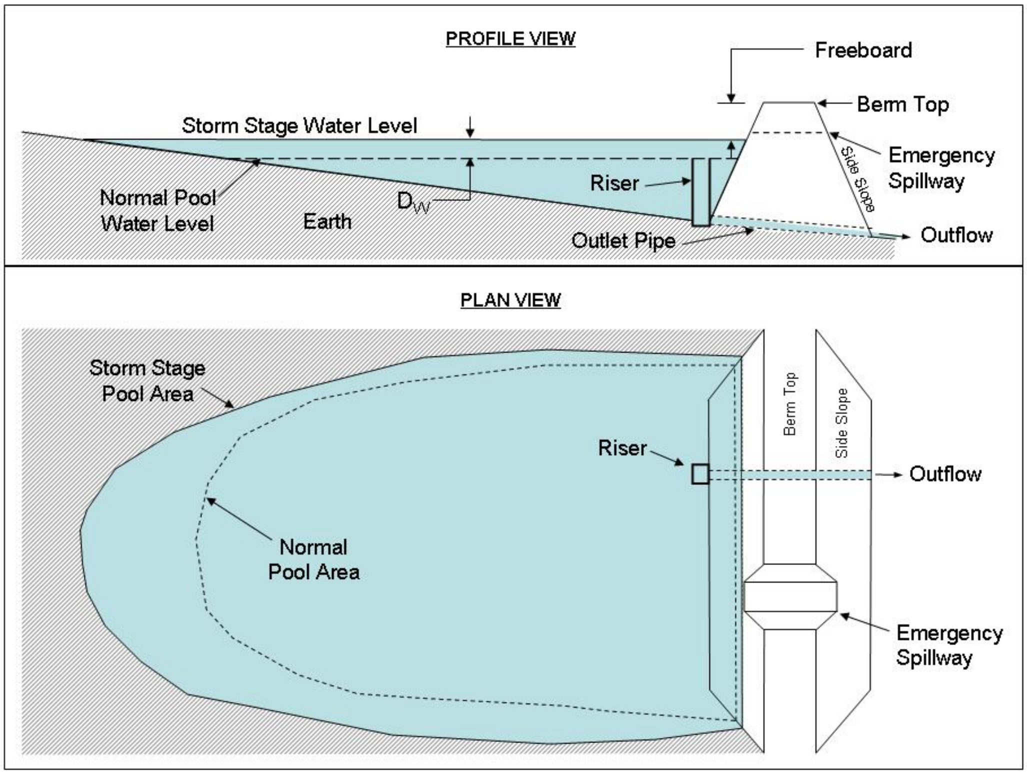
The stage-discharge and stage-storage ratings were calculated for the same representative stage values, and together they provided the stage-storage-discharge rating for a site.

Stage-Discharge Ratings. The stage-discharge ratings were determined by calculating discharge (Q) through the outlet structures at representative storm stages. For sites with multiple outlet structures, the Q was calculated for each structure at the selected storm stage values, and the individual Q values were summed. When a site had multiple outlets set at different elevations, the total Q was determined at the storm stage that was equal in elevation to the higher spillway (i.e., at just the point before flow would occur through the spillway set at the higher level), and again at the storm stage 3.05 cm (0.1 ft) above the higher spillway. This ensured a smooth transition in the rating curve when discharge would change from flowing through a single structure to flowing through two structures.

Sites with only a single outlet had either a broad-crested earthen weir or discharged over natural ground. Sites with multiple outlets typically had a water control structure (WCS) as the primary spillway, and a broad-crested earthen weir or natural ground as an emergency spillway (ES). An illustration of a site with a WCS and an ES is provided in Figure 7.

Discharge through a broad-crested weir or natural ground was calculated using the weir flow formula. Discharge capacity through a WCS can be controlled by weir flow, pipe flow, or orifice flow. The Q_{max} for each type of flow was calculated using the applicable flow equations, with the representative storm stage (D) as the basis for the hydraulic head. The lowest Q_{max} value was assumed to be the discharge at the specific storm stage. See Appendix C for stage-discharge rating calculations, flow formulas, and outlet descriptions.

(a)



(b)

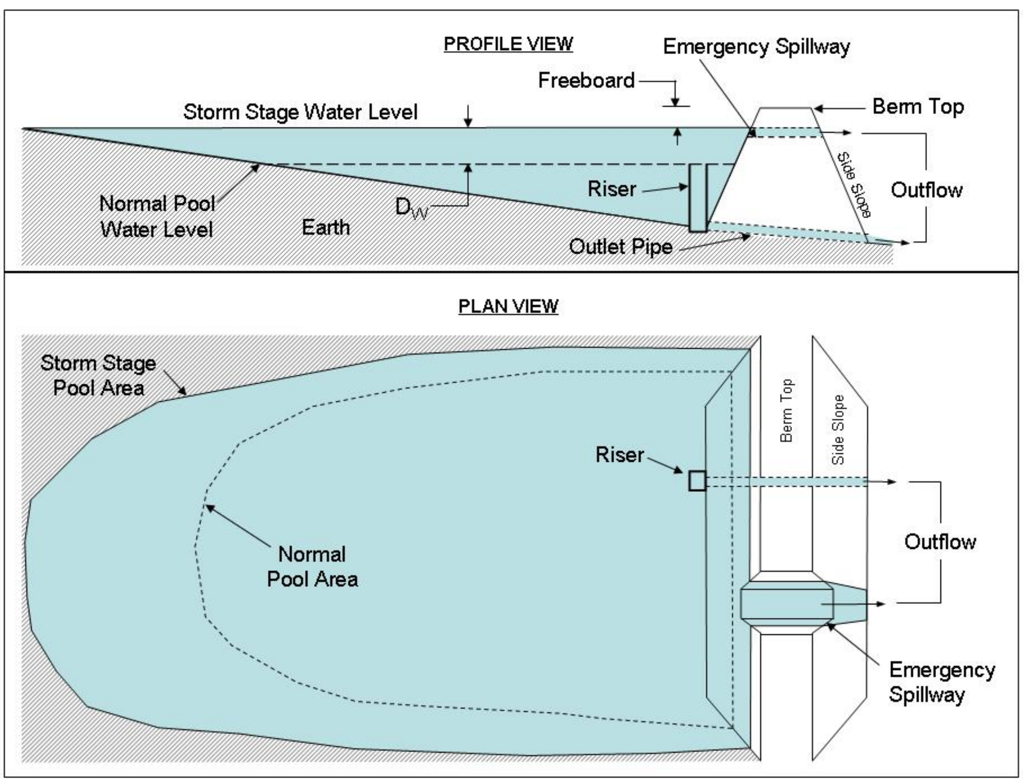


Figure 7. Diagrams of a wetland designed with both primary and emergency spillways. The "riser" and attached "outlet pipe" function as the primary spillway. The emergency spillway is

often earthen or rock-lined. In (a), the storm stage level causes flow through the primary spillway only. In (b), the higher storm stage causes flow through both spillways.

Stage-Storage Ratings. The stage-storage rating was determined by assuming a linear relationship between the surface area of the wetland at the normal pool elevation and the surface area of the wetland at a defined elevation above normal pool. The surface areas and elevations were determined from engineering designs and construction surveys and verified with GIS using contours developed from LIDAR. For each corresponding storm stage in the stage-discharge rating, the storage volume was determined by averaging the surface areas at the selected storm stage and normal pool elevations, and multiplying the average by the storm stage. Assuming that the change in surface area was proportional to the change in stage, the following equation was used to calculate the storage volume at each representative storm stage:

$$\text{Storage Volume} = [\ (A_0+A)\ /\ 2\ ]\ D \qquad (7)$$

where, $A = SD + A_0$

D = representative storm stage (m)

$S = (A_1 - A_0)\ /\ D_1$

S = change in surface area per unit change in stage (ha/m)

A = wetland surface area at storm stage (ha)

A_0 = wetland surface area at normal pool elevation (ha)

A_1 = wetland surface area at defined elevation above normal pool (ha)

D_1 = defined elevation above normal pool (m)

See Appendix D for stage-storage rating calculation data.

Design Storms

Six storm events were modeled using the Delmarva dimensionless unit hydrograph. Three of the storm events, the ½-in 1-hr, 1-in 1-hr, and 1-in 4-hr storms, were modeled as constant intensity storms with antecedent runoff condition (ARC) 3, which represents the wetter pre-storm watershed condition in TR-20. These storms were used because it is often assumed that flooding is commonly caused by short-duration, high-intensity storms, where storm duration is equal to the time of concentration for the watershed (McCuen 1998). The ARC3 was used because runoff from high intensity storms can decrease infiltration as a result of the destructive action on soil surface structure (Schwab, et al. 1993). Subsequently, high intensity storms can create conditions similar to those defined as having an ARC3. Furthermore, surface runoff is more frequent during the winter and spring months, due to climatic and soil conditions (e.g., low evaporation and evapotranspiration rates, less vegetative cover on agricultural fields, higher water tables), at the same time when nutrients are most available for removal by surface runoff. The other three modeled storms were based on the NRCS type II storm event and NRCS rainfall data: 1-yr 24-hr ARC2, 1-yr 24-hr ARC3, and 10-yr 24-hr ARC2. An ARC of 2 represents an "average" condition. The 1-yr 24-hr and 10-yr 24-hr storms are commonly modeled design storm events. The 10-yr 24-hr ARC2 storm event is typically used as the design storm for structures in agricultural landscapes. For all storm events, the wetlands were assumed to be filled to the normal pool stage at the beginning of the storm event. As a result, the difference between the start of inflow and outflow was minimal. See Appendix E for WinTR-20 input data, as entered into the WinTR-20 model.

Calculations Based on WinTR-20 Output

The output of WinTR-20 (see Appendix F for sample output) provided runoff depths, and peak flows and hydrographs for both the inflow (i.e., runoff upstream of the wetland outlet) and outflow. The hydrograph output was represented by instantaneous flow values at constant time intervals, for the duration of runoff and outflow. Time intervals were determined by the WinTR-20 model, and were typically in hundredths of an hour.

Calculation of Peak Storm Stage and Storage Volume

The storm stage (D) and storm storage volume (V_W) for each design storm for each site were calculated from the stage-storage-discharge rating, using linear interpolation, based on the following equations:

$$D = \frac{(D_{(j)} - D_{(i)})}{(Qp_{out(j)} - Qp_{out(i)})} (Qp_{out} - Qp_{out(i)}) + D_{(i)} \tag{8}$$

$$V_W = \frac{(V_{W(j)} - V_{W(i)})}{(Qp_{out(j)} - Qp_{out(i)})} (Qp_{out} - Qp_{out(i)}) + V_{W(i)} \tag{9}$$

where $D_{(j)}$ = the stage (m) at or above D in the discharge-storage relationship

$D_{(i)}$ = the stage (m) below D in the discharge-storage relationship

$V_{W(j)}$ = the storage volume (ha-m) at or above V_W in the discharge-storage relationship

$V_{W(i)}$ = the storage volume (ha-m) below V_W in the discharge-storage relationship

Qp_{out} = the peak discharge (m^3/s) flowing out of the wetland for the design storm

$Qp_{out(j)}$ = the peak discharge (m^3/s) at or above Qp_{out} in the discharge-storage relationship

$Qp_{out(i)}$ = the peak discharge (m^3/s) below Qp_{out} in the discharge-storage relationship

Figure 8 provides a graphical representation of the relationship used to determine the storm storage from the peak discharge. The stage-storage-discharge relationships for each site are in Appendix G.

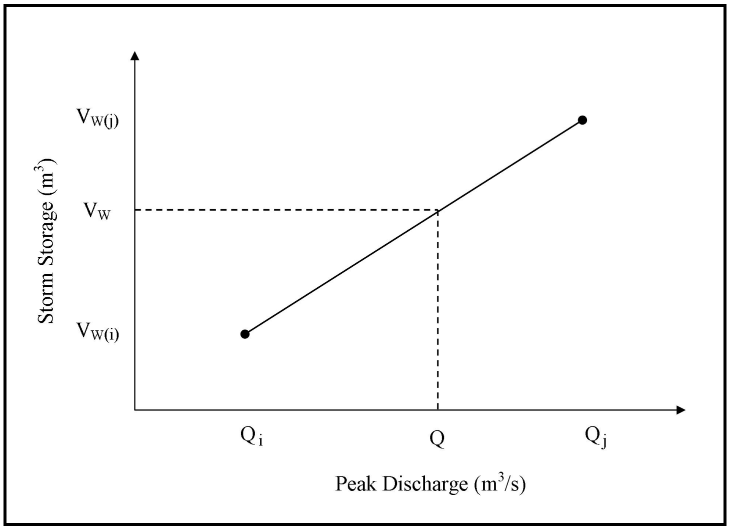


Figure 8. Graphical representation of the relationship used to linearly interpolate storm storage from peak discharge. The slope line represents a single segment in the discharge-storage rating. By replacing V_w with D, the figure would represent the relationship used to calculate storm stage.

Calculation of Hydraulic Residence Time

The inflow and outflow hydrographs were transferred from WinTR-20 to Microsoft Excel and transformed into two columns of data. Hydraulic residence times (HRT) were calculated for each storm event at each site by two methods.

Nominal Hydraulic Residence Time. The nominal HRT (NHRT) was calculated based on the following equation:

$$HRT = \frac{V_W}{V_R T^{-1}} \qquad (10)$$

where V_W = the storm storage volume (ha-m), which is the volume of water in the wetland between the normal pool elevation and the peak storm stage (Figure 1)

V_R = the total runoff volume from the design storm (ha-m)

T = duration of flow, which is the time from the initiation to the cessation of flow at the wetland outlet (hr)

The runoff volume (V_R) was calculated as the product of the runoff depth provided by WinTR-20 and the watershed area. The duration of flow (T) was calculated as the difference between the beginning and end times of the WinTR-20 outflow hydrograph.

Mean Hydraulic Residence Time. The mean HRT (MHRT) provides a more precise estimate of HRT than the NHRT. The MHRT was calculated from the WinTR-20 output using a weighted average method, as shown in Equation 11, based on an average of residence times for increments of flow. Both the inflow and outflow volumes were calculated for each time increment of the hydrograph by taking the average of two consecutive instantaneous flow values and multiplying it by the hydrograph constant time increment, as shown in Equations 12a and 12b. The residence time for an incremental flow volume was calculated as the difference in inflow and outflow time for the volume (Equation 13). The residence time was multiplied by the incremental flow volume to provide a volume-weighted residence time. The weighted incremental residence times were summed and divided by the total outflow volume to determine the MHRT.

The incremental flow volume differed between inflow and outflow because the outflow rate was often lower than the inflow rate. This meant that the time of inflow for a particular outflow volume could not be directly obtained from the hydrograph output. Instead, it was necessary to determine the two inflow time increments between which the outflow incremental volume had entered the wetland. The inflow time was then linearly interpolated from the two time increments based on the proportion of the corresponding inflow incremental volumes that was represented by the outflow incremental volume.

$$MHRT = [\sum_{j=2}^{n} [V_j \text{ x } \Delta T_j]\ ] / V_{cum,j=n} \qquad (11)$$

where $V_i = [(Q_i - Q_{i-\Delta t}) / 2] \text{ x } (T_i - T_{i-\Delta t}) \text{ x } 60 \text{ min/hr x } 60 \text{ s/min}$ (12a)

$V_j = [(Q_j - Q_{j-\Delta t}) / 2] \text{ x } (T_j - T_{j-\Delta t}) \text{ x } 60 \text{ min/hr x } 60 \text{ s/min}$ (12b)

$\Delta T_j = T_j - T_i(V_{cum,j})$ (13)

$T_i(V_{cum,j}) = m \text{ x } V_{cum,j} + b$ (13a)

$m = (T_i - T_{i-\Delta t}) / (V_{cum,i} - V_{cum,i-\Delta t})$ (13b)

$b = T_{avg} - mV_{avg} = [(T_i + T_{i-\Delta t}) / 2] - (V_{cum,i} + V_{cum,i-\Delta t})$ (13c)

$V_{cum,i} = V_i + V_{cum,i-\Delta t}$ (14a)

$V_{cum,j} = V_j + V_{cum,j-\Delta t}$ (14b)

where MHRT = mean hydraulic residence time (hr)

T = time of flow (hr)

Q = instantaneous flow from hydrograph (m^3/s)

V = flow volume between time increments of hydrograph (m^3)

ΔT = time increment between instantaneous flow values of hydrograph (hr)

i = inflow time increment

j = outflow time increment

n = number of time increments (Δt) for duration of outflow

V_j = volume of outflow between T_j and $T_{j-\Delta t}$

V_i = volume of outflow between T_i and $T_{i-\Delta t}$

ΔT_j = the approximate amount of time between when a specific volume flowed into and out of the wetland

V_{cum} = cumulative flow volume (m^3)

$T_i(V_{cum,j})$ = inflow time for a specific cumulative volume of outflow, determined by linear interpolation

Note: Calculations were made in English units and converted to SI units.

Ratio of Wetland to Watershed Area. A third representation of HRT was calculated based on the assumption that HRT is proportional to the ratio of wetland to watershed area (RWW) (Jordan 2007).

Statistical Analysis

Statistical analyses were performed using SPSS 14.0 for Windows Student Version (SPSS, Inc. 2006). Descriptive statistics were determined from the plot sample data for each site. One-way ANOVA was performed to determine if the means of sample data amongst sites were significantly different from each other. Correlation and bivariate regression (when appropriate) analysis were performed to evaluate the relationships between the following:

- MHRT vs. NHRT;
- MHRT vs. RWW;
- NHRT vs. RWW;
- Aboveground plant biomass vs. MHRT;
- Aboveground plant biomass vs. NHRT;
- Total N standing stock vs. MHRT;
- Total N standing stock vs. NHRT;
- Total P standing stock vs. MHRT;
- Total P standing stock vs. NHRT.

Prior to conducting ANOVA, the Kolmogorov-Smirnov one-sample (KS) test (Ayyub and McCuen 2003) was used on sets of data to determine if the data could be considered to be from a normal distribution. If the KS test suggested the data were not from a normal distribution, the data were log-transformed to perform ANOVA. Levene's test for homogeneity of variances (SPSS, Inc. 2005) was used to determine if variances could be assumed to be equal. In cases where variances were assumed equal, the Tukeys HSD test (SPSS, Inc. 2005) was used to determine if the means between sites were significantly different ($p \leq 0.05$). The Dunnett T3 test assuming unequal variances (SPSS, Inc. 2005) was used to determine significance ($p \leq 0.05$) where equal variances could not be assumed.

Correlation analyses were conducted using the nonparametric Spearman's rho correlation to provide better consistency for comparison, because the distribution of variables was not consistent. Values of MHRT, NHRT, biomass, TN and TP were log-transformed prior to conducting regression analyses. The KS test was used to determine if it was reasonable to treat the data as if they were from a normal distribution. Measures of regression accuracy and strength, standardized residual normal probability plots, and plots of standardized residuals versus standardized predicted values were also used. (Regression measures are in Appendices I and J, and results of KS tests are in Appendix K).

Paired sample tests were used to determine if the means of MHRT and NHRT for a site were significantly different ($p \leq 0.05$).

Chapter 5: Results and Discussion

Hydrologic and Hydraulic Analysis

Table 3 shows the results of the WinTR-20 analysis, along with additional hydraulic characteristics, of each site (additional results in Appendix H). All calculations assume that the wetland is at the normal pool stage when the storm event occurs. The *MHRT* and *NHRT* are the calculated mean and nominal hydraulic residence times as described in the *methods* section. *Runoff depth* is the amount of runoff produced by the storm event over the entire watershed. *Runoff volume* is the product of the runoff depth and area of the watershed. Qp_{in} and Qp_{out} are the WinTR-20 determined peak flows entering and leaving the wetland, respectively. *Storm stage* is the maximum height of the water surface above the normal pool during the specified storm event.

Wetland Design and HRT

As shown in Table 3, there was a lack of significant difference between sites for variables related to the watershed (i.e., runoff depth, runoff volume, and Qp_{in}), suggesting that the watersheds were relatively similar to each other in hydrology and hydraulics, and therefore suitable for comparison. Site STN had the greatest values of HRT, and the values were significantly ($p \leq 0.05$) greater than for all other sites. Site WDF had the next greatest values of HRT, which were significantly greater than the other five sites. The

Table 3. Results of analysis with WinTR-20 and other hydraulic characteristics for each site (across top). Storm abbreviations: CI = constant intensity; T2 = Type II; ARC = Antecedent runoff condition. Storms are listed in order of increasing peak inflow (Qp_{in}). Means with dissimilar superscripts are significantly different at $p \leq 0.05$ based on ANOVA and Tukey HSD.

	Design Storm	CON	GLP	GPT	SPF	STN	STS	WDF
MHRT (hr)	½-in 1-hr CI ARC3	0.2	6.0	0.3	9.1	23.6	1.4	18.7
	1-in 4-hr CI ARC3	0.2	5.7	0.3	9.3	33.3	1.4	30.6
	1-in 1-hr CI ARC3	0.2	5.8	0.3	9.3	33.3	1.4	**30.6**
	1-yr 24-hr T2 ARC2	0.2	**8.7**	0.3	9.3	31.8	1.4	**15.9**
	1-yr 24-hr T2 ARC3	0.2	**8.1**	0.3	7.7	25.7	1.2	7.8
	10-yr 24-hr T2 ARC2	0.2	5.4	0.2	6.3	22.0	1.1	5.2
	Mean	^{a}0.2	^{ab}6.6	^{ab}0.3	^{b}8.5	^{d}28.3	^{ab}1.3	^{c}18.1
	$S_e(1)$	0.002	0.57	0.01	0.52	2.09	0.06	4.44
NHRT (hr)	½-in 1-hr CI ARC3	0.6	25.2	0.7	38.7	68.5	4.5	43.0
	1-in 4-hr CI ARC3	0.5	31.2	0.8	53.2	144.9	5.5	134.2
	1-in 1-hr CI ARC3	0.6	32.6	0.9	53.3	145.9	5.4	**133.6**
	1-yr 24-hr T2 ARC2	0.8	**31.4**	1.2	43.1	141.2	5.1	**78.7**
	1-yr 24-hr T2 ARC3	1.1	**31.0**	1.5	46.8	145.0	5.9	68.1
	10-yr 24-hr T2 ARC2	1.0	20.9	1.3	41.9	144.7	5.0	54.9
	Mean	^{a}0.8	^{ab}28.7	^{a}1.1	^{b}46.2	^{d}131.7	^{a}5.2	^{c}85.4
	$S_e(1)$	0.1	1.9	0.1	2.5	12.7	0.2	16.1
Storm Stage (cm)	½-in 1-hr CI ARC3	0.1	2.7	0.1	0.2	0.2	0.2	0.1
	1-in 4-hr CI ARC3	0.4	13.9	1.5	1.6	1.9	1.6	1.4
	1-in 1-hr CI ARC3	0.5	14.8	2.3	1.6	1.9	1.8	**1.4**
	1-yr 24-hr T2 ARC2	0.7	**29.9**	2.7	3.2	4.7	2.8	**2.5**
	1-yr 24-hr T2 ARC3	1.7	**45.3**	7.0	6.3	9.3	5.9	5.2
	10-yr 24-hr T2 ARC2	2.9	51.3	9.1	9.4	15.0	8.5	7.1
	Mean	^{a}1.1	^{b}26.3	^{a}3.8	^{a}3.7	^{a}5.5	^{a}3.5	^{a}3.0
	$S_e(1)$	0.4	7.9	1.4	1.4	2.3	1.3	1.1
Storm Storage (ha-m)	½-in 1-hr CI ARC3	0.001	0.011	0.0002	0.014	0.003	0.005	0.001
	1-in 4-hr CI ARC3	0.006	0.059	0.002	0.094	0.027	0.035	0.029
	1-in 1-hr CI ARC3	0.009	0.063	0.004	0.096	0.027	0.039	0.029
	1-yr 24-hr T2 ARC2	0.013	0.134	0.004	0.188	0.067	0.062	0.053
	1-yr 24-hr T2 ARC3	0.030	0.211	0.012	0.374	0.140	0.129	0.111
	10-yr 24-hr T2 ARC2	0.051	0.243	0.018	0.562	0.231	0.186	0.152
	Mean	^{a}0.018	^{ab}0.120	^{a}0.007	^{b}0.221	^{ab}0.083	^{ab}0.076	^{ab}0.063
	$S_e(1)$	0.008	0.038	0.003	0.085	0.036	0.028	0.023

Table 3. (continued)

	Design Storm	CON	GLP	GPT	SPF	STN	STS	WDF
Runoff Depth (mm)	½-in 1-hr CI ARC3	1.1	1.4	0.2	1.1	0.4	0.8	0.2
	1-in 4-hr CI ARC3	7.2	8.1	3.9	7.2	5.0	6.4	3.9
	1-in 1-hr CI ARC3	7.2	8.1	3.9	7.2	5.0	6.4	3.9
	1-yr 24-hr T2 ARC2	20.8	23.4	12.2	20.8	16.2	18.4	13.1
	1-yr 24-hr T2 ARC3	41.4	43.5	32.3	41.4	35.8	39.5	32.3
	10-yr 24-hr T2 ARC2	70.7	75.4	53.2	70.7	61.7	66.2	55.3
	Mean	[a]24.7	[a]26.7	[a]17.6	[a]24.7	[a]20.7	[a]23.0	[a]18.1
	$S_e(1)$	10.9	11.5	8.5	10.9	9.7	10.3	8.8
Runoff Volume (ha-m)	½-in 1-hr CI ARC3	0.017	0.015	0.001	0.019	0.002	0.012	0.002
	1-in 4-hr CI ARC3	0.111	0.085	0.017	0.123	0.029	0.099	0.033
	1-in 1-hr CI ARC3	0.111	0.085	0.017	0.123	0.029	0.099	0.033
	1-yr 24-hr T2 ARC2	0.319	0.245	0.055	0.354	0.093	0.282	0.111
	1-yr 24-hr T2 ARC3	0.635	0.456	0.145	0.706	0.206	0.605	0.275
	10-yr 24-hr T2 ARC2	1.085	0.790	0.239	1.205	0.355	1.015	0.470
	Mean	[a]0.380	[a]0.279	[a]0.079	[a]0.422	[a]0.119	[a]0.352	[a]0.154
	$S_e(1)$	0.168	0.121	0.038	0.186	0.056	0.158	0.075
Qp_{in} (m^3/s)	½-in 1-hr CI ARC3	0.03	0.04	0.003	0.04	0.01	0.02	0.004
	1-in 4-hr CI ARC3	0.11	0.10	0.03	0.14	0.04	0.11	0.04
	1-in 1-hr CI ARC3	0.18	0.19	0.05	0.23	0.11	0.16	0.07
	1-yr 24-hr T2 ARC2	0.25	0.27	0.05	0.32	0.15	0.22	0.09
	1-yr 24-hr T2 ARC3	0.57	0.55	0.20	0.73	0.39	0.56	0.30
	10-yr 24-hr T2 ARC2	0.95	0.94	0.31	1.23	0.67	0.91	0.50
	Mean	[a]0.35	[a]0.35	[a]0.11	[a]0.45	[a]0.23	[a]0.33	[a]0.17
	$S_e(1)$	0.14	0.14	0.05	0.18	0.10	0.14	0.08
Qp_{out} (m^3/s)	½-in 1-hr CI ARC3	0.026	0.005	0.002	0.004	0.0002	0.010	0.0001
	1-in 4-hr CI ARC3	0.11	0.02	0.02	0.03	0.002	0.07	0.003
	1-in 1-hr CI ARC3	0.17	0.03	0.04	0.03	0.002	0.08	0.003
	1-yr 24-hr T2 ARC2	0.24	0.03	0.04	0.06	0.007	0.13	0.02
	1-yr 24-hr T2 ARC3	0.54	0.22	0.17	0.17	0.019	0.37	0.12
	10-yr 24-hr T2 ARC2	0.91	0.61	0.28	0.36	0.037	0.66	0.24
	Mean	[a]0.33	[a]0.15	[a]0.09	[a]0.11	[a]0.011	[a]0.22	[a]0.06
	$S_e(1)$	0.14	0.10	0.05	0.06	0.006	0.10	0.04
RWW		0.09	0.04	0.03	0.34	0.24	0.14	0.25

next greatest values of HRT were for sites SPF and GLP, which were not significantly different from each other. The lowest values of HRT were for sites CON, GPT, and STS, with mean NHRT values that were less than even some of the lowest reported values for constructed wetlands of 2.4 h (Arheimer and Wittgren 2002) and 11 h (Maynard et al. 2009). Values of NHRT for the other sites in this study were within the ranges reported in studies of constructed wetlands (Arheimer and Wittgren 2002; Tuncsiper 2007), but less than some reported values, including values of 7 d (Coveney et al. 2002) and 12 d (Tuncsiper 2007). In a more comparable study that looked at a constructed wetland subject to flood events, Reinhardt et al. (2005) calculated theoretical residence times of 0.9 to 50 d within the same wetland.

The results illustrate, to a certain extent, the effects of outlet structure design on HRT. Three sites (GLP, STN, WDF) were designed with two-stage outlets, consisting of a riser and outlet pipe (i.e., water control structure) as the *primary spillway* and a broad-crested earthen weir as the *emergency spillway*. Four sites (CON, GPT, SPF, STS) were designed with single-stage outlets, using broad-crested earthen weirs or natural topography that functioned similarly to broad-crested weirs. Three of the four sites with greatest values of HRT had two-stage outlets, and the two sites (STN and WDF) with the largest values of HRT had two-stage outlets. In contrast, the three sites (CON, GPT, STS) with the smallest values of HRT had one-stage outlets.

In the two-stage design, the primary spillway was set at an elevation below that of the emergency spillway. With this design, some runoff events resulted in flow through only the primary spillway, as illustrated in Figure 7a, while larger storm events resulted in flow through both spillways, as illustrated in Figure 7b. If a storm is large enough to result in flow through both the primary and emergency spillways, the rate of release will increase, and typically result in a decrease in HRT. In the single-stage design, the riser structure was either absent or set at an elevation above the broad-crested weir, and the broad-crested weir functioned as both the primary and emergency spillways. As a result, flow from all storm events occurred through only a broad-crested weir. Because the capacity of the broad-crested weir was large compared to that of the riser structure, inflow to the site was released at a greater rate, and the values of HRT tended to be smaller.

Inherent in the design of the wetland is the influence of the stage-storage-discharge relationship. Inflow to a wetland (i.e., runoff) must be accommodated by outflow and/or storage. If the outlet capacity is designed for large storm events (e.g., the 10-yr 24-hr ARC2 design storm), then a greater portion of inflow will be accommodated by outflow rather than storage capacity. If the outlet capacity is small, storage will accommodate a greater portion of inflow, to the extent that storage volume is available. As long as the storage volume can accommodate the runoff volume, MHRT will increase with greater runoff. As runoff volume becomes greater than that which can be accommodated by storage volume, the increased runoff will be accommodated by the flow capacity of the outlet, and the MHRT will decrease.

This relationship is shown in Figure 9a, which shows the rating curves for discharge and storage, and the storm runoff volume and MHRT for site GLP, a site with a two-stage outlet. The rating curves represent the capacity of the site to store and discharge runoff. The runoff volume and MHRT are calculated values, and are ordered from left to right by increasing runoff volume. The water control structure (WCS) capacity was relatively small. At the stage of the emergency spillway, the WCS could only carry 0.034 m^3/s, which is about the same as the Qp_{in} for the ½-in 1-hr ARC3 design storm (0.04 m^3/s). For this design storm (Figure 9a, first marker on left), the runoff volume and storage volume were nearly equal, but for the next two storms, the runoff volume was greater than the storage volume. As a result, the MHRT was greater for the first storm than for the second two storms. For the fourth storm, the outlet capacity remained small, because the stage had not yet attained the stage of the emergency spillway, and outflow was constrained by the WCS. However, from the third to fourth storm event, the storage rating curve increased. Since the outlet capacity was small relative to the storage volume, the greater runoff volume for this storm was accommodated more by the storage volume, and subsequently, MHRT increased. At the fifth storm event, the runoff flow and volume were great enough to exceed the storm stage of the emergency spillway (as shown by the vertical line). Once outflow occurred through the emergency spillway, the discharge rating curve increased sharply and became more accommodating of the runoff volume than the storage volume. Subsequently, a reduction in MHRT from the fourth to fifth storm was seen. The same pattern existed for the sixth and largest storm event, at which the increased runoff volume was accommodated more by the outlet capacity than the storage volume, and resulted in an even smaller MHRT.

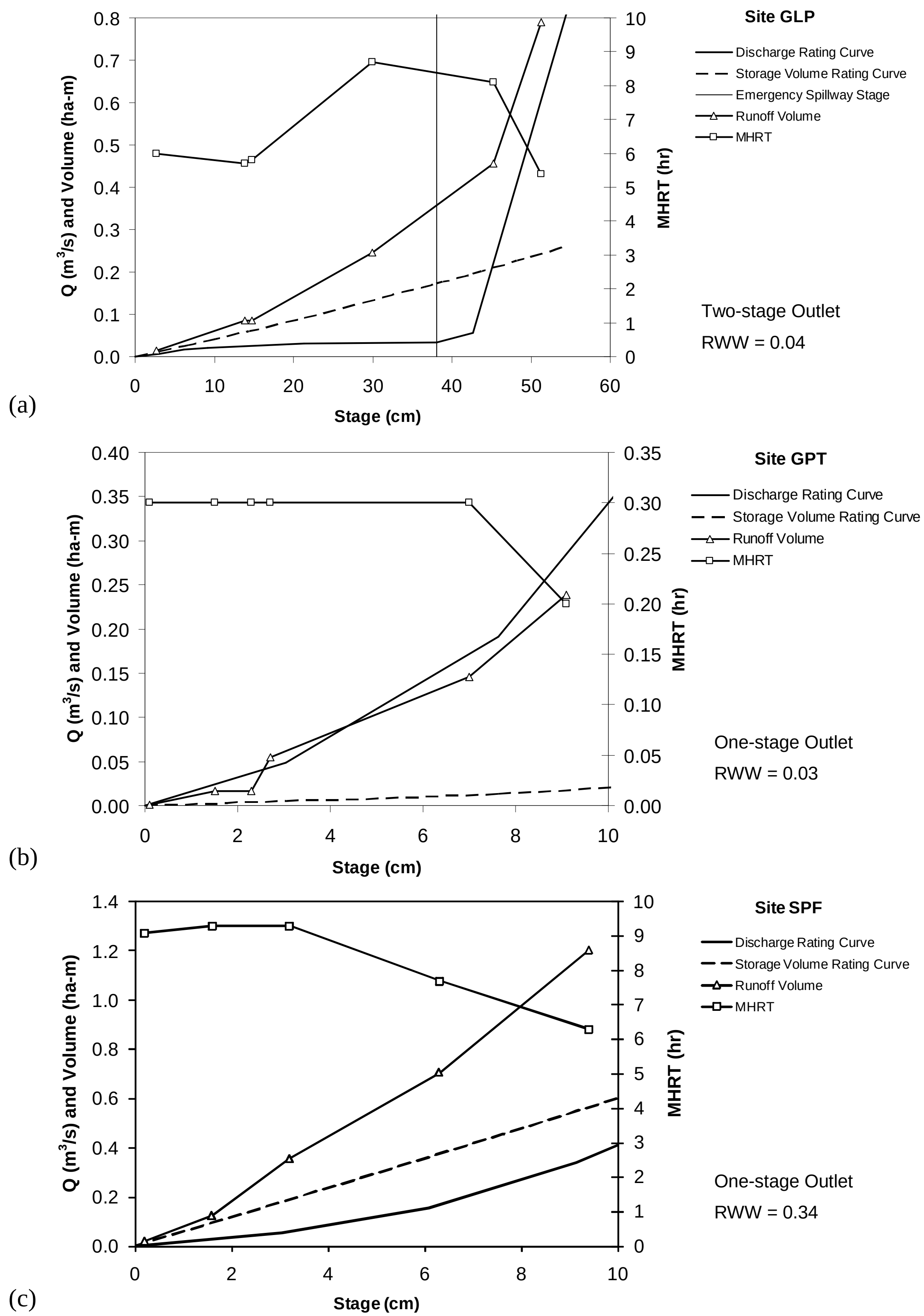


Figure 9. Stage-storage-discharge relationships for sites GLP, GPT, and SPF, with overlays of storm event runoff volume and MHRT. Markers represent storm events, in order from left to right of increasing storm runoff volume. MHRT increases as the runoff volume is more closely aligned to the stage-storage relationship, but decreases as runoff volume becomes more aligned with the stage-discharge relationship. Plots for all sites are in Appendix G.

In contrast to site GLP, sites with a one-stage outlet tended to show less variability in both MHRT and NHRT over the range of storm events. This can be seen in the stage-storage-discharge relationship plot for site GPT (Figure 9b), in which the discharge rating curve more closely followed the runoff volume curve. Because the increase in flow with each storm event was accommodated by the increase in the outlet capacity, the MHRT remained essentially constant. Adding to the influence of the outlet capacity on MHRT was the relatively small storage volume. Consistency in HRT, however, came at a cost of low values of HRT for three out of the four sites with single-stage outlets. These three sites (CON, GPT, and STS) had the least variation in HRT across storms, and the lowest values of HRT for all sites ($\bar{x}$(MHRT) $\leq$ 1.3 hr; $\bar{x}$(NHRT) $\leq$ 5.2 hr).

Although outlet design was a significant factor in HRT, other factors can produce significant effects on values of HRT. For example, values of HRT for sites GLP and SPF were similar, even though site GLP had a two stage-outlet and site SPF had a one-stage outlet. These two sites had similarly sized watersheds, but site SPF had a much greater RWW than site GLP. The RWW for site SPF exceeded the next greatest value for a site by 36 percent (Table 3), and exceeded the RWW for site GLP by 750 percent. The effect of a large RWW is that the wetland storage is large relative to the size of the watershed. This can be seen in the stage-storage-discharge relationship (Figure 9c) for site SPF, in which the storage rating curve remained above the discharge rating curve for all storm events. Thus, the large storage volume allowed site SPF to have values of HRT similar to that of site GLP, and significantly greater ($p \leq 0.05$) than those for other sites with one-stage outlets.

Values of HRT at site GLP were controlled, to a large extent, by the type and size of the outlet, while values of HRT at site SPF were controlled by the RWW. If the criteria for site design was to optimize HRT and minimize the amount of land area occupied by the wetland (i.e., RWW), then site SPF had a much less efficient design than site GLP. Use of a WCS at site SPF could have allowed for similar values of HRT with a much smaller RWW. However, the 10-yr 24-hr ARC2 design storm stage for site GLP was significantly greater than for site SPF (51.3 cm vs. 9.4 cm), and subsequently, site GLP would have required construction of a taller berm. This demonstrates the need to weigh design factors based upon multiple efficiencies, such as land area and berm heights.

Relationship between MHRT, NHRT, and RWW

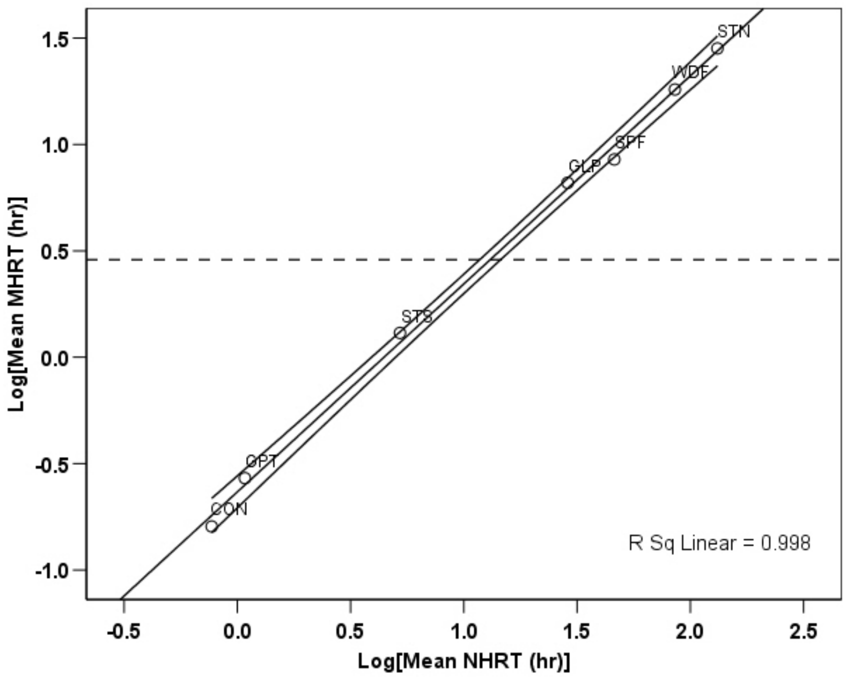
As seen in Table 4, correlations between MHRT and NHRT were very significant ($p < 0.003$) for all storm events. Correlation between the means of all storms for each site were very significant at $p < 0.001$. Regression of the log-transformed values of mean MHRT and mean NHRT explained 99.8 percent of the variability in predicting mean MHRT (Figure 10 and Appendix I). The high correlation between MHRT and NHRT was expected because both were derived from the same data. Because of the high correlation, MHRT, which is a more precise estimate of HRT, could accurately be predicted from NHRT, which is easier to calculate. However, it is important to recognize that for individual sites, values of NHRT were significantly greater than MHRT (paired samples test, 2-tailed $p \leq 0.003$) for all comparisons (Table 3). This suggests that NHRT, which is often used in wetland studies, is likely to provide an overestimate of the "true" HRT when flow is highly variable, as is the case with storm-driven hydrology. In these cases, it would be preferable to use MHRT as the indicator of HRT. The greater precision of MHRT would also make it more useful for relation to studies involving mass balance analyses.

Correlations between both MHRT and NHRT and RWW were similar. However, the correlations between MHRT and RWW were significant ($p \leq 0.05$) for only four out of the six design storms, while correlations between NHRT and RWW were significant ($p \leq 0.05$) for all storm events. The better consistency in correlations between NHRT and RWW is expected because NHRT is calculated as a nominal average value based on a single duration (i.e., outflow duration), and consequently, is less sensitive to time than MHRT, which is calculated as a weighted average based on many relatively small, discrete time increments.

Table 4. Spearman's rho correlation coefficients (R) for MHRT and NHRT, and RWW and both MHRT and NHRT for six design storms. Significance level (p) of correlations (1-tailed) is also shown. Storm means are the mean HRT's for all storms for each site.

		½-in 1-hr ARC3	1-in 4-hr ARC3	1-in 1-hr ARC3	1-yr 24-hr ARC2	1-yr 24-hr ARC3	10-yr 24-hr ARC2	Storm Means
MHRT and NHRT	R	**1.000	**1.000	**1.000	**1.000	**0.893	**0.893	**1.000
	p	<0.001	<0.001	<0.001	<0.001	0.003	0.003	<.001
MHRT and RWW	R	*0.679	*0.679	*0.679	*0.679	0.357	0.571	
	p	0.047	0.047	0.047	0.047	0.216	0.090	
NHRT and RWW	R	*0.679	*0.679	*0.679	*0.679	*0.679	*0.679	
	p	0.047	0.047	0.047	0.047	0.047	0.047	

* Correlation significant at the 0.05 level (1-tailed).
** Correlation significant at the 0.01 level (1-tailed).

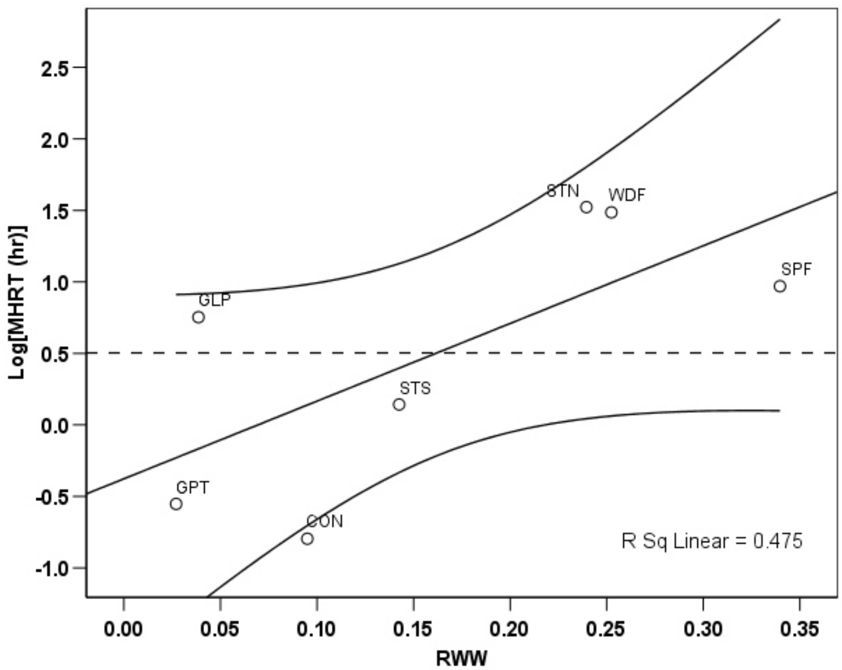


R^2 = 0.998 (good)
S_e/S_y = 0.052 (good)
$Se(b_0)/b_0$ = 0.046 (good)
$Se(b_1)/b_1$ = 0.021 (good)

Figure 10. Scatter plot and linear regression for log-transformed MHRT versus log-transformed NHRT for the means of design storms for each site. The horizontal dashed line represents the mean. Upper and lower 95% confidence intervals on the mean of the line are also shown. Criteria for qualitative assessment (shown in parentheses) of GOF statistics are in Appendix I.

While correlations between RWW and MHRT and RWW and NHRT were mostly significant ($p \leq 0.05$ for 10 out of 12 correlations), linear regression analysis of the log-transformed MHRT for the 1-in 4-hr design storm versus RWW (Figure 11) displayed relatively poor explanation of the variance ($R^2 = 0.475$), and the S_e/S_y of 0.793 suggests a poor improvement of the estimate with regression over use of the mean. (See Appendix I for full regression statistics.) The scatter plot in Figure 11 shows that sites with one-stage outlets fall below the regression line, while sites with two-stage outlets are all above the regression line. The scatter plot also shows that the two sites with the most similar values of MHRT, one of which had a single-stage outlet (SPF) and one of which had a two-stage outlet (GLP), had the second-greatest difference in RWW. These results suggest that

RWW may be insufficient as an indicator of HRT, for which it is sometimes used (Jordan et al. 2003), because it does not account for variability in outlet design.



R^2 = 0.475 (fair)
S_e/S_y = 0.793 (poor)
$S_e(b_0)/b_0$ = 1.324 (poor)
$S_e(b_1)/b_1$ = 0.470 (fair)

Figure 11. Scatter plot and linear regression for the log-transformed MHRT of the 1-in 4-hr ARC3 design storm versus RWW. The horizontal dashed line represents the mean for all sites. Upper and lower 95% confidence intervals on the mean of the line are also shown. Criteria for qualitative assessment (shown in parentheses) of GOF statistics are in Appendix I.

BIOMASS AND NUTRIENT ANALYSIS

Values of mean standing above-ground biomass (AB) for the study sites (range of 395 – 1,117 g/m^2) were generally greater than the approximate range of 200 to 450 g/m^2 reported by Whigham et al. (2002) and the range of 200 to 570 g/m^2 reported by Hoagland et al. (2001), but similar to the range (330 – 1,160 g/m^2) found in emergent wetlands in the prairie pothole region by van der Valk and Davis (1978). Three out of the four sites with the highest mean AB were dominated by one species in four or more plots: Site CON was dominated by *P. australis* in 4 plots; site GPT was dominated by *Typha* spp. in 5 plots; and site STN was dominated by *J. effusus* in 5 plots. Sites STN and GPT had the highest and second-highest AB values, respectively. The dominant and common plant species found at each site are presented in Table 5.

Table 5. General characterization of wetland vegetation at each site. Plant characterization was focused on identifying plots that were dominated by the clonal species *Typha* spp. and *Phragmites australis*.

Site	**Species**
CON	*Phragmites australis* dominant in 4 out of 10 plots; remainder of site composed of low-growing grasses and *polygonum* spp.
GLP	Predominant vegetation was *Polygonum* spp., *Juncus effusus*, *Scirpus americanus*
GPT	*Typha* spp. dominant in 5 out of 10 plots; *Scirpus americanus* was other dominant
SPF	*Echinochloa crus-galli, Echinochloa esculenta*, *Panicum dichotomiflorum*, sedge spp., *Polygonum* spp.
STN	*Juncus effusus* dominant at 5 out of 10 plots; other dominants were *Sparganium americanum, Leersia oryzoides, Polygonum* spp., *Bidens* spp.
STS	*Echinochloa crus-galli, Echinochloa esculenta*, sedge spp., *Polygonum* spp.
WDF	*Typha* spp. dominant at one plot; other common species were *Bidens* spp., *Xanthium strumarium, Polygonum* spp., *Echinochloa crus-galli*

Concentrations of N and P in AB were within the range for temporary and emergent wetland zones reported by Whigham et al. (2002) of approximately 0.75 to 1.45 % N and 0.14 to 0.24 % P. Both % N and % P in this study (ranges of 0.54 – 0.93 % N and 0.07 – 0.18 % P; also see Table 6) were towards the lower end of these (Whigham et al. 2002) ranges, and were generally within the approximate ranges for the temporary zone (0.75 - 1.20 for % N and 0.14 - 0.18 for % P). As defined by Whigham et al. (2002), the temporary zone was the area of the wetland that was usually flooded only during the non-growing season, and the emergent zone was the area between the temporary zone and the area that was usually permanently flooded. Although plots in my study were dominated by emergent wetland plants, drought conditions during the growing season prior to sampling may have resulted in conditions more similar to the temporary zone as defined in Whigham et al. (2000). Whigham et al. (2002) is a good study for comparison because the wetlands were located in the same region of the MES, and biomass and tissue samples were taken in autumn (mid to late October), about the same time as they were for this study. However, because AB in this study was generally higher (range of 395.4 – 1,116.5 g/m^2) than that reported in Whigham et al. (2002), ranges of both TN and TP were higher in this study. Comparisons between the studies of the ranges of all measured variables are in Figure 12.

Both TN and TP were significantly different ($p \leq 0.05$) between STN and all other sites, but not significantly different between the other six sites. The difference in TN and TP between STN and other sites was likely at least partially related to the high biomass production at site STN, since there was no significant difference in concentrations of N and P between site STN and other sites. Only sites GPT and SPF differed significantly in N:P ratio, but all sites had N:P ratios well below 14:1, which suggests N-limiting conditions in emergent wetland vegetation (Koerselman and Meuleman 1996).

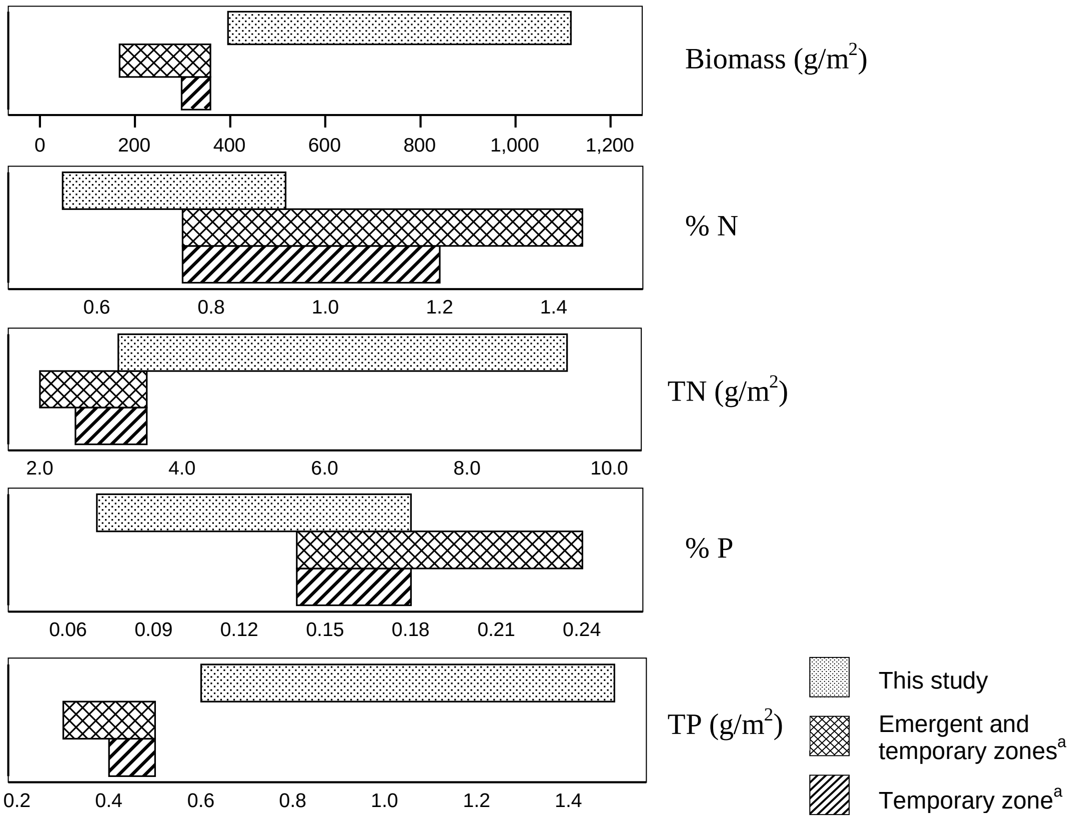


Figure 12. Ranges of measured variables for this study compared to ranges for the same variables reported in Whigham et al. (2002)[a]. Ranges for % N and % P for both studies overlap, but biomass, TN, and TP values are generally greater than for the study by Whigham et al.

Table 6. Means and comparisons of biomass, nutrient concentrations, and nutrient standing stocks. Superscripts are used to show comparisons between sites. Means with similar superscripts are not significantly different at $p \leq 0.05$. SE(1) is one standard error and N is the number of samples.

		CON	GLP	GPT	SPF	STN	STS	WDF	All
Biomass (g/m^2)	Mean	^{a}641.1	^{a}395.4	^{ab}811.1	^{a}582.5	^{b}1116.5	^{a}423.4	^{ab}666.7	662.4
	SE(1)	96.4	106.8	135.2	77.9	152.0	65.5	73.3	46.9
	N	10	10	10	10	10	10	10	70
% N	Mean	^{ab}0.72	^{b}0.93	^{a}0.54	^{ab}0.70	^{ab}0.83	^{b}0.93	^{ab}0.68	0.76
	SE(1)	0.02	0.10	0.04	0.14	0.07	0.09	0.03	0.03
	N	8	10	10	10	10	10	10	68
TN (g/m^2)	Mean	^{a}4.66	^{a}3.13	^{a}4.06	^{a}3.33	^{b}9.44	^{a}3.82	^{a}4.49	4.70
	SE(1)	0.92	0.66	0.60	0.28	1.69	0.61	0.50	0.40
	N	8	10	10	10	10	10	10	68
% P	Mean	^{abc}0.12	^{bc}0.17	^{a}0.07	^{bc}0.17	^{abc}0.14	^{c}0.18	^{ab}0.12	0.14
	SE(1)	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.01
	N	10	10	10	10	10	10	10	70
TP (g/m^2)	Mean	^{a}0.74	^{a}0.60	^{a}0.57	^{a}0.89	^{b}1.49	^{a}0.72	^{a}0.76	0.82
	SE(1)	0.06	0.14	0.10	0.12	0.19	0.11	0.08	0.06
	N	10	10	10	10	10	10	10	70
% C	Mean	^{ab}44.45	^{a}41.10	^{b}46.97	^{b}45.80	^{b}46.18	^{ab}43.62	^{b}45.20	44.77
	SE(1)	0.85	1.72	0.43	0.25	0.62	0.89	0.24	0.38
	N	8	10	10	10	10	10	10	68
TC (g/m^2)	Mean	^{a}286.82	^{a}174.12	^{ab}384.94	^{a}267.87	^{b}512.99	^{a}189.37	^{ab}302.52	303.13
	SE(1)	54.70	51.51	65.97	36.50	69.26	32.53	34.38	22.80
	N	8	10	10	10	10	10	10	68
C:N	Mean	^{ab}61.95	^{a}50.04	^{c}91.82	^{bc}86.03	^{ab}59.92	^{ab}49.71	^{abc}68.28	66.96
	SE(1)	2.05	6.40	6.78	12.50	5.68	3.55	3.07	3.09
	N	8	10	10	10	10	10	10	68
C:P	Mean	^{a}375.68	^{a}266.89	^{b}709.94	^{a}315.55	^{a}343.16	^{a}272.94	^{a}401.79	383.94
	SE(1)	35.72	31.55	80.73	35.61	15.55	33.21	29.64	23.20
	N	8	10	10	10	10	10	10	68
N:P	Mean	^{ab}6.11	^{ab}5.54	^{b}7.66	^{a}4.25	^{ab}6.09	^{ab}5.70	^{ab}5.93	5.89
	SE(1)	0.63	0.43	0.55	0.66	0.50	0.76	0.41	0.24
	N	8	10	10	10	10	10	10	68

RELATIONSHIP BETWEEN HRT AND PLANT BIOMASS AND NUTRIENTS

Relationship Based on ANOVA Results

Site STN was shown to have significantly higher mean biomass than all but two other sites, and significantly higher TN and TP than all other sites (Table 6). As previously mentioned, the values of MHRT and NHRT for site STN were significantly greater ($p \leq 0.05$) than other sites. For example, the mean MHRT for all design storms for site STN was 28.3 hr, or 1.2 d, and the mean NHRT for all design storms for site STN was 131.7 hr, or 5.5 d. The mean MHRT's for all other sites were less than 1 d, ranging from 0.2 to 18.1 hr, while the mean NHRT's for all other sites ranged from 0.8 to 85.4 hr (3.6 d). Assuming that HRT does have a positive effect on plant biomass and nutrient stocks, then the higher HRT for site STN compared to all other sites would be expected.

The fact that the high TN and TP at site STN is a function of biomass does not diminish the significance of the relationship between HRT and TN and TP. Greater HRT would likely result in greater plant biomass production, especially in the sampling year, in which a severe drought affected the entire region during the growing season. A site with greater HRT would be able to store relatively more storm runoff, providing more water and nutrients for plant growth, and ultimately more retention of nutrients. Retention of storm runoff would be even more important in a year when water may have been a limited resource, even in wetlands. The relationship between high HRT and P retention is supported by Mitsch (1992), in which TP in AB in wetlands was found to be similar to net retention of P as measured in experimental wetlands using a mass balance approach, and that wetlands with longer residence times retained more P than those with shorter residence times (83 – 96% versus 63 – 68% P). Research conducted by Silvan et al. (2004) supports the relationship between high nutrient availability and greater biomass. Silvan et al. found that when nutrients were added to wetland vegetation, there was an increase in biomass rather than an increase in the concentration of nutrients in the plant tissue. Herr-Turoff and Zedler (2005) also found that high-N treatment of wetland plants resulted in an increase in AB of greater than 90 %.

Correlation Analyses

The only significant correlations between measured values and HRT were between TP and both MHRT and NHRT at $p < 0.05$ for all but the MHRT's for the 1-yr 24-hr ARC3 and 10-yr 24-hr ARC2 design storms (Table 7). In contrast, correlations between HRT and both biomass and TN were not statistically significant ($p \leq 0.05$) for any of the design storms. Total P was also the only measured variable that was significantly correlated ($p = 0.007$) with RWW (Table 8). These results suggest that P retention is more significantly a function of HRT than TN for storm-driven hydraulic loadings. One likely explanation for this is the relationship between the preferential flow paths of P and N and the hydrology of the studied wetlands. Transport of P from agricultural watersheds is more often linked to overland flow, while N transport has a significant linkage with subsurface flow (Royer et al. 2006; Domagalski et al. 2008; Sharpley et al. 2008). The wetlands in this study are fed primarily by surface runoff, as suggested by their relatively small size, fine soil textures (silt loam), and designs (i.e. berms and ditch plugs), which impede the movement of surface water. So it may be that these wetlands received relatively greater P loadings than N loadings, and were therefore, N-limited for biomass production. The results also suggest that although RWW may provide a good indication of P retention, it explains nothing about N retention.

Table 7. Spearman's rho correlation coefficients (R) for measured variables (biomass, TN and TP) and MHRT and NHRT for six design storms. Significance level (p) of correlations (1-tailed) is also shown.

Design Storm		1/2-in 1-hr ARC3	1-in 4-hr ARC3	1-in 1-hr ARC3	1-yr 24-hr ARC2	1-yr 24-hr ARC3	10-yr 24-hr ARC2
MHRT							
Biomass	R	0.286	0.286	0.286	0.286	0.071	0.071
	p	0.267	0.267	0.267	0.267	0.440	0.440
TN	R	0.143	0.143	0.143	0.143	-0.036	-0.107
	p	0.380	0.380	0.380	0.380	0.470	0.410
TP	R	*0.714	*0.714	*0.714	*0.714	0.464	0.643
	p	0.036	0.036	0.036	0.036	0.147	0.060
NHRT							
Biomass	R	0.286	0.286	0.286	0.286	0.286	0.286
	p	0.267	0.267	0.267	0.267	0.267	0.267
TN	R	0.143	0.143	0.143	0.143	0.143	0.143
	p	0.380	0.380	0.380	0.380	0.380	0.380
TP	R	*0.714	*0.714	*0.714	*0.714	*0.714	*0.714
	p	0.036	0.036	0.036	0.036	0.036	0.036

* Correlation is significant at the 0.05 level (1-tailed).

Table 8. Spearman's rho correlation coefficients (R) for measured variables (biomass, TN and TP) and RWW. For n = 6, site STN was excluded. Significance level (p) of correlations (1-tailed) is also shown.

			Biomass	TN	TP
RWW	n=7	R	0.071	0.107	**0.857
		p	0.440	0.410	0.007
	n=6	R	-0.143	-0.029	**0.943
		p	0.394	0.479	0.002

** Correlation is significant at the 0.01 level (1-tailed).

The more significant relationship between TP and HRT may also have been due to the difference in transport mechanisms between N and P. Nitrogen is most often transported in solution, while P can be transported either in solution or as particulates attached to suspended sediment. Reinhardt et al. (2005) determined that when P-loading was mainly driven by short-term flood events, corresponding with water residence times of less than 3 d, TP retention was primarily due to settling of particulate P (PP) attached to soil particles. In contrast, Reinhardt et al. (2005) found that dissolved reactive P (DRP) was not retained during short-term flood events. The DRP was being converted to PP in the form of phytoplankton, but the phytoplankton was not able to settle and be retained because of the low residence times. Even with greater HRT, TP removal may be mostly in the form of PP, as suggested by Coveney et al. (2002), who found this to be the case in wetlands with a mean HRT of 7 d. The significant correlations between HRT and TP in this study, are therefore, a likely indication that the wetlands were retaining soil-attached P, but were inefficient at retaining dissolved nutrients because of the short residence times (< 2 d for all sites). It is also possible, however, that these watersheds may not have had much DRP available because of limited use of land application of animal waste.

The difference in nutrient removal pathways between N and P, and the relation of nutrient retention to plant uptake in this study were also likely responsible for the difference in correlations between TN and TP with HRT. Plant uptake only accounts for nutrients that remain in the wetland. Whereas both N and P can be removed from surface waters in dissolved or solid forms, via sediment storage, assimilation, or surface discharge, only N can be removed as a gas, via denitrification or volatilization. Because denitrification is considered a major pathway for N removal in wetlands (Johnston 1991), it would likely have reduced the amount of N available for plant uptake.

Correlation significance between both TN and TP and HRT was relatively consistent across design storms (TN vs. HRT: $p = 0.380$ for 10 out of 12 cases; TP vs. HRT: $p = 0.036$ for 10 out of 12 cases). The less significant correlations were between both TN and TP and MHRT for the 1-yr 24-hr ARC3 and 10-yr 24-hr ARC2 design storms, the two storms with the greatest runoff. This is consistent with most studies, which indicate that net retention of N and P in wetlands will be less in the case of higher flows (Mitsch 1992; Raisin and Mitchell 1995; Spieles and Mitsch 2000; Fisher and Acreman 2004). However, the overall consistency in correlations across design storms could be related to greater nutrient loading during storm events (Crumpton 2001; Reinhardt et al. 2005; Sharpley et al. 2008), which could offset the lower nutrient retention during higher flows.

Regression Analyses

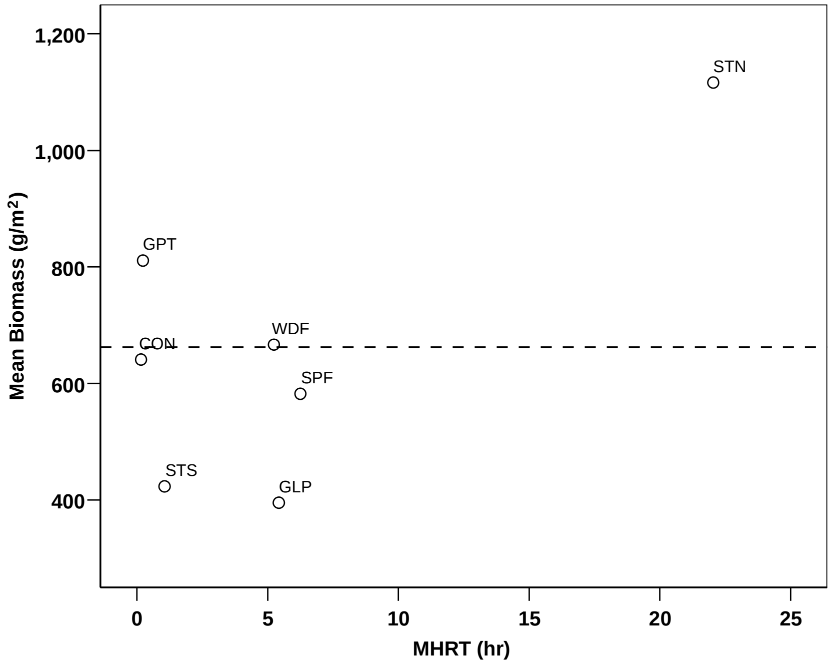
The scatter plots shown in Figure 13 display the importance of site STN on the correlations with measured variables and HRT. Modeled values (i.e., MHRT and NHRT) for site STN were significantly ($p \leq 0.05$) greater than other sites. Any analysis including site STN and using non-transformed values would effectively be based upon two points – one for STN and the cluster of points for other sites. However, the log-transformed values resulted in less of an outlier effect, as can be seen in the scatter plots of Figure 14. Therefore, regression analyses that included site STN were conducted with the log-transformed values of measured variables and HRT. Because correlations between both biomass and TN and values of HRT were relatively poor, regression analyses were only conducted on TP. Total P was linearly regressed on both MHRT ($R = 0.653$, $p = 0.056$) and NHRT ($R = 0.683$, $p = 0.045$) for the 10-yr 24-hr ARC2 design storm. Total P was also regressed against RWW for n = 7 and n = 6, because of the significance of the correlations (n = 7, $R = 0.666$, $p = 0.051$; n = 6, $R = 0.931$, $p = 0.003$). Graphical representations and goodness-of-fit (GOF) statistics of the regression analyses are shown in Figures 14 and 15 (additional GOF statistics and criteria for qualitative assessment are in Appendix J).

The regression of TP on MHRT and NHRT explained 43 and 47 percent, respectively, of the variation in TP. A t-test on the slope coefficient suggested that it was not significantly ($\alpha = 0.05$) different from zero for MHRT ($p = 0.115$) or NHRT ($p = 0.095$). Goodness-of-fit (GOF) statistics for TP versus MHRT ($S_e/S_y = 0.835$ and Figure 14a) and NHRT ($S_e/S_y = 0.806$ and Figure 14b) were fair to poor, and residuals were normally distributed based on the probability plot (Appendix J). Although the linear regression model explained some of the variation, consideration of other factors would likely improve the accuracy. Residuals showed a pattern with respect to TP (Appendix J), which suggests that a linear model structure may not be appropriate. The number of data points (n = 7) combined with the outlier effect of site STN did not allow for multiple regression analyses, because with few degrees of freedom ($df \leq 5$), almost any variation renders the analysis insignificant . However, Figure 13c is somewhat suggestive of the hypothesized model structure discussed in Chapter 1 and shown in Figure 4. In Figure 13c, the hypothesized first inflection point occurs at about 7 hr. This would be the point where the HRT became great enough to display a significant increase in retention of TP. Because site STN had both significantly greater HRT and TP than other sites, the trajectory of the line after the first inflection point is toward the point for site STN. The second inflection point in the hypothesized relationship, which occurs when increased HRT begins to show less of an effect on nutrient retention, is not shown by this data set. How far beyond the site STN data point the line trajectory would continue cannot be determined. However, studies of P removal in surface flow wetlands suggest the inflection point may occur at an HRT of 6 to 7 d. Reinhardt et al. (2005) reported a minimum HRT of 7 d for 50 percent NPSP P retention, while Coveney et al. (2002) reported a mass removal efficiency for TP of 30 to 67 percent in surface flow wetlands with a mean HRT of about 7 d. Tuncsiper (2007) reported peak removal efficiency of TP at an HRT of 6 d in constructed wetlands for tertiary treatment of wastewater. These studies suggest that the second inflection point would occur far beyond that of the site STN data point.

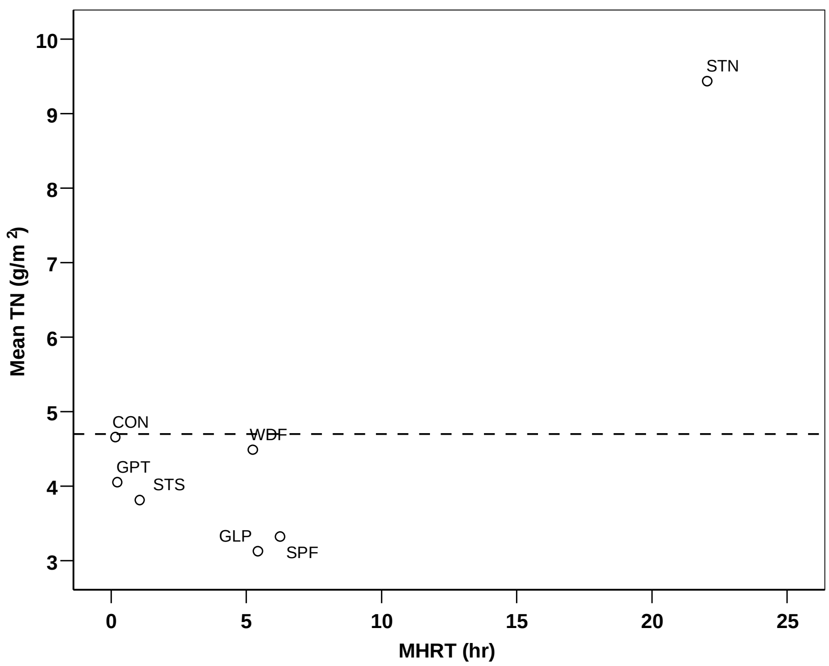
Linear regression of TP on RWW explained 44 percent of the variation. A t-test on the slope coefficient suggested that it was not significantly ($\alpha = 0.05$) different from zero ($p = 0.103$). Goodness-of-fit statistics for TP versus RWW ($S_e/S_y = 0.820$ and Figure 15a) with all sites included ($n = 7$) were fair to poor, suggesting little improvement of the estimate over use of the mean. When site STN was excluded ($n = 6$), linear regression on RWW explained 87 percent of the variation in TP, and the slope coefficient was significantly different from zero ($p = 0.008$). GOF statistics ($S_e/S_y = 0.407$ and Figure 15b) and residuals (Appendix J) indicated that RWW may be a good predictor of TP.

However, the Dixon-Thompson outlier test (Davis and McCuen 2005) was inconclusive as to whether TP at site STN was an outlier ($R > R_c(\alpha=0.05)$, $R < R_c(\alpha=0.01)$, Appendix M). Hence, this model would require data collection and analysis at additional sites to determine if site STN could accurately be considered an outlier, and subsequently, whether the model is statistically valid.

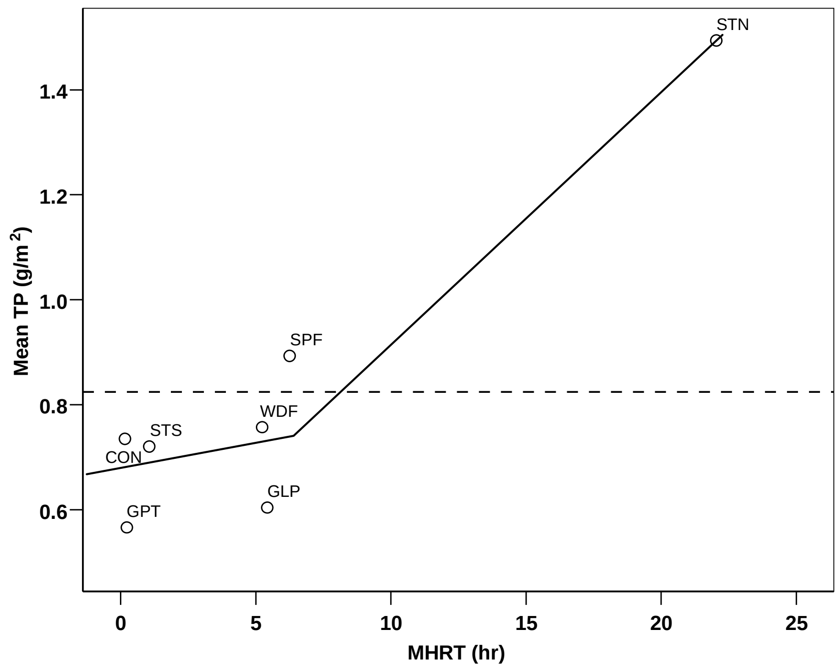
The inclusion of site STN in regression analyses of TP on all three indicators of HRT (Figures 14a, 14b, 15a) resulted in unreliable models. Additional data could improve the linear model, or indicate the need for a different model structure, which perhaps, would be similar to the one hypothesized in this study (Figure 13c). If the latter was the case, then regression models of TP on indicators of HRT, excluding site STN, would be representative of the first segment of the hypothesized model. To evaluate this, TP was linearly regressed on MHRT and NHRT, excluding site STN (Figures 16a and 16b). Both models (MHRT: $R^2 = 0.200$, $S_e/S_y = 1.000$; NHRT: $R^2 = 0.322$, $S_e/S_y = 0.923$), however, provided relatively little explanation of the variation in TP, and were unreliable, suggesting little improvement over use of the mean. Student t-tests on the slope coefficients suggested both regression lines were not significantly different from zero ($p > 0.200$ for both MHRT and NHRT). Therefore, the first segment of the hypothesized model may best be represented by a line with zero slope. Speculation of the other segments of the hypothesized model could not be made without collection of additional data.


Mean Biomass (g/m²)
1,200
1,000
800
600
400
STN
GPT
CON
WDF
SPF
STS
GLP
0
5
10
15
20
25
MHRT (hr)

(a)


Mean TN (g/m 2)
10
9
8
7
6
5
4
3
STN
CON
WDF
GPT
STS
GLP
SPF
0
5
10
15
20
25
MHRT (hr)

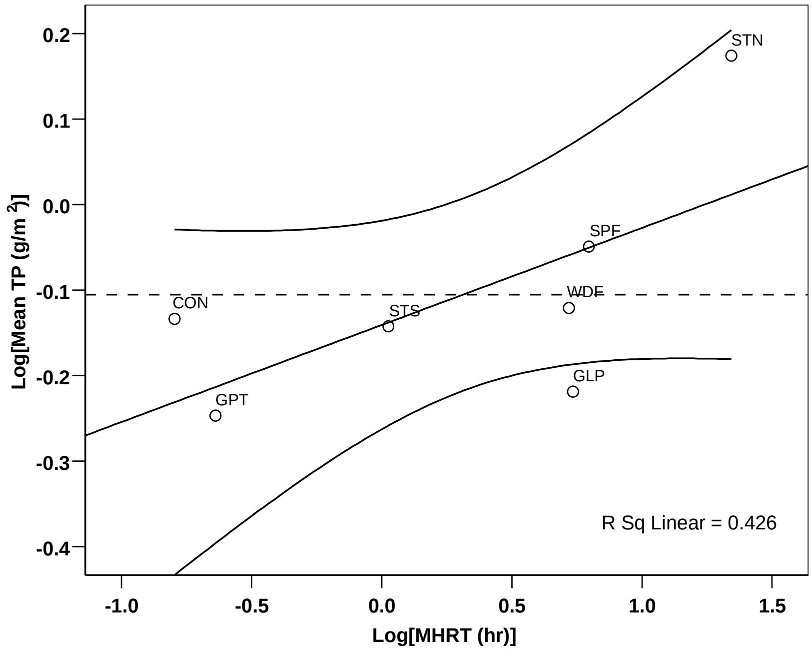
(b)



(c)

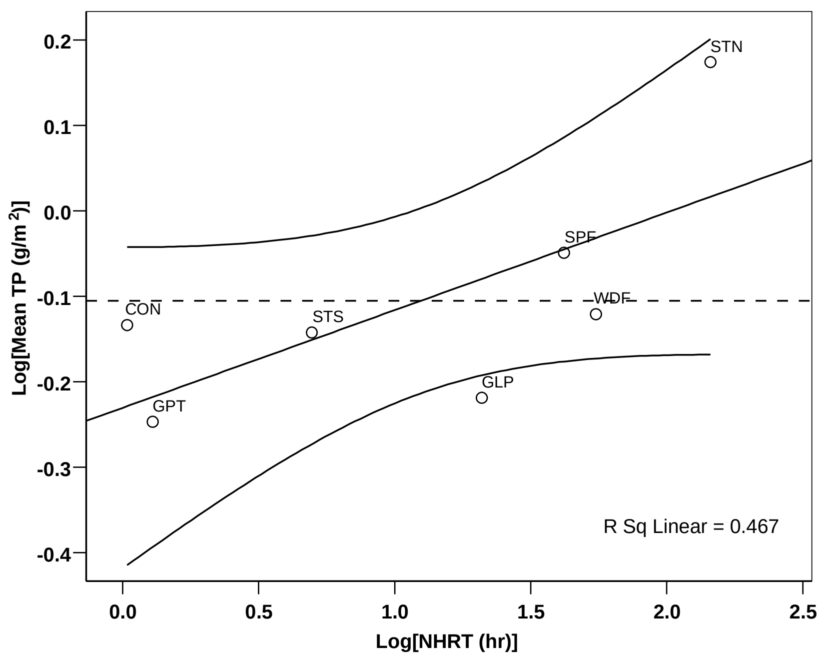
Figure 13. Scatter plots for biomass (a), TN (b), and TP (c) versus MHRT for the 10-yr 24-hr ARC2 design storm. The horizontal dashed line represents the mean for all sites. The solid line in (c) was drawn (not fitted) to show the similarity with the hypothesized relationship displayed in Figure 4.

(a)



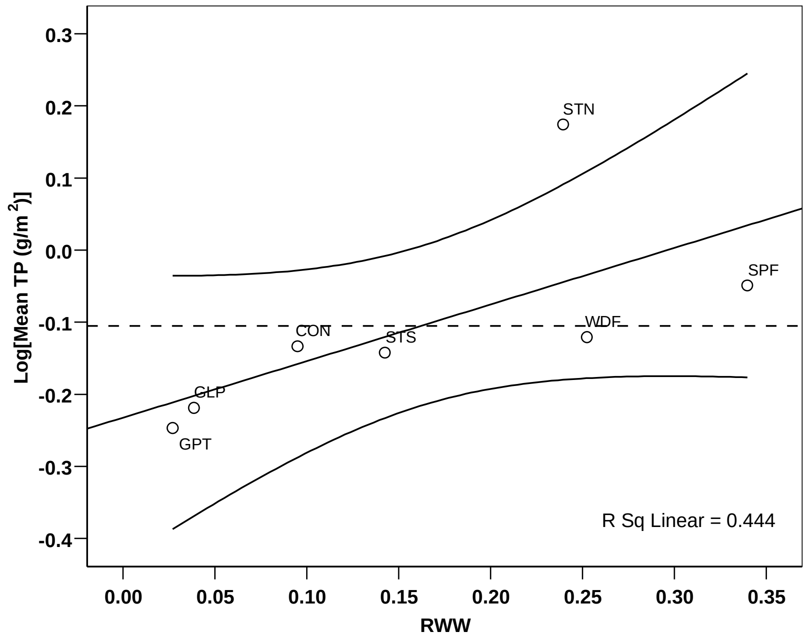
R^2 = 0.426 (fair)
S_e/S_y = 0.835 (poor)
$Se(b_0)/b_0$ = 0.333 (fair)
$Se(b_1)/b_1$ = 0.518 (poor)

(b)



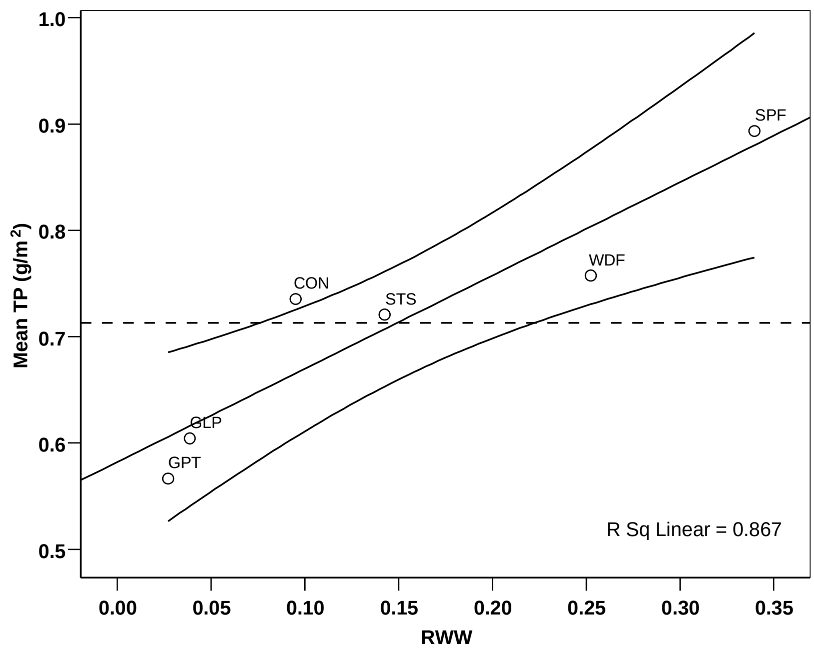
R^2 = 0.467 (fair)
S_e/S_y = 0.806 (poor)
$Se(b_0)/b_0$ = 0.317 (fair)
$Se(b_1)/b_1$ = 0.482 (fair)

Figure 14. Scatter plots and linear regression for log-transformed TP versus the log-transformed MHRT (a) and NHRT (b) for the 10-yr 24-hr ARC2 design storm. The horizontal dashed line represents the mean for all sites. Upper and lower 95% confidence intervals on the mean of the line are also shown. Criteria for qualitative assessment (shown in parentheses) of GOF statistics are in Appendix J.



(a)

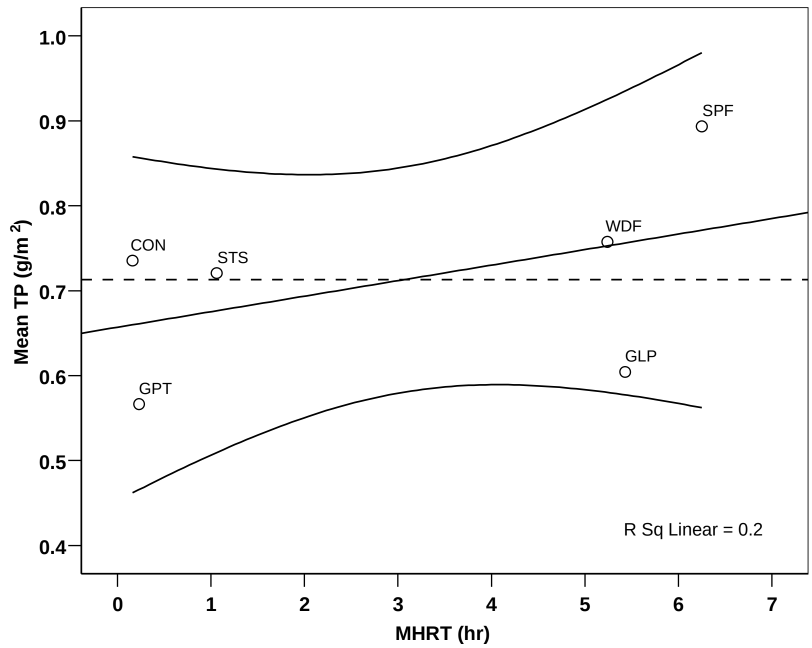
R^2 = 0.444 (fair)
S_e/S_y = 0.820 (poor)
$Se(b_0)/b_0$ = 0.332 (fair)
$Se(b_1)/b_1$ = 0.501 (poor)



(b)

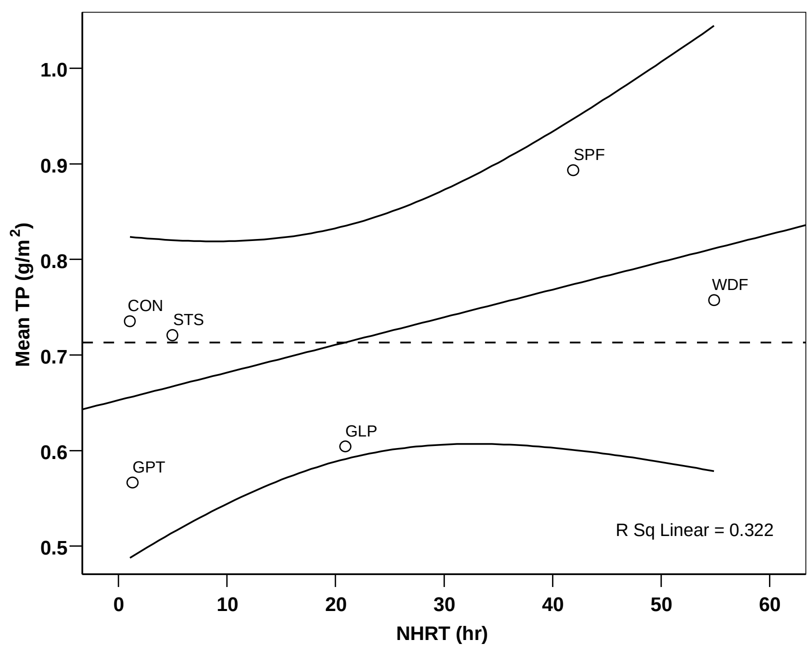
R^2 = 0.867 (good)
S_e/S_y = 0.407 (fair)
$Se(b_0)/b_0$ = 0.055 (good)
$Se(b_1)/b_1$ = 0.195 (good)

Figure 15. Scatter plot and linear regression for TP versus the ratio of wetland area to watershed area. In 15a, TP is log-transformed. In 15b, site STN is excluded. The horizontal dashed line represents the mean for the sites. Upper and lower 95% confidence intervals on the mean of the line are also shown. Criteria for qualitative assessment (shown in parentheses) of GOF statistics are in Appendix J.



R^2 = 0.200 (poor)
S_e/S_y = 1.000 (poor)
$Se(b_0)/b_0$ = 0.113 (good)
$Se(b_1)/b_1$ = 1.000 (poor)

(a)



R^2 = 0.322 (fair)
S_e/S_y = 0.923 (poor)
$Se(b_0)/b_0$ = 0.095 (good)
$Se(b_1)/b_1$ = 0.667 (poor)

(b)

Figure 16. Scatter plots and linear regression for TP versus MHRT (a) and NHRT (b) for the 10-yr 24-hr ARC2 design storm, excluding site STN. The horizontal dashed line represents the mean for all sites. Upper and lower 95% confidence intervals on the mean of the line are also shown. Criteria for qualitative assessment (shown in parentheses) of GOF statistics are in Appendix J.

Chapter 6: Conclusion

One objective of this study was to evaluate the relationship between HRT and indicators of nutrient retention – above-ground plant biomass and total above ground nutrient stocks of N and P in plants – and provide a model for optimizing HRT for nutrient retention. Although the analysis was not robust enough to produce a reliable model, the results provided some evidence for a significant relationship between storm event HRT and nutrient retention in wetland restorations in agricultural landscapes. One of the most significant relationships was between HRT and TP in above-ground plant biomass. The site with HRT values that were significantly greater than all other sites was also the only site with significantly greater TP, suggesting that greater storm event HRT's are more effective for P removal. Based on other studies, this was thought to be more a result of retention of soil-attached P rather than soluble P, and subsequently, the storm event HRT's for the studied wetlands may not have been effective for retention of dissolved nutrients.

The other objectives were to evaluate the effects of typical wetland restoration design on HRT and nutrient retention, and to provide design recommendations for optimizing HRT. The study revealed some conclusions about the design of wetlands for treatment of NPSP:

1. If one of the objectives of wetland restoration is to remove nutrients from surface runoff, then HRT needs to be considered in the design. It is likely that HRT was

not considered in the design for sites in this study, because values of HRT were lower than the recommended values for nutrient retention. Mitsch and Gosselink (2000) indicated that optimal nominal HRT for treatment of municipal wastewater ranges from 5 to 14 d, while Reinhardt et al. (2005) indicated a minimum HRT of 7 d for 50 percent P removal from agricultural NPSP, and Tuncsiper (2007) indicated peak removal efficiencies for NO_3-N, NH_4-N, and TP at an HRT of approximately 6 d. All of the sites in this study had NHRT values of 5.5 d or less, with values as low as 0.8 hr. Values of MHRT were significantly less (range: 0.2 – 28.3 hr).The pollutant form should also be taken into consideration, because retention of dissolved nutrients requires greater HRT than sediment-attached nutrients.

2. The method for determination of HRT should take into account the variability of the discharge to the wetland. When hydrology of a wetland is primarily driven by storm runoff, nominal values of HRT may overestimate the "true" HRT. The calculation of MHRT in this study is more precise than the calculation of NHRT, so it is most likely a better measure of HRT for wetlands with storm-driven hydrology. Because of the greater precision of MHRT, it also would be more useful for relating HRT to mass balance studies. Calculation of MHRT is more time-intensive than the calculation of NHRT, but because MHRT can be accurately predicted from NHRT, it is possible that the time required for calculating MHRT can be reduced by developing regional models of the two types of HRT.

3. The ratio of wetland to watershed (RWW) is not always a good indicator of HRT. The RWW was inaccurate at predicting MHRT for the sites in this study. This was demonstrated by comparison of sites GLP and SPF, which had similar values of HRT, but the second largest difference in RWW between any of the sites. Although correlations between RWW and HRT were mostly significant, linear regression analysis provided a poor model for predicting HRT based on RWW. One reason for the poor model prediction was that RWW does not account for flow variability related to the design of the outlet.

4. Outlet design is important for optimizing HRT and two-stage outlets are more land-efficient than single-stage outlets. Single-stage outlets designed to accommodate a large, infrequent storm, such as the 10-yr 24-hr ARC2 design storm, will typically result in consistently low values of HRT for all storms. The only way to increase HRT with a single-stage outlet is to increase the size of the wetland relative to the watershed. But it may be impractical to increase the RWW to the extent required for significant values of HRT. The study site with a single-stage outlet that had the largest RWW had significantly lower values of HRT than two out of the three sites with two-stage outlets. The use of two-stage or multi-stage outlets can more precisely accommodate a range of storm events, and provide consistent and significant values of HRT, while being more land-efficient in design.

Although NPSP is a major concern on the MES and in agricultural watersheds in general, it is clear that the wetlands in this study were not designed for the retention of dissolved nutrients. Because wetlands have the capacity for nutrient removal from agricultural non-point sources, wetland restoration designs should incorporate the necessary components for nutrient removal, to the extent practical within the overall goals of the restoration project. A critical component lacking in these wetland designs was an adequate HRT for retention of dissolved nutrients. Because storm runoff is responsible for much of the pollution, wetlands should be designed to provide adequate HRT's for a broad range of storm events. Futhermore, the design HRT should be estimated by a method that takes into account storm-driven hydraulic loading. A practical approach to achieve this is to utilize two-stage outlet designs that provide the minimum required HRT for the 1-yr 24-hr design storm, to the extent that the HRT does not preclude the establishment and survival of emergent vegetation, which is critical for nutrient retention. For practicality of construction, a two-stage design would require that the emergency spillway be staged approximately 15 cm (0.5 ft) above the primary spillway. This would result in higher construction costs because freeboard requirements would necessitate that the top of the berm be 18 to 30 cm above the emergency spillway. However, these costs would be negligible compared to the costs of NPSP.

Chapter 7: Suggestions for Further Study

To test the hypothetical model proposed in this study, an expansion of this study to include wetland restorations with greater HRT's would be required. Calculations of HRT for potential study sites could be performed prior to biomass sampling and analysis to ensure that sites with greater HRT's were included, assuming they exist. Further testing of the hypothetical model and validation of the relationship between biomass nutrient stocks and nutrient retention would be supported by real-time sampling of nutrient inputs and outputs during storm events, along with a mass balance analysis. This would most likely require the use of automated sampling devices because the typical watersheds are of a size that tend to produce ephemeral inflows and outflows. Analysis of the forms of N entering and leaving the wetlands during storm events would support a better understanding of factors affecting biomass production and nutrient uptake, because the form affects the potential for loss (e.g. through denitrification) and assimilation within the soils and biomass. The study of storm-driven hydrology at typical wetland restoration sites poses many challenges, and is evidenced by a lack of research on the topic, but it is critical for a more accurate assessment of the nutrient retention benefits of wetlands in agricultural landscapes.

The design recommendations from this study would be supported by further research, similar to that by Sharpley et al. (2008), to determine the proportion of nutrients that are transported to surface waters in typical agricultural watersheds during storm events of various return periods. This information could be used to determine the range of storm events to which the design HRT (e.g. 7 d) should be applied, and subsequently, to determine the most efficient wetland design. Additionally, this information would support improved accounting of the nutrient reduction benefits of wetland restorations, and could be used for cost/benefit analyses of agricultural best management practices.

Appendix A: Runoff Curve Number (CN) Data

Table A1. Watershed land cover and soils data used for runoff curve number determination.

Site	Land Cover	Map Unit	Soil Map Unit Description	Area (ac)	Hydrologic Group
CON	Cropland	HnA	Hammonton sandy loam, 0 to 2 percent slopes	12.2	B
		HnB	Hammonton sandy loam, 2 to 5 percent slopes	0.5	B
		IgA	Ingleside sandy loam, 0 to 2 percent slopes	2.2	B
		IgB	Ingleside sandy loam, 2 to 5 percent slopes	6.7	B
		PiB	Pineyneck silt loam, 2 to 5 percent slopes	3.2	B
		Hr	Hurlock sandy loam	5.6	D
	Grass/Brush	HnA	Hammonton sandy loam, 0 to 2 percent slopes	0.9	B
		IgB	Ingleside sandy loam, 2 to 5 percent slopes	0.6	B
		Hr	Hurlock sandy loam	6.0	D
GLP	Cropland	IgB	Ingleside sandy loam, 2 to 5 percent slopes	5.4	B
		NsA	Nassawango silt loam, 0 to 2 percent slopes	2.3	B
		NsB	Nassawango silt loam, 2 to 5 percent slopes	2.2	B
		PiA	Pineyneck silt loam, 0 to 2 percent slopes	0.2	B
		UsB	Unicorn-Sassafras loams, 2 to 5 percent slopes	1.8	B
		MtA	Mattapex-Butlertown silt loams, 0 to 2 percent slopes	11.6	C
		Wh	Whitemarsh silt loam	1.4	D
	Grass/Brush	NsA	Nassawango silt loam, 0 to 2 percent slopes	0.5	B
		Wh	Whitemarsh silt loam	0.5	D
GPT	Cropland	IgC	Ingleside sandy loam, 5 to 10 percent slopes	0.4	B
		PiA	Pineyneck silt loam, 0 to 2 percent slopes	2.4	B
		Wh	Whitemarsh silt loam	2.5	D
	Grass/Brush	IgC	Ingleside sandy loam, 5 to 10 percent slopes	0.1	B
		PiA	Pineyneck silt loam, 0 to 2 percent slopes	3.7	B
		Wh	Whitemarsh silt loam	2.0	D
SPF	Cropland	MpA	Mattapex fine sandy loam, 0 to 2 percent slopes	4.5	C
		MtA	Mattapex silt loam, 0 to 2 percent slopes	8.9	C
		Fh	Fallsington loam	0.6	D
	Wetland Area (Grass/Brush)	MpA	Mattapex fine sandy loam, 0 to 2 percent slopes	3.9	C
		MtA	Mattapex silt loam, 0 to 2 percent slopes	2.7	C
		Fa	Fallsington sandy loam	1.9	D
		Fh	Fallsington loam	3.7	D
		Oh	Othello silt loam	2.0	D

Table A1. (Continued)

SPF (con't)	Buffer Area (Grass/Brush)	MpA	Mattapex fine sandy loam, 0 to 2 percent slopes	4.9	C
		MtA	Mattapex silt loam, 0 to 2 percent slopes	3.2	C
		Fa	Fallsington sandy loam	0.5	D
		Fh	Fallsington loam	2.8	D
		Oh	Othello silt loam	2.5	D
STN	Cropland	HnB	Hammonton sandy loam, 2 to 5 percent slopes	1.0	B
		IgB	Ingleside sandy loam, 2 to 5 percent slopes	8.2	B
		Wh	Whitemarsh silt loam	0.2	D
	Wetland Area (Grass/Brush)	HnB	Hammonton sandy loam, 2 to 5 percent slopes	0.7	B
		Wh	Whitemarsh silt loam	2.7	D
	Buffer Area (Grass/Brush)	HnB	Hammonton sandy loam, 2 to 5 percent slopes	1.2	B
		Wh	Whitemarsh silt loam	0.2	D
STS	Cropland	HnB	Hammonton sandy loam, 2 to 5 percent slopes	1.4	B
		IgB	Ingleside sandy loam, 2 to 5 percent slopes	0.6	B
		PiA	Pineyneck silt loam, 0 to 2 percent slopes	11.3	B
		Ca	Carmichael loam	3.8	D
		Kn	Kentuck mucky silt loam	0.5	D
	Grass/Brush	HnB	Hammonton sandy loam, 2 to 5 percent slopes	0.6	B
		PiA	Pineyneck silt loam, 0 to 2 percent slopes	1.8	B
		Ca	Carmichael loam	2.9	D
		Kn	Kentuck mucky silt loam	5.8	D
	Woodland	HnB	Hammonton sandy loam, 2 to 5 percent slopes	1.2	B
		IgB	Ingleside sandy loam, 2 to 5 percent slopes	0.2	B
		PiA	Pineyneck silt loam, 0 to 2 percent slopes	0.7	B
		Ca	Carmichael loam	0	D
		Kn	Kentuck mucky silt loam	7.1	D
WDF	Cropland	IgB	Ingleside sandy loam, 2 to 5 percent slopes	1.9	B
		PiA	Pineyneck silt loam, 0 to 2 percent slopes	1	B
	Grass/Brush	IgB	Ingleside sandy loam, 2 to 5 percent slopes	1.3	B
		PiA	Pineyneck silt loam, 0 to 2 percent slopes	1	B
		PiB	Pineyneck silt loam, 2 to 5 percent slopes	0.9	B
		MtA	Mattapex-Butlertown silt loams, 0 to 2 percent slopes	0.8	C
		Ca	Carmichael loam	3.6	D
		Ot	Othello silt loam	5.3	D
		UoB	Unicorn silt loam, 2 to 5 percent slopes	1.7	D
		Wh	Whitemarsh silt loam	3.5	D

Note: Data reported in units collected and calculated.

Table A2. Weighted runoff curve number (CN) calculation data. CN was calculated based on the method described in Chapter 3, Hydrologic Analysis.

Site	Cover Description	Area and CN for Hydrologic Soils Groups					Totals	Weighted CN
			A	B	C	D		
CON	Row crop – SR + crop residue - good	Area (ac)	0	24.8	0	5.6		
		CN	64	75	82	85		
		Area x CN	0	1860	0	476		
	Brush – brush, weed, grass mix - fair	Area (ac)	0	0	0	6		
		CN	35	56	70	77		
		Area x CN	0	0	0	462		
	Brush – brush, weed, grass mix - good	Area (ac)	0	1.5	0	0		
		CN	30	48	65	73		
		Area x CN	0	72	0	0		
	Totals	Area (ac)	0	26.3	0	11.6	37.9	
		Area x CN	0	1932	0	938	2870	76
GLP	Row crop – SR + crop residue - good	Area (ac)	0	11.9	11.6	1.4		
		CN	64	75	82	85		
		Area x CN	0	892.5	951.2	119		
	Brush – brush, weed, grass mix - poor	Area (ac)	0	0	0	0.5		
		CN	48	67	77	83		
		Area x CN	0	0	0	41.5		
	Brush – brush, weed, grass mix - good	Area (ac)	0	0.5	0	0		
		CN	30	48	65	73		
		Area x CN	0	24	0	0		
	Totals	Area (ac)	0	12.4	11.6	1.9	25.9	
		Area x CN	0	916.5	951.2	160.5	2028.2	78
GPT	Row crop – SR + crop residue - good	Area (ac)	0	2.8	0	2.5		
		CN	64	75	82	85		
		Area x CN	0	210	0	212.5		
	Brush – brush, weed, grass mix - good	Area (ac)	0	3.8	0	2		
		CN	30	48	65	73		
		Area x CN	0	182.4	0	146		
	Totals	Area (ac)	0	6.6	0	4.5	11.1	
		Area x CN	0	392.4	0	358.5	750.9	68

Table A2. (Continued)

Site	Cover Description	Area and CN for Hydrologic Soils Groups					Totals	Weighted CN
			A	B	C	D		
SPF	Row crop – SR + crop residue - good	Area (ac)	0	0	13.4	0.6		
		CN	64	75	82	85		
		Area x CN	0	0	1098.8	51		
	Brush – brush, weed, grass mix - poor	Area (ac)	0	0	0	7.6		
		CN	48	67	77	83		
		Area x CN	0	0	0	630.8		
	Brush – brush, weed, grass mix - fair	Area (ac)	0	0	6.6	0		
		CN	35	56	70	77		
		Area x CN	0	0	462	0		
	Brush – brush, weed, grass mix - good	Area (ac)	0	0	8.1	5.8		
		CN	30	48	65	73		
		Area x CN	0	0	526.5	423.4		
	Totals	Area (ac)	0	0	28.1	14	42.1	
		Area x CN	0	0	2087.3	1105.2	3192.5	76
STN	Row crop – SR + crop residue - good	Area (ac)	0	9.2	0	0.2		
		CN	64	75	82	85		
		Area x CN	0	690	0	17		
	Brush – brush, weed, grass mix - fair	Area (ac)	0	0.7	0	2.7		
		CN	35	56	70	77		
		Area x CN	0	39.2	0	207.9		
	Brush – brush, weed, grass mix - good	Area (ac)	0	1.2	0	0.2		
		CN	30	48	65	73		
		Area x CN	0	57.6	0	14.6		
	Totals	Area (ac)	0	11.1	0	3.1	14.2	
		Area x CN	0	786.8	0	239.5	1026.3	72
STS	Row crop – SR + crop residue - good	Area (ac)	0	13.3	0	4.3		
		CN	64	75	82	85		
		Area x CN	0	997.5	0	365.5		
	Brush – brush, weed, grass mix - good	Area (ac)	0	2.4	0	8.7		
		CN	30	48	65	73		
		Area x CN	0	115.2	0	635.1		
	Woods - fair	Area (ac)	0	2.1	0	7.1		
		CN	36	60	73	79		
		Area x CN	0	126	0	560.9		
	Totals	Area (ac)	0	17.8	0	20.1	37.9	
		Area x CN	0	1238.7	0	1561.5	2800.2	74

Table A2. (Continued)

Site	Cover Description	Area and CN for Hydrologic Soils Groups					Totals	Weighted CN
			A	B	C	D		
WDF	Row crop – SR + crop residue - good	Area (ac)	0	2.9	0	0		
		CN	64	75	82	85		
		Area x CN	0	217.5	0	0		
	Brush – brush, weed, grass mix - good	Area (ac)	0	3.2	0.8	14.1		
		CN	30	48	65	73		
		Area x CN	0	153.6	52	1029.3		
	Totals	Area (ac)	0	6.1	0.8	14.1	21	
		Area x CN	0	371.1	52	1029.3	1452.4	69

Note: Data reported in units collected and calculated.

Appendix B: Time of Concentration (T_c) Data

Table B1. Time of concentration (T_c) calculation data. T_c was calculated based on the method described in Chapter 3, Hydrologic Analysis.

Site	Flow Type	Length (L, ft)	Slope (S)	Surface Cover	Manning's n	T_t (hr)
CON	Sheet	100	0.0158	Cultivated > 20% residue	0.17	0.195
	Shallow Concentrated	1900	0.0158	Unpaved	0.05	0.260
	Shallow Concentrated	1000	0.0010	Unpaved	0.05	0.544
	Total	3000				0.999
GLP	Sheet	100	0.0260	Cultivated > 20% residue	0.17	0.160
	Shallow Concentrated	470	0.0089	Unpaved	0.05	0.086
	Shallow Concentrated	1220	0.0025	Unpaved	0.05	0.420
	Total	1790				0.666
GPT	Sheet	100	0.0300	Cultivated > 20% residue	0.17	0.151
	Shallow Concentrated	970	0.0050	Unpaved	0.05	0.236
	Shallow Concentrated	275	0.0010	Unpaved	0.05	0.150
	Total	1345				0.537
SPF	Sheet	100	0.0056	Cultivated > 20% residue	0.17	0.296
	Shallow Concentrated	1370	0.0163	Unpaved	0.05	0.185
	Shallow Concentrated	750	0.0013	Unpaved	0.05	0.358
	Total	2220				0.839
STN	Sheet	100	0.0286	Cultivated > 20% residue	0.17	0.154
	Shallow Concentrated	320	0.0281	Unpaved	0.05	0.033
	Shallow Concentrated	430	0.0023	Unpaved	0.05	0.154
	Total	850				0.341
STS	Sheet	100	0.0100	Cultivated > 20% residue	0.17	0.235
	Shallow Concentrated	1300	0.0073	Unpaved	0.05	0.262
	Shallow Concentrated	900	0.0011	Unpaved	0.05	0.467
	Total	2300				0.964
WDF	Sheet	100	0.0100	Grass Dense	0.24	0.309
	Shallow Concentrated	1400	0.0032	Unpaved	0.05	0.426
	Total	1500				0.735

Note: Data reported in units collected and calculated.

Appendix C: Stage-Discharge Rating Calculations and Outlet Descriptions

FORMULAS FOR OUTLET STRUCTURE DISCHARGE RATING CALCULATIONS

Some study sites had only broad-crested weirs for outlet structures. The weir flow formula was used to determine discharge at these sites. Some study sites used water control structures (diagram shown in Figure C1) as the primary spillway and used either broad-crested weirs or flow over natural ground as the emergency spillway. The flow capacity (Q_{max}) of the water control structure can be controlled by the weir, pipe, or orifice. To determine the Q_{max} for the structure, the Q_{max} for each type of flow was calculated using the desired head (H) value. The lowest Q_{max} value was assumed to be the limiting flow value. Weir, pipe, and orifice flow was calculated based on the following equations:

Weir Flow Formula: $Q = C_w L_w H_w^{3/2}$ (C1)

Where, C_w = weir coefficient
L_w = length of weir (ft)
H_w = head on weir (ft)

Orifice Flow Formula: $Q = C_o A_o (2gH_o)^{0.5}$ (C2)

Where, C_o = orifice coefficient
A_o = cross-sectional area of orifice (in^2)
g = 32.2 ft/s
H_o = head on orifice (ft)

Pipe Flow Formula: $Q = A_p [(2gH_p) / (1 + K_e + K_b + K_p L_p)]^{0.5}$ (C3)

Where, A_p = cross-sectional area of flow (ft^2)
g = 32.2 ft/s
H_p = head on pipe (ft)
K_e = entrance coefficient
K_b = bend coefficient
$K_p = (5087 n^2) / d_p^{4/3}$
L_p = pipe length (ft)
n = manning's coefficient
d_p = diameter of pipe (in)

Note: Variables reported in units collected and calculated.

Site CON

Site CON does not have a designed structure. Overflow occurs over natural ground on an area that is approximately 180 ft in length.

L_w = 180 ft
C_w = 2.7
Weir elevation[a] = 40.0

Table C1. Stage-discharge rating for site CON.

Water Elevation (ft)[a]	Weir Head (ft)	Weir Q_{max} (cfs)[b]
40.0	0.0	0.0
40.5	0.5	171.8
41.0	1.0	486.0
42.0	2.0	1374.6

a/ Elevations at a site are relative to each other, but are not tied to a true ground elevation.
b/ Calculated using equation C1.

Note: Data reported in units collected and calculated.

Site GLP

Site GLP has an Agri Drain inlet-style water control structure (WCS). The boards in the structure are kept in place through the fall, winter and early spring. The emergency spillway (ES) is natural ground at the end of the berm. At 1.3 ft above normal pool, the emergency spillway has a length of 8 ft. At 1.4 ft above normal pool, the emergency spillway has a length of 38 ft.

Primary Water Control Structure (WCS)
Type: Agri Drain inlet-style structure, made of PVC
Weir elevation[a] = 50.8 ft
L_W = 2.17 ft
(See Table C8 and Figure C1 for additional structure values.)

Emergency Spillway (ES)
Type: Flow over natural ground (vegetated)
L_W @ elevation[a]: 8.0 ft @ elevation = 52.1 ft; 38 ft @ elevation = 52.2 ft
C_W = 2.7

Table C2. Stage-discharge rating values for site GLP. The flow controls for the water control structure at each water elevation are shown in bold. Total Q = WCS Q + ES Q.

Water Elevation (ft)[a]	Weir/ Orifice Head (ft)	Weir Q_{max} (cfs)[b]	Orifice Q_{max} (cfs)[c]	Pipe Head (ft)	Pipe Q_{max} (cfs)[d]	WCS Q (cfs)	ES Head (ft)	ES Q (cfs)[b]	Total Q (cfs)
50.8	0.00	0	0	0	0	0	0	0	0.0
50.9	0.10	**0.2**	0.4	1.35	1.0	0.2	0	0	0.2
51.0	0.20	**0.6**	0.6	1.45	1.0	0.6	0	0	0.6
51.1	0.30	1.1	**0.7**	1.55	1.0	0.7	0	0	0.7
51.5	0.70	3.9	**1.1**	1.95	1.2	1.1	0	0	1.1
52.05	1.25	9.4	1.5	2.50	**1.2**	1.2	0	0	1.2
52.2	1.40	11.1	1.6	2.65	**1.3**	1.3	0.1	0.7	2.0
52.6	1.80	16.3	1.8	3.05	**1.4**	1.4	[f]0.5	28.1	29.5

a/ Elevations at a site are relative to each other, but are not tied to a true ground elevation.
b/ Calculated using eq. C1.
c/ Calculated using eq. C2.
d/ Calculated using eq. C3.

Note: Data reported in units collected and calculated.

Site GPT

Site GPT has only a broad-crested, vegetated earthen spillway.

L_w = 20 ft
C_w = 2.7
Weir elevation[a] = 49.1 ft

Table C3. Stage-discharge rating for site GPT.

Water Elevation (ft)[a]	Weir Head (ft)	Weir Q_{max} (cfs)[b]
49.1	0.00	0.0
49.2	0.10	1.7
49.35	0.25	6.75
49.6	0.50	23.9

a/ Elevations at a site are relative to each other, but are not tied to a true ground elevation.
b/ Calculated using eq. C1.

Note: Data reported in units collected and calculated.

Site SPF

Site SPF has two broad-crested weirs and a pipe structure. The pipe structure is a PVC standpipe with a 90^o elbow that can be turned down to partially drain the wetland for management. All three structures are set at different elevations. For the pipe structure, both weir and orifice flows were calculated at each water elevation to determine which one was the control. The lesser of the flow values was the assumed flow capacity (Q_{max}) of the pipe structure. The pipe flow equation was not used to calculate flow capacity for the pipe drawdown structure because, when in the upright position, the pipe entrance functions as a weir or orifice. The pipe drawdown structure normally remains in the upright position.

Primary Structures
Type: Broad-crested earthen weir
L_w = 22 ft (each)
C_w = 2.7
Weir 1 elevation[a] = 50.3
Weir 2 elevation[a] = 50.5

Pipe Drawdown Structure
Type: Schedule 40 PVC standpipe with 90^o elbow
C_w = 3.1
C_o = 0.6
D = 6 in
Top of pipe elevation[a] = 50.4

Table C4. Stage-discharge rating values for site SPF. The flow controls for the pipe structure at each water elevation are shown in bold. Total Q = Weir 1 Q + Pipe Q + Weir 2 Q.

Water Elevation (ft)[a]	Weir 1 Head (ft)	Weir 1 Q (cfs)[b]	Pipe Head (ft)	Pipe Weir Q_{max} (cfs)[b]	Pipe Orifice Q_{max} (cfs)[c]	Pipe Q (cfs)	Weir 2 Head (ft)	Weir 2 Q (cfs)[b]	Total Q (cfs)
50.3	0	0	0	0	0	0	0	0	0
50.4	0.1	1.88	0	0	0	0	0	0	1.88
50.5	0.2	5.31	0.1	**0.15**	0.30	0.15	0	0	5.46
50.6	0.3	9.76	0.2	0.44	**0.42**	0.42	0.1	1.88	12.06
50.7	0.4	15.03	0.3	0.80	**0.52**	0.52	0.2	5.31	20.86
50.8	0.5	21	0.4	1.23	**0.60**	0.60	0.3	9.76	31.36
51.3	1	59.4	0.9	4.16	**0.90**	0.90	0.8	42.5	102.8

a/ Elevations at a site are relative to each other, but are not tied to a true ground elevation.
b/ Calculated using eq. C1.
c/ Calculated using eq. C2.

Note: Data reported in units collected and calculated.

Site STN

Site STN has a Agri Drain inlet-style PVC water control structure (WCS) and an earthen weir emergency spillway (ES). The total flow was calculated as the combined flow for the WCS and the ES. The WCS had removable boards, but the boards were left in place, with the controlling board at an elevation 0.8 ft below the top of the structure. Because of this setup, weir flow was calculated separately for flow over the board and flow over the top of the structure. The two weir flow values were summed to obtain the total weir flow. Both weir and pipe flow was calculated for each water elevation to determine the flow control. The lesser of the flow values was the assumed value through the WCS. Orifice flow was not assumed because the controlling board was at an elevation below the top of the WCS.

<u>Primary Water Control Structure (WCS)</u>
Type: Agri Drain inlet style structure, made of PVC
Weir 1 L_w = 1.17 ft
Weir 1 elevation[a] = 46.0 ft
Weir 2 L_w = 1.17 ft + 0.67 ft + 1.17 ft + 0.67 ft = 3.68 ft
Weir 2 elevation[a] = 46.8 ft
(See Table C8 and Figure C1 for additional structure values.)

<u>Emergency Spillway (ES)</u>
Type: Broad-crested earthen weir
L_w = 40 ft
C_w = 2.7
Weir elevation[a] = 46.8 ft

Table C5. Stage-discharge rating values for site STN. The flow controls for the water control structure at each water elevation are shown in bold. Total Q = WCS Q + ES Q.

Water Elevation (ft)[a]	WCS Weir 1 Head (ft)	WCS Weir 1 Q_{max} (cfs)[b]	WCS Weir 2 Head (ft)	WCS Weir 2 Q_{max} (cfs)[b]	WCS Weir 1+2 Q_{max} (cfs)	WCS Pipe Head (ft)	WCS Pipe Q_{max} (cfs)[d]	WCS Q (cfs)	ES Q (cfs)[b]	Total Q (cfs)
46.0	0.0	0	0	0	0	0	0	0	0	0
46.1	0.1	0.12	0	0	**0.12**	1.685	3.4	0.12	0	0.12
46.2	0.2	0.33	0	0	**0.33**	1.785	3.5	0.33	0	0.33
46.5	0.5	1.32	0	0	**1.32**	2.085	3.7	1.32	0	1.32
46.7	0.7	2.18	0	0	**2.18**	2.285	3.9	2.18	0	2.18
46.8	0.8	2.66	0	0.00	**2.66**	2.385	4.0	2.66	0.00	2.66
46.9	0.9	3.18	0.1	0.36	**3.54**	2.485	4.1	3.54	3.42	6.96
47.0	1.0	3.72	0.2	1.02	4.74	2.585	**4.2**	4.2	9.66	13.86
47.5	1.5	6.83	0.7	6.66	13.49	3.085	**4.5**	4.5	63.25	67.75

a/ Elevations at a site are relative to each other, but are not tied to a true ground elevation.
b/ Calculated using eq. C1.
d/ Calculated using eq. C3.

Note: Data reported in units collected and calculated.

Site STS

Site STS has only a vegetated earthen spillway.

L_w = 56 ft
C_w = 2.7
Weir elevation[a] = 40.0 ft

Table C6. Stage-discharge rating for site STS.

Water Elevation (ft)[a]	Weir Head (ft)	Weir Q_{max} (cfs)[b]
40.0	0.00	0.00
40.1	0.10	4.78
40.2	0.20	13.52
40.4	0.40	38.25
40.5	0.50	53.46

a/ Elevations at a site are relative to each other, but are not tied to a true ground elevation.
b/ Calculated using eq. C1.

Note: Data reported in units collected and calculated.

Site WDF

Site WDF had an Agri Drain inlet-style PVC water control structure (WCS) and an earthen weir emergency spillway (ES). The normal condition for the WCS was to have all the boards in place, so that the top board was at the top of the WCS. Weir, orifice, and pipe flows were calculated to determine the flow control.

Primary Water Control Structure (WCS)
Type: Agri Drain inlet style structure, made of PVC
L_w = 3.67 ft
Weir elevation[a] = 49.94
(See Table C8 and Figure C1 for additional structure values.)

Emergency Spillway (ES)
Type: Broad-crested earthen weir
L_w = 31 ft
C_w = 2.7
Weir elevation[a]: 50.00

Table C7. Stage-discharge rating values for site WDF. The flow controls for the pipe structure at each water elevation are shown in bold. Total Q = Weir 1 Q + Pipe Q + Weir 2 Q.

Water Elevation (ft)[a]	Weir/ Orifice Head (ft)	Weir Q_{max} (cfs)[b]	Orifice Q_{max} (cfs)[c]	Pipe Head (ft)	Pipe Q_{max} (cfs)[d]	WCS Q (cfs)	ES Head (ft)	ES Q (cfs)[b]	Total Q
49.94	0.00	0	0	0	0	0	0	0	0
49.99	0.05	**0.1**	0.84	0.50	1.2	0.1	0	0	0.1
50.00	0.06	**0.2**	0.92	0.51	1.2	0.2	0	0	0.2
50.10	0.16	**0.8**	1.50	0.61	1.40	0.80	0.10	2.65	3.45
50.50	0.56	4.77	2.80	1.01	**1.60**	1.6	0.50	29.60	31.2
51.00	1.06	12.42	3.85	1.51	**1.90**	1.9	1.00	83.70	85.6

a/ Elevations at a site are relative to each other, but are not tied to a true ground elevation.
b/ Calculated using eq. C1.
c/ Calculated using eq. C2.
d/ Calculated using eq. C3.

Note: Data reported in units collected and calculated.

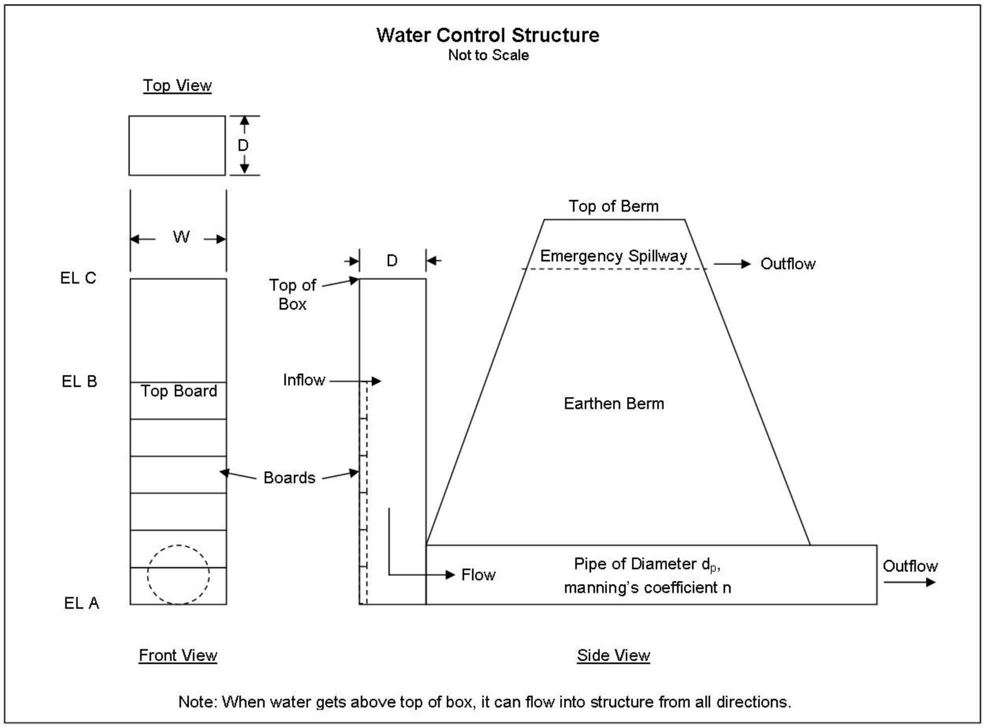


Figure C1. Diagram of Agri Drain inlet-style water control structure.

Table C8. Structure values for Agri Drain water control structures at sites GLP, STN, and WDF. Measurements are identified in Figure C1. Where EL B = EL C, the boards were set at the top of the structure.

Measurement	Site GLP	Site STN	Site WDF
Inlet elevation - EL A (ft)*	49.3	44.0	49.16
Normal pool elevation - EL B (ft)*	50.8	46.0	49.94
Top of box elevation - EL C (ft)*	50.8	46.8	49.94
Top of berm elevation (ft)*	52.6	48.6	51.6
Emergency spillway elevation (ft)*	52.1	46.8	50.0
W (in)	8	14	14
D (in)	5	8	8
C_w	3.1	3.1	3.1
Orifice area (W x D, in^2)	40	112	112
C_o	0.6	0.6	0.6
d_p (in)	6	10	8
Pipe length, L_p (ft)	31	40	28
Pipe manning's n	0.012	0.012	0.012
Pipe head, H_p (ft)	1.25	1.585	0.45
Pipe entrance coefficient, K_e	0.5	0.5	0.5
Pipe bend coefficient, K_b	0	0	0

* Elevations are relative to each other at a site, but are not tied to a true ground elevation.
Data reported in units collected and calculated.

Figure C2. Photo of Agri Drain inlet-style water control structure.

Appendix D: Stage-Storage Rating Calculation Data

The following data was used to determine the storage volume of the wetland above the normal pool elevation, based on equation 7.

Table D1. Values for calculating stage-storage relationship for sites.

Site	A_0 (ac)	A_1 (ac)	D_1 (ft)	S (ac/ft)	D (ft)	Storage Volume (ac-ft)
CON	3.6	6.9	1.0	3.3	0.00	0.0
					0.50	2.21
					1.00	5.25
					2.00	13.80
GLP	1.0	1.2	1	0.2	0.00	0.00
					0.10	0.10
					0.20	0.20
					0.30	0.31
					0.70	0.75
					1.25	1.41
					1.40	1.60
					1.80	2.12
					2.30	2.83
GPT	0.3	0.9	0.5	1.2	0.00	0.00
					0.10	0.04
					0.25	0.11
					0.50	0.30
SPF	14.3	17.7	1.0	3.4	0.00	0.00
					0.10	1.45
					0.20	2.93
					0.30	4.44
					0.40	5.99
					0.50	7.58
					1.00	16.00
STN	3.4	4.7	0.8	1.625	0.00	0.00
					0.10	0.35
					0.20	0.71
					0.50	1.90
					0.70	2.78
					0.80	3.24
					0.90	3.72
					1.00	4.21
					1.50	6.93
STS	5.4	5.4	0.5	0	0.00	0.00
					0.10	0.54
					0.20	1.08
					0.40	2.16
					0.50	2.70

Table D1. (Continued)

Site	A_0 (ac)	A_1 (ac)	D_1 (ft)	S (ac/ft)	D (ft)	Storage Volume (ac-ft)
WDF	5.3	5.3	1.0	0	0.00	0.00
					0.05	0.27
					0.06	0.32
					0.16	0.85
					0.56	2.97
					1.06	5.62

Note: Data reported in units collected and calculated.

Appendix E: TR-20 Input Data

The follow is the TR-20 input data, as entered into WinTR-20. Data reported in units collected and calculated.

SUB-AREA:

Sub-area	Sub-area Reach ID	Area (sqmi)	CN	Tc (hr)
WDF	WDF	0.033	69	0.735
CON	CON	0.059	76	0.999
GLP	GLP	0.040	78	0.666
GPT	GPT	0.017	68	0.537
SPF	SPF	0.066	76	0.839
STN	STN	0.022	72	0.341
STS	STS	0.059	74	0.964

STREAM REACH:

Reach ID	Receiving Reach	Reach Structure ID
WDF	Outlet	str WDF
CON	Outlet	str CON
GLP	Outlet	str GLP
GPT	Outlet	str GPT
SPF	Outlet	str SPF
STN	Outlet	str STN
STS	Outlet	str STS

STORM ANALYSIS:

Storm ID	Rainfall (in)	Rainfall Distribution Type	ARC
1/2in 1hr	0.5	Custom: Constant Intensity 1 hr	3
1in 1hr	1.0	Custom: Constant Intensity 1 hr	3
1in 4hr	1.0	Custom: Constant Intensity 4 hr	3
1y 24h a2	2.7	Type II	2
1y 24h a3	2.7	Type II	3
10y 24h a2	5.3	Type II	2

STRUCTURE RATING:

Structure	Elev (ft)*	Discharge (cfs)	Storage (ac-ft)
str WDF			
	49.94	0.00	0.000
	49.99	0.10	0.265
	50.00	0.20	0.318
	50.10	3.45	0.848
	50.50	31.20	2.968
	51.00	85.60	5.620
str CON			
	40.00	0.00	0.000
	40.50	171.80	2.210
	41.00	486.00	5.250
	42.00	1374.60	13.800
str GLP			
	50.80	0.00	0.000
	50.90	0.20	0.100
	51.00	0.60	0.200
	51.10	0.70	0.310
	51.50	1.10	0.750
	52.05	1.20	1.410

	52.20	1.98	1.600
	52.60	29.53	2.120
	53.10	136.30	2.830
str GPT			
	49.10	0.00	0.000
	49.20	1.71	0.040
	49.35	6.75	0.110
	49.60	23.86	0.300
str SPF			
	50.30	0.00	0.000
	50.40	1.88	1.450
	50.50	5.46	2.930
	50.60	12.06	4.440
	50.70	20.86	5.990
	50.80	31.36	7.580
	51.30	102.80	16.000
str STN			
	46.00	0.00	0.000
	46.10	0.12	0.350
	46.20	0.33	0.710
	46.50	1.32	1.900
	46.70	2.18	2.780
	46.80	2.66	3.240
	46.90	6.96	3.720
	47.00	13.86	4.210
	47.50	67.75	6.930
str STS			
	40.00	0.00	0.000
	40.10	4.78	0.540
	40.20	13.52	1.080
	40.40	38.25	2.160
	40.50	53.46	2.700

* Elevation is based on a benchmark that was not tied to actual (i.e., mean sea level) elevations.

DIMENSIONLESS UNIT HYDROGRAPH: Delmarva

0.	.111	.356	.655	.896
1.	.929	.828	.737	.656
.584	.521	.465	.415	.371
.331	.296	.265	.237	.212
.190	.170	.153	.138	.123
.109	.097	.086	.076	.066
.057	.049	.041	.033	.027
.024	.021	.018	.015	.013
.012	.011	.009	.008	.008
.006	.006	.005	.005	0.

RAINFALL DISTRIBUTION:

Type:	Custom: Constant Intensity 1 hr				
Mass Rainfall Points:	0.	.25	.5	.75	1.
@ Time Increment:	0.25 hr				
Type:	Custom: Constant Intensity 4 hr				
Mass Rainfall Points:	0.	.25	.5	.75	1.
@ Time Increment:	1.00 hr				

Appendix F: TR-20 Output Data

The following is a portion of the TR-20 output data, described in TR-20 as the *printed page file*. The output shown here is for the 1-yr 24-hr ARC2 storm for site WDF. Units are shown in English because the data was outputted in English units and converted to SI units as part of the data analysis. The full output data and Win-TR20 input file are provided on disk.

As shown, there are three sets of data for a storm event at a site. The first set of data has no rain gage ID or location name, and is the data representing the runoff hydrograph for the watershed. The second set of data is for the location identified as *Upstream*, and represents the hydrograph upstream of the outlet structure of the site. Because each site was modeled as a single watershed draining to a single outlet, the runoff hydrograph data and the data upstream of the outlet structure are the same. The third set of data is for the location identified as *Downstream*, and represents the flow hydrograph just downstream of the outlet structure. The downstream data differs from the other two sets of data because it takes into account the flow limitations of the outlet structure and the storage volume of the area upstream of the structure.

Note: Data reported in units collected and calculated.

STORM 1y 24h a2

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
WDF	0.033		0.516		12.44	3.23	97.93

Line Start Time (hr)	Flow Values @ time increment of 0.098 hr (cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
11.753	0.013	0.115	0.458	1.100	1.904	2.634	3.090
12.439	3.232	3.195	3.103	2.988	2.862	2.732	2.606
13.125	2.485	2.368	2.256	2.150	2.051	1.956	1.867
13.811	1.782	1.703	1.628	1.557	1.488	1.422	1.361
14.497	1.304	1.250	1.199	1.151	1.105	1.061	1.019
15.183	0.981	0.950	0.921	0.893	0.866	0.842	0.820
15.869	0.799	0.778	0.759	0.740	0.722	0.705	0.689
16.555	0.672	0.653	0.638	0.627	0.616	0.606	0.597
17.241	0.588	0.580	0.572	0.565	0.558	0.551	0.544
17.927	0.537	0.531	0.525	0.519	0.513	0.507	0.501
18.613	0.495	0.489	0.483	0.477	0.472	0.466	0.460
19.299	0.455	0.449	0.443	0.437	0.431	0.426	0.420
19.985	0.414	0.408	0.402	0.397	0.391	0.386	0.382
20.671	0.378	0.374	0.371	0.368	0.365	0.362	0.360
21.357	0.357	0.355	0.353	0.351	0.349	0.348	0.346
22.043	0.345	0.343	0.342	0.340	0.339	0.338	0.337
22.729	0.335	0.334	0.333	0.332	0.331	0.330	0.329
23.415	0.328	0.327	0.326	0.324	0.323	0.322	0.321
24.101	0.317	0.306	0.287	0.262	0.234	0.208	0.185
24.787	0.165	0.146	0.130	0.116	0.103	0.091	0.081
25.473	0.072	0.063	0.056	0.049	0.044	0.038	0.034
26.159	0.029	0.026	0.022	0.019	0.016	0.014	0.012
26.845	0.010	0.009	0.007	0.006	0.005	0.004	0.004
27.531	0.003	0.003	0.002	0.002	0.002	0.001	0.001

Area or	Drainage	Rain Gage	Runoff	------------ Peak Flow ------------

Reach Identifier	Area (sq mi)	ID or Location	Amount (in)	Elevation (ft)	Time (hr)	Rate (cfs)	Rate (csm)
WDF	0.033	Upstream	0.516		12.44	3.23	97.93

Line Start Time (hr)	------------ Flow Values @ time increment of 0.098 hr ------------ (cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
11.753	0.013	0.115	0.458	1.100	1.904	2.634	3.090
12.439	3.232	3.195	3.103	2.988	2.862	2.732	2.606
13.125	2.485	2.368	2.256	2.150	2.051	1.956	1.867
13.811	1.782	1.703	1.628	1.557	1.488	1.422	1.361
14.497	1.304	1.250	1.199	1.151	1.105	1.061	1.019
15.183	0.981	0.950	0.921	0.893	0.866	0.842	0.820
15.869	0.799	0.778	0.759	0.740	0.722	0.705	0.689
16.555	0.672	0.653	0.638	0.627	0.616	0.606	0.597
17.241	0.588	0.580	0.572	0.565	0.558	0.551	0.544
17.927	0.537	0.531	0.525	0.519	0.513	0.507	0.501
18.613	0.495	0.489	0.483	0.477	0.472	0.466	0.460
19.299	0.455	0.449	0.443	0.437	0.431	0.426	0.420
19.985	0.414	0.408	0.402	0.397	0.391	0.386	0.382
20.671	0.378	0.374	0.371	0.368	0.365	0.362	0.360
21.357	0.357	0.355	0.353	0.351	0.349	0.348	0.346
22.043	0.345	0.343	0.342	0.340	0.339	0.338	0.337
22.729	0.335	0.334	0.333	0.332	0.331	0.330	0.329
23.415	0.328	0.327	0.326	0.324	0.323	0.322	0.321
24.101	0.317	0.306	0.287	0.262	0.234	0.208	0.185
24.787	0.165	0.146	0.130	0.116	0.103	0.091	0.081
25.473	0.072	0.063	0.056	0.049	0.044	0.038	0.034
26.159	0.029	0.026	0.022	0.019	0.016	0.014	0.012
26.845	0.010	0.009	0.007	0.006	0.005	0.004	0.004
27.531	0.003	0.003	0.002	0.002	0.002	0.001	0.001

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	------------ Peak Flow ------------ Elevation (ft)	Time (hr)	Rate (cfs)	Rate (csm)
WDF	0.033	Downstream	0.514	50.02	15.57	0.87	26.42

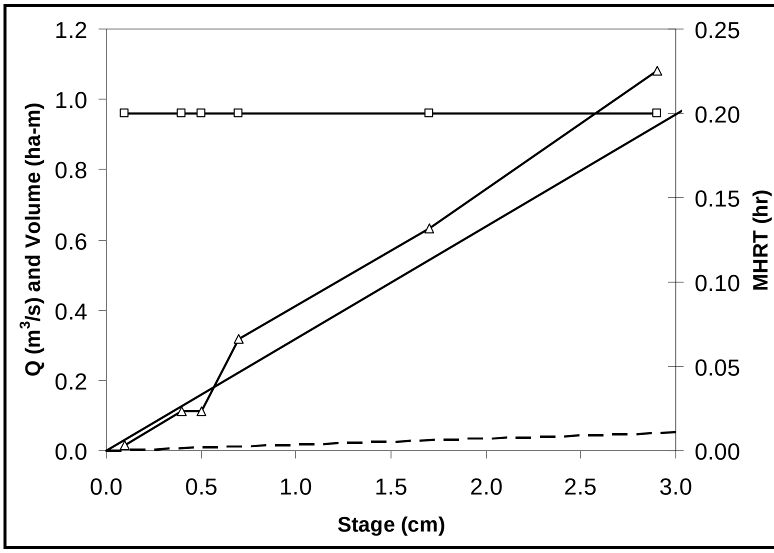
Line Start Time (hr)	------------ Flow Values @ time increment of 0.098 hr ------------ (cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
11.949	0.001	0.003	0.008	0.015	0.024	0.033	0.043
12.635	0.052	0.062	0.070	0.079	0.086	0.094	0.105
13.321	0.139	0.170	0.200	0.286	0.365	0.435	0.499
14.007	0.555	0.605	0.650	0.689	0.723	0.752	0.778
14.693	0.799	0.818	0.833	0.845	0.854	0.861	0.866
15.379	0.870	0.871	0.872	0.871	0.869	0.866	0.862
16.065	0.858	0.853	0.847	0.840	0.833	0.826	0.818
16.751	0.810	0.801	0.792	0.784	0.775	0.766	0.757
17.437	0.748	0.740	0.731	0.722	0.714	0.706	0.697
18.123	0.689	0.681	0.673	0.665	0.657	0.649	0.642
18.809	0.634	0.627	0.619	0.612	0.605	0.598	0.591
19.495	0.584	0.577	0.570	0.563	0.556	0.549	0.543
20.181	0.536	0.529	0.523	0.516	0.510	0.504	0.497
20.867	0.491	0.485	0.480	0.474	0.469	0.463	0.458
21.553	0.453	0.448	0.443	0.439	0.434	0.430	0.426
22.239	0.422	0.418	0.414	0.410	0.407	0.403	0.400
22.925	0.397	0.394	0.391	0.388	0.385	0.382	0.380
23.611	0.377	0.374	0.372	0.370	0.367	0.365	0.362
24.297	0.359	0.355	0.350	0.344	0.337	0.329	0.320
24.983	0.311	0.302	0.293	0.283	0.274	0.264	0.255
25.669	0.245	0.236	0.227	0.218	0.209	0.200	0.197
26.355	0.195	0.192	0.190	0.187	0.184	0.182	0.179
27.041	0.176	0.174	0.171	0.169	0.166	0.164	0.161
27.727	0.159	0.157	0.154	0.152	0.150	0.147	0.145
28.413	0.143	0.141	0.139	0.137	0.135	0.132	0.130
29.099	0.128	0.127	0.125	0.123	0.121	0.119	0.117
29.785	0.115	0.114	0.112	0.110	0.109	0.107	0.105
30.471	0.104	0.102	0.101	0.100	0.100	0.099	0.099
31.157	0.099	0.098	0.098	0.098	0.097	0.097	0.097
31.843	0.097	0.096	0.096	0.096	0.095	0.095	0.095
32.529	0.094	0.094	0.094	0.094	0.093	0.093	0.093
33.215	0.092	0.092	0.092	0.092	0.091	0.091	0.091
33.901	0.091	0.090	0.090	0.090	0.089	0.089	0.089

34.587	0.089	0.088	0.088	0.088	0.088	0.087	0.087
35.273	0.087	0.086	0.086	0.086	0.086	0.085	0.085
35.959	0.085	0.085	0.084	0.084	0.084	0.084	0.083
36.645	0.083	0.083	0.083	0.082	0.082	0.082	0.082
37.331	0.081	0.081	0.081	0.081	0.080	0.080	0.080
38.017	0.080	0.079	0.079	0.079	0.079	0.078	0.078
38.703	0.078	0.078	0.077	0.077	0.077	0.077	0.077
39.389	0.076	0.076	0.076	0.076	0.075	0.075	0.075
40.075	0.075	0.074	0.074	0.074	0.074	0.074	0.073
40.761	0.073	0.073	0.073	0.072	0.072	0.072	0.072
41.447	0.072	0.071	0.071	0.071	0.071	0.070	0.070
42.133	0.070	0.070	0.070	0.069	0.069	0.069	0.069
42.819	0.069	0.068	0.068	0.068	0.068	0.068	0.067
43.505	0.067	0.067	0.067	0.066	0.066	0.066	0.066
44.191	0.066	0.065	0.065	0.065	0.065	0.065	0.064
44.877	0.064	0.064	0.064	0.064	0.063	0.063	0.063
45.563	0.063	0.063	0.063	0.062	0.062	0.062	0.062
46.249	0.062	0.061	0.061	0.061	0.061	0.061	0.060
46.935	0.060	0.060	0.060	0.060	0.060	0.059	0.059
47.621	0.059	0.059	0.059	0.058	0.058	0.058	0.058
48.307	0.058	0.058	0.057	0.057	0.057	0.057	0.057
48.993	0.057	0.056	0.056	0.056	0.056	0.056	0.056
49.679	0.055	0.055	0.055	0.055	0.055	0.054	0.054
50.365	0.054	0.054	0.054	0.054	0.054	0.053	0.053
51.051	0.053	0.053	0.053	0.053	0.052	0.052	0.052
51.737	0.052	0.052	0.052	0.051	0.051	0.051	0.051
52.423	0.051	0.051	0.050	0.050	0.050	0.050	0.050
53.109	0.050	0.050	0.049	0.049	0.049	0.049	0.049
53.795	0.049	0.049	0.048	0.048	0.048	0.048	0.048
54.481	0.048	0.047	0.047	0.047	0.047	0.047	0.047
55.167	0.047	0.046	0.046	0.046	0.046	0.046	0.046
55.853	0.046	0.046	0.045	0.045	0.045	0.045	0.045
56.539	0.045	0.045	0.044	0.044	0.044	0.044	0.044
57.225	0.044	0.044	0.043	0.043	0.043	0.043	0.043
57.911	0.043	0.043	0.043	0.042	0.042	0.042	0.042
58.597	0.042	0.042	0.042	0.042	0.041	0.041	0.041
59.283	0.041	0.041	0.041	0.041	0.041	0.040	0.040
59.969	0.040	0.040	0.040	0.040	0.040	0.040	0.039
60.655	0.039	0.039	0.039	0.039	0.039	0.039	0.039
61.341	0.038	0.038	0.038	0.038	0.038	0.038	0.038
62.027	0.038	0.038	0.037	0.037	0.037	0.037	0.037
62.713	0.037	0.037	0.037	0.037	0.036	0.036	0.036
63.399	0.036	0.036	0.036	0.036	0.036	0.036	0.035
64.085	0.035	0.035	0.035	0.035	0.035	0.035	0.035
64.771	0.035	0.034	0.034	0.034	0.034	0.034	0.034
65.457	0.034	0.034	0.034	0.034	0.033	0.033	0.033
66.143	0.033	0.033	0.033	0.033	0.033	0.033	0.033
66.829	0.032	0.032	0.032	0.032	0.032	0.032	0.032
67.515	0.032	0.032	0.032	0.031	0.031	0.031	0.031
68.201	0.031	0.031	0.031	0.031	0.031	0.031	0.030
68.887	0.030	0.030	0.030	0.030	0.030	0.030	0.030
69.573	0.030	0.030	0.030	0.029	0.029	0.029	0.029
70.259	0.029	0.029	0.029	0.029	0.029	0.029	0.029
70.945	0.029	0.028	0.028	0.028	0.028	0.028	0.028
71.631	0.028	0.028	0.028	0.028	0.028	0.027	0.027
72.317	0.027	0.027	0.027	0.027	0.027	0.027	0.027
73.003	0.027	0.027	0.027	0.026	0.026	0.026	0.026
73.689	0.026	0.026	0.026	0.026	0.026	0.026	0.026
74.375	0.026	0.026	0.025	0.025	0.025	0.025	0.025
75.061	0.025	0.025	0.025	0.025	0.025	0.025	0.025
75.747	0.025	0.024	0.024	0.024	0.024	0.024	0.024
76.433	0.024	0.024	0.024	0.024	0.024	0.024	0.024
77.119	0.024	0.023	0.023	0.023	0.023	0.023	0.023
77.805	0.023	0.023	0.023	0.023	0.023	0.023	0.023
78.491	0.023	0.022	0.022	0.022	0.022	0.022	0.022
79.177	0.022	0.022	0.022	0.022	0.022	0.022	0.022
79.863	0.022	0.022	0.021	0.021	0.021	0.021	0.021
80.549	0.021	0.021	0.021	0.021	0.021	0.021	0.021
81.235	0.021	0.021	0.021	0.020	0.020	0.020	0.020
81.921	0.020	0.020	0.020	0.020	0.020	0.020	0.020
82.607	0.020	0.020	0.020	0.020	0.020	0.020	0.019
83.293	0.019	0.019	0.019	0.019	0.019	0.019	0.019
83.979	0.019	0.019	0.019	0.019	0.019	0.019	0.019
84.665	0.019	0.019	0.018	0.018	0.018	0.018	0.018
85.351	0.018	0.018	0.018	0.018	0.018	0.018	0.018
86.037	0.018	0.018	0.018	0.018	0.018	0.018	0.017
86.723	0.017	0.017	0.017	0.017	0.017	0.017	0.017

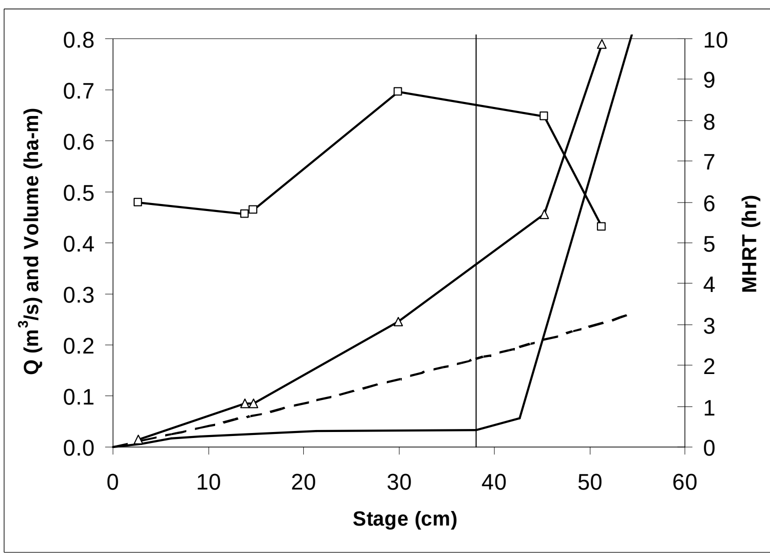
87.409	0.017	0.017	0.017	0.017	0.017	0.017	0.017
88.095	0.017	0.017	0.017	0.017	0.016	0.016	0.016
88.781	0.016	0.016	0.016	0.016	0.016	0.016	0.016
89.467	0.016	0.016	0.016	0.016	0.016	0.016	0.016
90.153	0.016	0.016	0.016	0.016	0.015	0.015	0.015
90.839	0.015	0.015	0.015	0.015	0.015	0.015	0.015
91.525	0.015	0.015	0.015	0.015	0.015	0.015	0.015
92.211	0.015	0.015	0.015	0.015	0.015	0.014	0.014
92.897	0.014	0.014	0.014	0.014	0.014	0.014	0.014
93.583	0.014	0.014	0.014	0.014	0.014	0.014	0.014
94.269	0.014	0.014	0.014	0.014	0.014	0.014	0.014
94.955	0.013	0.013	0.013	0.013	0.013	0.013	0.013
95.641	0.013	0.013	0.013	0.013	0.013	0.013	0.013
96.327	0.013	0.013	0.013	0.013	0.013	0.013	0.013
97.013	0.013	0.013	0.013	0.013	0.012	0.012	0.012
97.699	0.012	0.012	0.012	0.012	0.012	0.012	0.012
98.385	0.012	0.012	0.012	0.012	0.012	0.012	0.012
99.071	0.012	0.012	0.012	0.012	0.012	0.012	0.012
99.757	0.012	0.012	0.012	0.012	0.011	0.011	0.011
100.443	0.011	0.011	0.011	0.011	0.011	0.011	0.011
101.129	0.011	0.011	0.011	0.011	0.011	0.011	0.011
101.815	0.011	0.011	0.011	0.011	0.011	0.011	0.011
102.501	0.011	0.011	0.011	0.011	0.011	0.010	0.010
103.187	0.010	0.010	0.010	0.010	0.010	0.010	0.010
103.873	0.010	0.010	0.010	0.010	0.010	0.010	0.010
104.559	0.010	0.010	0.010	0.010	0.010	0.010	0.010
105.245	0.010	0.010	0.010	0.010	0.010	0.010	0.010
105.931	0.010	0.010	0.010	0.009	0.009	0.009	0.009
106.617	0.009	0.009	0.009	0.009	0.009	0.009	0.009
107.303	0.009	0.009	0.009	0.009	0.009	0.009	0.009
107.989	0.009	0.009	0.009	0.009	0.009	0.009	0.009
108.675	0.009	0.009	0.009	0.009	0.009	0.009	0.009
109.361	0.009	0.009	0.009	0.009	0.008	0.008	0.008
110.047	0.008	0.008	0.008	0.008	0.008	0.008	0.008
110.733	0.008	0.008	0.008	0.008	0.008	0.008	0.008
111.419	0.008	0.008	0.008	0.008	0.008	0.008	0.008
112.105	0.008	0.008	0.008	0.008	0.008	0.008	0.008
112.791	0.008	0.008	0.008	0.008	0.008	0.008	0.008
113.477	0.008	0.008	0.008	0.007	0.007	0.007	0.007
114.163	0.007	0.007	0.007	0.007	0.007	0.007	0.007
114.849	0.007	0.007	0.007	0.007	0.007	0.007	0.007
115.535	0.007	0.007	0.007	0.007	0.007	0.007	0.007
116.221	0.007	0.007	0.007	0.007	0.007	0.007	0.007
116.907	0.007	0.007	0.007	0.007	0.007	0.007	0.007
117.593	0.007	0.007	0.007	0.007	0.007	0.007	0.007
118.279	0.007	0.006	0.006	0.006	0.006	0.006	0.006
118.965	0.006	0.006	0.006	0.006	0.006	0.006	0.006
119.651	0.006	0.006	0.006	0.006	0.006	0.006	0.006
120.337	0.006	0.006	0.006	0.006	0.006	0.006	0.006
121.023	0.006	0.006	0.006	0.006	0.006	0.006	0.006
121.709	0.006	0.006	0.006	0.006	0.006	0.006	0.006
122.395	0.006	0.006	0.006	0.006	0.006	0.006	0.006
123.081	0.006	0.006	0.006	0.006	0.006	0.006	0.006
123.767	0.005	0.005	0.005	0.005	0.005	0.005	0.005
124.453	0.005	0.005	0.005	0.005	0.005	0.005	0.005
125.139	0.005	0.005	0.005	0.005	0.005	0.005	0.005
125.825	0.005	0.005	0.005	0.005	0.005	0.005	0.005
126.511	0.005	0.005	0.005	0.005	0.005	0.005	0.005
127.197	0.005	0.005	0.005	0.005	0.005	0.005	0.005
127.883	0.005	0.005	0.005	0.005	0.005	0.005	0.005
128.569	0.005	0.005	0.005	0.005	0.005	0.005	0.005
129.255	0.005	0.005	0.005	0.005	0.005	0.005	0.005
129.941	0.005	0.005	0.005	0.004	0.004	0.004	0.004
130.627	0.004	0.004	0.004	0.004	0.004	0.004	0.004
131.313	0.004	0.004	0.004	0.004	0.004	0.004	0.004
131.999	0.004	0.004	0.004	0.004	0.004	0.004	0.004
132.685	0.004	0.004	0.004	0.004	0.004	0.004	0.004
133.371	0.004	0.004	0.004	0.004	0.004	0.004	0.004
134.057	0.004	0.004	0.004	0.004	0.004	0.004	0.004
134.743	0.004	0.004	0.004	0.004	0.004	0.004	0.004
135.429	0.004	0.004	0.004	0.004	0.004	0.004	0.004
136.115	0.004	0.004	0.004	0.004	0.004	0.004	0.004
136.801	0.004	0.004	0.004	0.004	0.004	0.004	0.004
137.487	0.004	0.004	0.004	0.004	0.004	0.004	0.004
138.173	0.004	0.003	0.003	0.003	0.003	0.003	0.003
138.859	0.003	0.003	0.003	0.003	0.003	0.003	0.003
139.545	0.003	0.003	0.003	0.003	0.003	0.003	0.003

140.231	0.003	0.003	0.003	0.003	0.003	0.003	0.003
140.917	0.003	0.003	0.003	0.003	0.003	0.003	0.003
141.603	0.003	0.003	0.003	0.003	0.003	0.003	0.003
142.289	0.003	0.003	0.003	0.003	0.003	0.003	0.003
142.975	0.003	0.003	0.003	0.003	0.003	0.003	0.003
143.661	0.003	0.003	0.003	0.003	0.003	0.003	0.003
144.347	0.003	0.003	0.003	0.003	0.003	0.003	0.003
145.033	0.003	0.003	0.003	0.003	0.003	0.003	0.003
145.719	0.003	0.003	0.003	0.003	0.003	0.003	0.003
146.405	0.003	0.003	0.003	0.003	0.003	0.003	0.003
147.091	0.003	0.003	0.003	0.003	0.003	0.003	0.003
147.777	0.003	0.003	0.003	0.003	0.003	0.003	0.003
148.463	0.003	0.003	0.003	0.003	0.003	0.003	0.002
149.149	0.002	0.002	0.002	0.002	0.002	0.002	0.002
149.835	0.002	0.002	0.002	0.002	0.002	0.002	0.002
150.521	0.002	0.002	0.002	0.002	0.002	0.002	0.002
151.207	0.002	0.002	0.002	0.002	0.002	0.002	0.002
151.893	0.002	0.002	0.002	0.002	0.002	0.002	0.002
152.579	0.002	0.002	0.002	0.002	0.002	0.002	0.002
153.265	0.002	0.002	0.002	0.002	0.002	0.002	0.002
153.951	0.002	0.002	0.002	0.002	0.002	0.002	0.002
154.637	0.002	0.002	0.002	0.002	0.002	0.002	0.002
155.323	0.002	0.002	0.002	0.002	0.002	0.002	0.002
156.009	0.002	0.002	0.002	0.002	0.002	0.002	0.002
156.695	0.002	0.002	0.002	0.002	0.002	0.002	0.002
157.381	0.002	0.002	0.002	0.002	0.002	0.002	0.002
158.067	0.002	0.002	0.002	0.002	0.002	0.002	0.002
158.753	0.002	0.002	0.002	0.002	0.002	0.002	0.002
159.439	0.002	0.002	0.002	0.002	0.002	0.002	0.002
160.125	0.002	0.002	0.002	0.002	0.002	0.002	0.002
160.811	0.002	0.002	0.002	0.002	0.002	0.002	0.002
161.497	0.002	0.002	0.002	0.002	0.002	0.002	0.002
162.183	0.002	0.002	0.002	0.002	0.002	0.002	0.002
162.869	0.002	0.002	0.002	0.002	0.002	0.002	0.002
163.555	0.002	0.002	0.002	0.002	0.002	0.002	0.002
164.241	0.002	0.002	0.002	0.002	0.002	0.002	0.002
164.927	0.002	0.002	0.002	0.002	0.002	0.001	0.001
165.613	0.001	0.001	0.001	0.001	0.001	0.001	0.001
166.299	0.001	0.001	0.001	0.001	0.001	0.001	0.001
166.985	0.001	0.001	0.001	0.001	0.001	0.001	0.001
167.671	0.001	0.001	0.001	0.001	0.001	0.001	0.001
168.357	0.001	0.001	0.001	0.001	0.001	0.001	0.001
169.043	0.001	0.001	0.001	0.001	0.001	0.001	0.001
169.729	0.001	0.001	0.001	0.001	0.001	0.001	0.001
170.415	0.001	0.001	0.001	0.001	0.001	0.001	0.001
171.101	0.001	0.001	0.001	0.001	0.001	0.001	0.001
171.787	0.001	0.001	0.001	0.001	0.001	0.001	0.001
172.473	0.001	0.001	0.001	0.001	0.001	0.001	0.001
173.159	0.001	0.001	0.001	0.001	0.001	0.001	0.001
173.845	0.001	0.001	0.001	0.001	0.001	0.001	0.001
174.531	0.001	0.001	0.001	0.001	0.001	0.001	0.001
175.217	0.001	0.001	0.001	0.001	0.001	0.001	0.001
175.903	0.001	0.001	0.001	0.001	0.001	0.001	0.001
176.589	0.001	0.001	0.001	0.001	0.001	0.001	0.001
177.275	0.001	0.001	0.001	0.001	0.001	0.001	0.001
177.961	0.001	0.001	0.001	0.001	0.001		

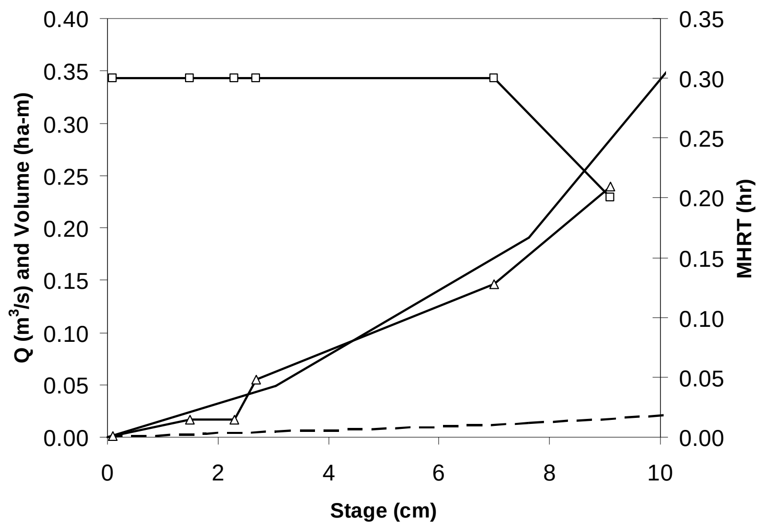
Appendix G: Stage-Storage-Discharge Relationships



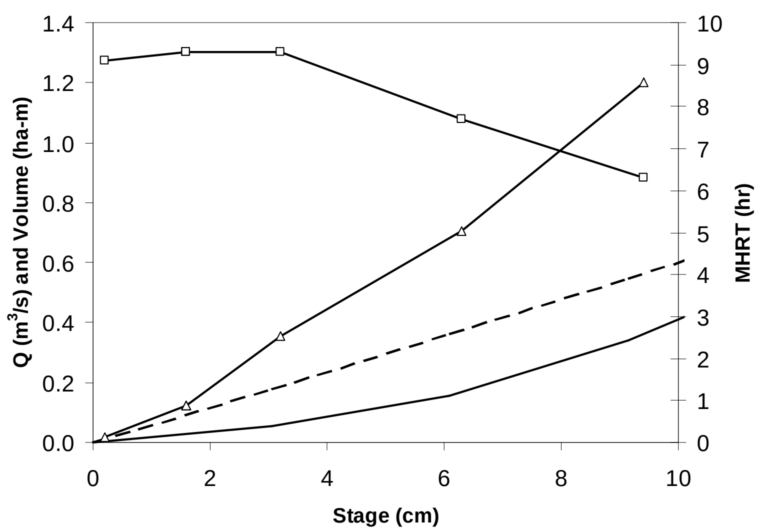
Q (m^3/s)	Stage (cm)	Storage (ha-m)
0.00	0.0	0.000
4.86	15.2	0.273
13.76	30.5	0.648
38.92	61.0	1.702



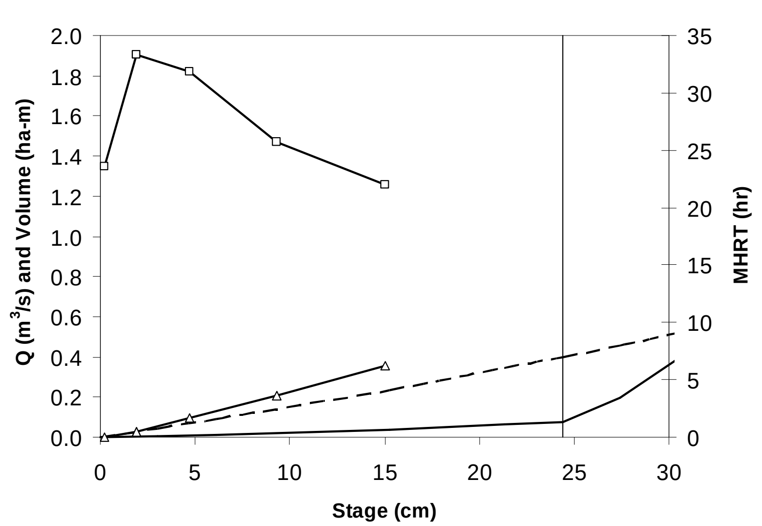
Q (m^3/s)	Stage (cm)	Storage (ha-m)
0.000	0.0	0.000
0.006	3.0	0.012
0.017	6.1	0.025
0.020	9.1	0.038
0.031	21.3	0.092
0.034	**38.1**	**0.173**
0.056	42.7	0.197
0.836	54.9	0.262



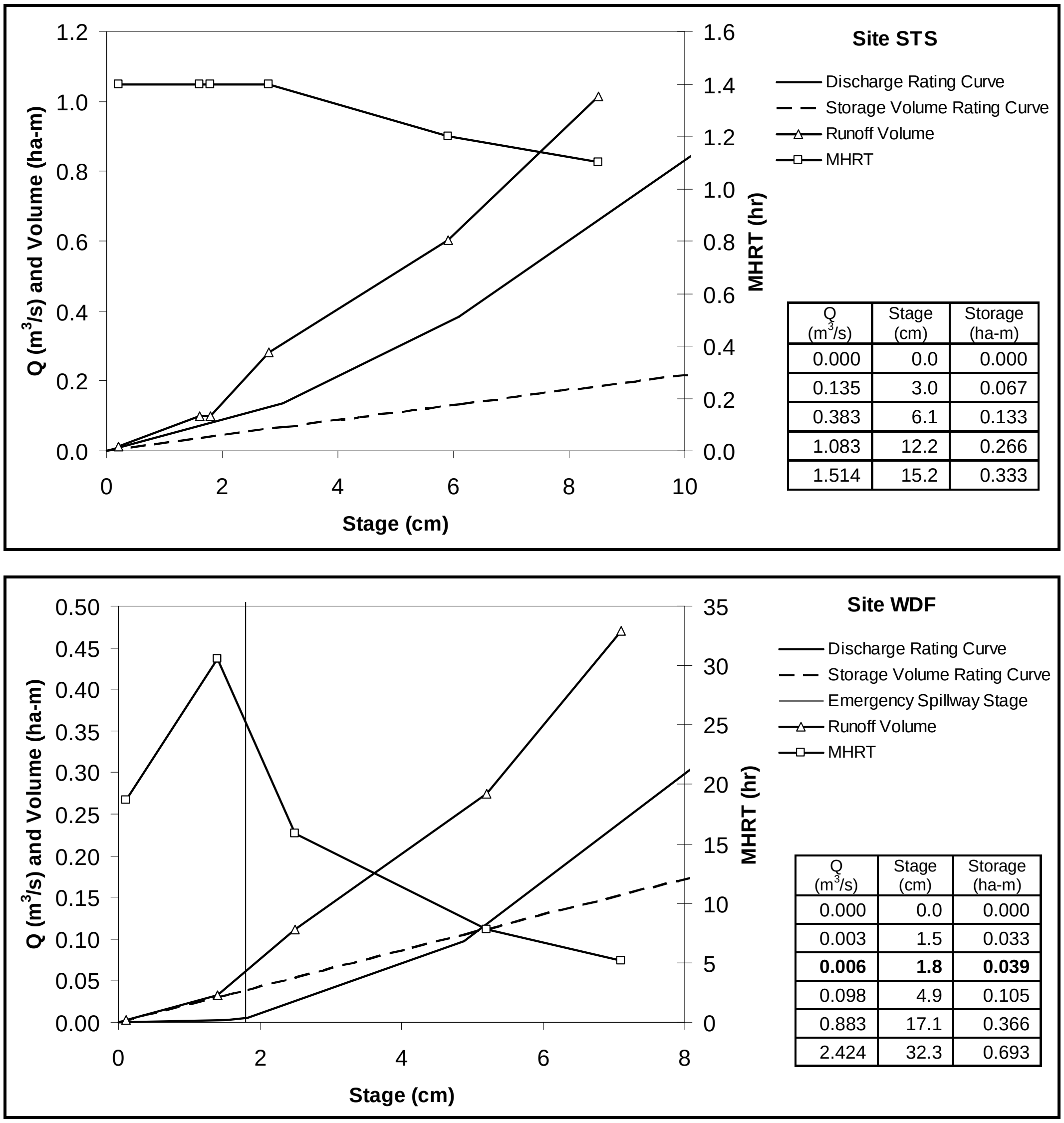
Q (m³/s)	Stage (cm)	Storage (ha-m)
0.000	0.0	0.000
0.048	3.0	0.005
0.191	7.6	0.014
0.676	15.2	0.037



Q (m³/s)	Stage (cm)	Storage (ha-m)
0.000	0.0	0.000
0.053	3.0	0.179
0.155	6.1	0.361
0.342	9.1	0.548
0.591	12.2	0.739
0.888	15.2	0.935
2.911	30.5	1.974



Q (m³/s)	Stage (cm)	Storage (ha-m)
0.000	0.0	0.000
0.003	3.0	0.043
0.009	6.1	0.088
0.037	15.2	0.235
0.062	21.3	0.343
0.075	**24.4**	**0.400**
0.197	27.4	0.459
0.392	30.5	0.520



Site STS

Q (m^3/s)	Stage (cm)	Storage (ha-m)
0.000	0.0	0.000
0.135	3.0	0.067
0.383	6.1	0.133
1.083	12.2	0.266
1.514	15.2	0.333

Site WDF

Q (m^3/s)	Stage (cm)	Storage (ha-m)
0.000	0.0	0.000
0.003	1.5	0.033
0.006	**1.8**	**0.039**
0.098	4.9	0.105
0.883	17.1	0.366
2.424	32.3	0.693

Figure G1. Stage-storage-discharge relationships for the seven study sites. For sites with two-stage outlets, a vertical line is shown to represent the stage of the emergency spillway, and the values at the vertical lines are in bold type in the associated table.

Appendix H: Additional Hydrologic and Hydraulic Analysis Results

Table H1. Additional results of storm analysis with WinTR-20 and other hydraulic characteristics of sites. See Table 3 for other results of analysis. Storm abbreviations are: CI = constant intensity; T2 = Type II. ARC = Antecedent runoff condition. Storms are listed in order of increasing peak inflow. Variable definitions provided at end of table.

	Design Storm	CON	GLP	GPT	SPF	STN	STS	WDF
Runoff Intensity (mm/hr)	½-in 1-hr CI ARC3	0.16	0.31	0.06	0.19	0.19	0.13	0.04
	1-in 4-hr CI ARC3	0.79	1.13	0.69	0.88	1.06	0.72	0.56
	1-in 1-hr CI ARC3	1.05	1.66	0.99	1.23	1.82	0.96	0.74
	1-yr 24-hr T2 ARC2	1.11	1.37	0.81	1.17	1.14	1.00	0.80
	1-yr 24-hr T2 ARC3	1.80	2.01	1.82	1.87	2.02	1.76	1.69
	10-yr 24-hr T2 ARC2	3.21	3.70	3.13	3.37	3.68	3.12	2.99
Inflow Duration (hr)	½-in 1-hr CI ARC3	6.7	4.6	2.9	5.7	2.3	6.4	4.3
	1-in 4-hr CI ARC3	9.2	7.2	5.6	8.2	4.7	8.9	6.9
	1-in 1-hr CI ARC3	6.9	4.9	3.9	5.9	2.8	6.7	5.2
	1-yr 24-hr T2 ARC2	18.7	17.1	15.0	17.8	14.2	18.3	16.4
	1-yr 24-hr T2 ARC3	23.0	21.6	17.8	22.2	17.7	22.4	19.1
	10-yr 24-hr T2 ARC2	22.0	20.4	17.0	21.0	16.8	21.2	18.5
Outflow Duration (hr)	½-in 1-hr CI ARC3	6.7	34.1	3.1	50.5	67.9	11.2	49.7
	1-in 4-hr CI ARC3	9.2	44.8	5.9	69.6	156.0	15.6	149.7
	1-in 1-hr CI ARC3	6.9	43.7	4.4	68.4	155.0	13.4	149.0
	1-yr 24-hr T2 ARC2	18.8	57.5	15.2	81.3	195.3	23.1	166.4
	1-yr 24-hr T2 ARC3	23.0	67.0	17.8	88.5	213.4	27.6	169.1
	10-yr 24-hr T2 ARC2	22.0	67.9	17.0	89.8	222.0	27.1	169.8
Δ Flow Duration (hr)	½-in 1-hr CI ARC3	0.0	29.5	0.2	44.8	69.8	4.8	45.4
	1-in 4-hr CI ARC3	0.0	37.6	0.3	61.4	428.4	6.7	142.8
	1-in 1-hr CI ARC3	0.0	38.8	0.5	62.5	429.6	6.7	143.8
	1-yr 24-hr T2 ARC2	0.1	40.4	0.2	63.5	591.7	4.8	150.0
	1-yr 24-hr T2 ARC3	0.0	45.4	0.0	66.3	705.2	5.2	150.0
	10-yr 24-hr T2 ARC2	0.0	47.5	0.0	68.8	771.0	5.9	151.3
ΔT_O (hr)	½-in 1-hr CI ARC3	0.0	29.5	0.2	44.8	69.8	4.8	45.4
	1-in 4-hr CI ARC3	0.0	36.1	0.3	61.4	428.4	6.7	142.8
	1-in 1-hr CI ARC3	0.0	37.3	0.5	62.5	429.6	6.7	143.8
	1-yr 24-hr T2 ARC2	0.1	39.0	0.2	63.5	591.7	4.8	150.0
	1-yr 24-hr T2 ARC3	0.0	44.1	0.0	66.3	705.2	5.2	150.0
	10-yr 24-hr T2 ARC2	0.0	46.3	0.0	68.8	771.0	5.9	151.3

Table H1 (continued)

	CON	GLP	GPT	SPF	STN	STS	WDF
Mean Depth (m)	0.30	0.39	0.19	0.50	0.36	0.26	0.56
Approximate Dead Storage Volume (ha-m)	0.45	0.15	0.02	2.88	0.51	0.58	1.17

Variable Definitions

Inflow Duration (hr) – Duration of time the wetland receives runoff. Calculated from TR-20 watershed hydrograph as: time of last flow value - time of first flow value.

Outflow Duration (hr) – Duration of time wetland outlet has flow from the design storm event. Calculated from TR-20 outlet hydrograph as: time of last flow value - time of first flow value.

Δ Flow Duration (hr) – Difference between outflow and inflow duration, calculated as: outflow duration (hr) - inflow duration (hr).

Mean Depth (m) – Mean depth of water in wetland when water surface is at normal pool elevation. Calculated from individual depths at sample locations.

Approximate Dead Storage Volume (ha-m) – Approximate volume of wetland between ground surface and normal pool elevation. Calculated as: mean depth (m) x wetland area (ha).

Appendix I: Results of Regression Analyses of HRT and RWW

Table I1. HRT and RWW linear regression analysis goodness of fit statistics, with qualitative assessment of measurements.

Statistic	Log(Mean MHRT) vs Log(Mean NHRT)		1-in 4-hr ARC3 Log(MHRT) vs RWW	
R	0.999	good	0.689	fair
R^2	0.998	good	0.475	fair
y□	0.459		0.504	
S_y	0.888		0.933	
S_e	0.046		0.740	
S_e/S_y	0.052	good	0.793	poor
b_0	-0.633		-0.377	
$S_e(b_0)$	0.029		0.499	
$S_e(b_0)/b_0$	0.046	good	1.324	poor
b_1	0.978		5.432	
$S_e(b_1)$	0.021		2.553	
$S_e(b_1)/b_1$	0.021	good	0.470	fair
e□	0.000		0.000	
e□/y□	0.000	good	0.000	good

Criteria for qualitative assessment.

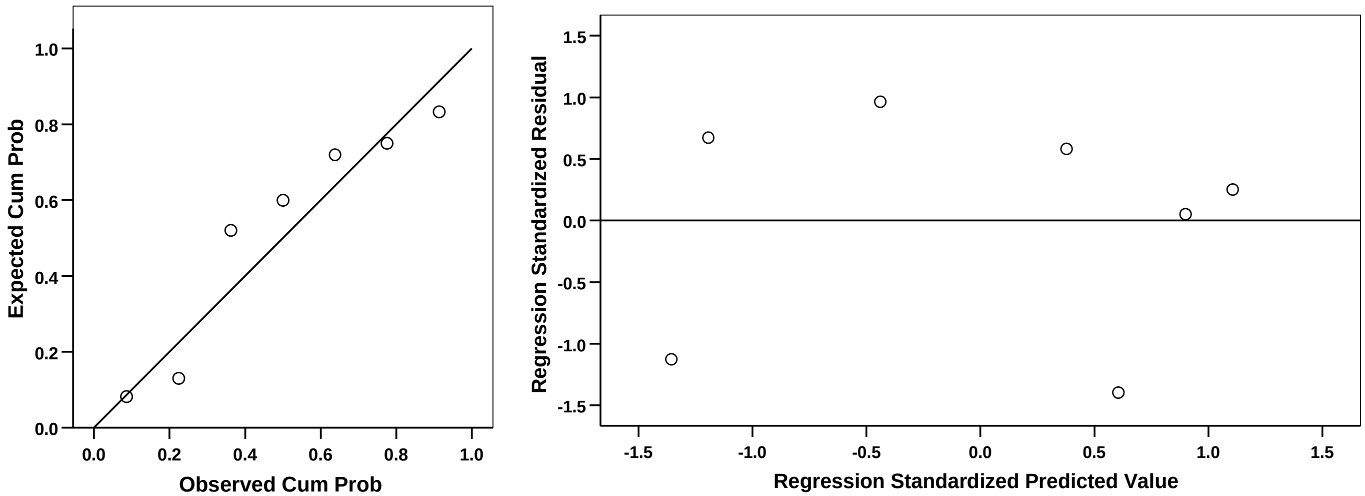
Statistic	good	fair	poor
R	≥ 0.84	$0.55 \leq R < 0.84$	< 0.55
R^2	≥ 0.7	$0.3 \leq R^2 < 0.7$	< 0.3
S_e/S_y	≤ 0.3	$0.3 < S_e/S_y \leq 0.7$	> 0.7
$S_e(b)/b$	≤ 0.3	$0.3 < S_e(b)/b \leq 0.5$	> 0.5
e□/y□	≤ 0.05	0.05 < e□/y□ ≤ 0.10	> 0.10

Regression equation model: $y = b_0 + xb_1$

Table I2. Hypothesis test on slope coefficient (H_O: $b_1 = 0$, H_A: $b_1 \neq 0$).

Regression Model	n	t	$\alpha = .05$		$\alpha = .01$	
			$t_{\alpha/2}$	Decision	$t_{\alpha/2}$	Decision
Log(Mean MHRT) vs. Log(Mean NHRT)	7	46.571	2.571	reject H_O	4.032	reject H_O
1-in 4-hr ARC3 Log(MHRT) vs RWW	7	2.128	2.571	accept H_O	4.032	accept H_O

Log(Mean MHRT) vs Log(Mean NHRT)



1-in 4-hr ARC3 Log(MHRT) vs RWW

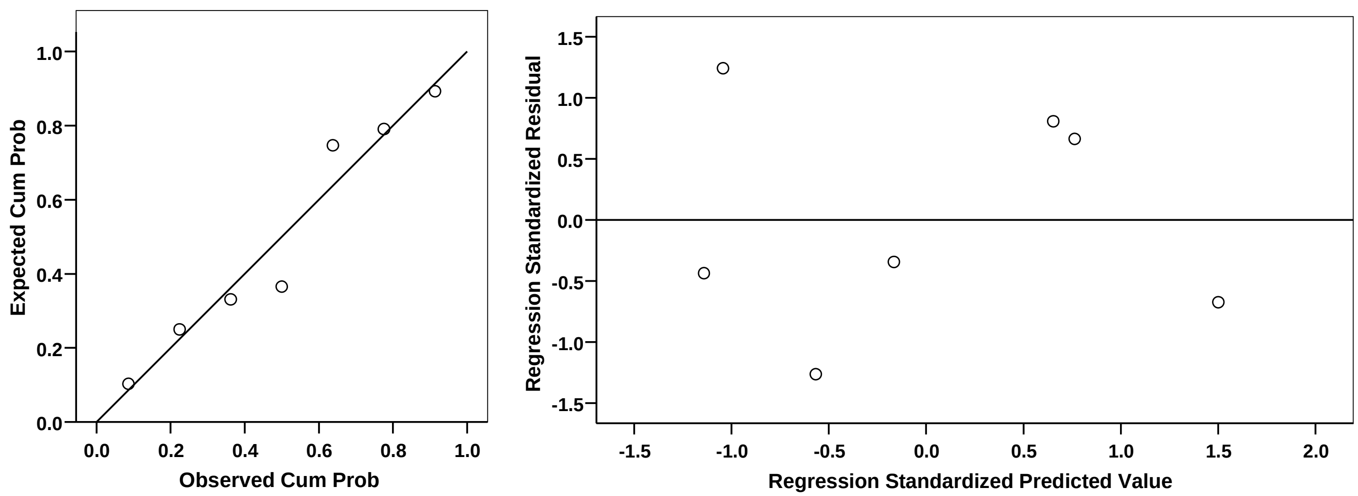


Figure I1. Residual plots for regression analysis of the log-transformed mean MHRT versus the log-transformed mean NHRT and the log-transformed MHRT for the 1-in 4-hr ARC3 design storm versus RWW.

Appendix J: Results of Regression Analyses of Measured and Modeled Variables

Table J1. Linear regression analysis goodness of fit statistics for TP versus hydrologic variables, with qualitative assessment of measurements. Where n = 6, site STN was excluded.

Statistic	Log(Mean TP) vs. 10-yr 24-hr ARC2 Log(MHRT) n=7		Log(Mean TP) vs. 10-yr 24-hr ARC2 Log(NHRT) n=7		Log(Mean TP) vs. RWW n=7		Mean TP vs. RWW n=6		Mean TP vs. 10-yr 24-hr ARC2 MHRT n=6		Mean TP vs. 10-yr 24-hr ARC2 NHRT n=6	
R	0.653	fair	0.683	fair	0.666	fair	0.931	good	0.448	poor	0.567	fair
R^2	0.426	fair	0.467	fair	0.444	fair	0.867	good	0.200	poor	0.322	fair
y□	-0.105		-0.105		-0.105		0.713		0.713		0.713	
S_y	0.139		0.139		0.139		0.109		0.117		0.117	
S_e	0.116		0.112		0.114		0.048		0.117		0.108	
S_e/S_y	0.835	poor	0.806	poor	0.820	poor	0.407	fair	1.000	poor	0.923	poor
b_0	-0.141		-0.230		-0.232		0.582		0.657		0.653	
$S_e(b_0)$	0.047		0.073		0.077		0.032		0.074		0.062	
$S_e(b_0)/b_0$	0.333	fair	0.317	fair	0.332	fair	0.055	good	0.113	good	0.095	good
b_1	0.114		0.114		0.785		0.877		0.018		0.003	
$S_e(b_1)$	0.059		0.055		0.393		0.171		0.018		0.002	
$S_e(b_1)/b_1$	0.518	poor	0.482	fair	0.501	poor	0.195	good	1.000	poor	0.667	poor
e□	0.000		0.000		0.000		0.000		0.000		0.000	
e□/y□	0.000	good	0.000	good	0.000	good	0.000	good	0.000	good	0.000	good

Criteria for qualitative assessment.

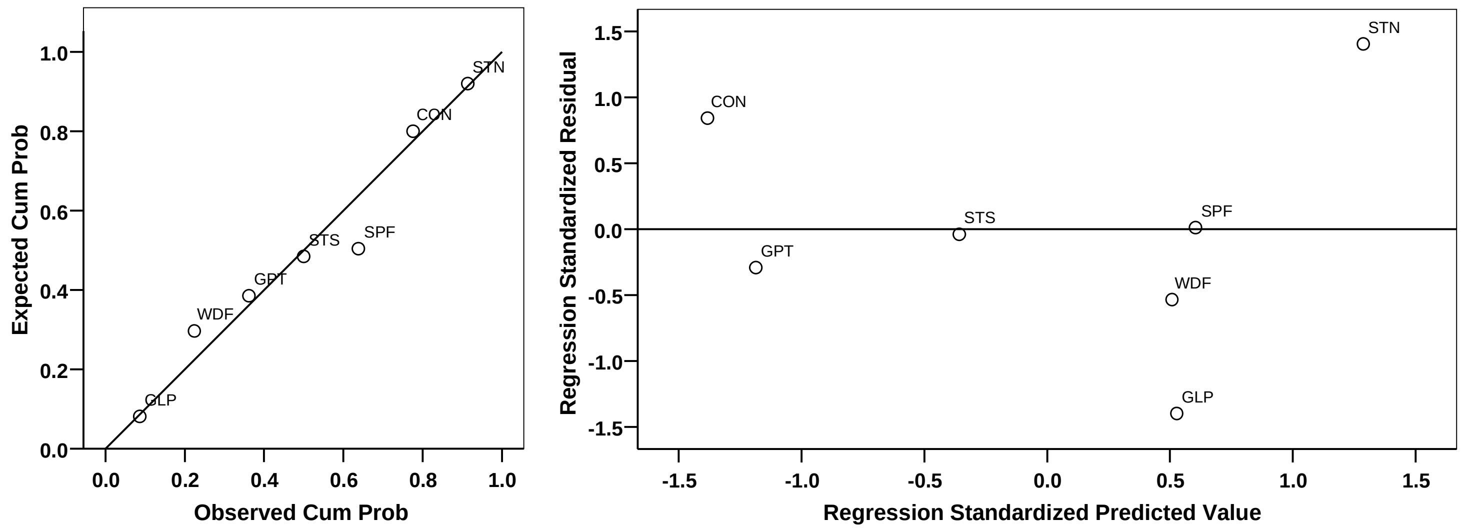
Statistic	good	fair	poor
R	≥ 0.84	$0.55 \leq R < 0.84$	< 0.55
R^2	≥ 0.7	$0.3 \leq R^2 < 0.7$	< 0.3
S_e/S_y	≤ 0.3	$0.3 < S_e/S_y \leq 0.7$	> 0.7
$S_e(b)/b$	≤ 0.3	$0.3 < S_e(b)/b \leq 0.5$	> 0.5
e□/y□	≤ 0.05	0.05 < e□/y□ ≤ 0.10	> 0.10

Regression equation model: $y = b_0 + xb_1$

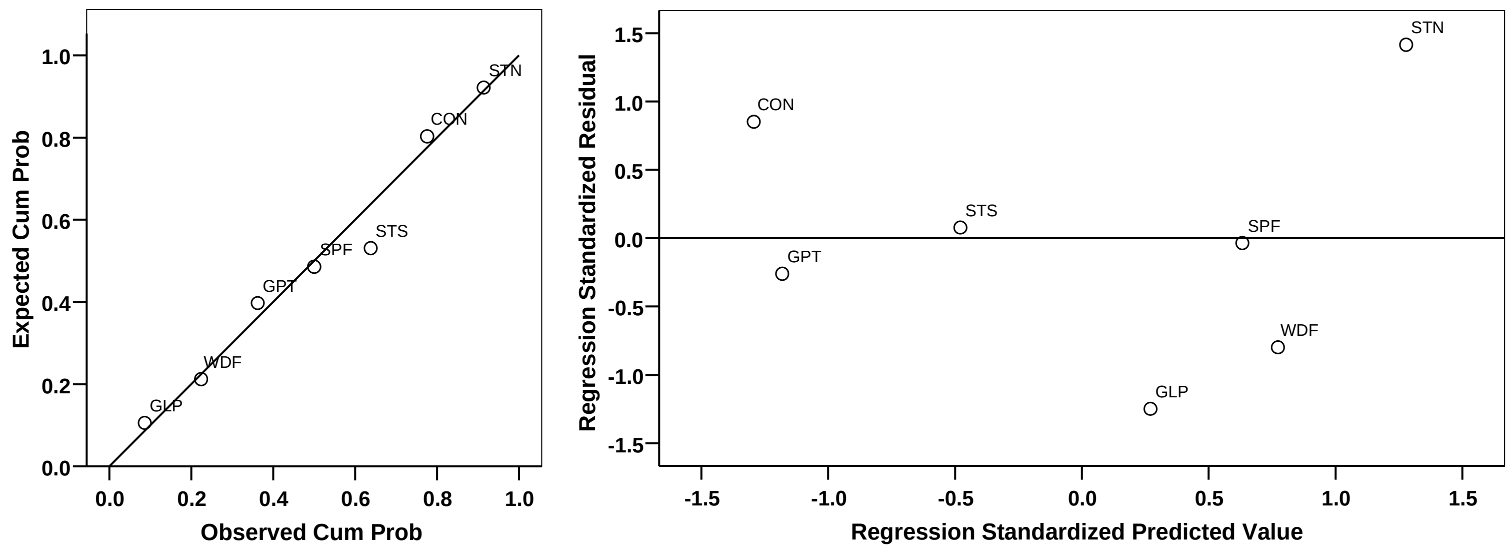
Table J2. Hypothesis test on slope coefficient (H_O: $b_1 = 0$, H_A: $b_1 \neq 0$). Where n = 6, site STN was excluded.

Regression Model	n	t	p	α = .05		α = .01	
				$t_{\alpha/2}$	Decision	$t_{\alpha/2}$	Decision
Log(Mean TP) vs. 10-yr 24-hr ARC2 Log(MHRT)	7	1.932	0.115	2.571	accept H_O	4.032	accept H_O
Log(Mean TP) vs. 10-yr 24-hr ARC2 Log(NHRT)	7	2.073	0.095	2.571	accept H_O	4.032	accept H_O
Log(Mean TP) vs. RWW	7	1.997	0.103	2.571	accept H_O	4.032	accept H_O
Mean TP vs. RWW	6	5.129	0.008	2.776	reject H_O	4.604	reject H_O
Mean TP vs. 10-yr 24-hr ARC2 MHRT	6	1.000	> 0.200	2.776	accept H_O	4.604	accept H_O
Mean TP vs. 10-yr 24-hr ARC2 NHRT	6	1.500	> 0.200	2.776	accept H_O	4.604	accept H_O

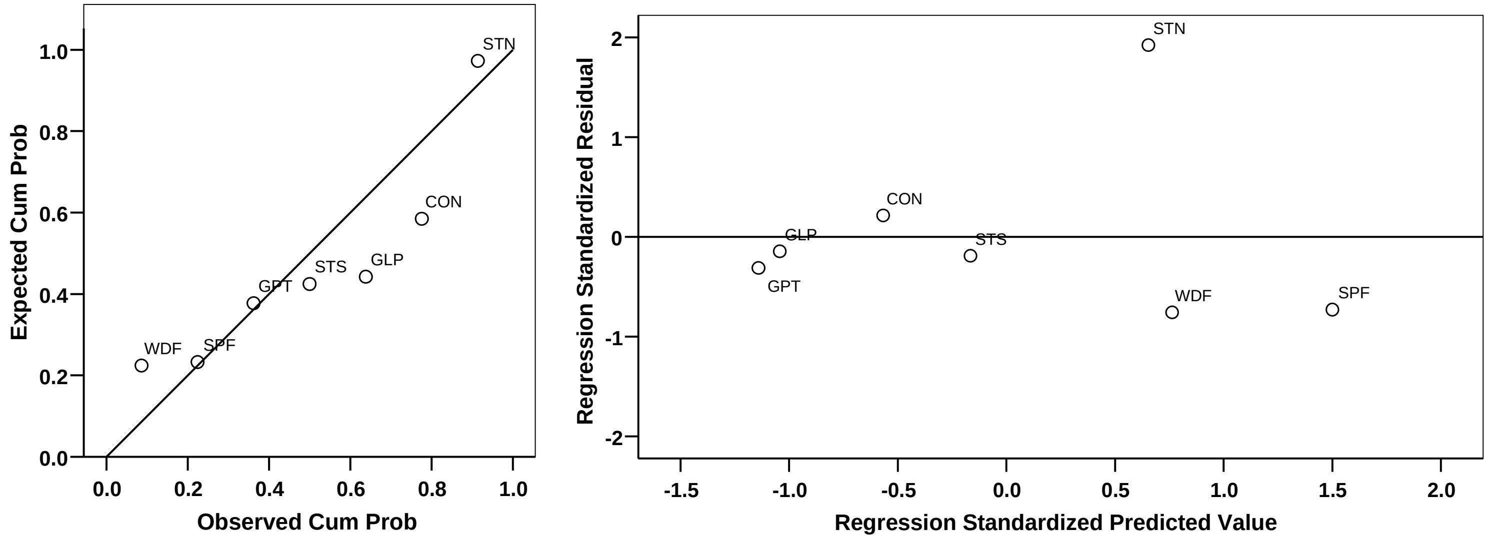
Log(Mean TP) vs 10-yr 24-hr ARC2 Log(MHRT) (n=7)



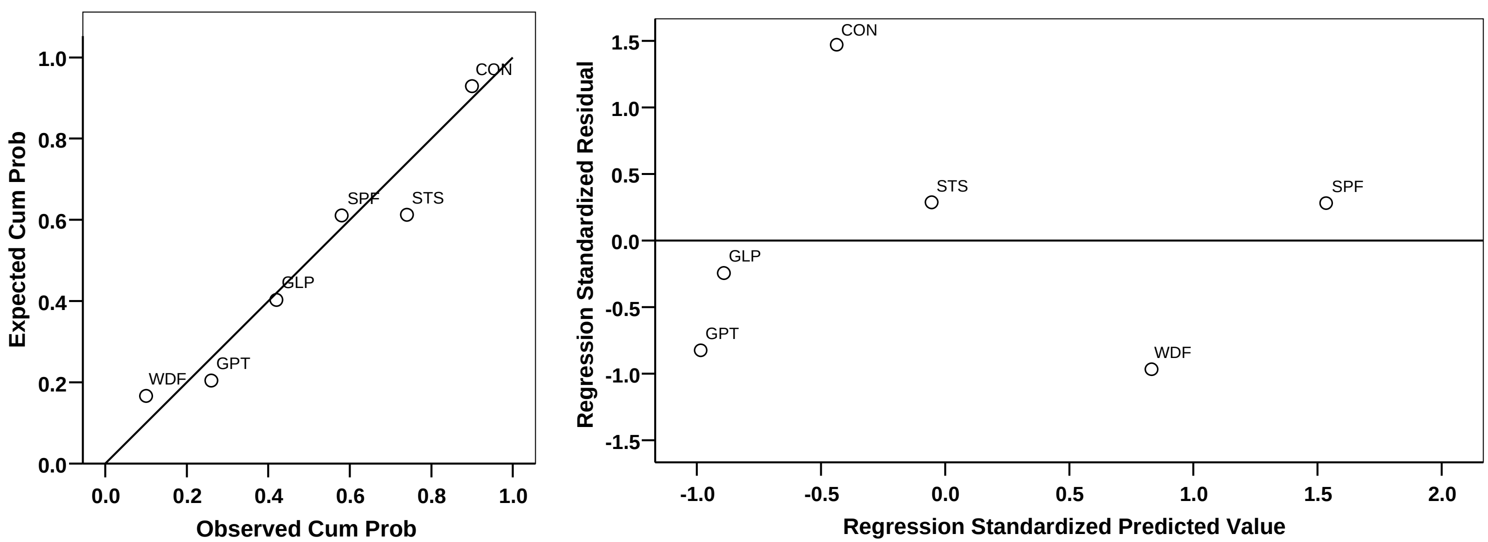
Log(Mean TP) vs 10-yr 24-hr ARC2 Log(NHRT) (n=7)



Log(Mean TP) vs RWW (n=7)



Mean TP vs RWW (n=6)



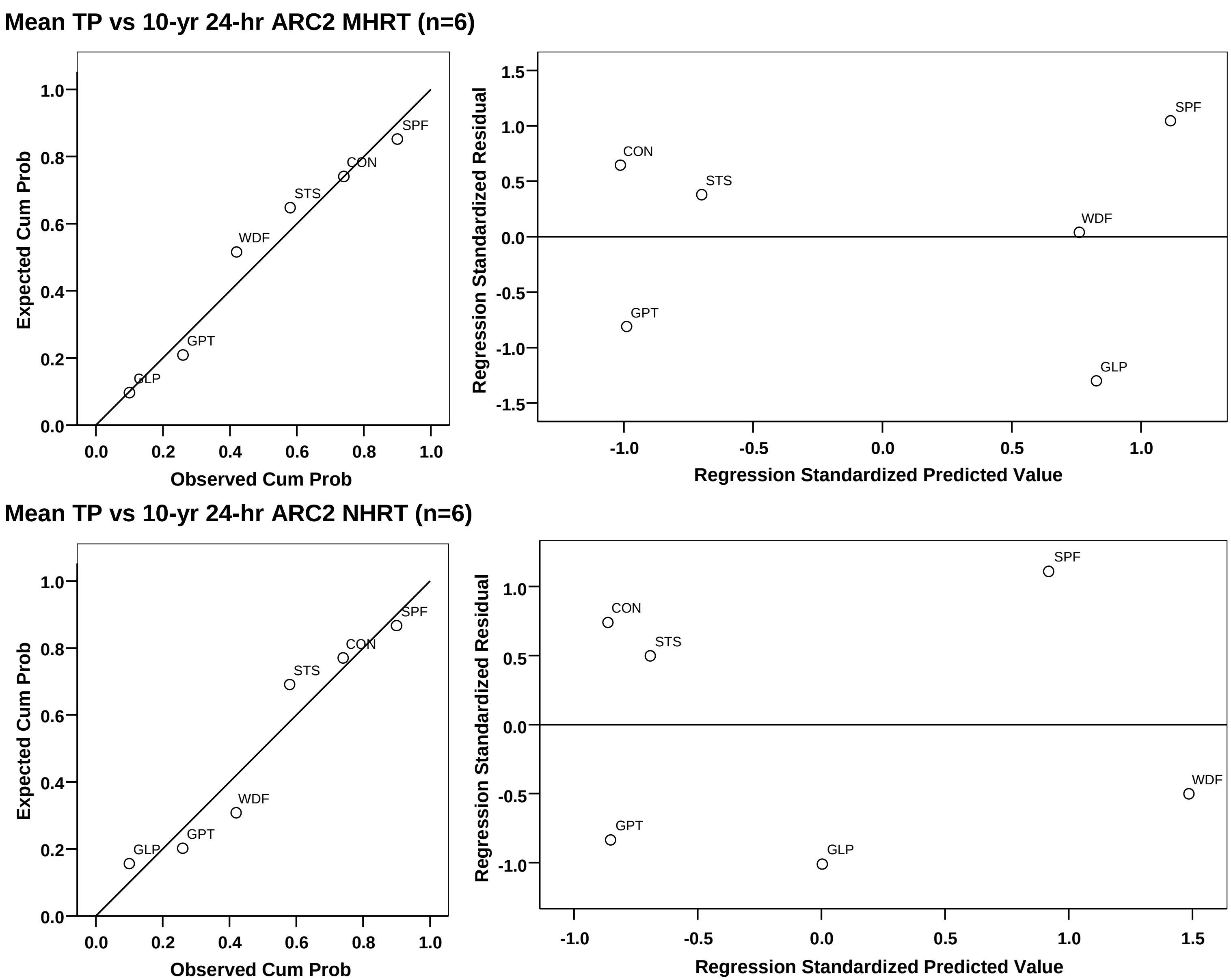


Figure J1. Graphs for analysis of residuals for regression of mean TP on HRT and RWW.

Appendix K: Results of Tests for Normality

Table K1. One-sample Kolmogorov-Smirnov tests for a normal distribution for MHRT, NHRT, and log-transformed values of both variables for each design storm for all sites.

½-in 1-hr Design Storm		MHRT (hr)	Log(MHRT)	NHRT (hr)	Log(NHRT)
N		7	7	7	7
Normal Parameters(a,b)	Mean	8.4529	.4556	25.8943	.9586
	Std. Deviation	9.35049	.86729	25.85157	.87596
Most Extreme Differences	Absolute	.204	.215	.225	.265
	Positive	.204	.160	.225	.188
	Negative	-.188	-.215	-.164	-.265
Kolmogorov-Smirnov Z		.539	.569	.594	.701
Asymp. Sig. (2-tailed)		.934	.902	.872	.710
1-in 4-hr Design Storm		MHRT (hr)	Log(MHRT)	NHRT (hr)	Log(NHRT)
N		7	7	7	7
Normal Parameters(a,b)	Mean	11.5357	.5037	52.9029	1.1260
	Std. Deviation	14.35707	.93253	62.23485	1.01436
Most Extreme Differences	Absolute	.275	.177	.213	.213
	Positive	.275	.157	.213	.170
	Negative	-.214	-.177	-.200	-.213
Kolmogorov-Smirnov Z		.728	.468	.563	.564
Asymp. Sig. (2-tailed)		.663	.981	.909	.908
1-in 1-hr Design Storm		MHRT (hr)	Log(MHRT)	NHRT (hr)	Log(NHRT)
N		7	7	7	7
Normal Parameters(a,b)	Mean	11.5557	.5034	53.1771	1.1432
	Std. Deviation	14.34443	.93674	62.27767	.99234
Most Extreme Differences	Absolute	.276	.181	.214	.217
	Positive	.276	.153	.214	.167
	Negative	-.213	-.181	-.199	-.217
Kolmogorov-Smirnov Z		.730	.479	.565	.573
Asymp. Sig. (2-tailed)		.661	.976	.907	.898
1-yr 24-hr ARC2 Design Storm		MHRT (hr)	Log(MHRT)	NHRT (hr)	Log(NHRT)
N		7	7	7	7
Normal Parameters(a,b)	Mean	9.6343	.4856	43.0857	1.1236
	Std. Deviation	11.38215	.89647	51.68452	.89549
Most Extreme Differences	Absolute	.226	.264	.214	.233
	Positive	.226	.162	.214	.162
	Negative	-.203	-.264	-.207	-.233
Kolmogorov-Smirnov Z		.598	.699	.566	.617
Asymp. Sig. (2-tailed)		.867	.713	.906	.841

Table K1 (continued)

1-yr 24-hr ARC3 Design Storm		MHRT (hr)	Log(MHRT)	NHRT (hr)	Log(NHRT)
N		7	7	7	7
Normal Parameters(a,b)	Mean	7.2800	.3967	42.7857	1.1648
	Std. Deviation	8.92941	.84653	51.72590	.83470
Most Extreme Differences	Absolute	.320	.290	.210	.224
	Positive	.320	.167	.191	.166
	Negative	-.213	-.290	-.210	-.224
Kolmogorov-Smirnov Z		.846	.768	.556	.592
Asymp. Sig. (2-tailed)		.472	.596	.917	.875
10-yr 24-hr ARC2 Design Storm		MHRT (hr)	Log(MHRT)	NHRT (hr)	Log(NHRT)
N		7	7	7	7
Normal Parameters(a,b)	Mean	5.7729	.3121	38.5243	1.0950
	Std. Deviation	7.63422	.80154	51.28821	.83364
Most Extreme Differences	Absolute	.332	.266	.232	.178
	Positive	.332	.168	.232	.167
	Negative	-.231	-.266	-.232	-.178
Kolmogorov-Smirnov Z		.879	.703	.615	.471
Asymp. Sig. (2-tailed)		.422	.706	.844	.980

a Test distribution is Normal.
b Calculated from data.

Table K2. One-sample Kolmogorov-Smirnov test for mean MHRT and NHRT, log-transformed mean MHRT and NHRT, and RWW for each site.

		Mean MHRT (hr)	Log(Mean MHRT)	Mean NHRT (hr)	Log(Mean NHRT)	RWW
N		7	7	7	7	7
Normal Parameters(a,b)	Mean	9.0386	.4585	42.7286	1.1159	.1621
	Std. Deviation	10.60700	.88755	49.75295	.90669	.11835
Most Extreme Differences	Absolute	.234	.230	.203	.219	.172
	Positive	.234	.162	.203	.169	.143
	Negative	-.201	-.230	-.200	-.219	-.172
Kolmogorov-Smirnov Z		.620	.608	.537	.578	.455
Asymp. Sig. (2-tailed)		.837	.854	.935	.892	.986

a Test distribution is Normal.
b Calculated from data.

Table K3. One-Sample Kolmogorov-Smirnov Tests for paired differences in MHRT (hr) and NHRT (hr) at each site, as a precursor to paired samples T-test.

		CON	GLP	GPT	SPF	STN	STS	WDF
N		6	6	6	6	6	6	6
Normal Parameters(a,b)	Mean	-0.612	-22.113	-0.810	-37.660	-103.423	-3.923	-67.287
	Std. Deviation	0.247	4.162	0.342	5.721	29.074	0.524	31.039
Most Extreme Differences	Absolute	0.256	0.229	0.180	0.193	0.415	0.166	0.223
	Positive	0.194	0.229	0.159	0.193	0.415	0.161	0.208
	Negative	-0.256	-0.133	-0.180	-0.138	-0.254	-0.166	-0.223
Kolmogorov-Smirnov Z		0.628	0.562	0.440	0.472	1.017	0.407	0.547
Asymp. Sig. (2-tailed)		0.826	0.910	0.990	0.979	0.253	0.996	0.926

a Test distribution is Normal.
b Calculated from data.

Table K4. One-Sample Kolmogorov-Smirnov Tests for sample plot values of biomass, TN, TP, %N and %P at each site.

Site CON		Biomass (g/m^2)	TN (g/m^2)	TP (g/m^2)	%N	%P
N		10	8	10	8	10
Normal Parameters(a,b)	Mean	641.1000	4.65863	.73540	.7225	.1240
	Std. Dev.	304.84657	2.606138	.197867	.05676	.02675
Most Extreme Differences	Absolute	.243	.236	.197	.186	.189
	Positive	.243	.224	.197	.148	.115
	Negative	-.186	-.236	-.117	-.186	-.189
Kolmogorov-Smirnov Z		.769	.667	.622	.526	.597
Asymp. Sig. (2-tailed)		.595	.766	.834	.945	.868
Site GLP		Biomass (g/m^2)	TN (g/m^2)	TP (g/m^2)	%N	%P
N		10	10	10	10	10
Normal Parameters(a,b)	Mean	395.4000	3.12940	.60430	.9330	.1710
	Std. Dev.	337.57607	2.079547	.452172	.30670	.05405
Most Extreme Differences	Absolute	.212	.261	.276	.235	.217
	Positive	.200	.261	.276	.235	.217
	Negative	-.212	-.225	-.211	-.162	-.124
Kolmogorov-Smirnov Z		.669	.826	.872	.744	.686
Asymp. Sig. (2-tailed)		.762	.503	.432	.637	.735
Site GPT		Biomass (g/m^2)	TN (g/m^2)	TP (g/m^2)	%N	%P
N		10	10	10	10	10
Normal Parameters(a,b)	Mean	811.1000	4.05570	.56650	.5370	.0740
	Std. Dev.	427.68146	1.908184	.304790	.12499	.02633
Most Extreme Differences	Absolute	.162	.161	.176	.227	.210
	Positive	.159	.160	.176	.227	.210
	Negative	-.162	-.161	-.119	-.146	-.140
Kolmogorov-Smirnov Z		.513	.510	.556	.718	.664
Asymp. Sig. (2-tailed)		.955	.957	.917	.681	.771

Table K4 (continued)

Site SPF		Biomass (g/m^2)	TN (g/m^2)	TP (g/m^2)	%N	%P
N		10	10	10	10	10
Normal Parameters(a,b)	Mean	582.5000	3.32500	.89340	.6970	.1660
	Std. Dev.	246.45768	.899895	.364451	.43318	.07168
Most Extreme Differences	Absolute	.143	.177	.221	.306	.218
	Positive	.143	.141	.213	.306	.218
	Negative	-.077	-.177	-.221	-.180	-.145
Kolmogorov-Smirnov Z		.451	.560	.698	.969	.688
Asymp. Sig. (2-tailed)		.987	.913	.715	.305	.731
Site STN		Biomass (g/m^2)	TN (g/m^2)	TP (g/m^2)	%N	%P
N		10	10	10	10	10
Normal Parameters(a,b)	Mean	1116.5000	9.43560	1.49390	.8270	.1370
	Std. Dev.	480.59460	5.345275	.613168	.21135	.01947
Most Extreme Differences	Absolute	.196	.205	.164	.235	.161
	Positive	.163	.181	.164	.127	.119
	Negative	-.196	-.205	-.162	-.235	-.161
Kolmogorov-Smirnov Z		.619	.647	.517	.743	.510
Asymp. Sig. (2-tailed)		.838	.796	.952	.638	.957
Site STS		Biomass (g/m^2)	TN (g/m^2)	TP (g/m^2)	%N	%P
N		10	10	10	10	10
Normal Parameters(a,b)	Mean	423.4000	3.81570	.72070	.9340	.1840
	Std. Dev.	207.25518	1.920764	.333133	.29508	.07501
Most Extreme Differences	Absolute	.149	.204	.145	.265	.221
	Positive	.149	.204	.145	.265	.221
	Negative	-.146	-.136	-.112	-.204	-.131
Kolmogorov-Smirnov Z		.472	.645	.458	.838	.700
Asymp. Sig. (2-tailed)		.979	.800	.985	.484	.712
Site WDF		Biomass (g/m^2)	TN (g/m^2)	TP (g/m^2)	%N	%P
N		10	10	10	10	10
Normal Parameters(a,b)	Mean	666.7000	4.49110	.75740	.6750	.1180
	Std. Dev.	231.94302	1.589336	.244004	.10384	.02700
Most Extreme Differences	Absolute	.147	.221	.212	.257	.170
	Positive	.134	.186	.212	.257	.170
	Negative	-.147	-.221	-.086	-.156	-.130
Kolmogorov-Smirnov Z		.465	.699	.670	.814	.539
Asymp. Sig. (2-tailed)		.982	.713	.760	.521	.933

a Test distribution is Normal.
b Calculated from data.

Table K5. One-sample Kolmogorov-Smirnov tests for mean values of biomass, TN, TP, %N, %P, and log-transformed mean values of biomass, TN, and TP for all sites.

		Mean Biomass (g/m^2)	Mean %N	Mean TN (g/m^2)	Mean %P	Mean TP (g/m^2)	Log (Mean Biomass)	Log (Mean TN)	Log (Mean TP)
N		7	7	7	7	7	7	7	7
Normal Parameters(a,b)	Mean	662.3857	.7608	4.7013	.1391	2.7967	.6431	-.1052	.8245
	Std. Dev.	246.1654	.1455	2.1616	.0380	.1562	.1593	.1394	.3139
Most Extreme Differences	Absolute	.207	.175	.365	.189	.147	.294	.258	.299
	Positive	.207	.175	.365	.119	.147	.294	.258	.299
	Negative	-.139	-.167	-.234	-.189	-.135	-.177	-.155	-.206
Kolmogorov-Smirnov Z		.548	.464	.966	.499	.791	.390	.779	.684
Asymp. Sig. (2-tailed)		.924	.983	.309	.965	.559	.998	.578	.738

a Test distribution is Normal.
b Calculated from data.

Table K6. One-sample Kolmogorov-Smirnov tests for mean values of biomass, TN, and TP, and values of RWW for all sites excluding site STN.

		Mean Biomass (g/m^2)	Mean TN (g/m^2)	Mean TP (g/m^2)	RWW
N		6	6	6	6
Normal Parameters(a,b)	Mean	586.7000	3.9121	.7130	.1492
	Std. Dev.	156.84065	.61321	.11692	.12415
Most Extreme Differences	Absolute	.184	.164	.193	.188
	Positive	.184	.164	.185	.188
	Negative	-.156	-.161	-.193	-.163
Kolmogorov-Smirnov Z		.452	.402	.473	.461
Asymp. Sig. (2-tailed)		.987	.997	.979	.984

a Test distribution is Normal.
b Calculated from data.

Appendix L: Biomass Sample Collection and Handling

Table L1. Biomass sample collection and handling for each study site.

Site	Date Collected	Climatic Conditions	Date Transferred to Paper Bags	Date Transferred to Environmental Chamber	Environmental Chamber Temperature
CON	10/25/07	AM: Wind and light rain; PM: overcast	10/27/07	11/1/07	30.6° C
GLP	10/26/07	Steady rain all day	10/27/07	11/1/07	30.6° C
GPT	10/28/07	Sunny and windy	10/28/07	11/1/07	30.6° C
SPF	10/8/07	Sunny and dry	10/27/07	11/1/07	30.6° C
STN	11/11/07	Sunny with light breeze	11/11/07	11/14/07	2.8° C
STS	10/7/07	Sunny and dry	10/27/07	11/1/07	30.6° C
WDF	11/3/07	Overcast and windy	11/3/07	11/14/07	2.8° C

Figure L1. Photo of 1-m^2 quadrat frame used for biomass sampling.

Appendix M: Dixon-Thompson Outlier Test on TP

The Dixon-Thompson (Davis and McCuen 2005) outlier test was performed to determine if the mean TP for site STN could be considered an outlier. The test was performed on the log-transformed values of mean TP.

Ho: All sample points are from the same normal population.
Ha: The most extreme point in the sample is from either a population with a shifted mean or a population with the same mean but a larger variance.

Table M1. Data for Dixon-Thompson outier test on mean TP.

Site	i	Mean TP (g/m^2)	x = Log[mean TP (g/m^2)]	$\lvert x_i - \bar{x} \rvert$
GPT	1	0.57	-0.24	-0.14
GLP	2	0.60	-0.22	-0.12
STS	3	0.72	-0.14	-0.04
CON	4	0.74	-0.13	-0.03
WDF	5	0.76	-0.12	-0.01
SPF	6	0.89	-0.05	0.05
STN	7	1.49	0.17	0.28

$\bar{x} = -0.11$
$S_x = 0.14$
$n = 7$

High outlier test statistic for $3 \leq n \leq 7$:

$R = (x_n – x_{n-1}) / (x_n – x_1) = (0.17 – (-0.05)) / (0.17 – (-0.24)) = 0.536$

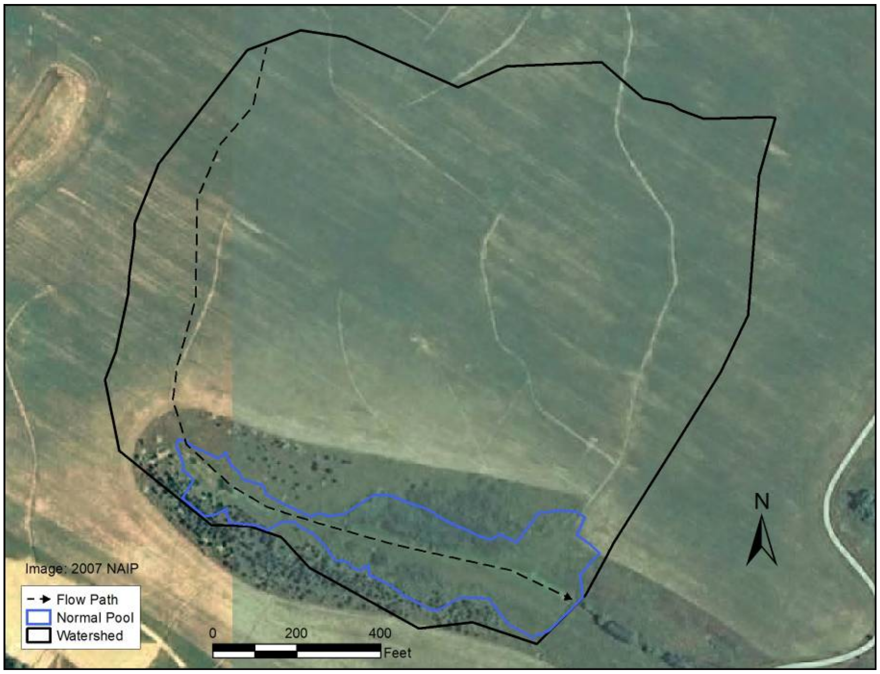
If $R > R_c$, reject H_o

$R_c(\alpha=0.05,n=7) = 0.503$ reject H_o
$R_c(\alpha=0.01,n=7) = 0.630$ accept H_o

$\therefore$ test is inconclusive

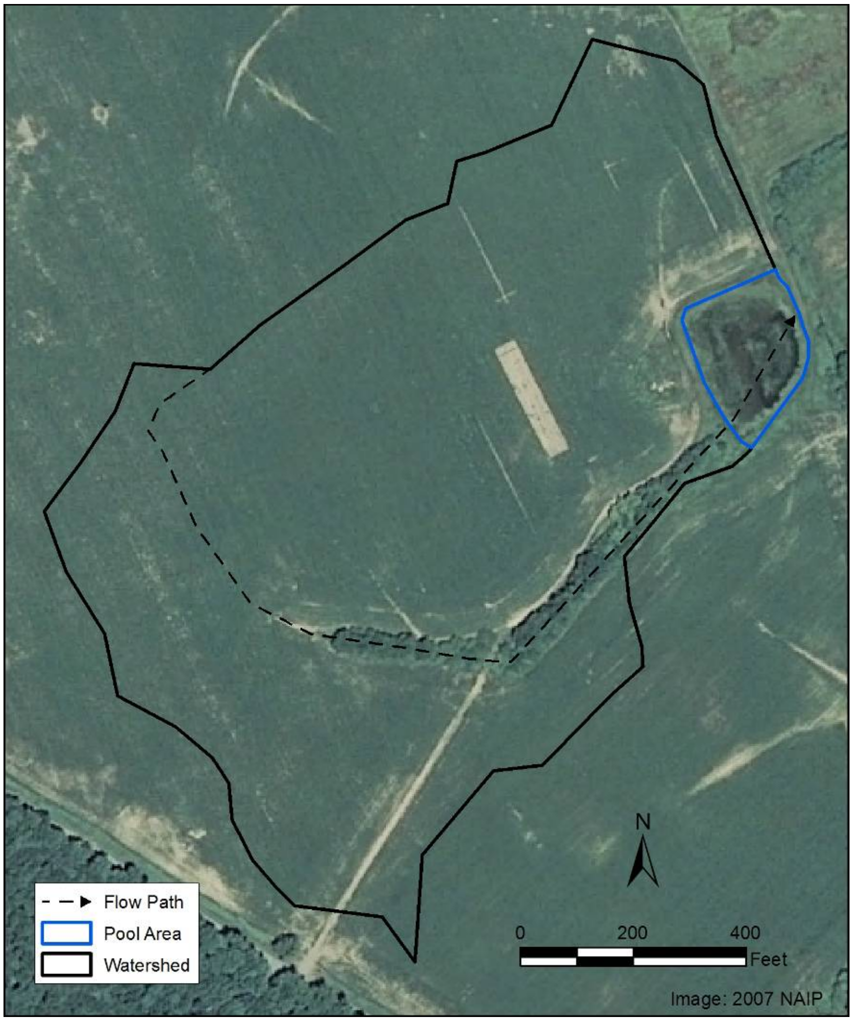
Appendix N: Study Site Photos

(a)



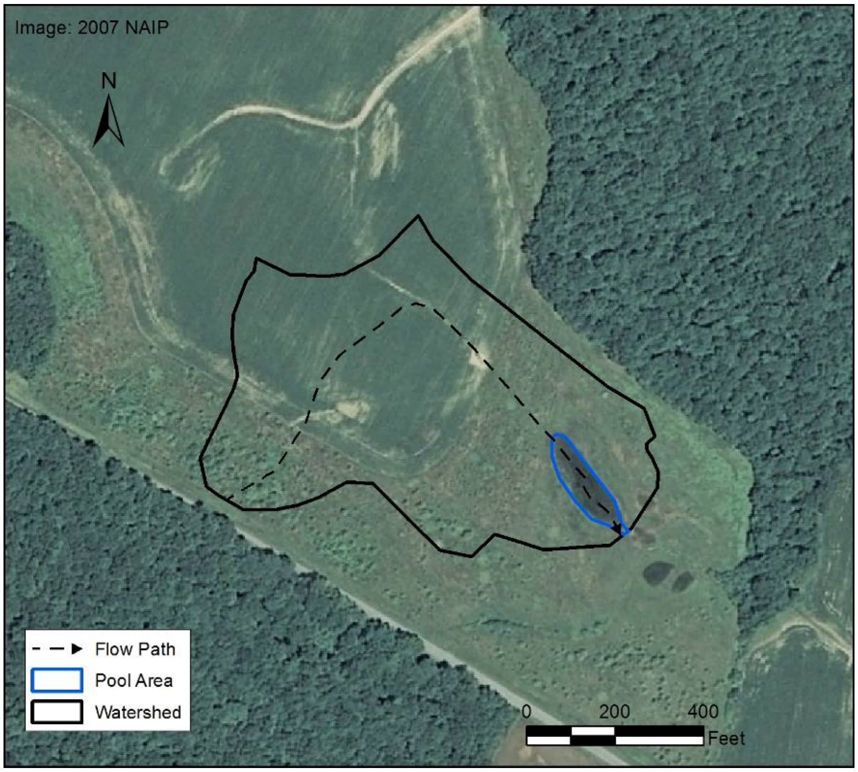
(b)

Figure N1. Site CON (a) aerial view with longest flow path, and wetland pool and watershed boundaries and (b) ground-level photo.

(a)


(b)


Figure N2. Site GLP (a) aerial view with longest flow path, and wetland pool and watershed boundaries and (b) ground-level photo.

(a)


(b)


Figure N3. Site GPT (a) aerial view with longest flow path, and wetland pool and watershed boundaries and (b) ground-level photo.

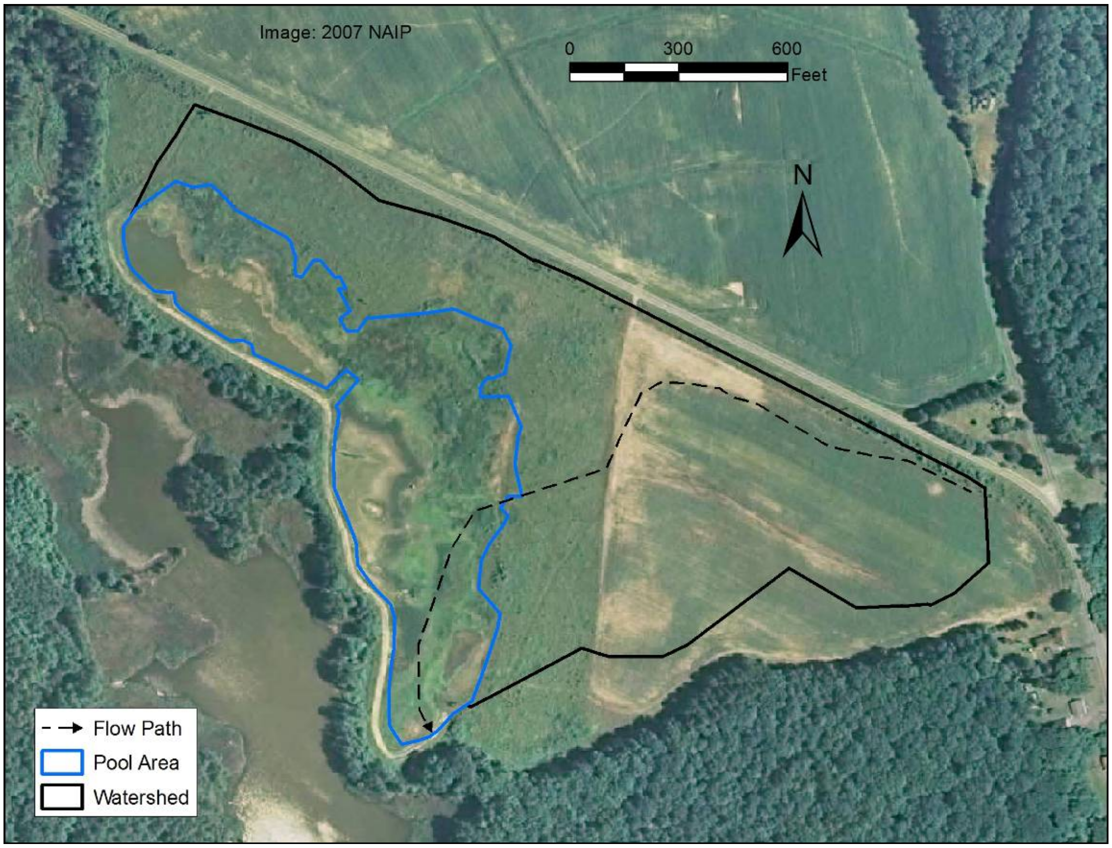
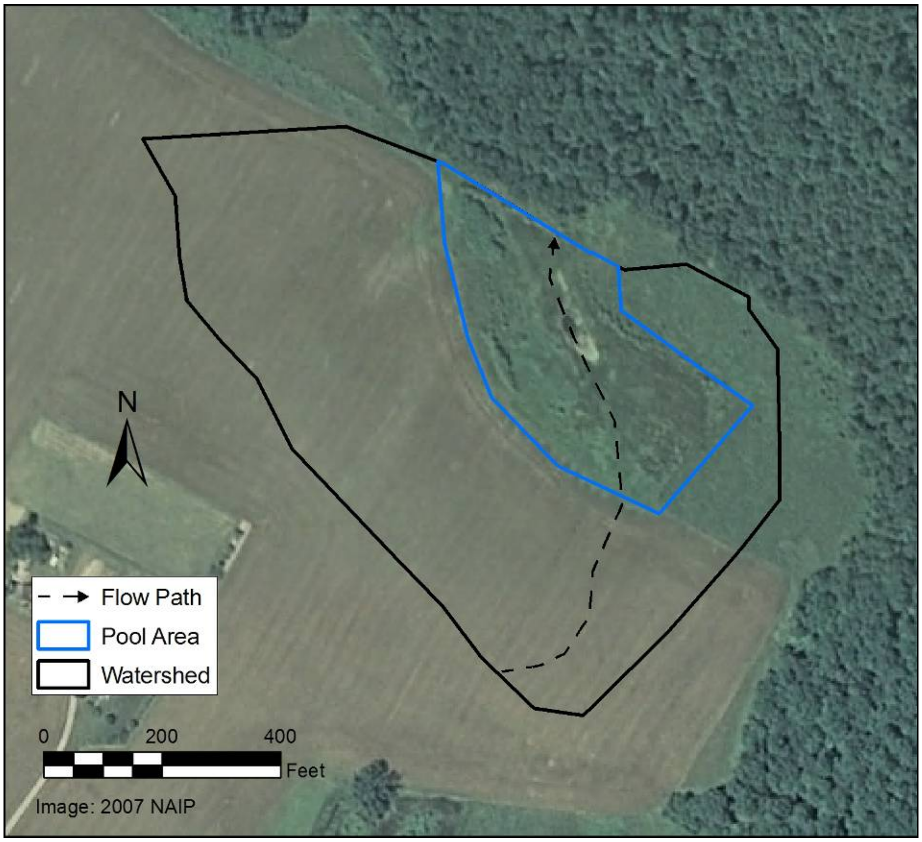
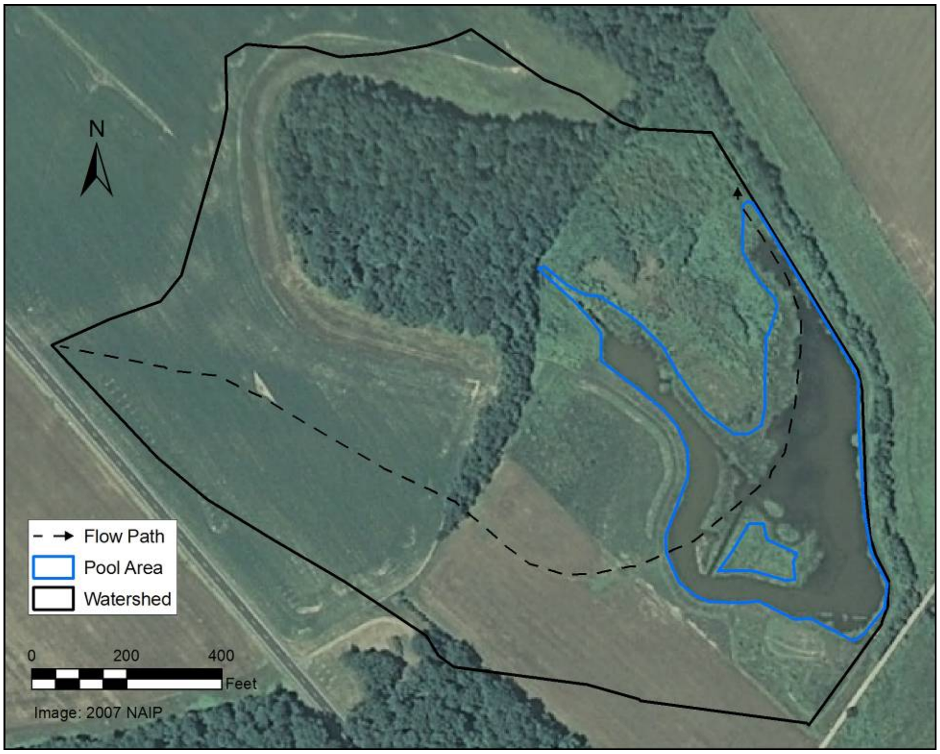


Figure N4. Site SPF aerial view with longest flow path, and wetland pool and watershed boundaries.

(a)


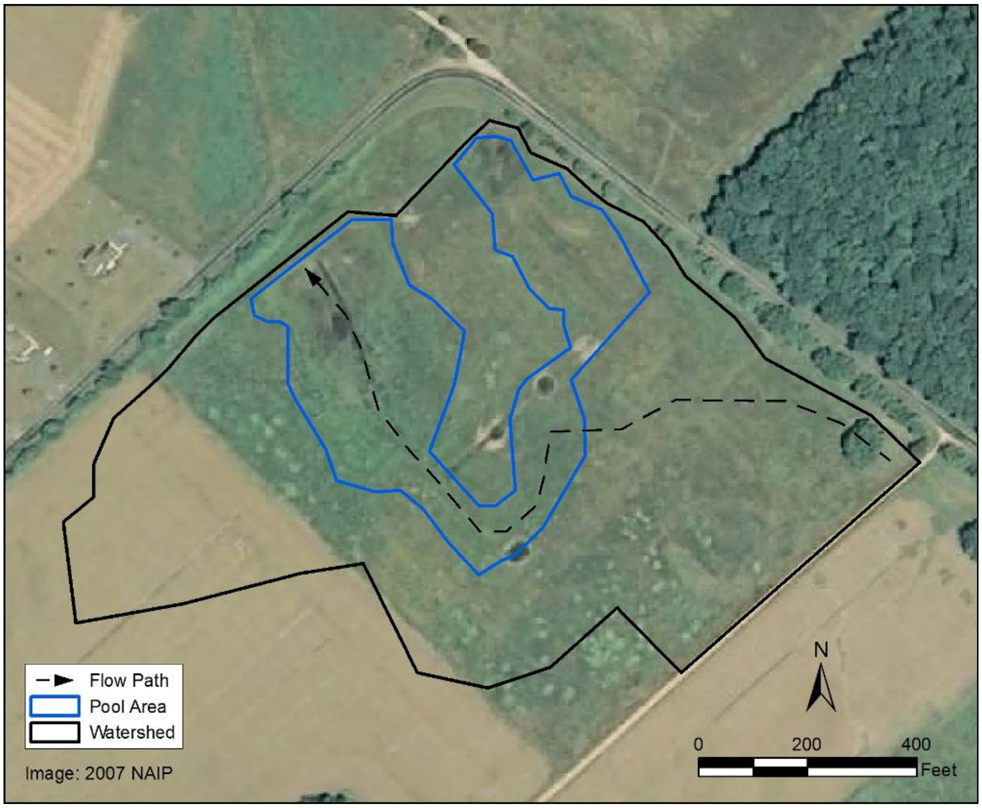
(b)


Figure N5. Site GPT (a) aerial view with longest flow path, and wetland pool and watershed boundaries and (b) ground-level photo.

(a) 

(b) 

Figure N6. Site STS (a) aerial view with longest flow path, and wetland pool and watershed boundaries and (b) ground-level photo.

(a) 

(b) 

Figure N7. Site WDF (a) aerial view with longest flow path, and wetland pool and watershed boundaries and (b) ground-level photo.

Bibliography

Almendinger, J. E. 1999. A method to prioritize and monitor wetland restoration for water-quality improvement. Wetlands Ecology and Management 6:241-251.

Arheimer, B. and H. B. Wittgren. 2002. Modelling nitrogen removal in potential wetlands at the catchment scale. Ecological Engineering 19:63-80.

Ayyub, B. M. and R. H. McCuen. 2003. Probability, statistics, and reliability for engineers and scientists. Chapman & Hall/CRC Press LLC, Boca Raton, FL.

Braskerud, B. C., H. Lundekvan and T. Krogstad. 2000. The impact of hydraulic load and aggregation on sedimentation of soil particles in small constructed wetlands. Journal of Environmental Quality 29:2013-2020.

Brix, H. 1997. Do macrophytes play a role in constructed treatment wetlands? Water Science and Technology 35:11-17.

Caffrey, J. M. and W. M. Kemp. 1992. Influence of the submersed plant, *Potamogeton perfoliatus*, on nitrogen cycling in estuarine sediments. Limnology and Oceanography 37:1483-1495.

Campbell, C. R. 1992. Determination of total nitrogen in plant tissue by combustion. In: Plant analysis reference procedures for the Southern Region of the U.S. Southern Cooperative Research Service Bulletin. USDA, Washington, DC, pp. 21-23.

Casey, R. E. and S. J. Klaine. 2001. Nutrient attenuation by a riparian wetland during natural and artificial runoff events. Journal of Environmental Quality 30:1720-1731.

Chescheir, G. M., J. W. Gilliam, R. W. Skaggs and R. G. Broadhead. 1991. Nutrient and sediment removal in forested wetlands receiving pumped agricultural drainage water. Wetlands 11:87-103.

Cirmo, C. P. and J. J. McDonnell. 1997. Linking the hydrologic and biogeochemical controls of nitrogen transport in near-stream zones of temperate-forested catchments: a review. Journal of Hydrology 199:88-120.

Comin, F. A., J. A. Romero, V. Astorga and C. Garcia. 1997. Nitrogen removal and cycling in restored wetlands used as filters of nutrients for agricultural runoff. Water Science and Technology 35:255-261.

Coveney, M. F., D. L. Stites, E. F. Lowe, L. E. Battoe and R. Conrow. 2002. Nutrient removal from eutrophic lake water by wetland filtration. Ecological Engineering 19:141-159.

Craft, C., K. Krull and S. Graham. 2007. Ecological indicators of nutrient enrichment, freshwater wetlands, Midwestern United States (U.S.). Ecological Indicators 7:733-750.

Craft, C. B. and C. J. Richardson. 1993. Peat accretion and phosphorus accumulation along a eutrophication gradient in the northern Everglades. Biogeochemistry 22:133-156.

Crumpton, W. G. 2001. Using wetlands for water quality improvement in agricultural watersheds; the importance of a watershed scale approach. Water Science and Technology 44:559-564.

Crumpton, W. G., G. A. Stenback, B. A. Miller and M. J. Helmers. 2006. Potential benefits of wetland filters for tile drainage systems: impact on nitrate loads to Mississippi River subbasins. Final project report to the U.S. Department of Agriculture, project number IOW06682.

Davis, A. P. and R. H. McCuen. 2005. Stormwater management for smart growth. Springer Science, New York, NY.

Davis, C. B. and A. G. van der Valk. 1983. Uptake and release of nutrients by living and decomposing *Typha glauca* Godr. tissues at Eagle Lake, Iowa. Aquatic Botany 16:75-89.

Domagalski, J. L., S. Ator, R. Coupe, K. McCarthy, D. Lampe, M. Sandstrom and N. Baker. 2008. Comparative study of transport processes of nitrogen, phosphorus, and herbicides to streams in five agricultural basins, USA. Journal of Environmental Quality 37:1158-1169.

Dorge, J. 1994. Modelling nitrogen transformations in freshwater wetlands. Estimating nitrogen retention and removal in natural wetlands in relation to their hydrology and nutrient loadings. Ecological Modelling 75-76:409-420.

Fink, D. F. and W. J. Mitsch. 2004. Seasonal and storm event nutrient removal by a created wetland in an agricultural watershed. Ecological Engineering 23:313-325.

Fisher, J. and M. C. Acreman. 2004. Wetland nutrient removal: a review of the evidence. Hydrology and Earth System Sciences 8:673-685.

Greenway, M. 1997. Nutrient content of wetland plants in constructed wetlands receiving municipal effluent in tropical Australia. Water Science and Technology 35:135-142.

Hammer, D. A. (Ed.) 1989. Constructed wetlands for wastewater treatment: municipal, industrial, and agricultural. CRC Press, LLC, Boca Raton, FL.

Hammer, D. A. 1992. Designing constructed wetlands systems to treat agricultural nonpoint source pollution. Ecological Engineering 1:49-82.

Herr-Turoff, A. and J. B. Zedler. 2005. Does wet prairie vegetation retain more nitrogen with or without *Phalaris arundinacea* invasion? Plant and Soil 277:19-34.

Hoagland, C. R., L. E. Gentry, M. B. David and D. A. Kovacic. 2001. Plant nutrient uptake and biomass accumulation in a constructed wetland. Journal of Freshwater Ecology 16:527-540.

Howard-Williams, C. 1985. Cycling and retention of nitrogen and phosphorus in wetlands: a theoretical and applied perspective. Freshwater Biology 15:391-431.

Johnston, C. A.1991. Sediment and nutrient retention by freshwater wetlands: effects on surface water quality. Critical Reviews in Environmental Control 21:491-565.

Jordan, T. E. 2007. Nutrient removal by restored wetlands in agricultural watersheds. Unpublished paper presented at the Chesapeake Bay Program LRSC/STAC wetlands workshop: Quantifying the role of wetlands in achieving nutrient and sediment reductions in Chesapeake Bay, Annapolis, Maryland, April.

Jordan, T. E., D. F. Whigham, K. H. Hofmockel and M. A. Pittek. 2003. Nutrient and sediment removal by a restored wetland receiving agricultural runoff. Journal of Environmental Quality 32:1534-1547.

Kadlec, R. H. 1999. Chemical, physical and biological cycles in treatment wetlands. Water Science and Technology 40:37-44.

Kadlec, R. H. and D. L. Hey. 1994. Constructed wetlands for river water quality improvement. Water Science and Technology 29:159-168.

Kadlec, R. H. and R. L. Knight. 1996. Treatment wetlands. Lewis Publishers, Boca Raton, Florida.

Kent, K.M. 1972. Chapter 15 – Travel Time, Time of Concentration and Lag. In: National Engineering Handbook, Part 630 – Hydrology, U.S. Department of Agriculture, Natural Resources Conservation Service. Available: http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/tech_info/engHbk.html.

Koerselman, W. and A.F.M. Meuleman. 1996. The vegetation N:P ratio: a new tool to detect the nature of nutrient limitation. Journal of Applied Ecology 33:1441-1450.

Kroger, R., M. M. Hollanda, M. T. Mooreb and C.M. Cooper. 2007. Plant senescence: A mechanism for nutrient release in temperate agricultural wetlands. Environmental Pollution 146:114-119.

Lee, E. R., S. Mostaghimi and T. M. Wynn. 2002. A model to enhance wetland design and optimize nonpoint source pollution control. Journal of the AWRA 38:17-32.

Martin, J. F. and K. R. Reddy. 1997. Interaction and spatial distribution of wetland nitrogen processes. Ecological Modelling 105:1-21.

Maryland Geologic Survey. 2001. Physiographic provinces and their subdivisions in Maryland [Online Map]. Maryland Geologic Survey, Baltimore, MD. Available: http://www.mgs.md.gov/indexmaps.html.

Maynard, J. J., A. T. O'Green and R. A. Dahlgren. 2009. Bioavailability and fate of phosphorus in constructed wetlands receiving agricultural runoff in the San Joaquin Valley, California. Journal of Environmental Quality 38:360-372.

McCuen, R. H. 1998. Hydrologic analysis and design, 2nd Ed. Prentice-Hall, Inc., Upper Saddle River, NJ.

Miao, S. L. and F. H. Sklar. 1998. Biomass and nutrient allocation of sawgrass and cattail along a nutrient gradient in the Florida Everglades. Wetlands Ecology and Management 5:245-263.

Miller, R. O. 1998. High-temperature oxidation: dry ashing. In: Kalra, Y. P. (Ed.), Handbook and Reference Methods for Plant Analysis. CRC Press, New York.

Mitsch, W. J. 1992. Landscape design and the role of created, restored, and natural riparian wetlands in controlling nonpoint source pollution. Ecological Engineering 1:27-47.

Mitsch, W. J. and J. G. Gosselink. 2000. Wetlands, 3rd Ed. John Wiley and Sons, New York, NY.

Munch, C., P. Kuschk and I. Roske. 2005. Root stimulated nitrogen removal: only a local effect or important for water treatment? Water Science and Technology 51:185-192.

Raisin, G. W. and D. S. Mitchell. 1995. The use of wetlands for the control of non-point source pollution. Water Science and Technology 32:177-186.

Raisin, G. W., D. S. Mitchell and R. L. Croome. 1997. The effectiveness of a small constructed wetland in ameliorating diffuse nutrient loadings from an Australian rural catchment. Ecological Engineering 9:19-36.

Reddy, K. R., W. H. Patrick, Jr. and C. W. Lindau. 1989. Nitrification-denitrification at the plant root-sediment interface in wetlands. Limnology and Oceanography 34:1004-1013.

Reinhardt, M., R. Gachter, B. Wehrli and B. Muller. 2005. Phosphorus retention in small constructed wetlands treating agricultural drainage water. Journal of Environmental Quality 34:1251-1259.

Royer, T. V., M. B. David and L. E. Gentry. 2006. Timing of riverine export of nitrate and phosphorus from agricultural watersheds in Illinois: implications for reducing nutrient loading to the Mississippi River. Environmental Science and Technology 40:4126-4131.

Schwab, G. O., D. D. Fangmeier, W. J. Elliot and R. K. Frevert. 1993. Soil and water conservation engineering, 4th Ed. John Wiley and Sons, Inc., New York, NY.

Sharpley, A. N., P. J. A. Kleinman, A. L. Heathwaite, W. J. Gburek, G. J. Folmar and J.P. Schmidt. 2008. Phosphorus loss from an agricultural watershed as a function of storm size. Journal of Environmental Quality 37:362-368.

Silvan, N., H. Vasander and J. Laine. 2004. Vegetation is the main factor in nutrient retention in a constructed wetland buffer. Plant and Soil 258:179-187.

Spieles, D. J. and W. J. Mitsch. 2000. The effects of season and hydrologic and chemical loading on nitrate retention in constructed wetlands: a comparison of low- and high-nutrient riverine systems. Ecological Engineering 14:77-91.

SPSS, Inc. 2005. SPSS Base 14.0 User's Guide. SPSS, Inc., Chicago, IL.

SPSS, Inc. 2006. SPSS 14.0 for Windows Student Version, Release 14.0.1.366 (5 Jan 2006). SPSS, Inc., Chicago, IL.

Toet, S., R. S. P. Van Logtestijn, R. Dampf, M. Schreijer and J. T. A. Verhoeven. 2005. The effect of hydraulic retention time on the removal of pollutants from sewage treatment plant effluent in a surface-flow wetland system. Wetlands 25:375-391.

Tuncsiper, B. 2007. Removal of nutrient and bacteria in pilot-scale constructed wetlands. Journal of Environmental Science and Health Part A: Toxic/Hazardous Substances & Environmental Engineering 42:1117-1124.

Tweedy, K. L. and R. O. Evans. 2001. Hydrologic characterization of two prior converted wetland restoration sites in eastern North Carolina. Transactions of the ASAE 44:1135-1142.

USDA-NRCS. 2004a. WinTR-20 (Project Formulation Hydrology Program System), Version 1.00. Available: http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/Tools_Models/WinTR20.html.

USDA-NRCS. 2004b. WinTR-55 Small Watershed Hydrology, Version 1.00.08. Available: http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/Tools_Models/WinTR55.html.

USDA-NRCS. 2006. Maryland Conservation Practice Standard: Wetland Restoration, Code 657 [Online]. U.S. Department of Agriculture, Natural Resources Conservation Service. Available: http://efotg.nrcs.usda.gov/references/public/MW/MD657_06.pdf.

USDA-NRCS. 2007. Land Capability Classification report [Online]. U.S. Department of Agriculture, Natural Resources Conservation Service. Available: http://soildatamart.nrcs.usda.gov/Default.aspx

USDA-SCS. 1983. Technical Release 20: Computer Program for Project Formulation Hydrology (TR-20).

USDA-SCS. 1986. Urban Hydrology for Small Watersheds, Technical Release 55, 156 pp.

van der Valk, A. G. and C. B. Davis. 1978. Primary production of prairie glacial marshes. In: R. E. Good, D. F. Whigham and R. L. Simpson (Eds.), Freshwater wetlands: ecological processes and management potential. Academic Press, New York, NY.

Whigham, D., M. Pittek, K. R. Hofmockel, T. Jordan and A. L. Pepin. 2002. Biomass and nutrient dynamics in restored wetlands on the outer coastal plain of Maryland, USA. Wetlands 22:562-574.