DEVELOPMENT AND APPLICATION OF A COUPLED SWMM–MODFLOW

MODEL FOR AN URBAN WETLAND

by

STEVEN EDWARD YERGEAU

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Abstract of the Dissertation

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Dissertation Director:

Christopher C. Obropta, Ph.D., P.E.

Kearny Marsh is located within the Hackensack Meadowlands and since it was formed almost forty years ago, has been negatively impacted by activities that have altered its hydrology (ditching, urban stormwater infrastructure, construction of the western spur of the New Jersey Turnpike). The primary goals of this research were to characterize existing hydrology of Kearny Marsh, to predict effects on marsh hydrology of proposals to redevelop and reuse the site, and to project future marsh water levels under drought and high precipitation conditions. To analyze various components of this complex system, a Storm Water Management Model (SWMM) surface water model and a Visual MODFLOW groundwater model were developed, calibrated, and validated. SWMM was linked to MODFLOW through exchange of evapotranspiration and infiltration data between the models. The coupled models provided water budgets for Kearny Marsh in order to characterize its hydrology. The validated SWMM and MODFLOW linked models were used to simulate hydrological impacts of a slurry wall around Keegan Landfill and redevelopment of portions of the wetland. Results from field

measurements and model simulations indicate that Kearny Marsh is a groundwater discharge wetland with a shallow groundwater table. Groundwater flow is in an eastern direction, towards the Hackensack River. Flow velocities are slow, which are consistent with measured hydraulic conductivities. Hydrology is also influenced by tidal action that affects flooding frequency in the surrounding area. A broken bulkhead between Kearny Marsh and Frank's Creek allows for additional water inputs into the marsh when high tides are occurring. If this situation is coupled with a storm event, flooding may occur in surrounding areas. This was both predicted in the SWMM model and observed in the field. This combination of a shallow water table that gets elevated during storm events, development reducing the areas available to infiltrate stormwater, and drainage deficiencies due to the broken bulkhead connecting Frank's Creek and Kearny Marsh account for flooding reported in Kearny, NJ. Proposed development and installation of a slurry wall around portions of Keegan Landfill was predicted to create hydrologic changes that are consistent with urban impacts (increased flows, decreased infiltration and increased evaporation).

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1. INTRODUCTION

1.1. Wetland Hydrology

Wetlands are dynamic ecosystems characterized by factors that affect their structure and function. The United States Army Corps of Engineers ([USACE] 1987) defines wetlands as "areas inundated or saturated by surface water or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions (p. 9)." The National Research Council (1995) defines a wetland as an "ecosystem that depends on constant or recurrent, shallow inundation or saturation at or near the surface of the substrate. The minimum essential characteristics of a wetland are recurrent, sustained inundation or saturation at or near the surface and the presence of physical, chemical and biological features reflective of recurrent, sustained inundation or saturation (p. 64)." Hydrology plays a critical role in wetland development and ecosystem structure and function. Wetland functions include providing critical habitat for many species of plants and animals, controlling floods through storage and retention of floodwaters, protecting water quality, trapping anthropogenic contaminants, and providing recreational opportunities for surrounding residents (Ehrenfeld et al. 2003).

In order to compile information available on wetland hydrology, Bullock and Acreman (2003) reviewed 169 studies on the hydrologic functions of wetlands. They concluded: 1) the majority of studies determined that wetlands either increase or decrease a particular component of the water cycle and this has led to the notion that wetlands perform hydrological functions; 2) most studies show that floodplain wetlands reduce or delay floods; 3) there is strong evidence that wetlands evaporate more water than other land types; 4) two-thirds of studies conclude that wetlands reduce flow of water in downstream rivers during dry periods; and 5) many wetlands exist because they overlie impermeable soils or rocks and there is little interaction with groundwater (Bullock and Acreman 2003). Basic hydrologic information, such as seasonal water balance and groundwater table dynamics, is needed to gain a better understanding of wetland ecosystem functions (Sun et al. 2002).

Wetland functions can be impaired if the surrounding watershed is urbanized (Ehrenfeld 2000). More lands are being converted to urban areas in order to accommodate the growing population on the planet, sometimes at the expense of wetlands. For example, Hasse and Lathrop (2003) used geographic information systems (GIS) land use and land cover data from the New Jersey Department of Environmental Protection (NJDEP) to determine the loss of undeveloped lands to urban land uses between 1986 and 1995 for New Jersey. Lands converted include many areas formerly occupied by farmlands, forests, and wetlands that were converted into residential areas. This urbanization was responsible for a total loss of 10,433 hectares (ha) of natural wetlands between 1986 and 1995 (Hasse and Lathrop 2003).

This pattern of development and wetland loss has affected many of New Jersey's wetlands, including the Hackensack Meadowlands. The Hackensack Meadowlands (also known as the Meadowlands, the Jersey Meadows, and the Newark and Hackensack Tidal Marsh) are made up of a large complex of tidal, brackish, and freshwater wetlands located in northeastern New Jersey. They previously surrounded most of the lower Hackensack River, bordered part of the lower Passaic River, and formed the western edge of Newark Bay. Today, much of the historic Meadowlands no longer exists. Between

1953 and 1995, an estimated 7,878 acres of the 13,419 acres of wetlands were lost due to development (Tiner et al. 2002). There is a long history of human alteration of wetlands in the Meadowlands since the area was settled. Marshall (2004) detailed this history and divided human disturbances of the Meadowlands into four categories: 1) extraction of natural resources by gathering fish and shellfish for food and removal of salt hay for livestock; 2) engineered alteration of water flow through freshwater diversions for drinking water and damming several rivers that drain the Meadowlands; 3) transformation of wetlands into dry upland through filling, diking, and draining; and 4) pollution by importing or depositing refuse, sewage, and/or hazardous materials in the wetlands. These wetland changes, along with increased development and anthropogenic alterations, have implications on water quantity, water quality and wetland functions. Wetlands in the Meadowlands, for example, are contaminated with heavy metals that affect benthic macroinvertebrate populations (Bentivegna et al. 2004; Weis et al. 2004; Barrett and McBrien 2007).

1.2. Urbanization Impacts to Wetland Hydrology

Urbanization alters wetlands in urban watersheds, such as the Meadowlands, by clearing vegetation, changing land uses, and fragmenting the landscape with development. The resulting altered hydrology affects runoff quantity and water quality at the watershed outlet (Ehrenfeld 2000). Shaw (1994) identified five major effects on hydrology due to urbanization: 1) a higher percentage of precipitation is converted to surface runoff; 2) precipitation is converted to runoff at a faster rate; 3) peak flows in streams are elevated; 4) low flow in streams is decreased due to reduced inputs from groundwater storage; and 5) stream water quality is degraded. These effects are echoed by Ehrenfeld (2000; Table 1-1) as likely to occur in wetlands, with direct hydrological changes in wetlands commonly occurring by filling, ditching, diking, draining, and damming.

Increasing impervious surfaces associated with urbanization account for many of the alterations to wetland hydrology. Urbanization converts natural habitats to land uses with impervious surfaces (such as asphalt and concrete) that reduce or prevent soil infiltration of precipitation. Impervious surfaces create surface runoff with greater velocities, larger volumes, and shorter times to flow concentration (Brun and Band 2000). Increased impervious surfaces contribute to decreased groundwater recharge by reducing available groundwater recharge area (Rose and Peters 2001). The rapid routing of water to urban streams reduces surface and shallow subsurface storage, which results in lower long-term groundwater recharge, and subsequently, reduced groundwater discharge during the period of baseflow (Rose and Peters 2001). Reductions in baseflow can: 1) cause a decline in water quality as pollutants become more concentrated; 2) degrade riparian habitats as water levels decrease; and 3) interfere with navigable waterways (Brun and Band 2000). Large amounts of impervious surface have negative impacts on wetland hydrology and other functions by increasing the amount of water and associated contaminants and sediments that flow through wetlands (Kentula et al. 2004).

1.3. Data Needs for Restoring Wetland Hydrology

As a result of the intensive land use and related habitat degradation in the Meadowlands, numerous restoration projects are being implemented, primarily to restore hydrology and replace *Phragmites*-dominated ecosystems with diverse vegetation in order to provide higher-quality habitat for fishery resources and other wildlife (New Jersey Meadowlands Commission [NJMC] 2004). Because of the intimate relationship between hydrology and the ability of a wetland to properly perform important ecological functions, an in-depth understanding of the hydrology of local wetlands is critical if efforts to conserve and restore these systems are to be effective (Montalto and Steenhuis 2004).

It is generally recognized that hydrology should be the starting point in planning mitigation and restoration activities. Yet, mitigation projects seem to be lacking this information. In reviewing mitigation sites in Tennessee, for example, Morgan and Roberts (2003) delineated wetland areas following USACE's Routine Determination Procedure outlined in the 1987 Wetland Delineation Manual. Mitigation typically involved restoring hydrology to drained wetlands, creating new wetlands, or enhancing or preserving existing wetlands. Regulatory agencies routinely issue permits that allow wetland loss contingent upon one or more of these mitigation activities (Morgan and Roberts 2003). Wetland area proposed in the Tennessee permits was compared to wetland area delineated in the field. The total area of wetlands lost to permitted development was 38.0 ha, and the replacement area proposed in the permits totaled 104.3 ha (Morgan and Roberts 2003). Of the proposed area, only 77.7 ha (74.5%) of wetland area was field-verified as constructed (Morgan and Roberts 2003). Field-verified data included 43 ha of enhancement or preservation of existing wetlands, which were excluded from the study because these mitigation practices did not produce additional wetland area (Morgan and Roberts 2003). This resulted in production of only 34.8 ha of wetland area by surveyed mitigation projects, representing a net loss of 3.2 ha (Morgan and Roberts 2003). The most common problems in field-verified sites were associated with planning and design that resulted in inappropriate hydrology and poor vegetation establishment. The most significant problem noted was that none of the available construction plans and associated documentation contained calculations or even estimates of water availability (i.e., a water budget) that would lend credence that the project would likely result in a wetland (Morgan and Roberts 2003).

In Massachusetts, results of wetland construction projects designed to offset wetland losses authorized under the state's wetland regulatory program were reviewed by Brown and Veneman (2001). The primary data collected for analysis consisted of species composition of wetland vegetation established at each site. Results were calculated as a weighted average wetland index (WI) used for statistical analysis of all sites studied (Brown and Veneman 2001). Lower weighted average WI values mean greater dominance by wetland plants (Brown and Veneman 2001). The majority of projects surveyed (54.4%) were not in compliance with the Massachusetts wetland regulations for a variety of reasons, including no attempt to build the project (21.9%), insufficient size or hydrology (29.8%), or insufficient cover of wetland plants (2.6%) (Brown and Veneman 2001). Many sites failed after being constructed at an appropriate size because they were designed too shallow to have appropriate wetland hydrology or failed to support adequate cover of wetland vegetation (Brown and Veneman 2001). Other studies measuring the success of wetland mitigation in New England have met with similar results (Minkin and Ladd 2003). A similar survey of mitigation sites in Illinois found that failed sites had vegetation more characteristic of upland communities (based on mean wetland indicator status), reflecting a lack of appropriate hydrology (Matthews and Endress 2008).

In New Jersey, a review of 90 freshwater wetland mitigation projects was also conducted to compare proposed wetland area from permits to actual created wetland area (NJDEP 2002). Created wetlands were delineated using the USACE's Wetland Delineation Manual and wetland area was field-delineated using a global positioning system (GPS) unit. Wetland acreage proposed in mitigation permits issued by the state were then compared to the field-collected data. Results indicate that, on average, for each acre of proposed wetland only 0.78 acres was actually created (NJDEP 2002). This resulted in a net loss of wetlands and it concluded that NJDEP had failed to achieve a net increase in wetland area as part of its mitigation efforts. In addition, relative wetland quality was determined through a Wetland Mitigation Quality Assessment (WMQA) score (NJDEP 2002). A relative value ranging from 0 to 3 was applied to various field indicators (with a higher WMQA score indicating a 'better quality' wetland) and an overall score was calculated for each site. Wetlands received low scores for hydrology resulting from extremes in water conditions, meaning either too little or too much water was present (NJDEP 2002). Inadequate hydrology was indicated as a "major contributing factor" to failure of wetland restoration (NJDEP 2002). Hydrology is the driving force of wetland functions, but, as discussed, there is a failure to properly incorporate adequate hydrology into mitigation and restoration projects.

1.4. Wetland Water Budget

It is essential to develop a hydrologic budget that is more detailed than just identifying the water source and what its movement is, and even a crude water budget will contribute to a better understanding of site hydrology and could greatly enhance the likelihood of successful mitigation and restoration (Morgan and Roberts 2003). The water budget is an accounting of each component of the hydrologic cycle in order to quantify its contribution in a particular system (Figure 1-1). A water budget is commonly calculated using a mass balance approach where inputs and outputs equal some change in water storage, either an increase or decrease in water level or volume (inputs – outputs = change in storage; Eq. 1-1). It is useful in determining changes in overall water storage based upon changes in any individual components of the equation. A common water budget equation is expressed by Mitsch and Gosselink (2000):

$$\Delta V/\Delta t = P + S_i + G_i + T_i - ET - S_o - G_o - T_o \qquad \text{[Eq. 1-1]}$$

where, $\Delta V/\Delta t$ = change (Δ) in water volume (V) in the wetland per unit time (t)

P = precipitation

S_i = surface water inflow

G_i = groundwater inflow

T_i = tidal inflow

ET = evapotranspiration

S_o = surface water outflow

G_o = groundwater outflow

T_o = tidal outflow

Many studies have calculated water budgets in a variety of areas at different scales (e.g., Watson et al. 1981; Owen 1995; Reinelt and Horner 1995; Hughes et al. 1998; Twilley and Chen 1998; Zhang and Mitsch 2005; Dadaser-Celik et al. 2006; Elkiran and Ergil 2006; Obropta et al. 2008). Of the examples cited, only Owen (1995) and Reinelt and Horner (1995) determined comprehensive hydrologic budgets for wetlands in urban settings. In fact, a literature search for urban wetland water budgets yielded only three peer-reviewed studies (Owen 1995; Reinelt and Horner 1995; Obropta et al. 2008). This paucity of information in determining a comprehensive hydrologic budget for an urban wetland may be due to the complexity of changes brought about by urbanization (Table 1-1) or the data requirements to accurately measure individual components in urban areas. All hydrologic processes in urban areas must be considered at much smaller temporal (usually a single storm event) and spatial scales (Niemczynowicz 1999). Urban hydrologists usually install their own data collection systems capable of delivering data on a small spatial scale and short time resolution in order to increase measurement accuracy (Niemczynowicz 1999). Another complication is that direct measurement is only available for precipitation, surface flows, and tidal flows; indirect measures or calculations are typically used in determining ET and groundwater flows.

These problems in characterizing altered hydrology can be overcome with hydrologic models (Vepraskas et al. 2006). Models, like water budgets, are simplified approximations of reality and therefore contain error. Models include the following types of error: 1) model error; 2) errors in state variables (dependent variables and initial conditions); 3) errors in input data used to drive the model; and 4) parameter error (rate constants, coefficients, and independent variables) (Schnoor 1996). Winter (1981) recommends that any hydrologic budget, however derived, include error analysis in order to allow for their realistic use.

In addition to modeling hydrology, water budgets have been useful in determining nutrient budgets for wetlands (LaBaugh and Winter 1984; Reinelt and Horner 1995; Raisin et al. 1999) and determining the impact(s) of wetland restoration on hydrology (Kreiser 2003; Vepraskas et al. 2006). The importance of wetland hydrology to the maintenance of urban wetland functions and successful restoration projects necessitates better documentation of urban wetland water budgets. Montalto and Steenhuis (2004) found that for the New York/New Jersey estuary's tidal wetlands "there is a need to document better the hydrological characteristics of existing and historical tidal wetlands, to improve hydrological modeling capabilities, and to accompany other ecological investigations in tidal marshes with hydrological documentation (p. 414)." The ability to better quantify urban wetland hydrology will have larger benefits for urban wetlands, especially in planning their restoration.

1.5. Project Description

Kearny Marsh is located in the Town of Kearny and is included in the New Jersey Meadowlands District. Although originally a brackish marsh, construction of the western spur of the New Jersey (NJ) Turnpike cut the marsh off from tidal flushing, creating conditions that led to formation of the current 332-acre freshwater marsh ecosystem. This freshwater marsh is contaminated due to historical and current inputs from improperly closed landfills, combined sewer overflows, municipal stormwater discharges, and regional atmospheric deposition. Like many other parts of the Meadowlands, current hydrologic conditions of the marsh are the result of human alterations including municipal stormwater inputs, creation of mosquito drainage ditches through the marsh, and redirecting of marsh drainages (Marshall 2004; NJMC 2004). Due to the surrounding urban land use and the adjacent Keegan and Town of Kearny Landfills, negative water quality effects are suspected from surface and groundwater interactions, and from storm drain discharges into the marsh.

The New Jersey Meadowlands Commission (NJMC) has determined that remediation and restoration of this ecosystem is a high priority. One aspect of the proposed restoration is the installation of a bentonite slurry wall that will enclose the 110-acre Keegan Landfill and stop the flow of contaminated leachate from the landfill into the marsh. It is anticipated that once contained, the Keegan Landfill adjacent to Kearny Marsh will commence accepting dry waste weekly. Full information on the remediation of Kearny Marsh can be found at the Rutgers Environmental Research Clinic website (http://www.rerc.rutgers.edu/kearnymarsh/index.html).

The research presented here is part of this larger effort working towards the restoration of Kearny Marsh. Other efforts are researching the impact of water quality contamination on biodiversity, specifically birds and macroinvertebrates, the effectiveness of a capping material on sequestering sediment contamination, and the role of bacteria in breaking down contaminants found in sediment and water. These research efforts are not, however, taking into account current hydrologic inputs into Kearny Marsh which may be responsible for re-contamination of marsh water and sediments if restoration plans move forward. In order to properly restore water quality and wetland function, a documentation of the hydrology of Kearny Marsh is needed.

The goal of this research is to develop a coupled hydrological model (surface water and groundwater) to describe urban wetland hydrology in the Meadowlands (Kearny Marsh) in order to fill data gaps for the restoration efforts, increase our understanding of the dynamics of urban wetland hydrology, and increase the likelihood of successful restoration of Kearny Marsh. Specific objectives of this research are to characterize Kearny Marsh groundwater and surface water hydrology through field-collected data and from this data develop, calibrate, and field verify a hydrologic model and water budget for the Kearny Marsh wetland system. Once completed, this model will be applied to determine the impacts of proposed development in Kearny Marsh. The study will provide fundamental information essential for future restoration and management of this valuable resource. It is extremely important to the maintenance of water quality to understand the impact of urban watersheds on wetlands and urban wetlands on surrounding areas.

Figure 1-1: Schematic of a generalized water budget. (Terms correspond to those given in Eq. 1-1).

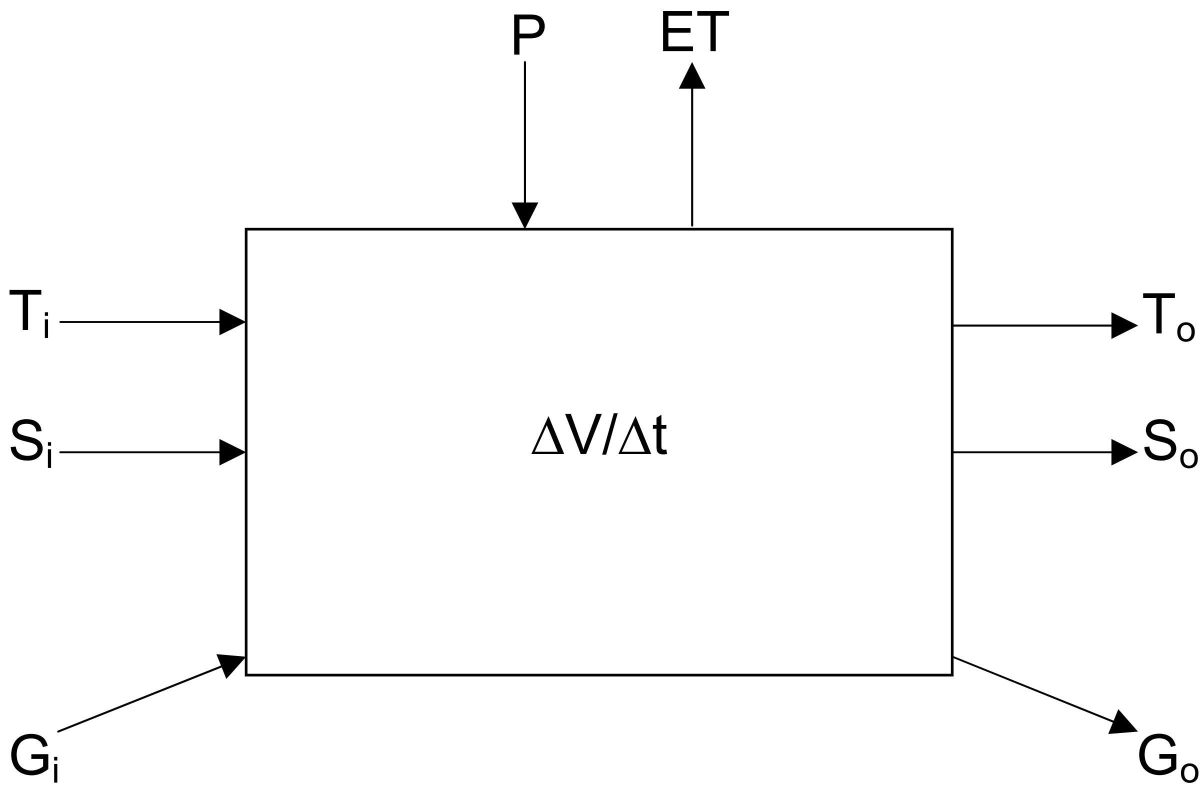


Table 1-1: Likely effects of urbanization on wetland hydrology (adapted from Ehrenfeld 2000).

Decreased surface storage of stormwater results in increased surface runoff (= increased surface water input to wetland)
Increased stormwater discharge relative to baseflow discharge results in increased erosive force within stream channels, which results in increased sediment inputs to recipient coastal systems
Changes occur in water quality (increased turbidity, increased nutrients, metals, organic pollutants, and decreased O_2)
Culverts and outfalls, replace low-order streams; this results in more variable baseflow and low-flow conditions
Decreased groundwater recharge results in decreased groundwater flow, which reduces baseflow and may eliminate dry-season streamflow
Increased flood frequency and magnitude result in more scour of wetland surface, physical disturbance of vegetation
Increase in range of flow rates (low flows are diminished; high flows are augmented) may deprive wetlands of water during dry weather
Greater regulation of flows decreases magnitude of spring flush

2. LITERATURE REVIEW

2.1. Study Site Description

Kearny Marsh is a 332-acre freshwater wetland located in the Town of Kearny in Hudson County, NJ (Figure 2-1). Situated in highly urbanized northeastern New Jersey, located between Jersey City and Newark, NJ and Manhattan, the Kearny Marsh watershed is characterized as 71% urban/developed. It is part of the larger Hackensack Meadowlands (also known as the Meadowlands, the Jersey Meadows, and the Newark and Hackensack Tidal Marsh), which are a large complex of tidal, brackish, and freshwater wetlands, with Kearny Marsh as the largest freshwater marsh. The history of the Hackensack Meadowlands and problems associated with that history, as presented in Marshall (2004), are reflective of the history and current conditions of Kearny Marsh.

Current hydrologic conditions of the marsh result from human alterations that have occurred over the past 200 years. Prior to the 19th century, Kearny Marsh, like much of the Meadowlands, was covered by large Atlantic white-cedar (*Chamaecyparis thyoides*) swamps (Kocis 1982). It is estimated that the United States is covered by approximately 115,000 acres of cedar swamps, but may have once been covered by upwards of 500,000 acres prior to European settlement (Kuser and Zimmermann 1995). Many cedar swamps in the Meadowlands were logged for lumber, but others were burned down in the 18th century to eliminate hiding places for pirates who preyed on Newark Bay (Kuser and Zimmermann 1995). Cedar stumps are visible in parts of Kearny Marsh to this day. Kearny Marsh was tidally connected to the Hackensack River as late as the 1970s, but after installation of the 1970 extension of the New Jersey Turnpike, the marsh became a closed water system separated from Hackensack River tidal flows on the east

(Mansoor et al. 2006). Without the flushing action of tides, this allowed contaminants to settle into and concentrate in its sediments. The Hudson County Mosquito Control Commission (HCMCC) created a series of swales and ditches throughout the marsh to prevent mosquito breeding (Figure 2-1) (Kocis 1982). Since dissolution of the HCMCC in the early 1970s, these swales and canals have not been maintained and have filled with sediment (Neglia 2001).

The marsh itself is ringed by rail lines, turnpikes, and service roads and cut through by utility corridors (Figure 2-1) (Kocis 1982). Decommissioned raised rail beds are found on the north, south and western boundaries of the marsh: Erie Lackawanna Railroad and Greenwood Lake Branch lines are on the north; Erie Lackawanna Railroad Company Newark and Hudson Branch on the south; and Erie Lackawanna Railroad Harrison-Kingsland Connecting Branch on the west (Neglia 2001). The eastern boundary is formed by the Belleville Turnpike and the western spur of the New Jersey Turnpike. The Keegan Landfill is located in the western portion of the marsh (Figure 2-1). This 110-acre landfill is believed to have started operation in the 1940s and was closed in 1972 (Camp Dresser and McKee 1998).

Prior to recent development of the surrounding area, Kearny Marsh was used as a detention system where runoff from the Town of Kearny was routed through a series of channels and culverts to eventually drain into the Passaic River (Neglia 2001). The majority of runoff is currently handled by Frank's Creek, a channelized stream that conveys runoff from the Town of Kearny as well as discharge from the town's wastewater treatment facility. In addition, a drainage network on the southern border of the marsh conveys marsh water to the Passaic River after connecting with Frank's Creek

(Figure 2-1). Marsh water level fluctuates seasonally and ranges approximately from 2.5 to 4 feet (Langan 1999; Mansoor et al. 2006; Mansoor and Slater 2007).

Kearny Marsh is affected by current and historical contaminant inputs of landfill leachate, CSOs, and municipal stormwater discharges. The NJMC has determined that remediation and restoration of the ecosystem is a high priority (NJMC 2004). Kearny Marsh is a Natural Heritage Priority Site representing some of the best remaining freshwater habitat for rare species in New Jersey and exemplary natural communities (NJMC 2004). Due to surrounding urban land uses and the adjacent Keegan Landfill, substantial water quality impacts are suspected from groundwater and surface water interactions and discharges from storm drains into the marsh. Although Kearny Marsh has been impacted due to urbanization, marshes have incredible regenerative ability and restoration of Kearny Marsh might improve its productivity (Bentivegna et al. 2004).

Kearny Marsh is a biologically diverse ecosystem. Common reed (*Phragmites australis*) is the dominant vegetation found throughout the area, with large stands covering 30% of the Kearny Marsh site. *Phragmites* may contribute to the abundance of birds found in Kearny Marsh, as it provides cover, food and protection for many species (Rice et al. 2000). Other vegetation found in the marsh includes white mulberry (*Morus alba*), Japanese knotweed (*Polygonum cuspidatum*) and purple loosestrife (*Lythrum salicaria*) (Kiviat and MacDonald-Beyers 2006). Bird species encountered in Kearny Marsh include the state threatened osprey (*Pandion haliaetus*), yellow-crowned night-heron (*Nyctanassa violaceus*), black-crowned night heron (*Nyctanassa nycticorax*), and the state endangered pied-billed grebe (*Podilymbus podiceps*) (Kiviat and MacDonald-

Beyers 2006). An extensive overview of the biodiversity and conservation issues in the Hackensack Meadowlands was presented by Kiviat and MacDonald (2004).

2.2. Wetland Hydrology Modeling

Use of computer models to evaluate hydrology has become commonplace. Such models are mathematical representations of reality that allow researchers and resource managers the opportunity to perform trial-and-error scenarios on physical structures or environmental landscapes. The ability of models to vary different input parameters in order to simulate and evaluate multiple scenarios aids water management. The method generally followed when modeling hydrology is to monitor a system to be modeled, model the system of interest, and alter the model in some way to represent/predict changes in the system. Surface water and groundwater have been effectively simulated as distinct models. However, groundwater and surface water are not separate parts of the hydrologic cycle, especially in some wetland systems (Bedford 1996; Winter 1999; Mitsch and Gosselink 2000; Sophocleous 2002). Bedford (1996) offers ‘templates’ that describe the diversity of settings in which climate, topography, and hydrology interact in order to create wetlands. Depressions in the landscape that lack drainage and collect precipitation, areas with little slope that have very slow infiltration rates that retain water for long periods of time, or areas with large changes in land slope that create groundwater discharge where water can accumulate, all result in the formation of wetlands (Bedford 1996). In order to fully account for all components of the hydrologic cycle, a need exists for surface water models to somehow incorporate groundwater, and vice versa. An understanding of how groundwater and surface water interact may help water resource managers deal with such issues as flood control, groundwater use, and land conservation, in a sustainable manner (Schot and Winter 2006). The complexity of modeling wetland hydrology is also increased in urban areas due to alteration of individual components in the hydrologic cycle (see section *1.2. Urbanization Impacts to Wetland Hydrology*).

Computer models exist to specifically address wetland hydrology. The FLATWOODS model (Sun et al. 1998a; Sun et al. 1998b; Sun et al. 2006) is a recent (ca. 1995) forest hydrology model originally designed to simulate hydrology in cypress swamps and pine forests in Florida. FLATWOODS combines models simulating groundwater, evapotranspiration (ET), surface flow, and unsaturated flows to determine hydrology on a daily basis (Sun et al. 1998a). WETLANDS (Mansell et al. 2000) is based on FLATWOODS as both were developed for cypress swamps and pine flatwoods. WETLANDS added equations that better account for interactions between surface water and groundwater systems (Mansell et al. 2000). DRAINMOD (Skaggs 1980) was developed to simulate hydrology of poorly-drained soils with high water tables. The impetus for development was the need for efficient agricultural water management in humid areas (Skaggs 1980). DRAINMOD has been applied to Carolina Bay wetlands in North Carolina in order to calculate a water budget as part of restoration efforts (Vepraskas et al. 2006).

The problem with these models is that they were developed and designed for specific wetland types (cypress swamps, forested wetlands, or agricultural wetlands) that limit their utility for other types of wetlands. There is a practical disadvantage in the use of such models, as well. Newly developed models need to undergo extensive testing and verification before becoming widely accepted and adopted by other researchers. Without such work, the chance of other researchers using new models remains small. Two models that have already undergone such rigor are the U.S. Environmental Protection Agency's (EPA) Storm Water Management Model (SWMM) and the U.S. Geological Survey's (USGS) Modular Three-Dimensional Finite-Difference Ground-Water Flow Model (MODFLOW). While the following is not a comprehensive list of all articles that include hydrology models, it is representative of ways in which these models have been utilized in *modeling wetland hydrology*.

2.2.1. Wetland Surface Water Modeling: Use of SWMM

SWMM is a dynamic rainfall-runoff simulator that can be used for single-event or continuous storm runoff quantity and quality modeling from urban areas (Rossman 2005). SWMM was first developed in the 1970s, with several updates occurring since (Rossman 2005). The current platform, SWMM Version 5 (abbreviated SWMM 5), is available for free from the EPA, which also provides software support. The runoff component of SWMM operates by breaking the area to be modeled into a collection of subcatchments that receive precipitation and generate runoff (quantity) and pollutant loads (quality) (Rossman 2005). SWMM is designed to simulate real-time storm events based on spatial and temporal rainfall data, evaporation, topography, impervious cover, percolation, storage values for impervious and pervious areas, storm drainage attributes such as slope and geometry, Manning's roughness, and infiltration rates (Rossman, 2005). SWMM also contains a flexible set of hydraulic modeling capabilities used to route runoff and external inflows through a drainage network of pipes, channels, storage and treatment units, and diversion structures, which can be used to simulate hydrology through man-made as well as natural areas (Rossman 2005). This flexibility allows for simulation of hydrology under changing conditions, whether altered hydrology due to the built environment (elevated flows, increased incidence of flooding, loss of infiltration from impervious cover) or engineered infrastructure used to manage such alterations (drainage networks, detention/retention ponds, constructed wetlands).

The body of literature contains examples of many reviews of urban runoff models (Tsihrintzis and Hamid 1997; Deliman et al. 1999; Zoppou 2001; U.S. Army Corps of Engineers et al. 2002; Clark et al. 2007; Obropta and Kardos 2007). The focus of these reviews is on their capability regarding modeling water quality as opposed to quantity. Zoppou (2001) stressed the need to properly model quantity, as flows or volumes, in dealing with water quality. The reasons are two-fold: "Firstly, in most water quality models, pollutant concentrations cannot be estimated without having estimated the flows" (Zoppou 2001, p. 200); "Secondly, procedures to mitigate quantity and quality are complementary" (Zoppou 2001, p. 200). If flow is not adequately modeled, then water quality predictions will be unreliable as well as not truly representative of actual conditions (Tsihrintzis and Hamid 1997; Zoppou 2001). All of these reviews do agree that SWMM is an excellent means to model surface water quantity in urban areas, while there are still issues that need to be resolved when simulating water quality (Tsihrintzis and Hamid 1997; Deliman et al. 1999; Zoppou 2001; U.S. Army Corps of Engineers et al. 2002; Clark et al. 2007; Obropta and Kardos 2007).

The effectiveness of SWMM in modeling urban environments is highlighted in several studies. Warwick and Tadepalli (1991) studied the ability of SWMM to effectively model hydrology in a conceptualized 10 square-mile urban area. The calibrated SWMM model was able to perform quite well in predicting total runoff volume and peak flow rate. Tsihrintzis and Hamid (1998) used SWMM to simulate runoff from four small catchments with varying land uses (low density residential, high density residential, highway, and commercial). The calibrated SWMM model simulated runoff well for all four catchments, with model runoff quantity uncertainty less than model runoff quality uncertainty (Tsihrintzis and Hamid 1998). Jang et al. (2007) used SWMM to predict pre- and post development conditions for four planned development areas in Korea. Pre-development conditions have been determined by applying Soil Conservation Service (SCS) hydrograph techniques and post-development conditions were modeled in SWMM (Jang et al. 2007). Their focus was on the effectiveness of using SWMM for both pre- and post-development simulations. They found that they were able to greatly improve their predictions when the SWMM-SWMM combination was used to develop hydrographs when compared to the SCS-SWMM combination (Jang et al. 2007). SWMM is the most widely used stormwater model for urban systems because of its proven ability to effectively simulate urban runoff and surface flows/volumes.

In urban environments, wetlands still persist and a few studies have been performed using SWMM to model wetland hydrologic processes. Tsihrintzis et al. (1998) used the link-node model, SWMM-EXTRAN, to design constructed wetlands to be used for flood control as part of a mitigation bank in Florida. SWMM-EXTRAN is a dynamic flow routing model that runs water through conduits (either open or closed channels) connecting nodes to create the hydrologic system (Tsihrintzis et al. 1998). The model structure was such that nodes represented different cells/basins of the created wetland, with some nodes capable of storing floodwater, and links between them represented water control structures between these cells (Tsihrintzis et al. 1998). They compared changes in water flows and levels prior to installation of flood control structures and after installation. The goals of their project were to test the applicability of SWMM-EXTRAN to wetland design, develop a methodology to calibrate such a model, and apply this calibrated model in order to design the best size for a constructed wetland (Tsihrintzis et al. 1998). They were able to successfully model water flows and elevations throughout the wetland area, when compared to measured flows and elevations, and to demonstrate that created wetlands would aid in reducing flood levels (i.e., water stages) during a variety of storm events (Tsihrintzis et al. 1998). Slight discrepancies between measured and modeled parameters (water flow and elevation) were accounted for mainly due to a lack of monitored flows and water stages for certain areas (Tsihrintzis et al. 1998). The main drawback to their model was that ET was not considered as part of the hydrologic balance (Tsihrintzis et al. 1998).

Obropta et al. (2008) used SWMM to create a water budget for an urban wetland in northern New Jersey. The wetland, located in the Teaneck Creek Conservancy, receives water from overflow of Teaneck Creek and from six storm drains that discharge directly into the wetland system that is on site (Obropta et al. 2008). SWMM was used to calculate the volume of water flowing into the wetland from these sources (Obropta et al. 2008). In addition, SWMM was used to calculate the infiltration rate of water through the soils (Obropta et al. 2008). The results showed only a 2.06% difference between modeled and measured water volumes for the site (Obropta et al. 2008). A water budget was calculated for the wetland, which will be used in future efforts to restore the Teaneck

Creek Conservancy. In this study, groundwater flows were determined to be "negligible" since surface water flows dominated the project wetlands (Obropta et al. 2008). These flows, therefore, were not included in the calculated water budget. This may account for differences between simulated and monitored volumes, considering that interactions between groundwater and surface water systems occur in areas where wetlands are located (Bedford 1996; Winter 1999; Mitsch and Gosselink 2000; Sophocleous 2002).

An effort was undertaken to investigate interactions between groundwater and surface water at a wetland near Duke University (Kazezyilmaz-Alhan et al. 2007; Kazezyilmaz-Alhan and Medina, Jr. 2008). The goal was to better understand the effect of wetland hydrology on water quality (Kazezyilmaz-Alhan et al. 2007; Kazezyilmaz-Alhan and Medina, Jr. 2008). The Duke University model accounted for groundwater flows by coupling SWMM with a wetland model: Wetland Solute Transport Dynamics (WETSAND) (Kazezyilmaz-Alhan et al. 2007; Kazezyilmaz-Alhan and Medina, Jr. 2008). WETSAND models wetland water quantity by accounting for water sources (rainfall, lateral inflow, and groundwater discharge) and water sinks (infiltration, ET, and groundwater recharge) (Kazezyilmaz-Alhan et al. 2007; Kazezyilmaz-Alhan and Medina, Jr. 2008). SWMM was used to simulate surface water flows into the wetland site from upstream urban sources (Kazezyilmaz-Alhan et al. 2007; Kazezyilmaz-Alhan and Medina, Jr. 2008). This was used as input data into WETSAND. The primary urban area upstream of the wetland of concern was the Duke University campus (Durham, NC) (Kazezyilmaz-Alhan et al. 2007; Kazezyilmaz-Alhan and Medina, Jr. 2008). They determined that under changing conditions (vegetation, slope of the land surface, and hydraulic conductivity), wetland hydrology responds with either a rise or drop in wetland water depth (Kazezyilmaz-Alhan and Medina, Jr. 2008).

SWMM possesses the capability of effectively simulating and predicting surface water flows, both in urban environments and wetlands. However, it is limited in the level of interaction it can obtain with the groundwater system. SWMM moves water to the subsurface through simplified infiltration (Rossman 2005). SWMM simply does not have the capability to model groundwater flow past the point of infiltration (USACE et al. 2002).

2.2.2. Wetland Subsurface Water Modeling: Use of MODFLOW

MODFLOW is a groundwater flow model that numerically solves groundwater flows for a porous medium (Harbaugh et al. 2000). In MODFLOW, an aquifer system is divided into rectangular blocks on a grid, which is organized into rows and columns (Harbaugh et al. 2000). Each grid represents a layer, with several layers stacked upon each other to represent different soils and layers in the aquifer in three dimensions. Layers can be defined as confined, unconfined, or a combination of both. MODFLOW is supported by a series of modules grouped into various packages that deal with specific features of the aquifer system that allow a user to model wells, rivers, streams, wetlands, and lakes (Harbaugh et al. 2000). This flexibility in configuring a model to a specific application also facilitates addition of new packages. A wide range of additional modules have been added since the original release of MODFLOW. Groundwater flow is determined from parameters such as hydraulic conductivity, water table depths, ET, recharge rate, and depth of each layer (Harbaugh et al. 2000). While packages exist in

MODFLOW to allow groundwater to interact with surface water systems (notably, the river, reservoir, stream, and lake packages), the model code only works for the saturated zone and cannot model overland flow (U.S. Army Corps of Engineers et al. 2002; Furman 2008).

Groundwater models have not had extensive reviews of their capabilities, unlike surface flow or stormwater models. This may be due to the predominant use of MODFLOW for groundwater modeling, with fewer models in general use and MODFLOW the accepted standard (Kumar n.d.; U.S. Army Corps of Engineers et al. 2002; Furman 2008).

The following is a representative sample of ways used to model wetland hydrology using MODFLOW. While not comprehensive, this review does highlight the effectiveness of MODFLOW as well as the adaptive nature of the model structure and its series of packages.

Winston (1996) determined hydrologic changes that affect a wetland in Washington, DC, the Barney Circle wetland, due to urbanization and proposed highway construction. Barney Circle was proposed as a site for wetland enhancement and creation and hydrological analysis was needed to provide design alternatives (Winston 1996). A MODFLOW model was developed and calibrated using current conditions and altered to predict impacts from future construction (Winston 1996). Because Barney Circle's hydrology is dominated by groundwater, and is maintained by discharge from groundwater, the DRAIN module (DRN) was used to simulate the wetland (Winston 1996). The DRN package was originally designed to simulate the effects of features such as agricultural drains (Batelaan and De Smedt 2004). The DRN module uses groundwater as the sole source of inflow into cells designated as part of the drain (Reilly 2001). Water is removed from the aquifer at a rate proportional to the difference between the groundwater level and the drain elevation (Batelaan and De Smedt 2004). If the groundwater level falls below the bottom elevation of the drain cell (i.e., the wetland), groundwater inflow ceases and the wetland dries up (Reilly 2001). It was found that proposed construction would deplete Barney Circle's recharge area by 13% and baseflow discharge would be reduced by 27%, resulting in less water entering the wetland and lowering water levels (Winston 1996). The author notes that his model is a mathematical representation of the true nature of wetland hydrology and any conclusions drawn should be viewed with uncertainty, but that he was able to adequately simulate general changes in hydrology as a result of the proposed highway (Winston 1996).

Similar to Winston (1996), Brennan et al. (2001) created a model to determine impacts from a proposed highway bypass and future development on wetland habitat for the federally threatened bog turtle (*Clemmys muhlenbergii*) in Maryland. A MODFLOW model was developed encompassing wetlands determined to have several bog turtle habitats (Brennan et al. 2001). These wetlands are groundwater-fed and experience year-round artesian conditions, which create soft muddy bottoms into which turtles burrow (Brennan et al. 2001). The model was designed based upon groundwater data collected from a network of fifteen deep wells (15 – 30 m deep) and forty-two shallow (1 – 3 m deep) piezometers established in areas around the wetland (Brennan et al. 2001). Because of previous agricultural practices on the site, tile drains, used to remove excess water from the soil, were present. These were simulated by using the DRN package set at the same elevation as tile drains in several cells in the model (Brennan et al. 2001). The primary hydrologic component of concern was recharge, which is assumed to be the only condition that would change due to alteration of the land surface, and this was the parameter changed between pre- and post-development model scenarios (Brennan et al. 2001). Simulations representing pre- and post-development conditions were run to determine impacts from proposed industrial areas and highway construction on groundwater, and therefore, bog turtle habitat. Simulations predicted that proposed construction of the highway bypass and industrial areas substantially impact the site, with a drop in groundwater level up to 10 m and a loss of groundwater discharge used to maintain the wetlands (Brennan et al. 2001).

There are drawbacks to using the DRN package, however. It is only useful if the surface inflows into the wetland are small compared to groundwater inflow and each cell designated as part of the drain acts independently of cells within the same drain (Reilly 2001). These shortcomings led to the development of the SEEPAGE package for MODFLOW (Batelaan and De Smedt 2004). With an unconfined aquifer, MODFLOW assumes that soil in the top unconfined layer extends towards infinity (Batelaan and De Smedt 2004). This results in overestimates of the degree of water remaining in cells above the drain in cases where inflows lie above the soil surface, as water flows higher than land surface elevation (Batelaan and De Smedt 2004; Batelaan et al. 2003). The SEEPAGE package limits groundwater level to land surface elevation and calculates groundwater discharge (‘seepage’) to the surface when groundwater levels reach or exceed surface elevation (Batelaan and De Smedt 2004). If groundwater elevation is below ‘seepage level,’ water is capable of recharging those cells if precipitation is occurring, for example. Batelaan and De Smedt (2004) compared groundwater simulations and the resulting water balance using both DRN and SEEPAGE on a one layer thick MODFLOW model. They found that errors in the water balance exceeded 0.01% in simulations using DRN, and 0% error using SEEPAGE (Batelaan and De Smedt 2004). After this comparison, they applied SEEPAGE to determine the discharge area in three catchments in Belgium. Results show that a combination of DRN and SEEPAGE was able to accurately determine areas of groundwater discharge in the catchments (Batelaan and De Smedt 2004; Batelaan et al. 2003).

The DRN package has been used in conjunction with other packages in order to properly simulate hydrology in specific wetland types. For example, Grapes et al. (2006) used drain cells in conjunction with the RIVER package (RIV) to represent ephemeral and perennial reaches of a river that provides water to a floodplain wetland in southern England. Their goal was to determine hydrological controls of floodplain wetland water table levels (Grapes et al. 2006). The DRN cells simulated flows to ephemeral river reaches, and RIV cells to perennial reaches (Grapes et al. 2006). RIV-denoted cells "estimate subsurface flow through the river bed between the river and the aquifer as a function of the hydraulic gradient and the 'river bed conductance', which is calculated from values for channel width, bed sediment thickness and bed sediment hydraulic conductivity" (Grapes et al. 2006; p. 336). Use of RIV cells allows groundwater flow between the river and aquifer, in either direction, depending upon the direction of the hydraulic gradient (Grapes et al. 2006). Water table levels were fairly well simulated when groundwater recharge was average during the study period (1978 – 1984), but the model overestimated or underestimated water levels when recharge levels changed drastically from average (Grapes et al. 2006). Seasonal discharge from the aquifer to the river and floodplain occurs in fall and winter, maintaining wetlands located along the floodplain (Grapes et al. 2006).

Bradley (1996; 1997; 2002) developed a floodplain wetland MODFLOW model for Narborough Bog, in central England. The RIV package was used to model flux of groundwater through the floodplain wetland and to determine impacts of the river on wetland hydrology (Bradley 1996; Bradley 1997; Bradley 2002). A combination of monitoring and modeling of the water fluxes (groundwater inflows and outflows, recharge, ET, precipitation, exchange between groundwater and river water) was illustrated to show the effectiveness of this approach when determining wetland hydrology (Bradley 1997). Measured water levels matched simulated water levels under varying meteorological (precipitation, ET, and recharge) conditions (Bradley 1996; Bradley 1997; Bradley 2002). Error between measured and simulated groundwater levels was below 2% (Bradley 1996). ET estimates, calculated using the Priestly and Taylor method, are a large source of possible error in the model (Bradley 1996).

Bradford and Acreman (2003) investigated groundwater dynamics of a wet coastal grassland in Sussex, UK. The goal was to apply a groundwater model to a wet grassland, which is underlain by a low permeability soil (Bradford and Acreman 2003). They limited their model to one field within the large wetland since channels surrounding individual fields acted as groundwater boundaries, but they also recognize that a regional groundwater flow may exist in soil layers below the localized aquifer they modeled (Bradford and Acreman 2003). This larger regional model was not developed as part of their study. Interaction between surface water and groundwater was pronounced at ditches surrounding the field, but groundwater was not influenced by ditches except in their immediate vicinity (Bradford and Acreman 2003). Water table fluctuations occurred only within a short distance of ditches, but also in times when water within ditches overflowed into the adjacent field (Bradford and Acreman 2003).

Similar results were found in perimeter ditches in a North Carolina wetland, Juniper Bay (Pati 2006). A MODFLOW model showed that perimeter ditches surrounding the wetland affected groundwater levels to a depth of 4 – 7 m and laterally to a maximum distance of 100 m (Pati 2006). Groundwater dynamics were affected by precipitation and evaporation in wet grasslands (Bradford and Acreman 2003). Prairie pothole wetlands in eastern North Dakota maintain groundwater levels through precipitation and ET, in addition to groundwater discharge (Gerla and Matheney 1996). Like wet grasslands in Sussex, UK, prairie pothole wetlands are areas dominated by grasslands and agriculture (Mitsch and Gosselink 2000).

In order to properly simulate the relationship between surface water levels and underlying groundwater systems, Restrepo et al. (1998) developed a wetland simulation package (WETLAND) for MODFLOW. The WETLAND package incorporates surface flow (as sheet flow through dense vegetation and as channel flow through a slough network), ET, and vertical and horizontal fluxes at the wetland-aquifer interface (Restrepo et al. 1998). When the WETLAND package is applied, the wetland flow system is modeled as the top layer of the model and underlying layer(s) can be simulated as part of this top layer, as an independent aquifer, or as part of the aquifer underneath (Restrepo et al. 1998; Wilsnack et al. 2001). Surface and subsurface systems can be simulated simultaneously. The WETLAND package was first applied to a regional groundwater flow model in Everglades National Park in northern Miami-Dade County, Florida (Wilsnack et al. 2001). Results showed that measured water levels matched “fairly well” with simulated water levels within wetlands modeled, with residuals (differences between measured and predicted water levels) usually less than 0.5 ft (Wilsnack et al. 2001). The authors hoped to use the results in the development of restoration plans and projects for the Everglades (Wilsnack et al. 2001). Use of the WETLANDS package was studied further, when it was used to develop an extended model that can be used to simulate water management scenarios in Miami-Dade County, Florida (Restrepo et al. 2006). The model was only developed further from previous work (as in Wilsnack et al. 2001) by extending its grid to a larger region of the study area, but was not run showing impacts from different water management scenarios. Average standard error between observed groundwater levels and those predicted in the model was 0.45 ft (Restrepo et al. 2006). Simulated groundwater levels are an average over the entire cell within the model, with the cell measuring 500 ft by 500 ft (Restrepo et al. 2006). Variations in groundwater levels still exist within the cell and may account for the difference seen in measured and predicted water levels (Restrepo et al. 2006). The WETLANDS package shows how well wetland levels can be simulated using a combination of surface and subsurface flows.

The WETLANDS package has a few drawbacks, however. It was designed to only simulate flow through swamp areas and not for grass wetlands (Bradford and Acreman 2003). This limits its applicability to other wetland types. In addition, both of the described applications of the WETLANDS package (Wilsnack et al. 2001; Restrepo et al. 2006) were used in conjunction with other methods previously described to simulate wetlands in MODFLOW, specifically the DRN and RIV packages. The capabilities of these packages (DRN and RIV) to adequately model wetlands where the hydrology is primarily driven by groundwater discharge (DRN; Winston 1996; Brennan et al. 2001; Grapes et al. 2006) or river flooding (RIV; Bradley 1996; Grapes et al. 2006) was previously described. While inclusion of surface water flows through the WETLANDS package allows for a complete picture of hydrology, there are still errors in estimates of ET rates (Wilsnack et al. 2001). Restrepo et al. (2006) estimated ET from a daily water balance for each vegetation and land cover type in the study area. ET measurements have shown an average variability of 42% when calculated using the water balance equation, indicating other methods may be more appropriate for determining ET (Villagra et al. 1995). Prior knowledge of hydrology, gained through monitoring of the wetland site, is necessary in order to determine the proper method of modeling wetland hydrology.

2.2.3. Integrated Wetland Model Systems

Since both surface water and groundwater systems are important in the creation and maintenance of wetlands, some level of integration between surface water and groundwater models is needed in order to accurately determine wetland hydrology. One way of accomplishing this is through coupled surface-subsurface flow models. The amount of coupling that can occur has been described in three levels. The first level is no coupling, or *uncoupled*, where a surface water model is created and simulations are run that provide data to be input as boundary conditions for a subsurface water model (Furman 2008). In this form of coupling, two models are run independently and there is no feedback to the surface water model. The second level of coupling, *iterative coupling*, does involve feedback from the subsurface flow model back to the surface flow model and then resolving the surface model and continuing this loop until both models meet predetermined criteria (Furman 2008). The third level, *fully coupled*, solves the two system models simultaneously at one time step before moving forward to the next time step (Furman 2008). Some examples of the first two levels of coupling can be seen in previous examples of modeling wetland hydrology (Brennan et al. 2001; Kazezyilmaz-Alhan et al. 2007; Kazezyilmaz-Alhan and Medina, Jr. 2008) and additional examples of model coupling follow.

In a review of coupled surface water and subsurface water models, Furman (2008) mentions the capabilities of SWMM and MODFLOW to *internally* couple these two systems. SWMM is coupled to the subsurface through simplified infiltration, which is modeled three ways: Horton infiltration, curve number abstraction, and the Green-Ampt method (Furman 2008). However, SWMM does not have the capability to model groundwater flow (U.S. Army Corps of Engineers et al. 2002). MODFLOW is coupled to the surface water system through simple interactions in many of its packages (such as RIV, DRN, and the lake (LAK) and stream (STR) packages) (Furman 2008). MODFLOW only works for the saturated zone and cannot model overland flow (U.S. Army Corps of Engineers et al. 2002; Furman 2008). Complex flows through structured drainage networks are not possible in MODFLOW. Urban areas with extensive drainage systems require more detail than available in MODFLOW packages.

With these limitations in mind, other researchers have modeled integrated surface and groundwater systems by combining two separate models. Yan and Smith (1994) describe integration of the South Florida Water Management Model (SFWMM) with MODFLOW for use in Dade County, Florida. The approach chosen was to simulate movement of water outside of the aquifer using SFWMM and water within the aquifer using MODFLOW, with water flow between the systems linked through recharge, infiltration, soil moisture changes, and ET (Yan and Smith 1994). The integrated model formulation was described without details on its application in simulating water dynamics. MODFLOW was also integrated with the WASIM-ETH-I model to describe the water balance of a watershed in Germany (Krause and Bronstert 2007). The coupling was achieved by "transmitting the fluxes into/from the WASIM-ETH-I soil storage as groundwater recharge or uptake to MODFLOW, and vice versa" (Krause and Bronstert 2007; p. 177). Parameters calculated using WASIM-ETH-I were used as input into MODFLOW. Results showed that the coupled model was able to accurately simulate groundwater levels over the course of two years (Krause and Bronstert 2007). The watershed model, Soil and Water Assessment Tool (SWAT), has been integrated with MODFLOW in South Korea (Kim et al. 2008). Separate SWAT and MODFLOW models were developed and then run with an exchange of data between the two (Kim et al. 2008). Integration of the two models was achieved so that after SWAT was run, recharge and river stage calculations from SWAT were used as input into MODFLOW (Kim et al. 2008). Parameters from MODFLOW simulations, primarily ET, recharge, and water exchange rate between the river and aquifer, were routed back into SWAT (Kim et al. 2008). Exchange of water between the river and groundwater was accomplished with the RIV package in MODFLOW. They were able to successfully replace the limited groundwater modeling capabilities of SWAT with MODFLOW (Kim et al. 2008). Linking SWAT to MODFLOW in Kansas enabled better representation of groundwater dynamics (Sophocleous et al. 1999; Sophocleous and Perkins 2000).

SWAT was initially developed primarily for agricultural watersheds and impacts derived from agricultural management (Arnold and Fohrer 2005). Therefore, the applicability of SWAT to urban watersheds may be limited.

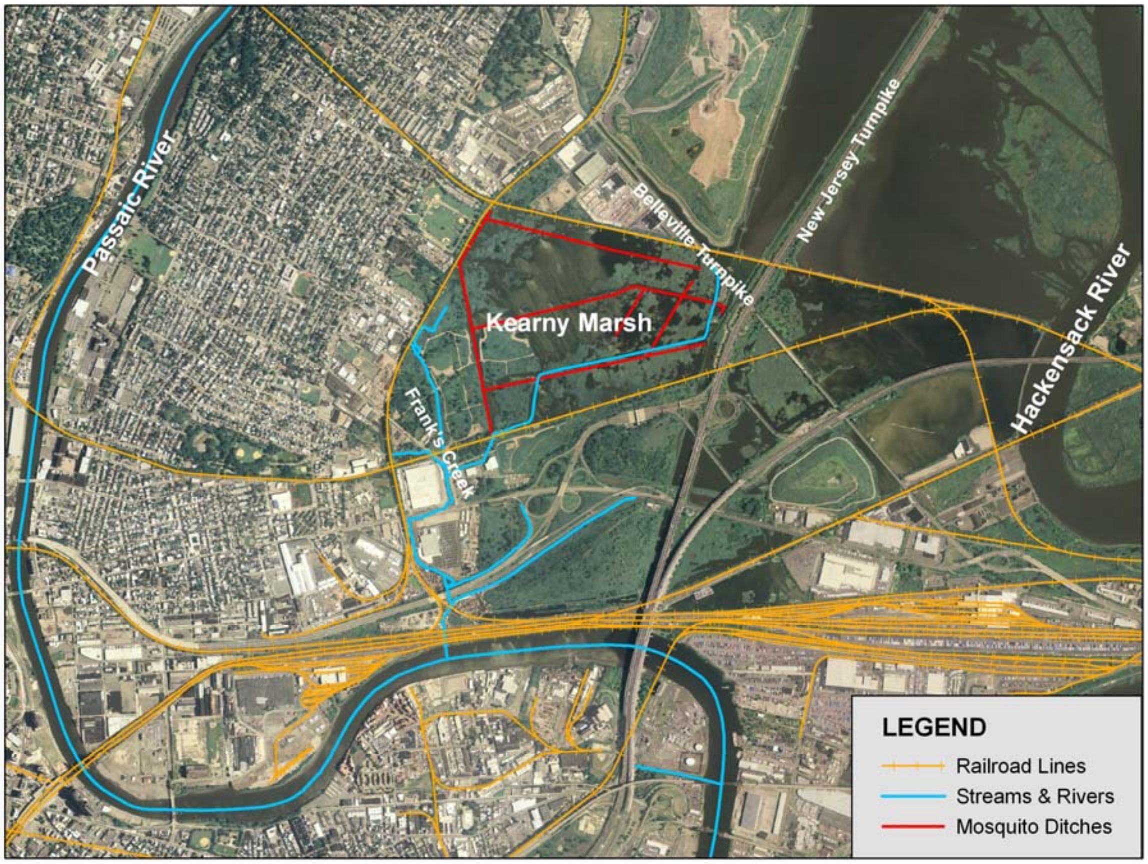
Despite SWMM and MODFLOW both effectively simulating their respective water systems (surface water for SWMM and groundwater for MODFLOW), a literature search provided only one example of their integration. Rowan (2001) integrated SWMM and MODFLOW to model two lakes in New Jersey in order to evaluate watersheds as whole systems. An intermediate program, the Multiple Model Broker (MMB), was created in order to facilitate exchange of data between the models (Rowan 2001). Infiltration data were calculated in SWMM and passed to MODFLOW as recharge and water table elevations calculated in MODFLOW were sent to SWMM. Exchange of data occurred after each time step where SWMM would run, and then the MMB passed infiltration predictions to MODFLOW, which would then run and pass water table elevation to SWMM before the next time step (Rowan 2001). Model results from two watersheds (West Milford Lake and Cranberry Lake Watersheds) showed satisfactory results and successful communication between the two models was achieved (Rowan 2001). One drawback was that integrated model performance was sensitive to the configuration of SWMM, which must define its subcatchments so that they are uniform in elevation (Rowan 2001). The applicability of this linkage was not explored, however, for simulating wetland hydrology or specific urban environments. In addition, ET rates which are important to wetland hydrology were not exchanged between the two models.

These examples are not specific to urban wetland hydrology but do illustrate the accuracy and benefits of integrating surface and subsurface models, especially surface models with MODFLOW. In addition, MODFLOW packages previously described to model wetlands (RIV, STR, and DRN) were used to simulate surface and groundwater interactions (Yan and Smith 1994; Krause and Bronstert 2007; Kim et al. 2008).

2.3. Summary

In order to simulate the interactions between surface water and groundwater that occur in wetlands, integrated surface water and groundwater models need to be developed and tested. Both SWMM and MODFLOW have been proven to effectively model wetland hydrology when used independently. Their integration has also been successfully accomplished, but not for urban wetlands (Rowan 2001). The drawback to each is that neither can model the system it was not designed to model; SWMM cannot model groundwater flow and MODFLOW cannot model the unsaturated zone. Urban wetland hydrology is driven by interactions between surface water and groundwater that are themselves impacted by the urban watersheds surrounding the wetland. The way to allow for proper modeling and estimation of urban wetland hydrology is to couple a surface water model to a groundwater flow model. SWMM was chosen due to its extensive use in urban areas and providing detailed analysis of flows through structured drainage systems. MODFLOW has the capability of modeling interactions with surface water systems through a variety of packages, but detailed analysis of overland flows are not possible. Overland flows are important to urban areas as they are the primary source of runoff. Linking SWMM to MODFLOW will create a more detailed representation of urban wetland hydrology, which can be highly complex. This was accomplished so that a complete picture of hydrologic processes can be determined and evaluated as part of the restoration of Kearny Marsh.

Figure 2-1: Kearny Marsh study area.



3. COMPARISON OF EVAPOTRANSPIRATION MEASUREMENT METHODS FOR AN URBAN WETLAND

3.1. Introduction

Evapotranspiration (ET) is the combination of evaporation from open water bodies and soil, and transpiration, moisture loss from plants. ET is an important component of water budgets, especially for wetlands where ET has been determined to be one of the largest if not the largest mechanism for water loss. For example, Dadaser-Celik et al. (2006) found that 95-100% of water loss in a marsh in Turkey was due to ET. Likewise, Owen (1995) found that ET accounted for 96.6% and 93.5% of wetland water losses for two consecutive years in an urban wetland in Wisconsin (USA).

The importance of ET as a major pathway for water loss from wetland systems requires accurately measuring or estimating this component of the hydrologic balance. Methods to determine ET include micrometeorological models (the Bowen ratio or eddy covariance), empirical equations (such as the Thornthwaite and Penman models), measuring the weight or volume of water percolation through soil (lysimetry), crop coefficient calculations, or as the remainder of the water budget equation after other input and output parameters are calculated (Drexler et al. 2004; Rosenberry et al. 2004). Drexler et al. (2004) reviewed various methods for determining wetland ET and their conclusions were that a variety of methods are widely used but no universally accurate model or measurement technique for ET has yet been found, and methods need site-specific calibration (Drexler et al. 2004). In addition, advantages and disadvantages based on cost, theoretical approach, underlying assumptions, and calibration and data requirements need to be considered when determining which method of ET estimation to utilize (Drexler et al. 2004).

While there may be no consensus on ET measurement methods, it is generally agreed that there is a high degree of error that is associated with them (Drexler et al. 2004). Owen (1995) presents one of the few urban wetland water budgets to perform an error analysis on the results. A mass balance approach was taken to account for all inputs (precipitation, surface runoff from upland, surface inflow from river, and groundwater input) and outputs (evapotranspiration, surface outflow to the river, and groundwater output) of water for a 92 ha urban peatland in Wisconsin (Owen 1995). Water budget components for the peatland were monitored for two years and reported in centimeters. ET accounted for 96.6% of output in year one, and 93.5% in the second (Owen 1995). Errors were determined as the remainder of the difference between water inputs and outputs then subtracting the change in storage from the water balance. Overall water budget error was estimated to be 7.1% in the first year of the study and 4.5% in the second (Owen 1995). However, a total seasonal error for ET estimates alone of 43% was calculated for the first year of the study, and 60% for the second (Owen 1995). Spatial variability may account for this high degree of error.

ET measurements have shown an average variability of 42% when calculated using the water balance equation, indicating other methods are more appropriate for determining ET (Villagra et al. 1995). Vepraskas et al. (2006) found that the two largest components of their water budget for a Carolina Bay wetland in Lumberton, North Carolina (USA), were precipitation and ET, and that these components were also the most difficult to accurately measure. In their hydrologic calculation, their estimate of ET is probably the largest single source of error, which has been estimated to be 10% (Vepraskas et al. 2006; Kreiser 2003). This study, however, was performed in a predominately agricultural watershed and error values used for each parameter (not overall error) were taken as reported in the literature and not confirmed with separate analyses (Kreiser 2003). Winter (1981) recommends that any hydrologic budget, however derived, include error analysis in order to allow for realistic use of water budgets.

Seasonal and spatial variability, multiple equations for individual parameters, equipment errors, and errors in measurement can compound and propagate error throughout the water balance. Quantification of error found in each step of the process of estimating a water balance will aid in increasing the accuracy of such estimates. The current error range in a few parameters, particularly precipitation and ET is known or assumed (usually on the order of 5 – 10%), whereas error associated with other parameters, particularly groundwater and tidal flows, are unknown. Few studies have been performed for wetlands, particularly urban wetlands, and those studies do not agree on the error associated with each component of the water budget. Those studies that have included error analysis cited values of error in the literature derived for lakes, which may not be appropriate for wetlands (Kreiser 2003). In order to reduce this error and to overcome the site-specific nature of ET, it is recommended that one use two or more measurement and estimation methods and compare the results (Drexler et al. 2004).

In order to reduce error due to ET measurements, a site specific ET rate needs to be determined for an urban wetland, Kearny Marsh. This was accomplished by estimating ET using three differing methods (Thornthwaite calculation, a non-weighing lysimeter, and eddy covariance) and comparing the results to determine the most appropriate for this urban wetland. This study hoped to determine which of the three methodologies (micrometeorological models, empirical equations, or lysimetry) would be appropriate for this urbanized marsh. Once an accurate method for estimating ET in this urban wetland is found, it will be used in surface and groundwater modeling of Kearny Marsh. This fundamental research is needed to help better understand and characterize the hydrology of Kearny Marsh.

3.2. Methods

3.2.1. Thornthwaite equation

Potential evapotranspiration (PET) was calculated using the Thornthwaite equation (Mitsch and Gosselink, 2000):

$$PET_i = 16(10T_i/I)^a \qquad \text{[Eq. 3-1]}$$

Where, PET_i = PET for month i (mm/mo)

T_i = mean monthly temperature (in ^oC)

I = local heat index, $\sum_{i=1}^{12} (T_i/5)^{1.514}$

$a = (0.675 \times I^3 - 77.1 \times I^2 + 17{,}920 \times I + 492{,}390) \times 10^{-6}$

PET values were divided by 25.4 to convert from millimeters per month (mm/mo) to inches per month (in/mo) to coincide with other methods used in this study.

The Thornthwaite equation is a temperature-based method of estimating ET that uses only mean monthly temperature and latitude (Thornthwaite 1948). The theory behind the Thornthwaite method is that all factors that determine PET are meteorological, including solar radiation, air temperature, humidity and wind (Thornthwaite 1948; Chang 1959). Thornthwaite (1948) concluded that all these factors vary with air temperature, and can be accounted for by incorporating the latitude of the area in question (Chang 1959). Mean monthly air temperature was obtained via web download from Newark Liberty International Airport in Newark, NJ (http://climate.rutgers.edu/stateclim_v1/monthlydata/index.html). Data were obtained for 2007 to coincide with the time frame for both lysimeter and eddy covariance measurements. The weather station at the airport is approximately 5.5 miles away from Kearny Marsh, but since reported temperature is a monthly average, differences are assumed to be slight between the two locations and data were deemed to be adequate for calculating PET. Temperature data were received in degrees Fahrenheit (^oF) and were converted to degrees Celsius (^oC) prior to calculation:

$$T_c = (5/9)(T_f - 32) \qquad \text{[Eq. 3-2]}$$

Where, T_c = temperature in ^oC

T_f = temperature in ^oF.

This conversion resulted in some mean monthly temperatures becoming negative during winter months. In the few cases where this occurred, equation values for I from Eq. 3-1 were assumed to equal 0.00, since raising a negative number to an uneven higher power (1.514 in Eq. 3-1) results in an indeterminate number. Since the Thornthwaite equation (Eq. 3-1) results in PET, actual evapotranspiration (AET) was calculated by multiplying resulting PET by a correction factor to account for the duration of sunshine for each month based on latitude (Table 3-1). Monthly AET values were converted to daily values (inches per day; in/day) by dividing AET for each month by the number of days in that particular month. All calculations were done in Microsoft Excel spreadsheets.

The Thornthwaite equation was chosen because it is relatively simple, frequently used, and has been shown to do well in estimating ET, especially for temperate areas (Xu and Singh 2001) and in the northeastern United States (Rosenberry et al. 2007). One problem often cited with the Thornthwaite equation is that it tends to underestimate ET values. This is the case for arid areas (Chen et al. 2005; Pereira and Pruitt 2004) or equatorial areas with high humidity (Tan et al. 2007, Lu et al. 2005; Amatya et al. 1995) where temperatures are generally higher than normal. Empirical equations for ET calculate ET based primarily on climatic data such as air temperature, relative humidity, and net radiation. Comparison between ET values determined by the more rigorous energy balance method (ET_{eb}) and calculated using a variety of empirical equations found that the Thornthwaite equation came within 5% of the ET_{eb} only 20% of the time (Rosenberry et al. 2004). The Thornthwaite method results also came within 10% of ET_{eb} 35% of the time (Rosenberry et al. 2004). The reliability of these results and the fact that the method was developed by correlating temperature with ET in the eastern United States (Thornthwaite 1948) were other factors that were used in making the decision to use the Thornthwaite method.

3.2.2. Lysimeter

Lysimetry involves measurement of a volume or weight of water that moves through soil contained within a lysimeter. Lysimeters are differentiated by their method of measurement: weighing lysimeters (weight) and non-weighing lysimeters (volume). Weighing lysimeters provide a direct measure of ET by the mass balance of water whereas non-weighing lysimeters indirectly measure ET (Rana and Katerji 2000). Lysimeters are considered to be "very suitable" for measurement of ET in wetlands (Lott and Hunt 2001) yet both types have their drawbacks (Rana and Katerji 2000). Lysimetry is also widely accepted as a standard to which other ET measurement methods may be compared (Farahani et al. 2007). Despite non-weighing lysimeters providing an indirect measure of ET, this type was chosen due to the remote locations and, hence, possible vandalism of equipment, and lower costs when compared to weighing lysimeters.

Two non-weighing lysimeters were constructed following Perkins (1999) and Lott and Hunt (2001). One lysimeter (LYSIMETER 1) was installed at the Keegan Landfill in Kearny Marsh in May 2007 and a second (LYSIMETER 2) was installed in October 2007 at the Gunnell Oval (Figure 3-1). A 2-gallon plastic bucket (the "tank") was connected via 10 feet of ¾-inch PVC pipe to a 5-gallon plastic bucket (the "receiver") with a sealed lid (Figure 3-2; Perkins 1999). A trench was dug to accommodate the lysimeters, ensuring that the receiver was lower in elevation to facilitate water flow from the tank. A small lip was left above the land surface for both the tank and the receiver to limit the local water budget to precipitation and ET by eliminating exchange with ground and surface waters (Lott and Hunt 2001). A one inch layer of pea-sized gravel was placed in the bottom of the tank to provide adequate drainage (Perkins 1999). Soil and plants excavated from the site were placed back into the tank. Care was taken to minimize disturbance of both the soil and plants during this process. ET readings were not taken for approximately two (2) weeks after installation to allow the lysimeters to reestablish plants and stabilize (Perkins 1999).

ET measurements were taken by removing water which collected in the receiver (the “percolate”) and measuring with a graduated cylinder (in milliliters). ET was measured biweekly and reported by converting the water volume to a length (inches) per time period (Perkins 1999). This conversion involved dividing the volume of water collected in the receiver by the area of the bottom of the receiver, i.e. the area of a circle with a radius of half the bucket’s diameter (Perkins 1999). If no water had collected in the receiver, a known measured volume of water was added to the tank and several (15-30) minutes were allowed to pass to ensure adequate seepage from the tank to the receiver. This additional water was collected from the receiver and the volume converted to a depth, in inches, by dividing it by the area of the bottom of the tank (Perkins 1999).

Any water added to the lysimeter tank (in inches) was added to the previous time period rainfall total (in inches) to get total water added to the lysimeter. Water collected in the receiver, in inches per time period, was subtracted from this total to get the ET for that time period (usually 2 weeks; Eq. 3-3; Perkins 1999). ET was divided by the number of days in the time period to get a daily ET values (in/day):

$$PET = WA + R - P \qquad \text{[Eq. 3-3]}$$

where, PET = potential evapotranspiration (in/day)

WA = water added to lysimeter tank, if no percolate had collected in the receiver since the previous visit (in/day); if there was percolate present in the receiver between visits, WA = 0 in/day

R = rainfall during sampling time period (in/day)

P = percolate collected in receiver (in/day)

Rainfall data were obtained via web download from Meadowlands Environmental Research Institute in Lyndhurst, NJ (http://merigis.njmeadowlands.gov/vdv/Index.php). This site is approximately 2.5 miles away from Kearny Marsh and is the closest weather station available. All calculations were done in Microsoft Excel spreadsheets.

The second lysimeter (LYSIMETER 2) installed near the Gunnell Oval Recreation Complex (Figure 3-1) did not function properly. Due to a break in the PVC pipe connecting the tank to the receiver combined with a shallow water table, groundwater infiltrated into this lysimeter adding excess water to the receiver and making data unusable. Results from this second lysimeter (LYSIMETER 2) are not included in analyses.

3.2.3. Eddy Covariance Measurement

Eddy covariance is a direct measure of latent and sensible heat flux from one surface to another (Campbell Scientific, Inc. 2006). As described by Drexler et al. (2004), the eddy covariance method involves wind turbulence as the transport mechanism for heat and moisture in the near surface atmospheric layer to and from a higher or lower layer (for example, to and from water bodies or soil):

> "The vertical component of the fluctuating wind is responsible for the flux across a plane above a horizontal surface. Because there is a net transport of energy across the plane, there will be a correlation between the vertical wind component and temperature or water vapor. For example, if water vapor is released into the atmosphere from the surface, updrafts will contain more vapor than downdrafts, and vertical velocity (positive upwards) will be positively correlated with vapor content. The covariance of vertical wind speed with temperature and water vapor are used to estimate the sensible and latent heat flux density." (Drexler et al. 2004, p. 2076)

ET measurements were estimated using Campbell Scientific, Inc.'s Open Path Eddy Covariance (OPEC) System (Campbell Scientific, Inc. 2006). Latent heat flux was measured following procedures outlined in Bidlake et al. (1995). A Campbell Scientific, Inc., three-dimensional sonic anemometer (Model CSAT3) and krypton hygrometer (Model KH20) were set up on a tripod 2 m off the ground (Figure 3-3) along train tracks in the southeastern part of Kearny Marsh (Figure 3-1). This location provided sufficient open water surface over which wind could travel (*fetch*) to provide a more accurate evaporation reading. A minimum recommended fetch is 100 times the height of the instrument, or 200 m for our survey. The sampling days (September 4, 2007 and December 6, 2007) had northeast winds and Kearny Marsh at this location provides over 4,000 feet (~1,220 m) of fetch. On September 4, readings were taken for 4 hours and 20 minutes, and on December 6 measurements were taken over an 8 hour and 20 minute span. Measurements were taken at a sampling rate of 10 Hz and were averaged over a 10 minute period as recommended by Tanner (1998) for work within a few meters of the land surface. The eddy covariance system used in this study directly measures latent and sensible heat flux (Campbell Scientific, Inc. 2006).

ET rates were calculated from latent heat measurements by dividing latent heat by the product of the density of water (1000 kg/m^3) multiplied by water's latent heat of vaporization ($2.5x10^6$ J/kg) (Shoemaker et al. 2008). Daily ET rates were calculated by determining ET rates for every 10 minute period and averaging these values for the sampling day.

Daily rates were measured on September 4 and December 6, 2007. These dates were chosen due to equipment availability, technical requirements, such as proper climate conditions, and with the hope to possibly represent the maximum (September 4) and minimum (December 6) theoretical ET rates for the year. Monthly rates were calculated by applying daily ET rate to days where there was no rain during a given month for 2007. Rainfall data were obtained during calculation of ET using the lysimeter (see section *3.2.2. Lysimeter*). The assumption was that the occurrence of precipitation during any given day would result in ET not occurring or occurring in a negligible amount when compared to the amount of precipitation. PET values are generally reduced in the presence of clouds and rain (Thornthwaite 1948). To coincide with the other time periods for this study, the September-based eddy covariance ET rate (0.259 in/day) was applied to May through September 2007 and the December ET rate (0.012 in/day) was applied to October through December 2007. Daily ET rates were totaled for each month and used in our analysis.

The eddy covariance method was chosen because it provides a direct measure of ET and it has been suggested that the best way to improve wetland ET estimates is to better account for surface variation by improving the measurement and relative weighting of net radiation and conductive (ground or water) heat flux density (Drexler et al. 2004). When compared to other methods that measure ET, eddy covariance methods may produce more reliable results (Shoemaker et al. 2008).

3.2.4. Statistics

A few statistics were used to compare the different methods of estimating ET rates. Standard deviation is a measure of the variability within and between sets of data, and specifically how widely values are dispersed from the mean (Fowler et al. 1999). It is calculated as:

$$s = \sqrt{\frac{\sum \left(O - \bar{O} \right)^2}{n - 1}} \qquad \text{[Eq. 3-4]}$$

where, s = standard deviation

O = the value of an observation

Ō = mean of the observations

n = number of observations.

The standard error of the mean is the standard deviation of a set of sample means (Fowler et al. 1999). It is useful when sample sizes are small. Standard error of the mean is the standard deviation (s; Eq. 3-4) divided by the square root of the number of samples (Eq. 3-5):

$$S.E. = {}^{s}\!\big/\!_{\sqrt{n}} \qquad \text{[Eq. 3-5]}$$

where, S.E. = standard error.

In addition, a one-way analysis of variance (ANOVA) was conducted on estimated ET rates. In its simplest form, ANOVA gives a statistical test of whether the means of two or more groups of data are equal (Fowler et al. 1999). Variance is the square of standard deviation, and is the measure of the amount of variation of all the scores for a variable. One-way ANOVA was chosen because the sample sizes being analyzed do not have to be equal (Fowler et al. 1999). All statistics were run in Microsoft Excel.

3.3. Results & Discussion

Since lysimeter data were only available from May through December 2007, all results and analyses reported are for this time period. This reflects the average growing season of plants for New Jersey, when ET rates are theoretically at their maximum due to increased daylight, increased temperature, and increased leaf surface area as vegetation matures. All results ranged from 0.004 – 0.466 in/day, with a mean ET rate of 0.183 $\pm$ 0.11 in/day (Figure 3-4; Table 3-2). Calculated results from the Thornthwaite equation provide ET rates ranging from 0.004 – 0.187 in/day and a mean ET rate of 0.113 $\pm$ 0.07 in/day. Lysimeter data result in a range of ET rates from 0.134 – 0.466 in/day, with a mean of 0.260 $\pm$ 0.13 in/day. Eddy covariance measurements ranged from 0.011 – 0.234 in/day with a mean rate of 0.176 $\pm$ 0.07 in/day. These measurements are comparable to ET rates measured in other studies (Fermor et al. 2001; results as reported in Burba et al. 1999; Table 3-3).

All ET rates follow a seasonal pattern (Figure 3-4) with higher rates occurring in summer months and lower rates in winter months. Rates from reedbeds in the United

Kingdom showed that maximum rates occurred during summer (May – September), as well (Table 3-3; Fermor et al. 2001). The maximum ET rate measured was in July using Thornthwaite calculations and lysimeter measurements (Table 3-2). The eddy covariance measurement was highest in September, with the second highest readings in July (Table 3-2). There are two factors that can account for this increase in ET rates during the summer and the drop in ET rates during the fall and winter. First, during the summer months longer days with more sunlight and higher temperatures can elevate the evaporation rate of water bodies and soil. As days grow shorter and temperatures decrease through the fall into winter, rates will lessen. Second, the growing season for New Jersey usually starts at the end of April and continues through mid-October. Increased plant growth will heighten rates at which these plants take up water (and nutrients) from the soil for growth as well as increase transpiration rates as more leaf cover is created during plant maturation. The combination of these creates the seasonal pattern experienced during this study.

One-way ANOVA analyses were performed on the datasets. Results of analysis of different ET rates/measurements show that there is a statistically significant difference ($F(1,14) = 7.399$, $p<.05$) between Thornthwaite and lysimeter methods. The lysimeter had a mean ET rate for the season that was more than double the mean Thornthwaite-derived rate (Table 3-2). There was no statistically significant difference, however, between lysimeter and eddy covariance methods ($F(1,14) = 2.368$, $p<.05$), and the Thornthwaite and eddy covariance methods ($F(1,14) = 3.301$, $p<.05$). The eddy covariance ET rate may reflect a 'middle ground' that may be reflective of both lower values seen in Thornthwaite results and higher rates found from the lysimeter (Table 3-2).

The Thornthwaite equation tends to underestimate potential evapotranspiration. When comparing various equations for calculating ET rates, Rosenberry et al. (2004) found that the Thornthwaite method underestimated ET rates for a prairie wetland in North Dakota (USA). This underestimation has been shown to be up to 25% of a reference ET rate (Pereira and Pruitt 2004). ET rates calculated by the Thornthwaite method for Kearny Marsh were consistently low (Table 3-2; Figure 3-4). Mean Thornthwaite results were 36% lower than mean eddy covariance results and 56% lower than mean lysimeter ET rates (Table 3-2). Garcia et al. (2004) found that the temperature-based Thornthwaite equation resulted in 50% or more underestimation of ET. This may be due to the fact that the Thornthwaite was developed for humid regions and underestimates under drier climates (Garcia et al. 2004). Taking this into account, along with statistical differences between it and other methods, it was decided that Thornthwaite values calculated for this study were too low to use for our purposes and were not used in subsequent modeling.

The lysimeter proved problematic due to several instances where it was broken or failed to transmit water to the receiver. Maintenance of the lysimeter proved to be a time-consuming task. This may have affected the accuracy of the ET rates measured by this device. The second lysimeter (LYSIMETER 2) installed near the Gunnell Oval (Figure 3-1) failed to operate properly almost immediately after installation. In addition, lysimeter derived ET rates were the highest during this study (Figure 3-4; Table 3-2). This increase may be due to the 'oasis effect' where, during dry weather, soil surrounding the lysimeter dries out causing ET rates to be abnormally high (Lott and Hunt 2001). In addition, 2007 represented an above average year for precipitation for New Jersey.

Average rainfall is 46.41 inches per year, and 56.25 inches fell in 2007. Prueger et al. (1997) found that improper drainage from lysimeters during years with above average precipitation did not remove excess water and kept the lysimeter saturated when no precipitation occurred, enhancing ET rates. The lysimeter was, therefore, able to evaporate more water than the surrounding area as water became trapped in the lysimeter. In addition, lysimeter ET values represent PET, which is the theoretical maximum ET rate given a sufficient supply of water whereas Thornthwaite and eddy covariance methods reflect AET. PET rates are generally higher when compared to AET rates. Due to these equipment and spatial limitations of having only one lysimeter present at Kearny Marsh, lysimeter measurements were not used in subsequent modeling efforts.

Standard errors were calculated on the data from each method of ET estimation. The Thornthwaite equation and eddy covariance methods had the same error (0.025). The lysimeter data had a much larger error (0.048), which is most likely due to the equipment problems experienced. The largest source of error in many wetland water budgets is due to ET (Favero et al. 2007; Vepraskas et al. 2006; Kreiser 2003). To reduce this error, methods that themselves have little error should be utilized, thus preventing it from propagating through the analytical process. The low error associated with its data and the reliability of readings were evidence that the eddy covariance data is the most suitable for use in models to determine the hydrology of Kearny Marsh.

While the datasets used in this analysis were small and varied depending on the method of ET estimation (Thornthwaite used 8 calculations; lysimeters were measured 15 times; EC was based on 2 measurements), they provided a good starting point for analysis of ET rates for Kearny Marsh and values useable in modeling both the surface water and groundwater hydrology of this urban wetland system. The statistical analyses, however, were chosen based upon their utility on small and unequal sample sizes (Fowler et al. 1999). The results as such should be viewed in this light and that larger datasets would have provided more robust conclusions on ET estimates for Kearny Marsh. One recommendation would be to extend these methods over the course of a longer time period, especially the summer months, in order to achieve this.

It has been suggested that the best way to improve wetland ET estimates is to better account for surface variation by improving the measurement and relative weighting of net radiation heat flux density (Drexler et al. 2004). Use of the more sophisticated eddy covariance method is one means to reduce problems associated with other methods used in this study (Lott and Hunt 2001). Eddy covariance makes possible direct determination of latent and sensible heat fluxes and thus avoids operational difficulties and errors that are associated with maintenance of lysimeters in wetland environments (Bidlake et al. 1995). Despite these advantages, several challenges to using eddy covariance to estimate ET still exist: (i) adequately accounting for errors in measurements, (ii) achieving good results under changing hydrological conditions and (iii) keeping instruments operational for long periods in order to assess interseasonal variability (Drexler et al. 2004). A review of available literature has not uncovered any previous studies using eddy covariance to estimate ET rates in an urban wetland system. The eddy covariance method was determined based on direct determination of latent and sensible heat fluxes to be the best available for estimating ET rates for Kearny Marsh.

3.4. Conclusions

1. Eddy covariance results are the only direct measure of ET rates used in this project. They were used in subsequent Kearny Marsh hydrologic models (SWMM and Visual MODFLOW). The smallest amount of standard deviation and standard error was found within this dataset.
2. One drawback to this study was that eddy covariance measurements were only taken on two dates in 2007 (September 4, and December 6) and then extrapolated for an entire year. This may also account for the small standard deviation and error seen in this dataset. A more accurate measure of ET using this method would be to measure continuously over a longer time period to adequately capture seasonal variability.
3. The lysimeter data correlated well with eddy covariance results and may be a suitable substitute if sufficient time and resources are available for data collection. Several lysimeters installed in more areas of Kearny Marsh may have performed as well, if not better, than the eddy covariance method, which is more costly.
4. The lysimeter method estimated high ET rates, possibly due to factors not described here. Average ET rates from this method were 47% higher than the eddy covariance method and 130% higher than the Thornthwaite estimation. If the lysimeter method were chosen to estimate ET rates, there would be a need to overcome the tendency of lysimeters to estimate high ET rates.
5. Equipment problems using the lysimeter method necessitated constant care and maintenance. This makes the lysimeter method feasible only if time and resources are available throughout the study period.

6. The Thornthwaite calculation method estimated lower ET rates for Kearny Marsh than other methods. ET rates from the Thornthwaite method are distinctly different than the results of other methods used in this study, with estimates below lysimeter and eddy covariance method ET rates by 56% and 36%, respectively.
7. The eddy covariance method displayed no statistically significant difference with the Thornthwaite equation. This may show that the eddy covariance method is underestimating ET rates in Kearny Marsh, as well. The ‘maximum ET rate’ for the season was measured on September 4, 2007, which may be past the actual maximum for the year, causing the eddy covariance method to underestimate ET rates. Other methods used in this study found a maximum ET during July. If eddy covariance measurements had been conducted in July, they may have also followed this pattern. Increasing the sampling frequency of the eddy covariance method over the course of several months, especially the summer months, may negate this problem and better represent ET rates for Kearny Marsh.

Figure 3-1: Study site with locations where lysimeter and eddy covariance methods were employed.

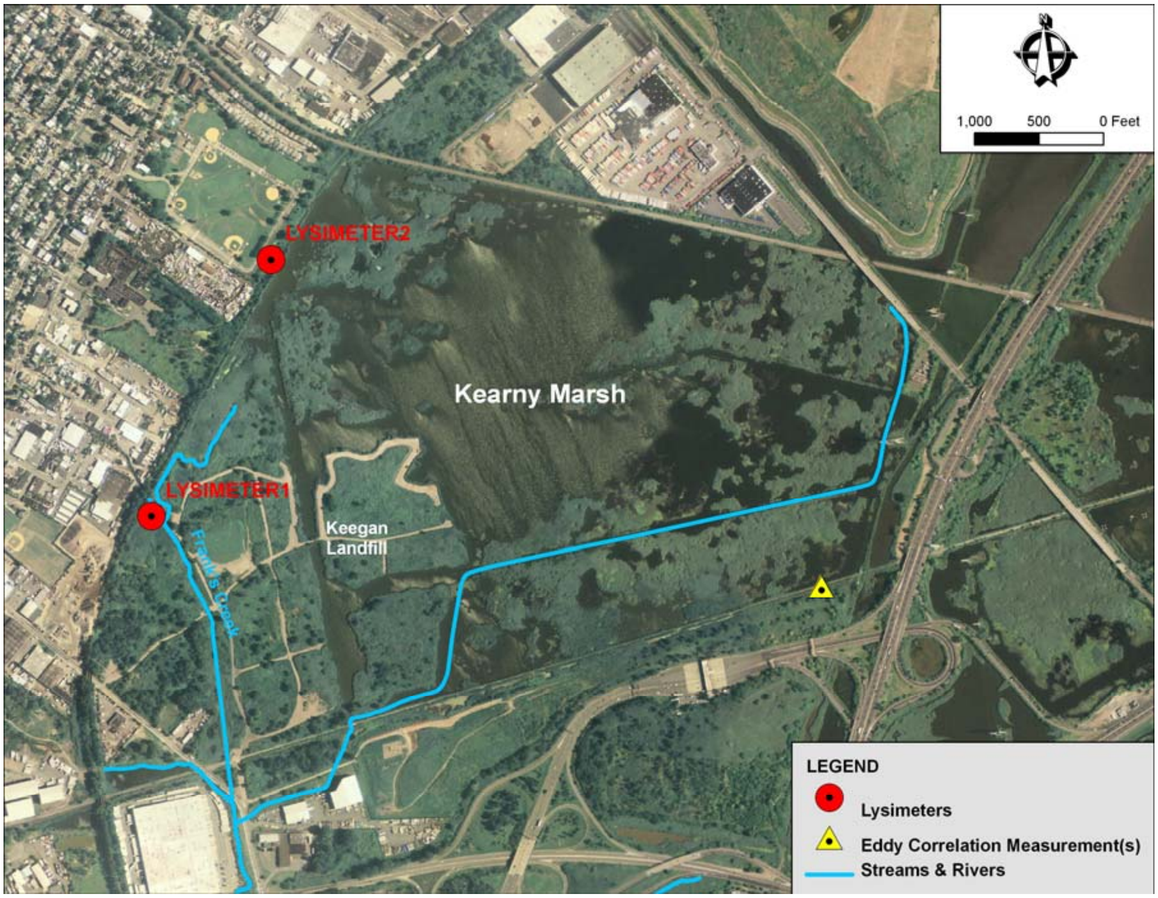


Figure 3-2: Non-weighing lysimeter set up used in Kearny Marsh. (Adapted from Perkins (1999).)

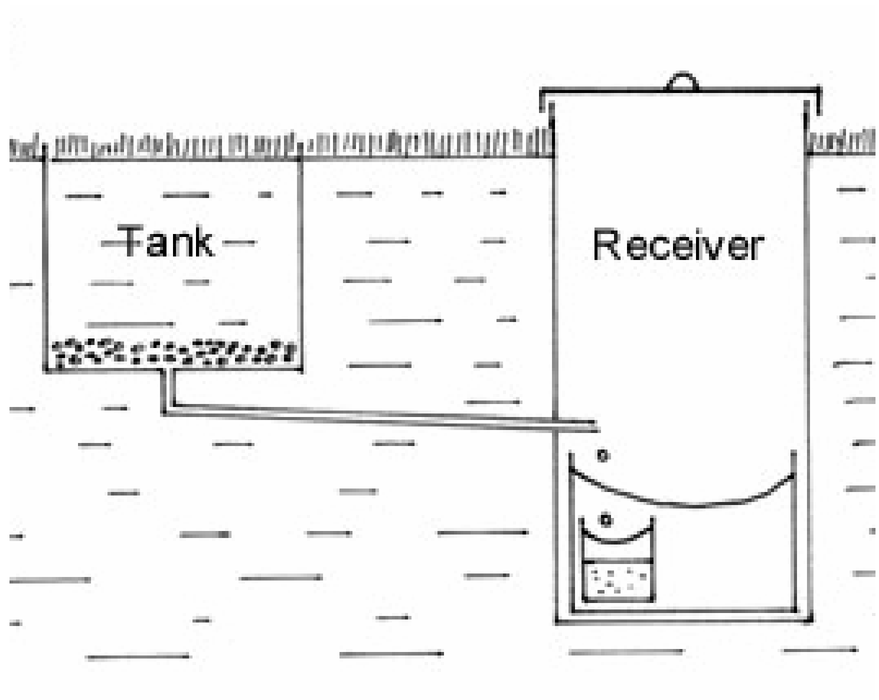


Figure 3-3: Open path eddy covariance (OPEC) measurement system configuration.

Figure 3-4: Plot of monthly evapotranspiration rates derived from all three methods. Error bars show standard error of the mean.

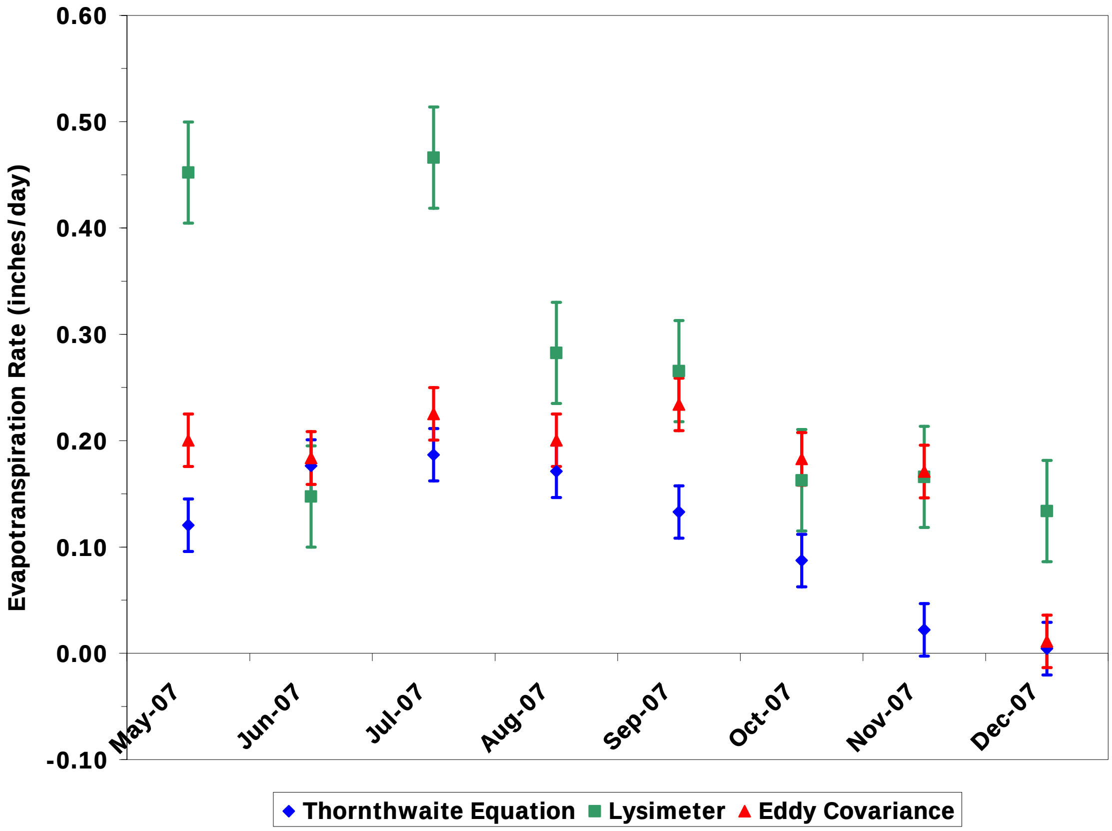


Table 3-1: Correction Factors for Monthly Sunshine Duration (from Dunne and Leopold (1978)).

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0.80	0.89	0.99	1.10	1.20	1.25	1.23	1.15	1.04	0.93	0.83	0.78

Table 3-2: Estimated 2007 evapotranspiration rates (in/day) for Kearny Marsh (SD = standard deviation; ERR = standard error of the mean).

METHOD	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	MEAN	SD	ERR
Thornthwaite	0.120	0.176	0.187	0.171	0.133	0.087	0.022	0.004	0.113	0.070	0.025
Lysimeter	0.452	0.148	0.466	0.283	0.265	0.163	0.166	0.134	0.260	0.135	0.048
Eddy Covariance	0.200	0.184	0.225	0.200	0.234	0.183	0.171	0.011	0.176	0.070	0.025

Table 3-3: Average monthly reedbed ET rates (1994-1998; in/day) from Fermor et al. 2001 (SD = standard deviation).

SITE	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	MEAN	SD
TINR	0.09	0.17	0.16	0.17	0.13	0.11	0.04	0.03	0.11	0.06
Himley	0.09	0.15	0.20	0.24	0.25	0.12	0.04	0.01	0.14	0.09
Walton	0.07	0.11	0.13	0.10	0.08	0.05	0.03	0.01	0.07	0.04

4. CHARACTERIZATION OF KEARNY MARSH HYDROLOGY

4.1. Model Development

Use of computer models to describe hydrology has become commonplace. Models are mathematical representations of reality that allow researchers and resource managers the opportunity to perform trial-and-error scenarios on physical structures or environmental landscapes. The ability of models to vary different input parameters in order to simulate and evaluate multiple scenarios is ideal for water management. The method generally followed when modeling hydrology is to monitor a system to be modeled, model the system of interest, calibrate and validate the model, and alter the model in some way to represent/predict changes in the system.

Surface water and groundwater have been effectively simulated as distinct models. However, groundwater and surface water are not separate parts of the hydrologic cycle, especially in some wetland systems (Bedford 1996; Winter 1999; Mitsch and Gosselink 2000; Sophocleous 2002). In order to fully account for all components of the hydrologic cycle, surface water models need to somehow incorporate groundwater, and vice versa. An understanding of how groundwater and surface water interact may help water resource managers deal with such issues as flood control, groundwater use, and land conservation, in a sustainable manner (Schot and Winter 2006). The complexity of modeling wetland hydrology is also increased in urban areas due to alteration of individual components in the hydrologic cycle (see section *1.2. Urbanization Impacts to Wetland Hydrology*).

Data were combined utilizing SWMM and Visual MODFLOW v.4.1 models to simulate water movement through the marsh. For descriptions of SWMM and MODFLOW, see sections *2.2.1. Wetland Surface Water Modeling: Use of SWMM* and *2.2.2. Wetland Subsurface Water Modeling: Use of MODFLOW*. MODFLOW is being used to simulate the groundwater system that underlies the marsh, while SWMM is being used to simulate surface water inputs to the marsh, including inflows from both stormwater discharges and overland flows. The goal was to link MODFLOW and SWMM to better describe interactions between Kearny Marsh and the underlying groundwater system. Using results of coupled SWMM and MODFLOW models after calibration and validation, a water budget was developed for this urban system that describes current inputs and outputs of the marsh. Simulations were used to predict possible changes to Kearny Marsh's water budget due to impacts from installation of a slurry wall and proposed future development of the Keegan Landfill (see section *5. Application of Coupled Model to Evaluate Hydrologic Impacts of Development in Kearny Marsh*).

4.1.1. SWMM Model Description

SWMM is a dynamic rainfall-runoff simulator that can be used for single-event or continuous storm runoff quantity and quality modeling from urban areas (Rossman 2005). The runoff component of SWMM operates by dividing the area to be modeled into a collection of subcatchments that receive precipitation and generate runoff (Rossman 2005). SWMM comprises various modules, which can simulate different components of the hydrological cycle. The foundations for runoff calculation in SWMM are the principle of mass balance and nonlinear reservoir formulation (Xiong and Melching 2005). Mass balance follows the continuity equation (Eq. 4-1), where changes in water storage in a subcatchment are a function of water inflows and outflows (Xiong and Melching 2005):

$$I - O = \frac{\partial S}{\partial t} \qquad \text{[Eq. 4-1]}$$

where, I = inflows at time, *t*

O = outflows at *t*

S = storage of water in the system at *t*

This equation is the same as the equation used to calculate water budgets (Eq. 1-1).

Runoff computation is founded on nonlinear reservoir theory, where time of concentration is modeled from kinetic wave theory (Tsihrintzis and Hamid, 1998; Xiong and Melching, 2005). In nonlinear reservoir theory, water storage is considered a nonlinear function of inflows and outflows (Xiong and Melching 2005). Overland flow from a wide subcatchment is computed using Manning's equation (Eq. 4-2; Rossman 2005; Xiong and Melching 2005):

$$Q = \frac{1.49}{n} AR^{2/3}S^{1/2} \qquad \text{[Eq. 4-2]}$$

where, Q = flow rate (in cubic feet per second, cfs)

n = Manning roughness coefficient

A = cross-sectional area of subcatchment or channel (in square feet, ft^2)

R = hydraulic radius (in feet, ft)

S = slope of subcatchment or channel (in ft/ft)

SWMM incorporates spatial and temporal rainfall data, evaporation, topography, impervious cover, percolation, storage values for impervious and pervious areas, storm drainage attributes such as slope and geometry, Manning's roughness, and infiltration rates (Rossman 2005). Surface runoff therefore considers land use type and topography, moisture conditions, infiltration losses in pervious areas, surface detention, overland flow, and channel/pipe flow. For a comprehensive treatment of the mathematical theory used to develop SWMM, refer to Rossman (2005), Xiong and Melching (2005), and Kazezyilmaz-Alhan and Medina, Jr. (2007).

The following are descriptions of key components, important parameters, or other features essential for proper assembly of the SWMM model for Kearny Marsh. Additional data not specifically mentioned below were determined by using a combination of parameter ranges supplied by the model manual, published data for sites similar to Kearny Marsh, and best judgement.

4.1.1.1. SWMM Model Domain

The SWMM domain for Kearny Marsh was built using delineated drainage basins from Neglia Engineering's storm water study as subcatchments (Figure 4-1; Rossman 2005; Neglia 2001). These drainage systems, which are designed to collect stormwater, were utilized because the majority of surface flows entering Kearny Marsh are from runoff (Neglia 2001). A drainage area for Bellville Turnpike not found in the report was added to 'Neglia-delineated' subwatersheds after water input at sampling location KM3 was discovered during site visits in February 2006. Dimensions for the Belleville Turnpike drainage area were obtained using ArcGIS 9 (ArcMap v.9.2). To verify the drainage basins impacting Kearny Marsh, the natural watershed and subwatersheds were delineated in ArcGIS 9 and compared to the 'Neglia-delineated' drainage areas. It was determined through visual inspection that these corresponded well to each other, and so the model structure was based upon basins described in the Neglia (2001) stormwater study, supplemented with the Belleville Turnpike basin. Dimensions for each subwatershed were taken from Neglia (2001), except for Belleville Turnpike as described above, and then verified using ArcGIS 9.

Much of the data used in the construction of the model (e.g., channel dimensions, subbasin sizes) were taken from a combination of published data (Neglia 2001) and field surveys where specific model input parameters were obtained. Deficiencies in subcatchment data such as land use data, lengths of subbasins, and distances were obtained and/or calculated in ArcGIS 9 and incorporated into the model. All data used in creating the model structure for the 2006 and 2007 SWMM models can be found in *Appendix A: SWMM Reports*.

Elevations of water control structures within Kearny Marsh (outfall pipes, culverts and channels) were surveyed on December 20, 2006, January 3, 2007, August 1, 2007, and October 26 2007. Surveys were carried out using a surveyor's level and leveling rod (English standard) with all readings calibrated to a National Oceanic Atmospheric Administration (NOAA) benchmark located on a cement culvert near sampling location KM3 (Figure 4-2; Figure 4-3). The NOAA benchmark is part of the

U.S. Coastal Geodetic Survey and is located at 7.834 feet above sea level (NAVD 88 datum; Figure 4-2). All elevation readings are referenced to this location. U.S. Department of Agriculture (USDA) protocols for conducting surveys were followed (Harrelson et al. 1994).

4.1.1.2. Precipitation

Daily rainfall information for 2006 and 2007 was obtained from the Meadowlands Environmental Research Institute (MERI) weather monitoring station located in Lyndhurst, NJ (http://merigis.njmeadowlands.gov/vdv/index.php); these data were supplemented with precipitation data from Newark Liberty International Airport (http://www4.ncdc.noaa.gov/cgiwin/wwcgi.dll?wwDI~StnSrch~StnID~20018901#ONLINE). These locations were chosen since they are closest to Kearny Marsh, with MERI located approximately 2.1 miles away and Newark Airport being approximately 5 miles away. Their proximity would likely reduce any error that may enter the model through spatial and temporal differences normally associated with rainfall data.

4.1.1.3. Evaporation

Monthly evapotranspiration (ET) rates estimated from eddy covariance methods were input as inches per day into SWMM. See section *3. Comparison of Evapotranspiration Measurement Methods for an Urban Wetland* for methods and results. ET rates for 2006 were estimated with the same method used for calculating 2007 ET rates.

4.1.1.4. Infiltration

SWMM has the capability to calculate infiltration rates through pervious areas in three ways: Horton's equation, curve number method, and Green-Ampt method (Rossman 2005). Horton's equation assumes that infiltration decreases exponentially from a maximum to a minimum rate for the duration of a precipitation event (Rossman 2005). Curve number method, developed by the Natural Resources Conservation Service (NRCS), assumes infiltration rates based upon the characteristics of soils and land uses combined into a Curve Number (Rossman 2005). The Green-Ampt method simulates infiltration under the assumption that a layer of soil with an initial moisture content exists between the saturated and unsaturated soil zones (Rossman 2005). The Green-Ampt equation (Eq. 4-3) has the advantage of using physically based parameters that can be determined a priori. These are the average capillary suction head at the wetting front, initial moisture deficit, and saturated hydraulic conductivity of soil (Tsihrintzis and Hamid 1998; Sample and Heaney 2006):

$$F(t) - \psi\Delta\theta \ln\left(1 + \frac{F(t)}{\psi\Delta\theta}\right) = Kt \qquad \text{[Eq. 4-3]}$$

where, F(t) = cumulative infiltration (inches)

t = time (in hours)

K = hydraulic conductivity (as inches per hour)

ψ = soil suction head (inches)

$\Delta\theta = \eta - \theta_i$; η = porosity and θ_i = initial moisture content of soil

The Green-Ampt method was used in the Kearny Marsh SWMM since it has shown to be successful in modeling infiltration rates for urban watersheds (Tsihrintzis and Hamid 1998; Sample and Heaney 2006; Kazezyilmaz-Alhan et al. 2007; Kazezyilmaz-Alhan and Medina, Jr. 2008).

4.1.2. Visual MODFLOW Model Description

MODFLOW has become the most widely used groundwater model (Harbaugh et al. 2000). In MODFOW, three-dimensional groundwater flow is described by the partial differential equation (Eq. 4-4; Harbaugh et al. 2000):

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) + W = S_s \frac{\partial h}{\partial t} \qquad \text{[Eq. 4-4]}$$

where, Kx, Ky, Kz = hydraulic conductivity (K) along the x, y, and z axes (in feet per day; ft/day)

h = potentiometric head (in feet)

W = volumetric flux per unit value representing sources and/or sinks of water; W < 0.0 for outflow, W > 0.0 for inflow (in per day; day^{-1})

S_S = specific storage of porous material (in per feet; ft^{-1})

t = time (in days).

This equation is combined with other conditions that affect the boundaries between adjacent cells within the model project to determine three-dimensional groundwater flow

(Harbaugh et al. 2000). These *boundary conditions* are unique to each system modeled and aid in accurately simulating hydrological parameters.

The partial differential equation is a combination of the continuity equation and Darcy velocity (Eq. 4-5), which describes groundwater flow in one-dimension (Freeze and Cherry 1979):

$$v_x = -K_x \frac{\partial h}{\partial x} \qquad \text{[Eq. 4-5]}$$

where, v_x = velocity in the x direction (in ft/day).

This equation may be replicated in the y and z axes by replacing all x values in Eq. 4-5 with y and z values as appropriate in order to simulate flows in three dimensions. Conservation of mass is satisfied by calculating all inflows and outflows for a cell and performing a mass balance to determine the storage. Temporal change is based on time steps, which are grouped into stress periods. The length of particular time steps is user-defined during the model setup (days, as used in Kearny Marsh MODFLOW). For a complete discussion on the formulation of MODFLOW, refer to Harbaugh et al. (2000).

The following are descriptions of key components, important parameters, or other features essential for proper assembly of the Visual MODFLOW model for Kearny Marsh. Additional data not specifically mentioned below were determined by using a combination of manual provided ranges for parameters, published data for sites similar to Kearny Marsh, and best judgement.

4.1.2.1. Visual MODFLOW Model Domain

Due to a lack of groundwater and hydrogeologic data for Hudson County and the Kearny Marsh area, the MODFLOW model was created from data primarily collected from the field, supplemented with information gathered from literature sources. The Visual MODFLOW representation of Kearny was kept as simple as possible, because a more sophisticated model would have required intensive sampling and more data than what was readily available for this area of New Jersey. The model grid was set up with 30 columns and 40 rows, which resulted in equidistant cells with a cell size of approximately 250 feet by 250 feet (62,500 ft^2; Figure 4-4). The model was created using only one layer, which stretched from the ground surface down to a depth of 25 feet, which was the depth of the deep groundwater monitoring wells drilled for this study (wells 1 – 12; Figure 4-3). Also, it was at or close to this depth that a clay layer was observed during the drilling of the twelve groundwater wells in February 2006. This clay layer was assumed to be the bottom layer of the modeled aquifer. Also, based upon the information available it is assumed that the area bounded by the groundwater wells overlays an unconfined aquifer. Information on the type(s) of soil was obtained from visual inspection of extruded soil during the well drilling process, and from soil logs obtained at that time. In addition, soil stratigraphy described in Mansoor et al. (2006) was used to reference the soil logs obtained during well drilling in February 2006. This soil information was used to determine input parameters for Visual MODFLOW. For example, hydraulic conductivity values measured in the field were compared to literature values to ensure that published data and collected data were comparable. Ground surface elevation for the area was imported into Visual MODFLOW using NJDEP's 10 m Digital

Elevation Grid for Watershed Management Area 4 (downloaded from http://www.nj.gov/dep/gis/digidownload/zips/wmalattice/wma03lat.zip on August 1, 2006). Additional parameters for the model were either delineated in ArcGIS 9 or obtained from published values in the literature or as guided by MODFLOW manuals.

4.1.2.2. Hydraulic Conductivity (K)

Hydraulic conductivity (K) is the "measure of the ability of fractured or porous media to transmit water" (Fetter 1999, p. 37). Higher K values represent media through which water may pass easily, and media with low K values are more impermeable to water flow (Freeze and Cherry 1979). Estimates of K were measured in five groundwater wells on February 28, May 30, and June 28, 2007. Monitoring wells 1, 4, 8, 9, and 12 (Figure 4-3) were used to measure K using the slug test method developed by Bouwer and Rice (1976). An amount of water (the 'slug') was removed from wells at a rapid rate. The time it takes for groundwater to refill the well and stabilize to pre-recorded water table elevations was recorded (Bouwer and Rice 1976). A Whale Submersible pump connected to a car battery was used to remove the sample 'slug' out of the well. A pressure transducer was placed in the well below the water-level at a sufficient depth to permit testing. The water depth was recorded and the pump was run for approximately one minute and water table depth was measured every 10 seconds. This series of water-level versus time measurements were made as the water-level returns to near its original depth (i.e., within 0.1 feet of original depth). A data-logger recorded water-depth above the transducer before, during, and after 'slug' removal. Hydraulic conductivity was calculated using the Hvorslev equation (Eq. 4-6; Bouwer and Rice 1976; Freeze and Cherry 1979):

$$K = \frac{r^2 \times \ln\left(L/R\right)}{2LT_0} \qquad \text{[Eq. 4-6]}$$

where, K = hydraulic conductivity (in feet per second; ft/sec)

r = well radius (in feet)

L = length of open screen (in feet)

R = filter pack (of bentonite clay) radius (in feet)

T_0 = basic time lag (in seconds; sec).

The basic time lag (T_0) is calculated as:

$$T_0 = \frac{1}{t} \ln \frac{H - h}{H - H_0} \qquad \text{[Eq. 4-7]}$$

where, t = time to reach recorded water level (h) (in sec)

H = initial water level prior to removal of slug (in ft)

H_0 = water level at t = 0, or time when removal of slug stopped (in ft)

h = recorded water level at t > 0 (in ft).

All equations were calculated in Microsoft Excel and converted to ft/day. These methods were chosen since they are appropriate for piezometers with slotted screens (Freeze and Cherry 1979; van der Kamp 2001) and have been shown to provide good estimates of K in wetlands with similar soils to Kearny Marsh (Waddington and Roulet

1997; Clymo 2004). The K values from the five wells ranged from 0.17 – 0.41 ft/day, with a mean K value of 0.26 ft/day. The mean K value was used in all directions (x, y and z) in the Visual MODFLOW model, based upon the assumption that the aquifer being modeled is isotropic (Freeze and Cherry 1979). Measured K values for Kearny Marsh were within the range for unconsolidated clays and peat, which were soil types observed in both the field during installation of the groundwater monitoring wells and as reported in the literature (Mansoor et al. 2006).

4.1.2.3. Water Table Elevation

During seasonal groundwater sampling events in 2006, depth to water level in the groundwater wells was measured to the nearest ¼ inch using a steel tape measure. All measurements were taken relative to the ground surface at each well, and then referenced to well elevation surveys conducted on December 20, 2006 and January 3, 2007 (see section *4.1.1.1. SWMM Model Domain*). Elevations surveyed were referenced to a NOAA elevation station located near surface water sampling site KM3 (Figure 4-2; Figure 4-3). To more accurately determine water table elevation, six pressure transducers collecting 'real time' depth data were installed in six shallow wells in 2007 (wells 7 – 12; Figure 4-3). Transducers were installed during the spring groundwater sampling event (April 11, 12 and 20, 2007) and recorded hourly depth measurements. These transducers were left in the wells until December 31, 2007. Data were downloaded from the transducers every other week to ensure proper functioning. These data were incorporated into the model to estimate groundwater flow direction and groundwater velocity. Results from these measurements were used in calibration and validation of Kearny Marsh's

Visual MODFLOW model (see sections *4.2. Model Calibration* and *4.3. Model Validation*).

4.1.2.4. Boundary Conditions

To simulate groundwater interactions with surface water in Kearny Marsh, the drain (DRN) boundary condition was used. Based upon water table elevations calculated in the groundwater monitoring wells, it was determined that Kearny Marsh is a groundwater discharge wetland (i.e., groundwater is discharging into the marsh, helping to maintain water levels). These water table elevations are generally higher than marsh water surface elevation as determined in the field as part of surveys for elevations needed for Kearny Marsh's SWMM model (see section *4.1.1.1. SWMM Model Domain*). The DRN boundary condition removes water from the aquifer at a rate proportional to the difference between the head in the aquifer and some fixed head or elevation (Reilly 2001). Discharge from the DRN is calculated as (Eq. 4-8; Batelaan et al. 2003):

$$D = C^*(h - h_d) \text{ for } h > h_d \qquad \text{[Eq. 4-8]}$$

$$D = 0 \text{ for } h \leq h_d$$

where, D = discharge (in cubic feet per day)

C = conductance (in square feet per day, ft^2/day)

h = groundwater head elevation (in feet)

h_d = drainage level (in feet)

The DRN package assumes the drain has no effect on discharge if the head in the aquifer falls below the fixed head of the drain (D = 0 in Eq. 4-8). This method has been successfully applied in an urban discharge wetland (Winston 1996). The DRN was delineated over the whole Kearny Marsh to simulate water loss to surface water which then flows out to the Passaic River (Figure 4-4). For more on use of DRN in wetland modeling, refer to section *2.2.2. Wetland Subsurface Water Modeling: Use of MODFLOW*. DRN elevation input into the model was equal to Kearny Marsh water levels recorded by NJMC periodically during 2006 and 2007 (B. Bragin, personal communication, May 18, 2007). Conductance values were adjusted during model calibration in order to achieve agreement between measured heads in the field and model predicted heads but were kept rather conservative based upon published values (see section *4.3. Model Calibration*). Using marsh water levels as DRN levels and maintaining a conservative estimate of conductance was done in order to maintain model stability (Batelaan et al. 2003).

Additional boundary conditions for the MODFLOW model were recharge (REC) and ET (abbreviated as EVT in MODFLOW). REC values for 2006 and 2007 were taken from the 2006 and 2007 SWMM models; infiltration loss from SWMM calculated water budgets (reported as in/yr; Table 4-11) was applied as daily REC (as ft/day) in Visual MODFLOW. For EVT, monthly evaporation rates from SWMM in 2006 and 2007 (entered as in/day) were entered as EVT (as ft/day, with conversions applied first) in Visual MODFLOW on a daily basis. In MODFLOW, ET is calculated as “a linearly varying rate that ranges from a maximum at elevations at or above land surface and decreases to zero below some depth, referred to as an extinction depth” (Reilly 2001, p.

11). Extinction depths for Kearny Marsh were kept shallow and input as 1.5 feet for 2006 and 2007 simulations. Refer to section *4.5. Surface Water and Groundwater Model Integration* for a description of how the models were linked using these boundary conditions.

4.2. Evaluation of Model Performance

In order to determine how well a model simulates the environment being investigated, one must compare parameters measured in the field to model output. This can be done through inspection of charts, graphs, or other visual representations which show both the "real-world" observed data and model predicted values for those same values. This, however, is a subjective method of comparison that can bring in many sources of bias and error. Therefore, objective comparisons that allow for comparison of field-observed data and predictions while reducing bias and error are necessary. Many statistics that measure data similarity have been developed for specific use in hydrologic modeling. Those chosen for this study include the Nash-Sutcliffe Efficiency Coefficient, index of agreement, RMSE-observation standard deviation ratio, Pearson's correlation coefficient, and coefficient of determination.

One of the most widely used comparison statistics in hydrologic modeling is the Nash-Sutcliffe Efficiency Coefficient (E). The coefficient, E, is used to compare predictive capability of hydrologic models and is calculated as "one minus the sum of the absolute squared differences between the predicted (P_i) and observed (O_i) values normalized by the variance of the observed values" (Eq. 4-9; Krause et al. 2005, p. 90):

$$E = 1 - \frac{\sum_{i=1}^{n} (Oi - Pi)^2}{\sum_{i=1}^{n} (Oi - \overline{O})^2} \qquad \text{[Eq. 4-9]}$$

where, $\bar{O}$ = mean of observed values.

Results of *E* range from -∞ (negative infinity) to 1, with values closer to 1 showing greater agreement between model predictions and observed values (Krause et al. 2005). Values calculated close to zero indicate that the mean of the observations is adequate for modeling and would be a better predictor than the model (Krause et al. 2005; Moriasi et al. 2007; Schaefli and Gupta 2007). Negative values of *E* may either indicate that the mean of observation data is a better predicator or indicate model bias (McCuen et al. 2006). Negative values of *E* are generally representative of an unsatisfactory model. For many hydrologic and watershed models, a value of 0.50 or greater indicates good agreement between the model and observed measurements and, therefore, a satisfactory model (Moriasi et al. 2007).

Another measure used to determine model performance is the index of agreement (*d*) proposed by Willmott (1982) to overcome the insensitivity of other statistics (Krause et al. 2005). The index of agreement (*d*) is calculated as the ratio of the mean square error and potential error (Eq. 4-10; Willmott 1982; Krause et al. 2005):

$$d = 1 - \frac{\sum_{i=1}^{n} (Oi - Pi)^2}{\sum_{i=1}^{n} \left(\left| Pi - \overline{O} \right| + \left| Oi - \overline{O} \right| \right)^2} \qquad \text{[Eq. 4-10]}$$

Potential error "represents the largest value that the squared difference of each pair can attain" (Krause et al. 2005, p. 91). Results for *d* range from 0 through 1, where 0 represents no agreement between the observed and predicted results and 1 indicates perfect agreement (Willmott 1982; Krause et al. 2005; Moriasi et al. 2007).

The root mean square error (RMSE) to observation standard deviation ratio (RSR) is a relatively new statistic (ca. 2004) used to evaluate model performance. The RSR standardizes the RMSE based on the standard deviation of the observations (Eq. 4-11; Moriasi et al. 2007):

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n}(Oi - Pi)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}(Oi - \overline{O})^2}\right]} \qquad \text{[Eq. 4-11]}$$

where, $STDEV_{obs}$ = standard deviation of the observation data

RSR values can range from 0 to a large positive value, with 0 being the optimal result (Moriasi et al. 2007). The lower the RSR, the lower the RMSE. A guideline put forth by Moriasi et al. (2007), suggests that RSR values be equal to or less that 0.70 in order for a model to be considered satisfactory.

Pearson's correlation coefficient (*r*) and the coefficient of determination (R^2) are two commonly used methods to determine the degree in which two variables are linearly related. Pearson's coefficient (r) is calculated as the covariance divided by the product of the standard deviations of observed data and simulated data (Eq. 4-12; Fowler et al. 1999):

$$r = \left(\frac{\sum_{i=1}^{n} \left(Oi - \overline{O}\right)\left(Pi - \overline{P}\right)}{\sqrt{\sum_{i=1}^{n} \left(Oi - O\right)^2} \sqrt{\sum_{i=1}^{n} \left(Pi - \overline{P}\right)^2}} \right) \qquad \text{[Eq. 4-12]}$$

where, $\overline{P}$ = mean of predicted values.

Pearson's coefficient (r) ranges from -1 to 1, with a value of 0 meaning there is no relationship between the observed and predicted parameters (Moriasi et al. 2007). A calculated r of 1 indicates a positive linear relationship, and -1 shows a negative linear relationship (Moriasi et al. 2007). Values above 0.70, either positive or negative, are generally assumed to show a "strong" correlation (Fowler et al. 1999). The coefficient of determination (R^2) is r raised to the second power (Krause et al. 2005; Moriasi et al. 2007). Resulting values for R^2 range from 0 to 1, where values above 0.50 typically indicate acceptable results (Moriasi et al. 2007). The advantage of R^2 is that its statistical significance can be determined (Fowler et al. 1999).

4.3. Model Calibration

In order to provide accurate predictions, models must be calibrated. Calibration is a "statistically acceptable comparison between model results and field measurements" (Schnoor 1996, p. 10). This process involves running a model simulation and comparing resulting output ('predicted data') with data collected in the field ('observed data'). The closer this output data is to these field measurements the closer the model is to accurately representing the real environment. For our purposes, this 'real environment' is the hydrology of Kearny Marsh. Mathematical methods used to describe similarity between these two sets of information are described in the previous section (*4.2. Evaluation of Model Performance*). If model output values did not adequately match observed data, parameters within models are adjusted and simulations are run again.

For the SWMM model, stormwater flows and depths were taken during rain events on February 17, May 12, and September 14, 2006 and used to calibrate the Kearny Marsh model. Sample locations were at sites KM1 (a drainage pipe at the end of East Midland Avenue in Kearny, NJ), KM2 (located in Keegan Landfill at a broken bulkhead between Frank's Creek and Kearny Marsh) and KM3 (located at a culvert along the railroad line adjacent to Belleville Turnpike) (Figure 4-3). These locations matched with nodes created in the SWMM model. Measurements were taken at three times over the course of each rain event: at the beginning of the storm (within 1 – 1½ hours of the start of rainfall), the height of the storm (the portion of the storm where highest flows are estimated, which varies with each storm), and the end of each rainfall event (1 – 1½ hours after cessation of rainfall). These times were estimated for each storm event based upon timely weather predictions. This method was followed in order to capture a representative hydrograph for each storm.

Flows were measured using a Marsh-McBirney, Inc., Flo-Mate Model 2000 portable flowmeter. The flowmeter was calibrated at the beginning of each sample day following guidelines in Marsh-McBirney, Inc. (1990). Transects were established at each station using a steel measuring tape with flow and depth measurements taken at 1 foot increments along this transect (Marsh-McBirney, Inc. 1990). The only exception was site KM1 which was a 3 foot diameter pipe draining into Kearny Marsh. No cross section was established and only one flow and depth measurement was taken at this site at the beginning, middle, and end of each storm. Depths were measured in feet to the nearest 0.1 foot using a top-setting wading rod that is marked at both 1 foot and 0.1 foot intervals (Marsh-McBirney, Inc. 1990). Flows were measured by following the "60% rule" (Marsh-McBirney, Inc. 1990). This method measures flow at a depth equal to 60% of the overall water depth, which is the theoretical mean velocity at that point along the transect (Marsh-McBirney, Inc. 1990). This is accepted as a valid method of obtaining mean velocity from streams, rivers, and open channels (Marsh-McBirney, Inc. 1990). After depths were measured, velocities were measured by pointing the flow sensor into the direction of flow and adjusting the sensor to 60% of water depth by lining up the foot scale on the sliding rod with the tenth scale on top of the depth gauge portion of the top-setting-wading rod (Marsh-McBirney, Inc. 1990). Velocities were recorded in feet per second (ft/s). The procedure that occurred at each 1 foot increment on the transect was: 1) measure depth, 2) adjust height of sensor to 60% of depth, and 3) measure velocity.

Flows were calculated as cubic feet per second (cfs) by multiplying cross sectional area by velocity (Marsh-McBirney, Inc 1990). Since the width of each increment along each transect was 1 foot, cross sectional area was equal to depth. At site KM1, however, cross-sectional area was calculated for circular conduits as described in Marsh-McBirney, Inc. (1990). Flow is calculated as (Eq. 4-13):

$$Q = K \times D^2 \times U \qquad \text{[Eq. 4-13]}$$

where, Q = flow (cfs)

K = flow unit multiplier

D = diameter of conduit (feet)

U = velocity (ft/sec)

The flow unit multiplier (K) is determined by dividing the water level (L; in feet) by D, then looking up K for each L/D ratio on a table of values (Marsh-McBirney, Inc. 1990).

Mean depths and flows were calculated for each cross section and sampling time (i.e., beginning, middle, end of storm) (Marsh-McBirney, Inc. 1990). This resulted in three mean depth and flow values for each sampling/rainfall event. For more information regarding flow and depth measurement procedures, refer to Marsh-McBirney, Inc. (1990).

A SWMM simulation for Kearny Marsh was run and each model's output (depths and flows) were compared to field-measured values using performance evaluation statistics described in the previous section (*4.2. Evaluation of Model Performance*). All calculations were conducted in Microsoft Excel. Effort was made to verify that times and locations of model output matched field collected data times and locations to ensure as accurate a calibration as possible. If results showed that model performance was "unsatisfactory" (i.e., E and R^2 were less than 0.50, RSR was greater than 0.70, and d and r were below 0.70), parameters within the model were manually changed to gain a better fit and the model was re-run. If changes resulted in model performance worse than previous simulation runs, parameters were reverted back to their original values and other parameters adjusted.

Parameters in the SWMM model for Kearny Marsh changed during calibration were Manning's roughness coefficient (n) of the drainage area and/or depression storage.

The desired result was to increase or decrease model predicted flows through the system, so that they better matched observed values. These parameters were chosen because previous research has shown that SWMM is sensitive to changes in these parameters when used in urban watersheds (Tsihrintzis and Hamid 1998; Barco et al. 2008). This trial-and-error process was repeated several times in order to obtain a calibrated surface water flow model for Kearny Marsh as evidenced by acceptable values calculated from model performance statistics.

For MODFLOW, the calibration parameter was groundwater head measured in wells that circle Kearny Marsh (Figure 4-3). Depth to groundwater was measured on site visits during 2006 in March (3/27 and 3/28), April (4/20), June (6/30), September (9/25, 9/27 and 9/29), October (10/27), November (11/22), and December (12/11, 12/12, and 12/14). Measurements were taken by hand using a steel tape measure, with all measurements taken to the nearest 1/8 inch. All depth to water measurements are in relation to elevations surveyed as part of model development (see section *4.1.1. SWMM Model Development*). Depth to water measurements were converted to hydraulic heads by subtracting depth to water (reported as feet) from the elevation in cells where wells are located in MODFLOW.

The trial-and-error calibration procedure used for SWMM was replicated for the Kearny Marsh MODFLOW model. A MODFLOW simulation for Kearny Marsh was run and each model's output (head) was compared to field-measured values using performance evaluation statistics described in the previous section (*4.2. Evaluation of Model Performance*). All calculations were conducted in Microsoft Excel. Effort was made to verify that times and locations of model output matched field collected data times and locations to ensure as accurate a calibration as possible. If results showed that model performance was "unsatisfactory" (i.e., E and R^2 were less than 0.50, RSR was greater than 0.70, and d and r were below 0.70), parameters within the model were manually changed to gain a better fit and the model was re-run. If changes resulted in model performance worse than previous simulation runs, parameters were reverted back to their original values and other parameters adjusted.

Parameters in the Kearny Marsh MODFLOW model that were adjusted during calibration were initial heads at each well at the start of the model, specific storage coefficient, and/or stage and conductance of the DRN that represents Kearny Marsh itself. The desired result was to increase or decrease model predicted groundwater heads through the system, so that they better matched observed values. These parameters were chosen because previous research has shown that MODFLOW is sensitive to changes in these parameters, and relatively insensitive to other parameters (Bradley 1996; Bradford and Acreman 2003; Restrepo et al. 2006). This process was repeated several times in order to obtain a calibrated groundwater model for Kearny Marsh as evidenced by acceptable values calculated from model performance statistics.

After several simulation runs for each model, the calibration procedure resulted in both SWMM and MODFLOW models showing good agreement between the predicted values and observed data (Figures 4-5 – 4-7, Tables 4-1 – 4-5). Results from SWMM calibration show good agreement between observed and predicted depths (E = 0.89, d = 0.97, RSR = 0.33, r = 0.94, R^2 = 0.89; Tables 4-1, 4-4; Figure 4-5) and flows (E = 0.60, d = 0.89, RSR = 0.61, r = 0.81, R^2 = 0.65; Tables 4-2, 4-4; Figure 4-6). One-way ANOVAs showed no statistically significant difference between observed and predicted flows ($F(1,28) = 4.20$, $p<.05$) or depths ($F(1,28) = 4.20$, $p<.05$). The MODFLOW model also showed good agreement between observed and predicted groundwater head (E = 0.72, d = 0.93, RSR = 0.57, r = 0.88, R^2 = 0.78; Tables 4-3, 4-5; Figure 4-7) after calibration. The coefficient of determination (R^2) was shown to be statistically significant (Fowler et al. 1999). One-way ANOVA results show no statistically significant difference between predicted and observed heads ($F(1,166) = 3.90$, $p<.05$). After review of calibration data and performance criteria, the model was deemed to be calibrated and could then be validated.

4.4. Model Validation

Validation is the process in which a second set of data are input into a calibrated model and results are compared to ensure that the model suitably describes observed phenomena (Schnoor 1996). Unlike calibration, no parameters that would affect predictions are altered during model validation. Model validation was accomplished by taking the calibrated models, entering appropriate data for 2007 (i.e., precipitation totals, evaporation rates, recharge rates, tide heights), then running simulations at appropriate time intervals (daily for MODFLOW; 15 minutes in SWMM) from January 1 through December 31, 2007. Similarly to calibration, outputs were compared and performance criteria calculated to determine validity.

Flows and depths were collected at KM1, KM2, and KM3 during two storm events on March 1 – 2 and October 19 – 20, 2007 for validation of the Kearny Marsh SWMM model. The procedure for collecting water depths and flows was the same as that used to collect 2006 calibration data.

For validation of MODFLOW, groundwater levels were measured using pressure transducers in 2007 instead of the steel-tape methods used in 2006. For a description of the theory of pressure transducers and their advantages over other means of measuring water level, see Keeland et al. (1997). Global Water WL16 Data Loggers (pressure transducers) were installed in six shallow wells (wells 7 – 12; Figure 4-3). Pressure transducers measure water depth by converting the amount of pressure exerted on the internal sensor to depth of water above the sensor. This data is recorded in an internal data logger attached to the sensor. Data loggers were programmed to record water levels every hour on the ½ hour. Wells 7 and 8 had pressure transducers installed on April 20, 2007, wells 9 and 10 on April 11, 2007 and wells 11 and 12 on April 20, 2007. All wells recorded water levels through December 31, 2007. Hourly measurements were averaged for each day prior to entry into MODFLOW. All water levels were referenced to ground surface elevations (as feet above mean sea level) obtained during model development (see section *4.1.1.1. SWMM Model Domain*).

Each model was run once, and resulting predicted values for the selected parameters (water depths and flows for SWMM and groundwater head for MODFLOW) were compared to observed values using statistics used to calibrate both models. The validation process shows that there is good agreement between observed data and predicted values for both models (Figures 4-8 – 4-10; Tables 4-6 – 4-10). SWMM validation shows agreement between observed and predicted values for depths (E = 0.81, d = 0.93, RSR = 0.43, r = 0.92, R^2 = 0.86; Tables 4-6, 4-9; Figure 4-8) and flows (E = 0.52, d = 0.87, RSR = 0.68, r = 0.78, R^2 = 0.61; Tables 4-7, 4-9; Figure 4-9). The coefficient of determination (R^2) was shown to be statistically significant (Fowler et al.

1999). In addition, one-way ANOVA showed no statistically significant difference between observed and simulated depths ($F(1,35) = 4.13$, $p<.05$) and flows ($F(1,35) = 4.13$, $p<.05$). The MODFLOW model showed strong agreement between measured and simulated groundwater heads ($E = 0.67$, $d = 0.92$, RSR = 0.57, $r = 0.88$, $R^2 = 0.77$; Tables 4-8, 4-10; Figure 4-10). Both models were considered valid and were used to predict hydrologic changes based upon proposed alterations to drainage of storm flows, development of a portion of Kearny Marsh, and installation of a slurry wall at Keegan Landfill (see section *5. Application of Coupled Model to Evaluate Hydrologic Impacts of Development in Kearny Marsh*).

4.5. Surface Water and Groundwater Model Integration

Since both surface water and groundwater systems are important in the creation and maintenance of wetlands, some level of integration between surface water and groundwater models is needed in order to accurately determine wetland hydrology. One way of accomplishing this is through coupled surface-subsurface flow models. The procedure followed in this study to create a linked SWMM-MODFLOW model was similar to coupling of SWAT to MODFLOW accomplished by Kim et al. (2008). Separate SWAT and MODFLOW models were developed and then run with an exchange of data between the two (Kim et al. 2008). Integration of the two models was achieved so that after SWAT was run, recharge and river stage calculations from SWAT were used as input into the MODFLOW model (Kim et al. 2008). Parameters from the MODFLOW simulation, primarily ET, recharge, and water exchange rate between the river and aquifer, were routed back into SWAT (Kim et al. 2008). Exchange of water between the river and groundwater was accomplished with the RIV package in MODFLOW. They were able to successfully replace the limited groundwater modeling capabilities of SWAT with the groundwater modeling ability of MODFLOW (Kim et al. 2008).

SWAT was primarily developed to predict the hydrology of large-scale watersheds, especially hydrology that results from impacts on water management and agriculture in ungauged streams (Arnold and Fohrer 2005). While this model has been used extensively, it is not well suited for smaller scale applications like Kearny Marsh. In addition, SWAT is generally used in non-urban settings, particularly agricultural watersheds (Deliman et al. 1999). SWMM is ideal for use in Kearny Marsh due to its applicability to both urban settings and small watersheds (Zoppou 2001; Rossman 2005).

Integration was facilitated through several steps: 1) calibrated SWMM model with 2006 input data (precipitation and tide heights) was run (see section *4.3. Model Calibration*); 2) output parameters from SWMM water budget (infiltration loss and evaporation loss) were used as input in uncalibrated MODFLOW (recharge and ET, respectively); 3) ran MODFLOW with 2006 input data (recharge, ET, and head elevation) and calibrate model (see section *4.3. Model Calibration*); 4) ran calibrated SWMM model using 2007 data and validated model (see section *4.4. Model Validation*); 5) used output (infiltration loss and evaporation loss) as input into calibrated MODFLOW model; 6) ran MODFLOW using 2007 data and validated (see section *4.4. Model Validation*). Furman (2008) refers to this level as “no coupling”, or *uncoupled*, where a surface water model is created and simulations are run that provide data to be input as boundary conditions for a subsurface water model. In Visual MODFLOW, recharge (RCH) and ET (abbreviated as EVT in MODFLOW) are boundary conditions. This coupling set up does not provide feedback into SWMM from MODFLOW, but water exchange between groundwater and the marsh was accomplished by using the DRN function to represent Kearny Marsh. This form of integration was chosen for Kearny Marsh since SWMM does not have the capability to model groundwater flow, MODFLOW only works for the saturated zone and cannot model overland flow, and the coupling would allow for a near complete representation of the hydrologic cycle (U.S. Army Corps of Engineers et al. 2002).

4.6. Results

4.6.1. Surface Water

Surface water budgets for 2006 and 2007 simulated in SWMM show that the largest water input to Kearny Marsh in both years modeled was precipitation, and the largest water loss was from infiltration into the ground (Table 4-11). Precipitation in 2006 was a little above average for New Jersey (2006 = 48.57 inches per year (in/yr); New Jersey average = 44.99 in/yr). In 2007, precipitation was higher than average (54.32 in/yr; Table 4-11). Infiltration into the ground accounted for a loss of 18.50 in/yr in 2006 and 21.41 in/yr in 2007 (Table 4-11). Evaporation accounted for a loss of 11.86 in/yr in 2006 and 12.91 in/yr in 2007 (Table 4-11). In 2006, runoff was predicted as 18.27 in/yr, and 19.57 in/yr in 2007 (Table 4-11). More water evaporated, infiltrated, and ran off in 2007 due to the higher amount of available water (as precipitation) versus 2006.

From the model, it was predicted that surface flooding occurred in both 2006 and 2007 at two locations: the area adjacent to Gunnell Oval (near site KM1 in Figure 4-3) and the headwaters of Frank's Creek (near site KM2 in Figure 4-3). Both of these locations are in the western portion of the marsh, in areas that have suffered flooding in the past. For example, between October 12 and October 14, 2005, 5.6 inches of rain fell in Kearny, resulting in flooding in the Keegan Landfill in the western portion of Kearny Marsh. This area is adjacent to the headwaters of Frank's Creek. Other areas surrounding Kearny Marsh, most notably the Belleville Turnpike (Route 7) have experienced flooding in the past (NJMC 2005), but this area is to the east of Kearny Marsh and outside of the domain of the surface water model (Figure 4-3). The simulated extent of flooding in 2006 was similar to 2007 (*Appendix A: SWMM Reports*). In addition, more runoff was generated in 2007 than in 2006 (Table 4-11). The runoff may be of a volume that is too large for drainage systems in Kearny Marsh, such as Frank's Creek, to adequately handle, with flooding occurring as a result.

Hydrology is being affected by a broken bulkhead connecting Frank's Creek to Kearny Marsh via Keegan Landfill (Figure 4-3; Figure 4-11). This break is located at site KM2 (Figure 4-3). The SWMM model predicted that during low tide, Frank's Creek drains water out of the marsh from both the broken bulkhead area and the designed drainage system in the southwestern section of Kearny Marsh (Figure 4-3). This situation changes, however, during high tide. Tide gates located along Frank's Creek and its tributaries are currently in working order (N. Agnoli, personal communication, April 10, 2006) and are closed during high tide. This builds water behind the gates and, under normal circumstances, would cause tide gates to open when water levels in Frank's Creek are higher than high tide levels. However, the break in the bulkhead upstream of the tide gates allows flows to short-circuit Frank's Creek and flow through the bulkhead directly into Kearny Marsh (Figure 4-12). When mean predicted flows are compared to mean tide heights for both years of the SWMM model, negative flows (Figure 4-12) which represent water backing up into Kearny Marsh from Frank's Creek are occurring when tides are higher (Table 4-12). Positive flows (Figure 4-12), or flows from Kearny Marsh into Frank's Creek, are simulated to occur during lower tides (Table 4-12). This phenomenon was observed during site visits when flow data were collected in both 2006 and 2007 (see sections *4.2. Model Calibration* and *4.3. Model Validation* for dates). Any water quality issues affecting Frank's Creek may have the potential to impact Kearny Marsh during high tides.

4.6.2. Groundwater

The Visual MODFLOW model was able to predict groundwater flow direction and velocity from the input data. The general groundwater flow direction was from west to east, towards the Hackensack River (Figures 4-13a and 4-13b). This prediction coincides with the direction of groundwater flow observed by Mansoor et al. (2006). Groundwater flow direction was confirmed with data obtained from water table levels in groundwater wells used in calibration and validation of the MODFLOW model (see sections *4.2. Model Calibration* and *4.3. Model Validation*; Figures 4-14a - 4-14f). The lowest water table elevations were seen at groundwater well 12 meaning that the groundwater flows are in a northeastern direction (Figure 4-3; Figure 4-14f; Table 4-13). Mean water table elevation at well 12 was 3.24 ft in 2006 and 3.54 ft in 2007 (Table 4-13). In addition, groundwater is flowing into Kearny Marsh (Figures 4-13a and 4-13b) confirming that it is a groundwater discharge wetland. This means that the water quality of the groundwater has the potential to impact water quality of marsh water as it flows towards Kearny Marsh. In addition, water table elevations show that the water table is relatively shallow in the Kearny Marsh vicinity (Figures 4-14a – 4-14f; Table 4-13). Water table elevations are above marsh surface elevations and drainage invert elevations (see section *4.1.1. SWMM Model Description* and *Appendix A: SWMM Reports*), indicating that Kearny Marsh is a groundwater discharge wetland, where groundwater is maintaining marsh water levels (Mitsch and Gosselink 2000). Groundwater is discharging into Kearny Marsh and flowing out as surface water into the Passaic River through Frank's Creek and its associated drainage network.

Groundwater velocities from MODFLOW simulations were variable throughout the year, depending on the amount of recharge and evaporation occurring in Kearny Marsh. Comparing the two years showed groundwater velocity estimates were similar (Table 4-14). Mean groundwater velocity in 2006 was estimated to be 0.0048 feet per day (ft/day), with a minimum of 0.00 ft/day and a maximum value of 0.0926 ft/day (Table 4-14). Predicted velocities for 2007 were similar, with mean velocity of 0.0053 ft/day, minimum velocity of 0.00 ft/day and a maximum velocity of 0.0968 ft/day (Table 4-14). Mean flows may have been higher in 2007 due to increased infiltration, and hence recharge rates, during that year when compared to 2006 (Table 4-11).

4.7. Discussion

It is essential to develop a hydrologic budget that is more detailed than just identifying the water source and what its movement is, and even a crude water budget will contribute to a better understanding of site hydrology and could greatly enhance the likelihood of successful mitigation and restoration (Morgan and Roberts 2003). The water budget is an accounting of each component of the hydrologic cycle in order to quantify its contribution in a particular system. A water budget is commonly calculated using a mass balance approach where inputs and outputs equal some change in water storage, either an increase or decrease in water level or volume. It is useful in determining the changes in overall water storage based upon changes in any individual input or output in the system (see section *1.4. Wetland Water Budget* for more information).

Models, like water budgets, are simplified approximations of reality and therefore contain error. However, relatively small errors were calculated in SWMM-produced water budget (*Appendix A: SWMM Reports*), possibly due to the calibration and validation processes showing good agreement between field observed data and model output. Input of ET rates for Kearny Marsh using methods that produce small error may also have helped to reduce propagation of errors in the models.

Data from the well pressure transducers indicated a shallow water table that responds to surface water hydrologic changes. Higher infiltration rates in 2007 (Table 4-11) resulted in higher groundwater tables (Table 4-13). Flooding was also predicted as slightly larger in 2007, possibly due to saturation of soils as water table rises and water infiltrates from precipitation (*Appendix A: SWMM Reports*). Complicating this issue is the broken bulkhead at Frank's Creek, which provides for additional water inputs into Kearny Marsh. If a storm event were to occur at high tide, the combination of events may exacerbate flooding problems in the study area.

Montalto and Steenhuis (2004) found that for the New York/New Jersey estuary's tidal wetlands,

> "There is a need to document better the hydrological characteristics of existing and historical tidal wetlands, to improve hydrological modeling capabilities, and to accompany other ecological investigations in tidal marshes with hydrological documentation (p. 414)."

Previously there was little to no knowledge about groundwater resources in the vicinity of Kearny Marsh and this model has provided some valuable information on the possible hydrologic dynamics of this system. The ability to better quantify hydrology will have larger benefits for restoring this urban wetland.

4.8. Conclusions

The hydrology of Kearny Marsh is a complicated mixture of runoff-driven surface waters interacting with groundwater discharging into the marsh. General conclusions that can be derived from field work and models are as follows:

1. Kearny Marsh is a groundwater discharge wetland, gaining water in the marsh surface from groundwater. This helps to maintain water levels in the marsh, provided that negative impacts to the quantity of groundwater are kept minimal.
2. The broken bulkhead between Kearny Marsh and Frank's Creek allows for additional water inputs into the marsh at high tide. If this situation is coupled with a storm event, then marsh water depths can be increased to the point that flooding occurs in surrounding areas. This was both predicted in the SWMM model and observed in the field.
3. Flooding is occurring in areas of the marsh due to a combination of the shallow water table, which gets elevated during storm events, development reducing the areas available to infiltrate stormwater, and drainage deficiencies due to the broken bulkhead connecting Frank's Creek and Kearny Marsh. Model results

show flooding occurs in areas along the western edge of the marsh, while other reports and observations confirm model results as well as show flooding occurs in areas adjacent to the marsh but outside the SWMM model boundaries.

4. Groundwater flow is generally in a northeastern direction, from the Town of Kearny towards the Hackensack River. Flow velocities are slow, which is consistent with hydraulic conductivity measured in the field.

Figure 4-1: Model domain/structure for Kearny Marsh SWMM model with subcatchment names.

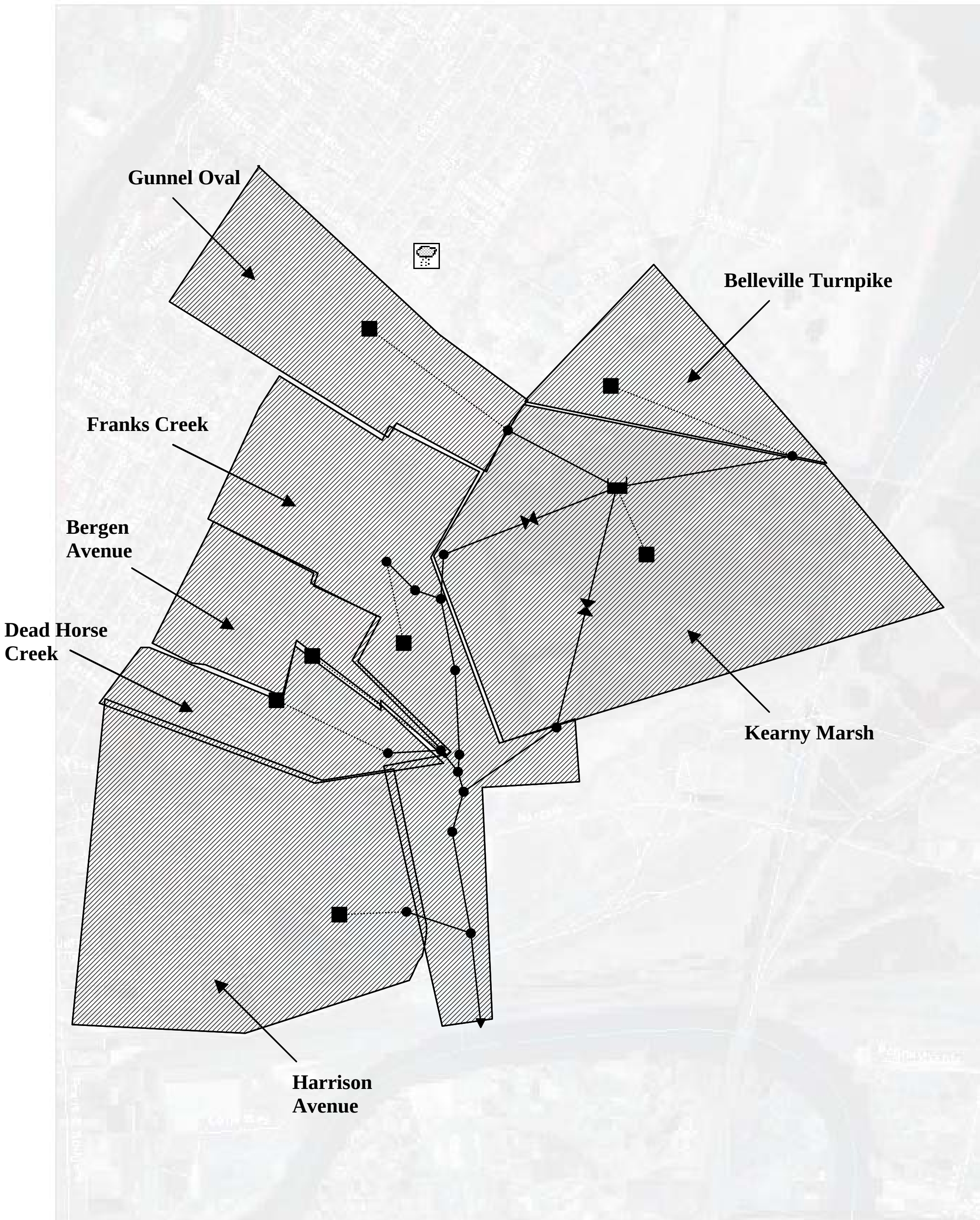


Figure 4-2: Elevation benchmark for all elevations used in Kearny Marsh SWMM model (7.834 feet asl; NAVD88 datum).

Figure 4-3: Kearny Marsh study site with locations showing where field data were obtained for calibration and validation of the surface water (SWMM) and groundwater (MODFLOW) models.

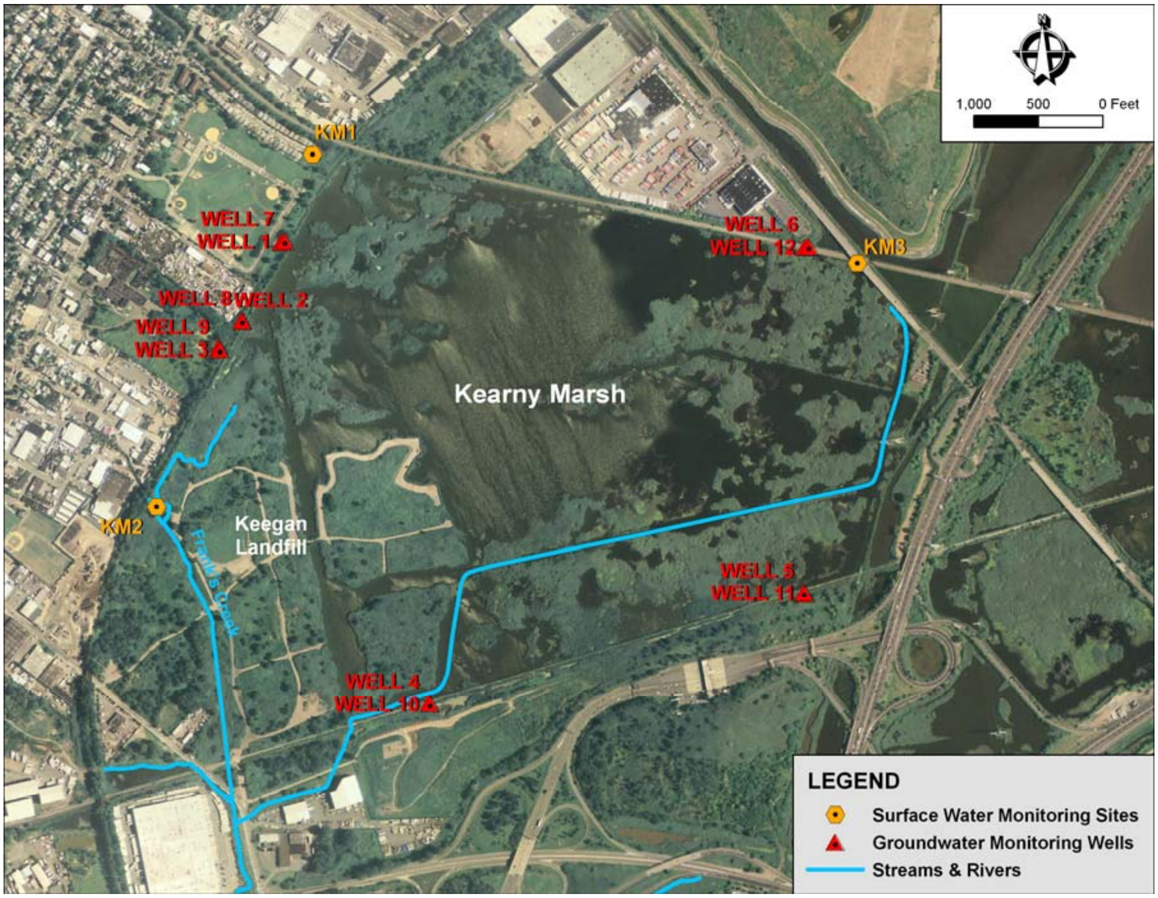


Figure 4-4: Visual MODFLOW grid for Kearny Marsh with drain (DRN) designated cells in gray and inactive cells in teal.

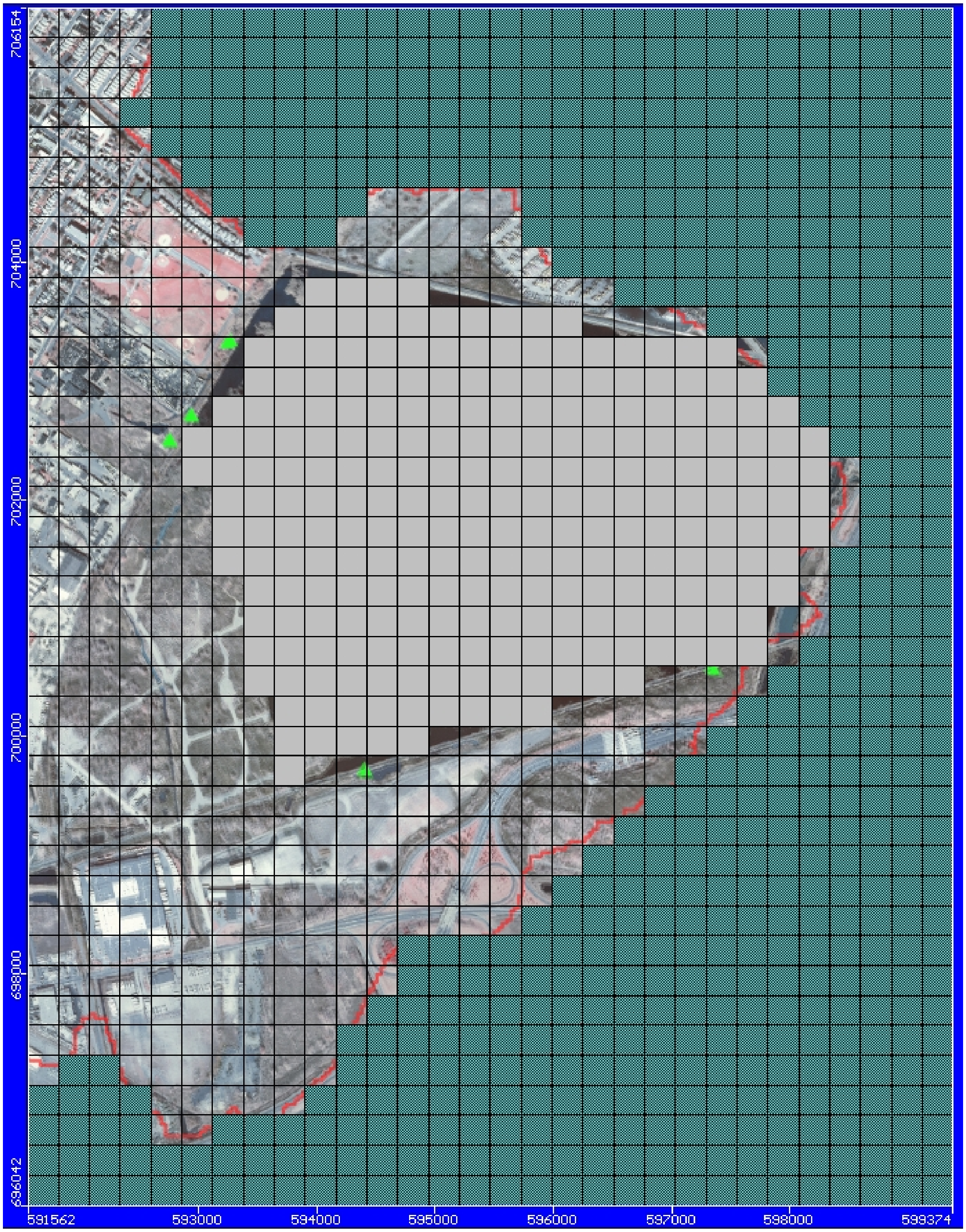


Figure 4-5: Linear relationship between observed and predicted depths for calibrated SWMM model (2006 data). Coefficient of determination (R^2) included.

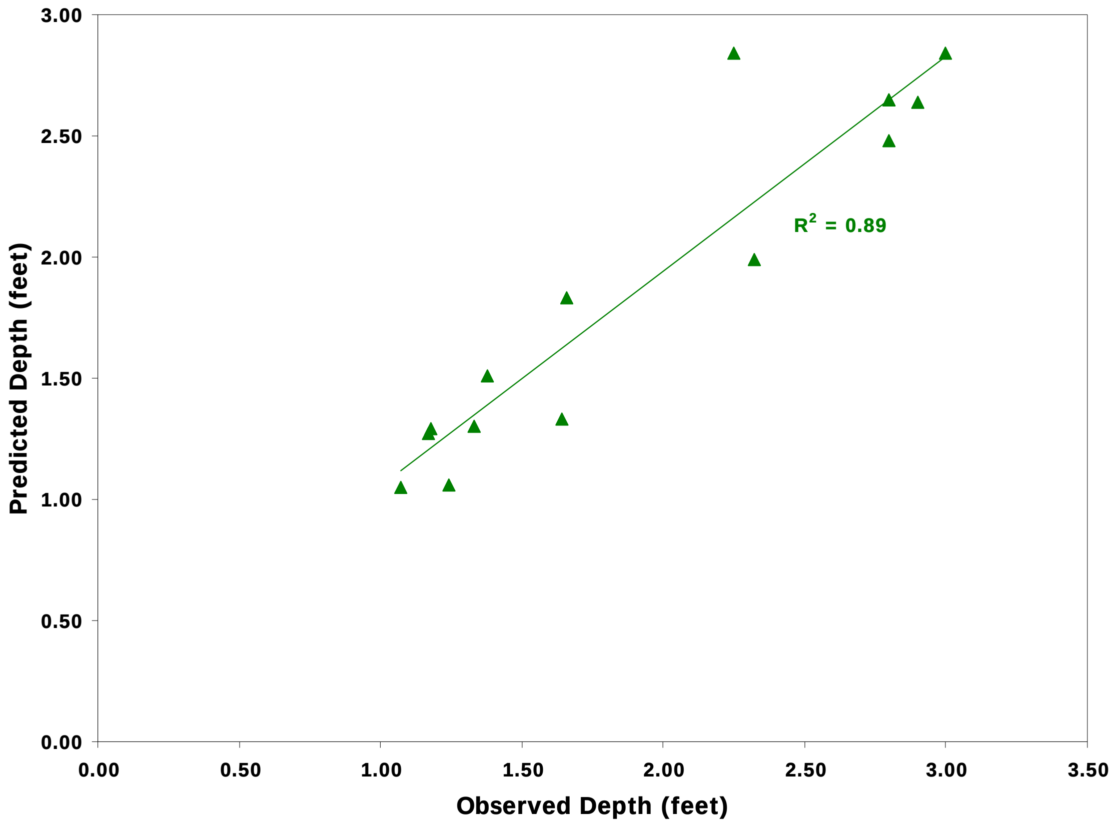


Figure 4-6: Linear relationship between observed and predicted flows for calibrated SWMM model (2006 data). Coefficient of determination (R^2) included.

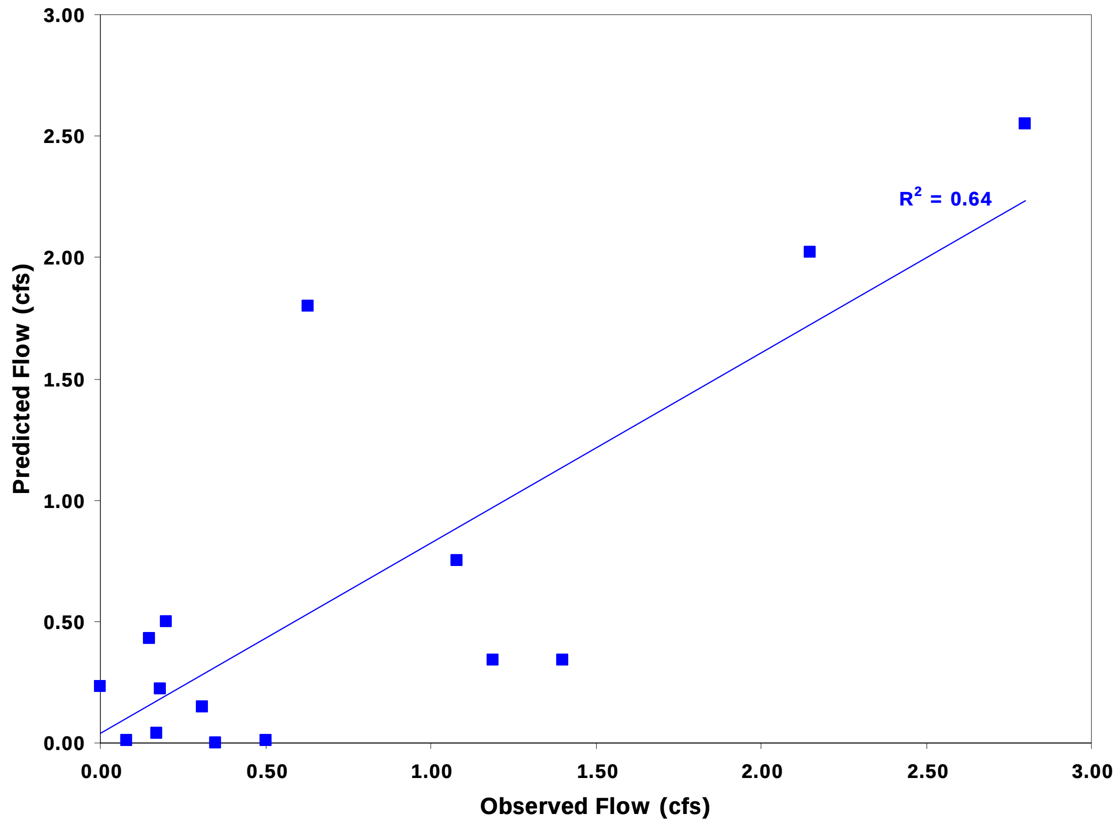


Figure 4-7: Linear relationship between observed and predicted groundwater heads for calibrated MODFLOW model (2006 data) by well. Coefficient of determination (R^2) included.

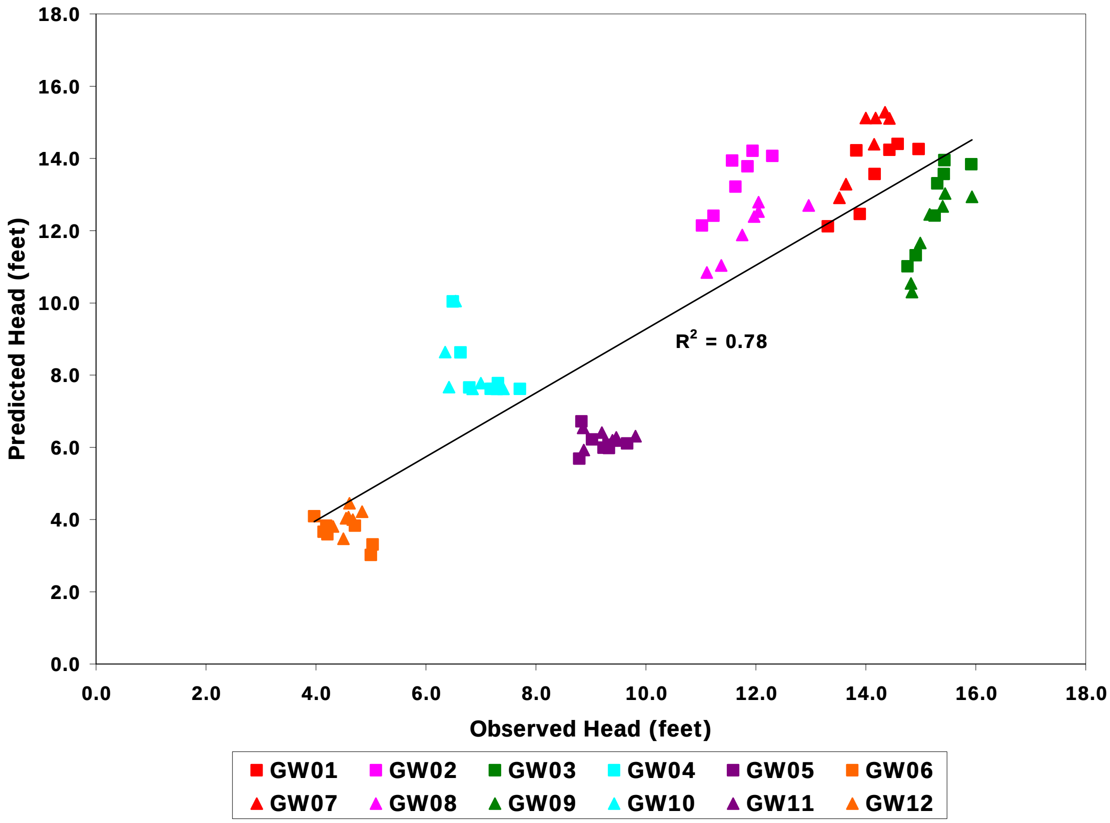


Figure 4-8: Linear relationship between observed and predicted depths for validated SWMM model (2007 data). Coefficient of determination (R^2) included.

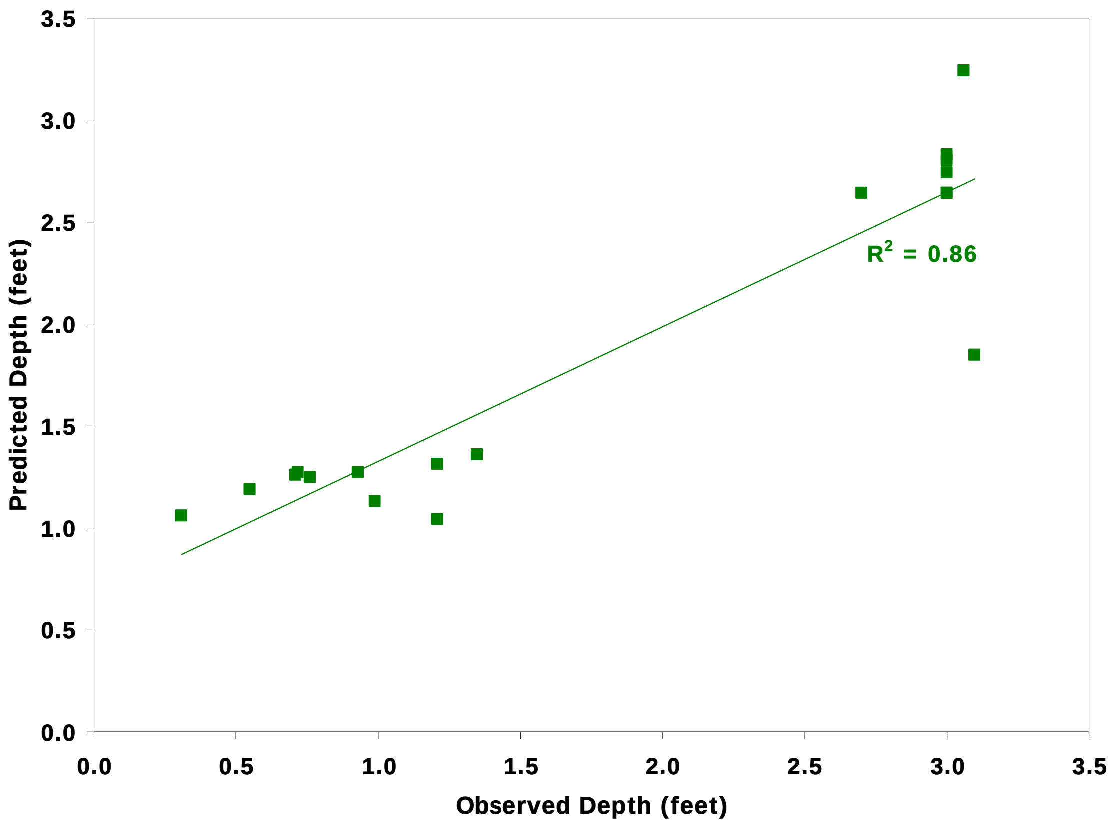


Figure 4-9: Linear relationship between observed and predicted flows for validated SWMM model (2007 data). Coefficient of determination (R^2) included.

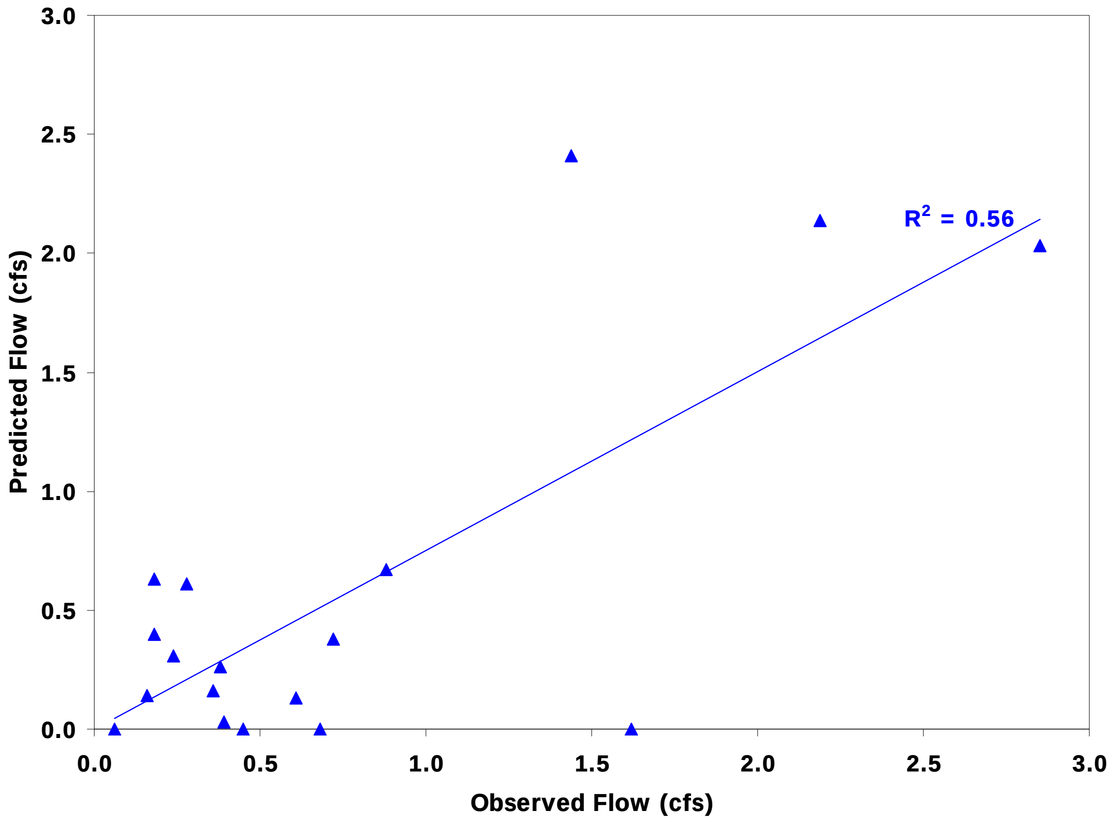


Figure 4-10: Linear relationship between observed and predicted groundwater heads for validated MODFLOW model (2007 data) by well. Coefficient of determination (R^2) included.

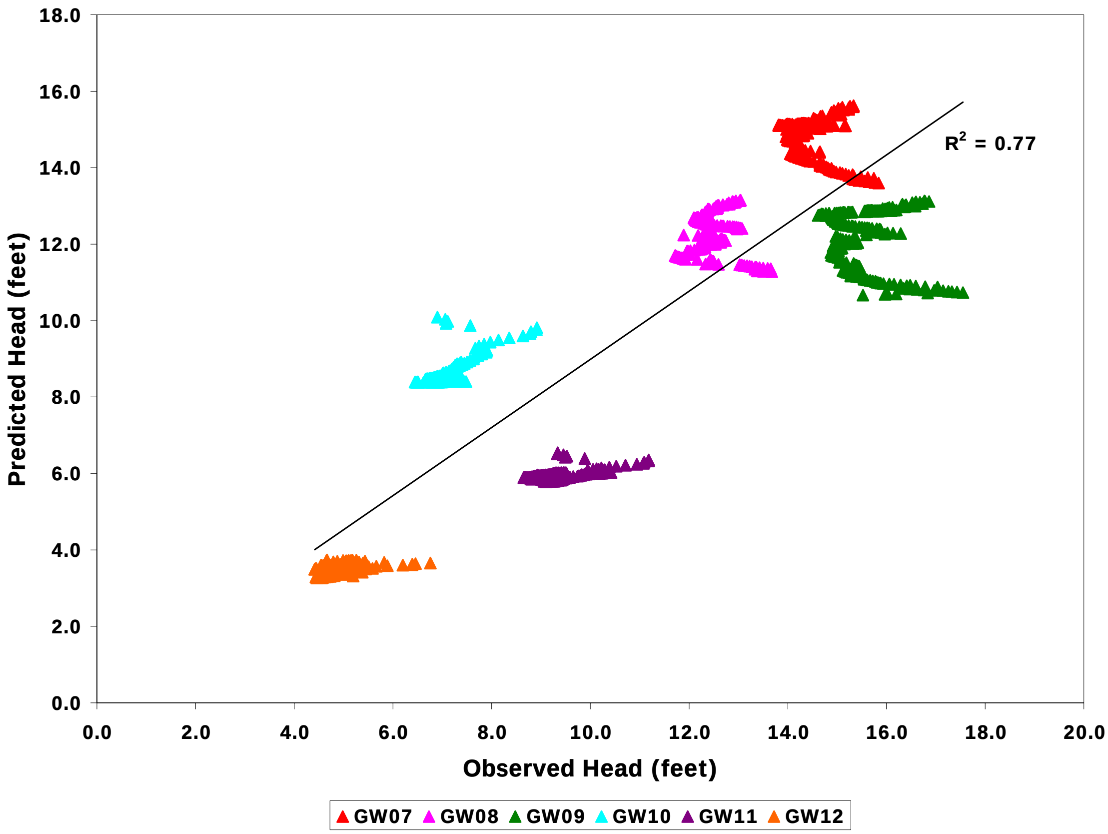


Figure 4-11: Photograph of the broken bulkhead connecting Frank's Creek and Kearny Marsh at the Keegan Landfill (June 16, 2006).

Figure 4-12: Simulated flows at the broken bulkhead connecting Frank's Creek to Kearny Marsh. Positive flows are directed from Kearny Marsh into Frank's Creek and negative flows are directed back into Kearny Marsh from Frank's Creek.

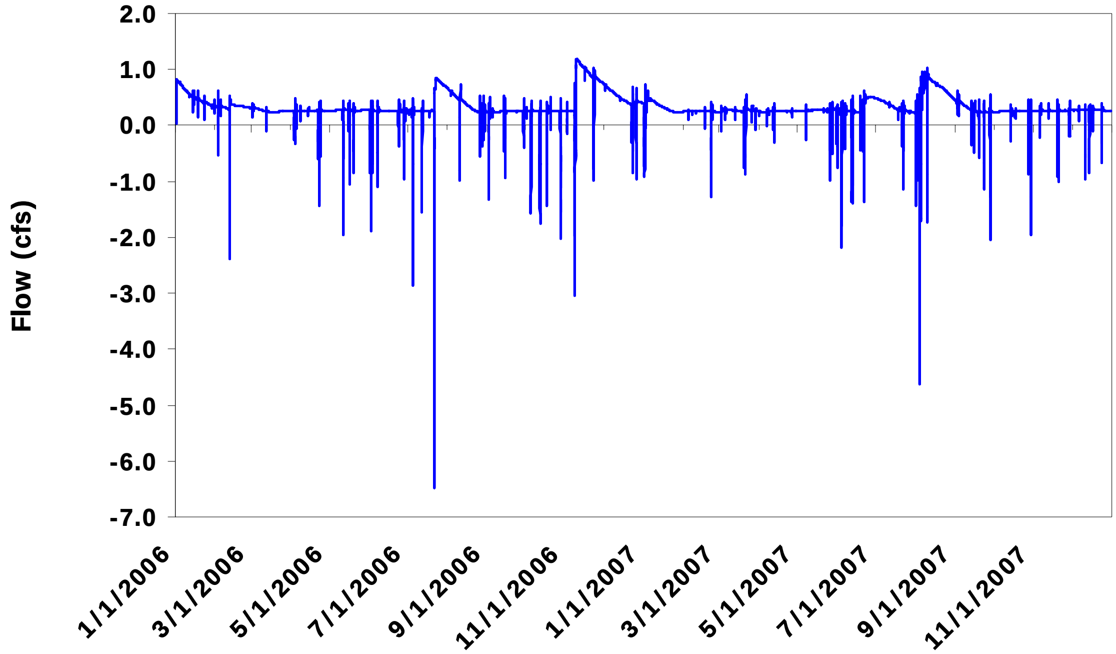


Figure 4-13a: Direction of groundwater flows (green arrows) in Kearny Marsh during 2006 as simulated in MODFLOW.

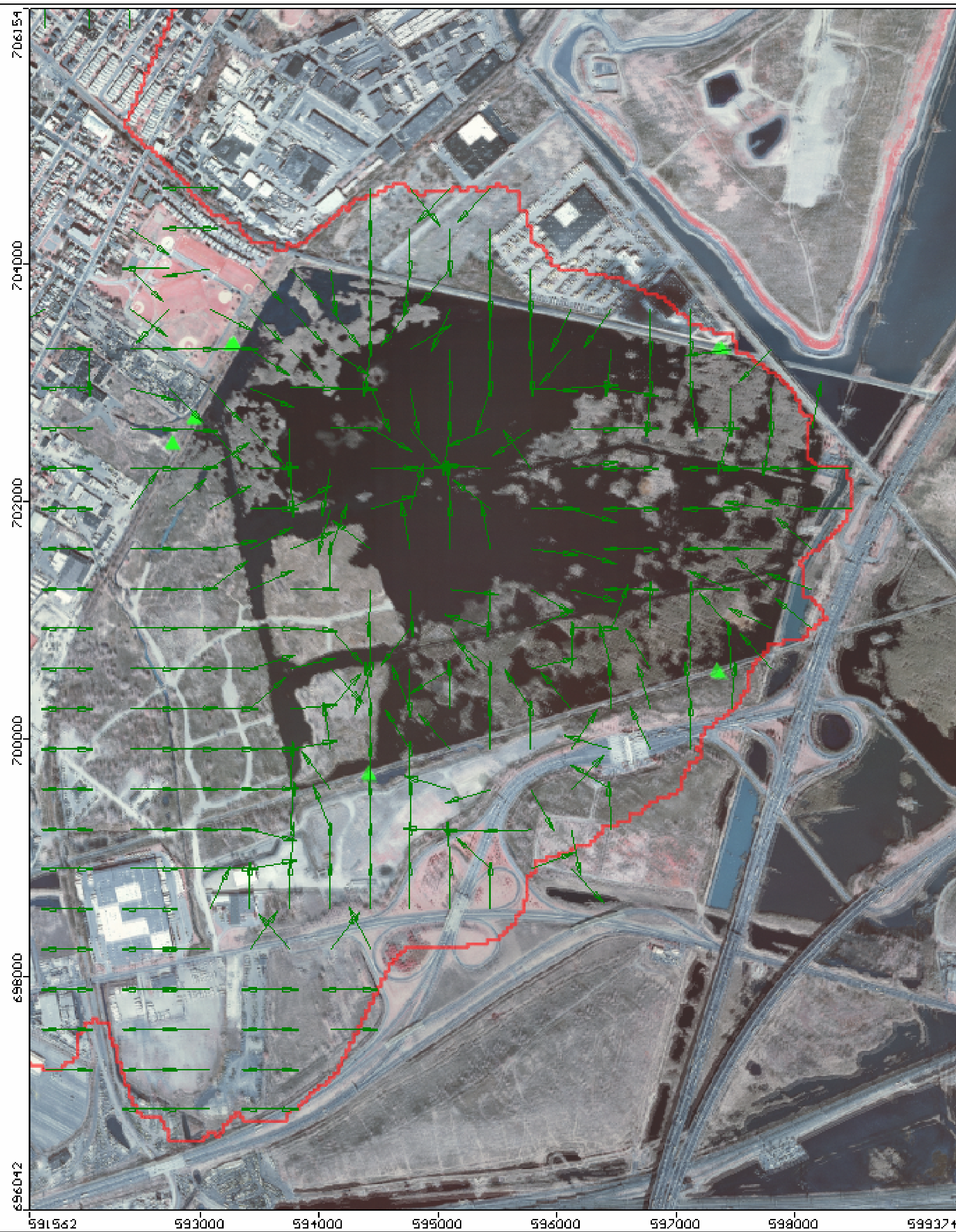


Figure 4-13b: Direction of groundwater flows (green arrows) in Kearny Marsh during 2007 as simulated in MODFLOW.

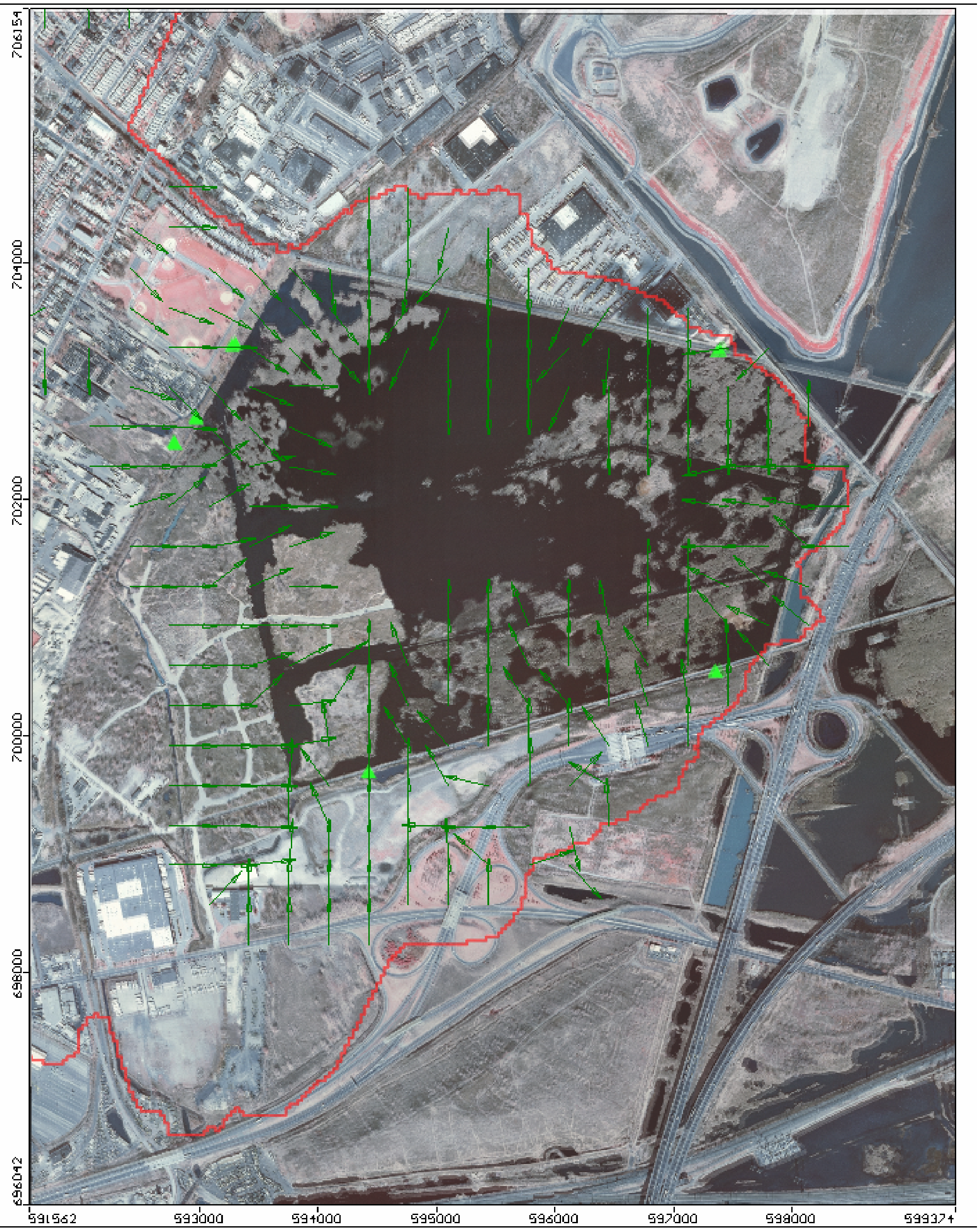


Figure 4-14a: Water table elevation at groundwater well 7 as obtained from pressure transducer.

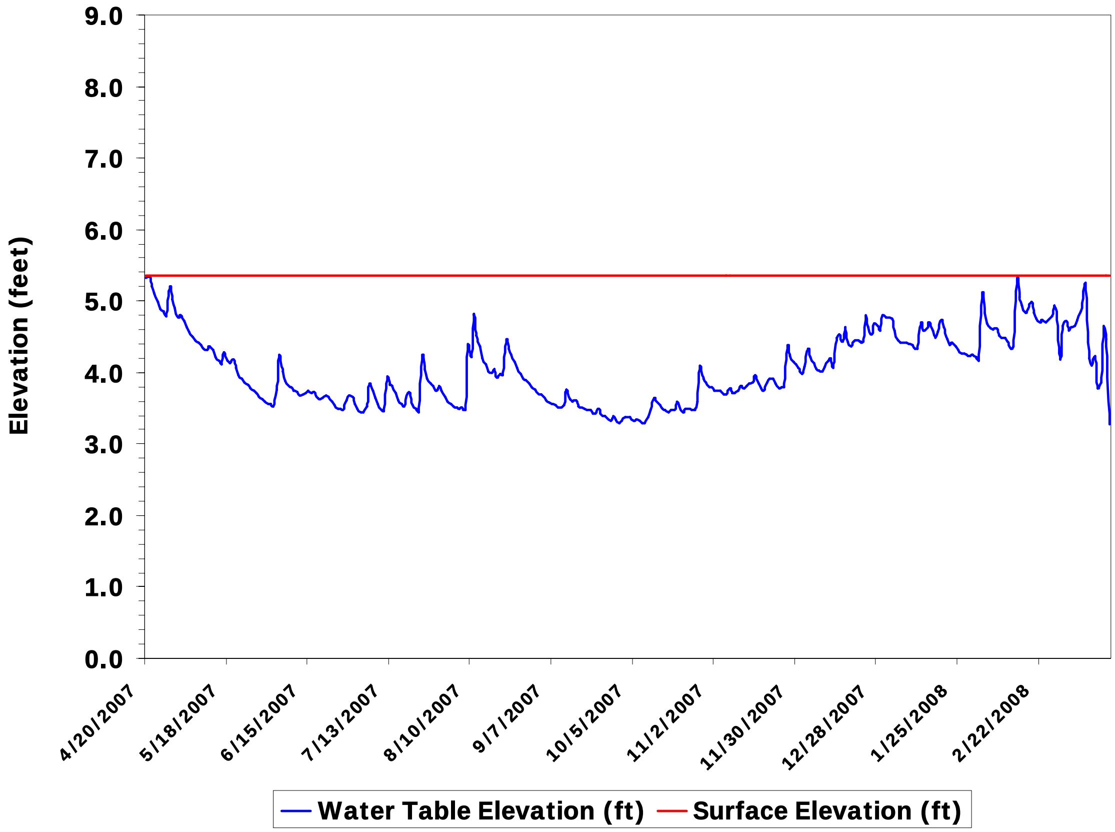


Figure 4-14b: Water table elevation at groundwater well 8 as obtained from pressure transducer.

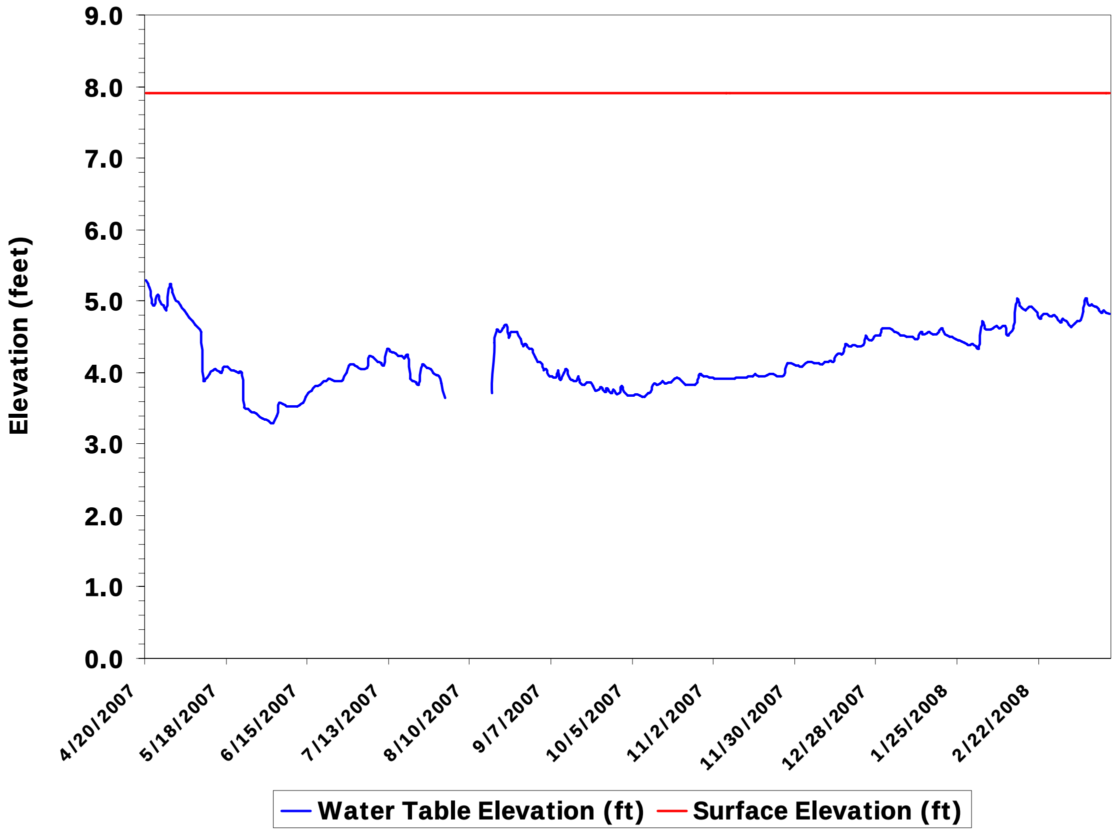


Figure 4-14c: Water table elevation at groundwater well 9 as obtained from pressure transducer.

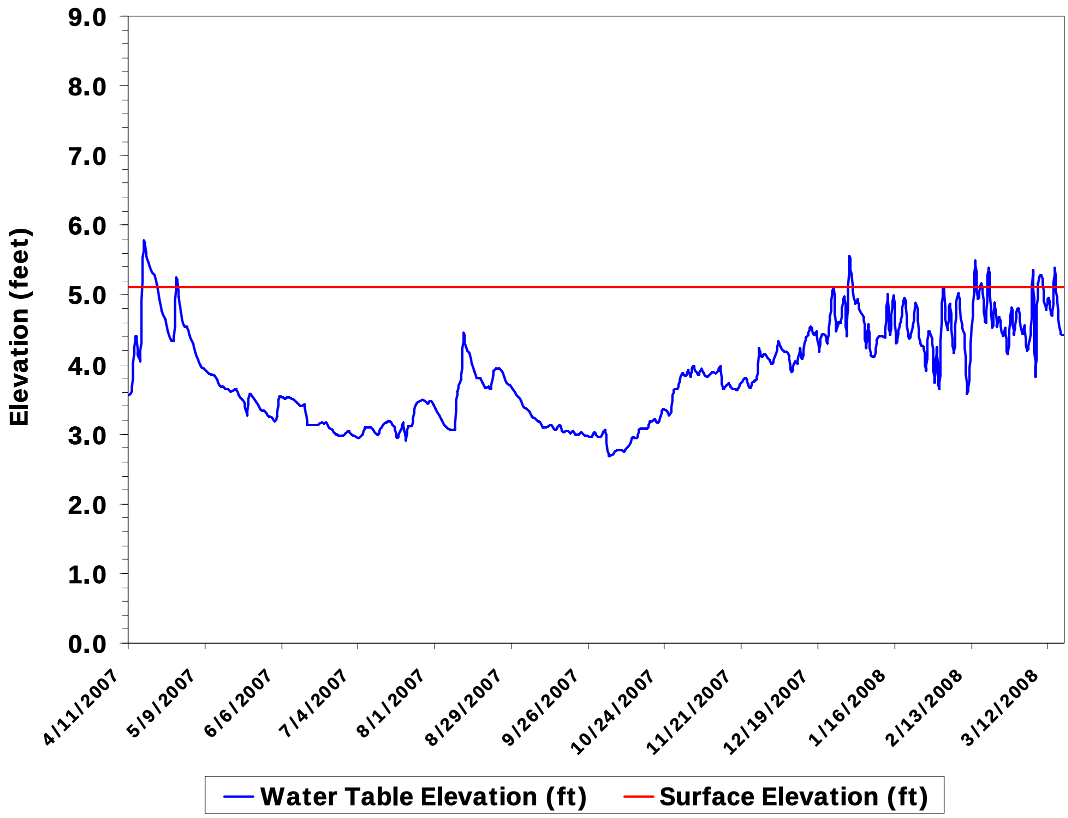


Figure 4-14d: Water table elevation at groundwater well 10 as obtained from pressure transducer.

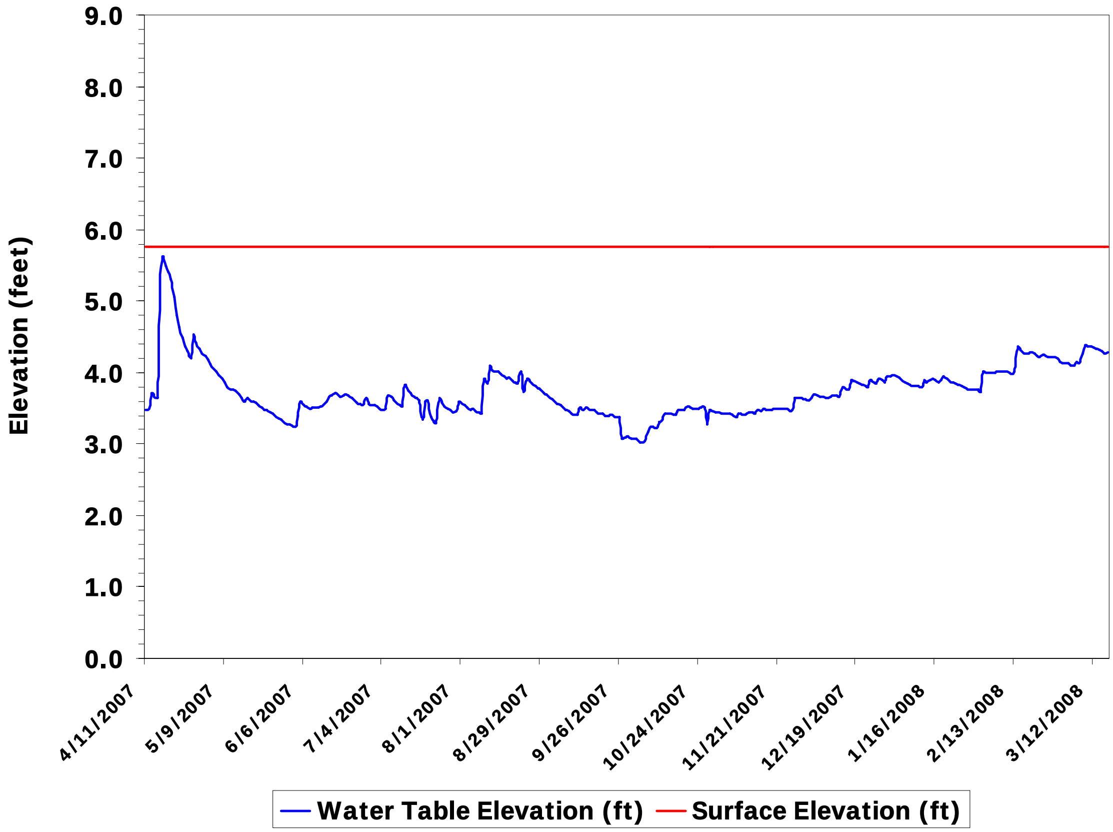


Figure 4-14e: Water table elevation at groundwater well 11 as obtained from pressure transducer.

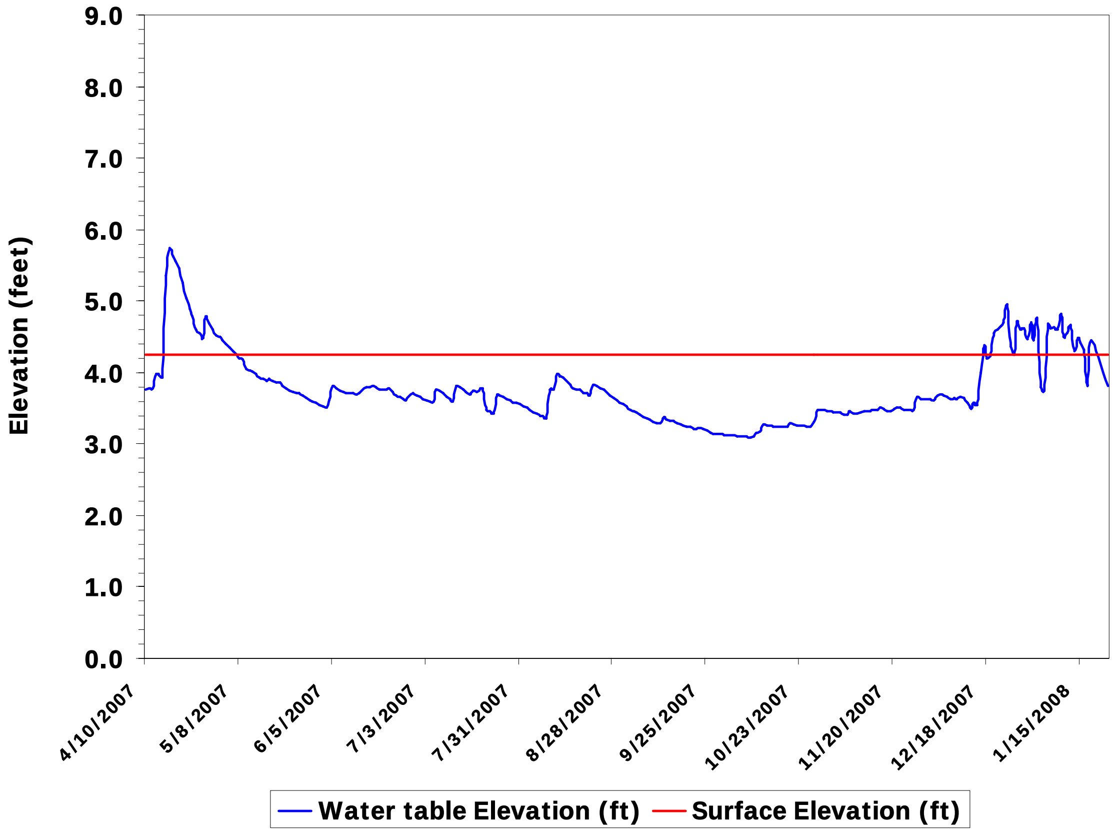


Figure 4-14f: Water table elevation at groundwater well 12 as obtained from pressure transducer.

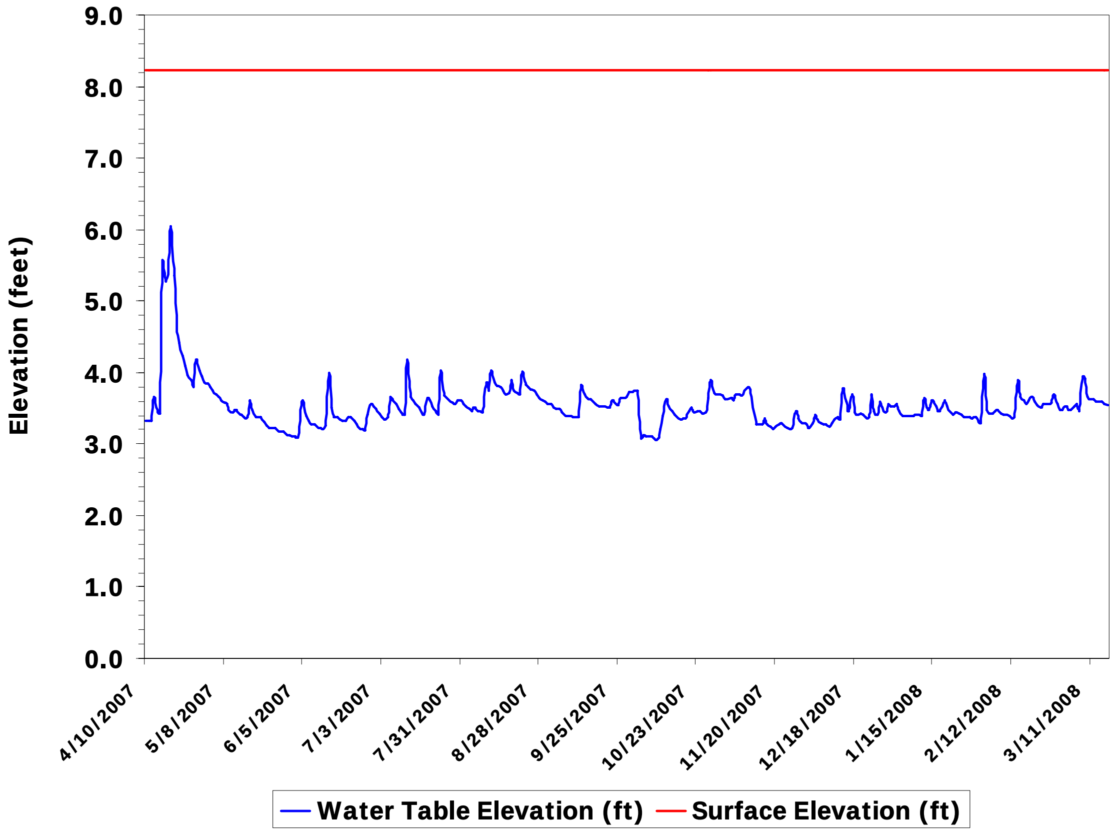


Table 4-1: Observed depths and SWMM-predicted depths resulting from calibration with 2006 data.

Site Name	Date	Observation Time (24:00)	Observed Depth (ft)	Predicted Depth (ft)
KM1	2/17/2006	09:58	3.00	2.84
KM1	2/17/2006	12:03	2.25	2.84
KM1	5/12/2006	09:30	2.80	2.48
KM1	9/14/2006	07:04	2.90	2.64
KM1	9/14/2006	10:45	2.80	2.65
KM1	9/14/2006	14:00	2.80	2.65
KM2	2/17/2006	11:00	1.07	1.05
KM2	2/17/2006	12:45	1.24	1.06
KM2	5/12/2006	11:20	1.64	1.33
KM2	9/14/2006	09:45	1.38	1.51
KM2	9/14/2006	13:00	1.66	1.83
KM2	9/14/2006	14:45	2.32	1.99
KM3	9/14/2006	08:20	1.33	1.30
KM3	9/14/2006	12:00	1.18	1.29
KM3	9/14/2006	15:50	1.17	1.27

Table 4-2: Observed flows and SWMM-predicted flows resulting from calibration with 2006 data.

Site Name	Date	Observation Time (24:00)	Observed Flow (CFS)	Predicted Flow (CFS)
KM1	2/17/2006	09:58	0.14	0.22
KM1	2/17/2006	12:03	0.06	0.23
KM1	5/12/2006	09:30	0.14	0.04
KM1	9/14/2006	07:04	0.28	0.00
KM1	9/14/2006	10:45	0.41	0.01
KM1	9/14/2006	14:00	0.07	0.01
KM2	2/17/2006	11:00	1.40	0.34
KM2	2/17/2006	12:45	1.19	0.34
KM2	5/12/2006	11:20	2.80	2.55
KM2	9/14/2006	09:45	1.08	0.75
KM2	9/14/2006	13:00	0.63	1.80
KM2	9/14/2006	14:45	2.15	2.02
KM3	9/14/2006	08:20	0.20	0.50
KM3	9/14/2006	12:00	0.15	0.43
KM3	9/14/2006	15:50	0.31	0.15

Table 4-3: Observed groundwater heads and MODFLOW-predicted heads resulting from calibration with 2006 data.

Well Number	Date	Observed Head (feet)	Predicted Head (feet)
GW01	3/27/2006	13.31	12.12
GW01	4/20/2006	13.89	12.46
GW01	6/30/2006	14.16	13.57
GW01	9/27/2006	13.83	14.22
GW01	10/27/2006	14.43	14.24
GW01	11/22/2006	14.96	14.26
GW01	12/14/2006	14.58	14.4
GW02	3/27/2006	11.02	12.14
GW02	4/20/2006	11.23	12.41
GW02	6/30/2006	11.63	13.22
GW02	9/27/2006	11.85	13.78
GW02	10/27/2006	11.57	13.94
GW02	11/22/2006	12.3	14.07
GW02	12/14/2006	11.94	14.21
GW03	3/27/2006	14.76	11.01
GW03	4/20/2006	14.91	11.32
GW03	6/30/2006	15.25	12.42
GW03	9/27/2006	15.3	13.31
GW03	10/27/2006	15.42	13.57
GW03	11/22/2006	15.92	13.84
GW03	12/12/2006	15.43	13.95
GW04	3/28/2006	6.49	10.04
GW04	4/20/2006	6.63	8.63
GW04	6/30/2006	6.79	7.66
GW04	9/29/2006	7.18	7.62
GW04	10/27/2006	7.21	7.62
GW04	11/22/2006	7.71	7.62
GW04	12/12/2006	7.31	7.78
GW05	3/28/2006	8.83	6.72
GW05	4/20/2006	8.79	5.69
GW05	6/30/2006	9.02	6.22
GW05	9/25/2006	9.23	5.99
GW05	10/27/2006	9.33	5.98
GW05	11/22/2006	9.66	6.11
GW05	12/11/2006	9.32	6.07
GW06	3/28/2006	5.03	3.31
GW06	4/20/2006	5	3.02
GW06	6/30/2006	3.97	4.09
GW06	9/29/2006	4.19	3.83

GW06	10/27/2006	4.21	3.59
GW06	11/22/2006	4.71	3.83
GW06	12/11/2006	4.14	3.66
GW07	3/27/2006	13.52	12.91
GW07	4/20/2006	13.64	13.29
GW07	6/30/2006	14.15	14.39
GW07	9/27/2006	14.43	15.11
GW07	10/27/2006	14	15.12
GW07	11/22/2006	14.18	15.12
GW07	12/14/2006	14.35	15.28
GW08	3/27/2006	11.11	10.84
GW08	4/20/2006	11.37	11.04
GW08	6/30/2006	11.75	11.88
GW08	9/27/2006	11.97	12.39
GW08	10/27/2006	12.05	12.53
GW08	11/22/2006	12.96	12.7
GW08	12/14/2006	12.05	12.79
GW09	3/27/2006	14.84	10.3
GW09	4/20/2006	14.82	10.54
GW09	6/30/2006	14.99	11.66
GW09	9/27/2006	15.16	12.45
GW09	10/27/2006	15.4	12.67
GW09	11/22/2006	15.93	12.94
GW09	12/12/2006	15.44	13.03
GW10	3/28/2006	6.54	10.05
GW10	4/20/2006	6.35	8.64
GW10	6/30/2006	6.42	7.67
GW10	9/29/2006	7.29	7.62
GW10	10/27/2006	6.85	7.62
GW10	11/22/2006	7.41	7.62
GW10	12/12/2006	7	7.78
GW11	3/28/2006	8.86	6.54
GW11	4/20/2006	8.87	5.93
GW11	6/30/2006	9.2	6.41
GW11	9/25/2006	9.39	6.2
GW11	10/27/2006	9.45	6.19
GW11	11/22/2006	9.81	6.31
GW11	12/11/2006	9.46	6.28
GW12	3/28/2006	4.31	3.81
GW12	4/20/2006	4.5	3.47
GW12	6/30/2006	4.61	4.45
GW12	9/29/2006	4.55	4.04
GW12	10/27/2006	4.67	4

GW12	11/22/2006	4.84	4.22
GW12	12/11/2006	4.59	4.07

Table 4-4: Model performance statistics comparing predicted versus observed measurements (depth and flow; 2006) for calibrated Kearny Marsh surface water model (SWMM).

Parameter	***E***	***d***	**RSR**	***r***	**R^2**
Depth	0.89	0.97	0.33	0.94	0.89
Flow	0.60	0.89	0.61	0.81	0.65

Table 4-5: Model performance statistics comparing predicted versus observed head measurements (2006) for calibrated Kearny Marsh groundwater model (MODFLOW).

Parameter	***E***	***d***	**RSR**	***r***	**R^2**
Head	0.72	0.93	0.57	0.88	0.78

Table 4-6: Observed depths and SWMM-predicted depths resulting from validation with 2007 data.

Site Name	Date	Observation Time (24:00)	Observed Depth (ft)	Predicted Depth (ft)
KM1	3/2/2007	01:49	3.00	2.74
KM1	3/2/2007	10:30	3.00	2.80
KM1	3/2/2007	13:40	3.00	2.83
KM1	10/19/2007	15:05	3.00	2.64
KM1	10/19/2007	17:15	2.70	2.64
KM1	10/20/2007	09:54	3.00	2.64
KM2	3/1/2007	23:45	1.21	1.04
KM2	3/2/2007	09:00	3.06	3.24
KM2	3/2/2007	12:17	3.10	1.85
KM2	10/19/2007	14:25	0.99	1.13
KM2	10/19/2007	16:41	0.55	1.19
KM2	10/20/2007	09:12	0.31	1.06
KM3	3/2/2007	01:07	0.93	1.27
KM3	3/2/2007	10:00	1.35	1.36
KM3	3/2/2007	13:11	1.21	1.31
KM3	10/19/2007	13:41	0.71	1.26
KM3	10/19/2007	15:45	0.72	1.27
KM3	10/20/2007	08:20	0.76	1.25

Table 4-7: Observed flows and SWMM-predicted flows resulting from validation with 2007 data.

Site Name	Date	Observation Time (24:00)	Observed Flow (CFS)	Predicted Flow (CFS)
KM1	3/2/2007	01:49	0.28	0.16
KM1	3/2/2007	10:30	0.57	0.38
KM1	3/2/2007	13:40	0.14	0.40
KM1	10/19/2007	15:05	0.35	0.00
KM1	10/19/2007	17:15	1.34	0.00
KM1	10/20/2007	09:54	0.05	0.00
KM2	3/1/2007	23:45	0.38	0.26
KM2	3/2/2007	09:00	2.19	2.14
KM2	3/2/2007	12:17	1.44	2.41
KM2	10/19/2007	14:25	0.18	0.63
KM2	10/19/2007	16:41	0.24	0.31
KM2	10/20/2007	09:12	0.28	0.61
KM3	3/2/2007	01:07	0.16	0.14
KM3	3/2/2007	10:00	2.85	2.03
KM3	3/2/2007	13:11	0.88	0.67
KM3	10/19/2007	13:41	0.39	0.03
KM3	10/19/2007	15:45	0.61	0.13
KM3	10/20/2007	08:20	0.68	0.00

Table 4-8: Observed groundwater heads and MODFLOW-predicted heads resulting from validation with 2007 data.

Well Number	Date	Observed Head (feet)	Predicted Head (feet)
GW07	4/20/2007	15.84	13.59
GW07	4/21/2007	15.77	13.61
GW07	4/22/2007	15.65	13.63
GW07	4/23/2007	15.56	13.65
GW07	4/24/2007	15.44	13.67
GW07	4/25/2007	15.36	13.69
GW07	4/26/2007	15.32	13.70
GW07	4/27/2007	15.75	13.72
GW07	4/28/2007	15.62	13.74
GW07	4/29/2007	15.48	13.76
GW07	4/30/2007	15.34	13.78
GW07	5/1/2007	15.24	13.80
GW07	5/2/2007	15.31	13.82
GW07	5/3/2007	15.18	13.83
GW07	5/4/2007	15.11	13.85
GW07	5/5/2007	15.06	13.87
GW07	5/6/2007	14.98	13.89
GW07	5/7/2007	14.94	13.91
GW07	5/8/2007	14.91	13.93
GW07	5/9/2007	14.87	13.94
GW07	5/10/2007	14.84	13.96
GW07	5/11/2007	14.89	13.98
GW07	5/12/2007	14.81	14.00
GW07	5/13/2007	14.78	14.02
GW07	5/14/2007	14.69	14.03
GW07	5/15/2007	14.66	14.05
GW07	5/16/2007	14.65	14.07
GW07	5/17/2007	14.72	14.09
GW07	5/18/2007	14.66	14.10
GW07	5/19/2007	14.65	14.12
GW07	5/20/2007	14.65	14.14
GW07	5/21/2007	14.53	14.16
GW07	5/22/2007	14.45	14.17
GW07	5/23/2007	14.40	14.19
GW07	5/24/2007	14.36	14.21
GW07	5/25/2007	14.32	14.23
GW07	5/26/2007	14.28	14.24
GW07	5/27/2007	14.23	14.26

GW07	5/28/2007	14.21	14.28
GW07	5/29/2007	14.16	14.30
GW07	5/30/2007	14.13	14.31
GW07	5/31/2007	14.10	14.33
GW07	6/1/2007	14.08	14.35
GW07	6/2/2007	14.05	14.37
GW07	6/3/2007	14.06	14.38
GW07	6/4/2007	14.65	14.40
GW07	6/5/2007	14.65	14.42
GW07	6/6/2007	14.46	14.43
GW07	6/7/2007	14.36	14.45
GW07	6/8/2007	14.31	14.47
GW07	6/9/2007	14.29	14.48
GW07	6/10/2007	14.25	14.50
GW07	6/11/2007	14.21	14.52
GW07	6/12/2007	14.19	14.53
GW07	6/13/2007	14.22	14.55
GW07	6/14/2007	14.24	14.56
GW07	6/15/2007	14.24	14.58
GW07	6/16/2007	14.22	14.59
GW07	6/17/2007	14.21	14.61
GW07	6/18/2007	14.15	14.62
GW07	6/19/2007	14.15	14.63
GW07	6/20/2007	14.22	14.65
GW07	6/21/2007	14.18	14.66
GW07	6/22/2007	14.17	14.67
GW07	6/23/2007	14.10	14.69
GW07	6/24/2007	14.04	14.70
GW07	6/25/2007	14.01	14.71
GW07	6/26/2007	14.00	14.73
GW07	6/27/2007	13.99	14.74
GW07	6/28/2007	14.19	14.75
GW07	6/29/2007	14.19	14.76
GW07	6/30/2007	14.13	14.77
GW07	7/1/2007	14.06	14.79
GW07	7/2/2007	14.00	14.80
GW07	7/3/2007	13.96	14.81
GW07	7/4/2007	13.99	14.82
GW07	7/5/2007	14.31	14.83
GW07	7/6/2007	14.33	14.84
GW07	7/7/2007	14.22	14.85
GW07	7/8/2007	14.13	14.86

GW07	7/9/2007	14.04	14.87
GW07	7/10/2007	13.99	14.88
GW07	7/11/2007	14.09	14.89
GW07	7/12/2007	14.41	14.90
GW07	7/13/2007	14.35	14.91
GW07	7/14/2007	14.27	14.92
GW07	7/15/2007	14.19	14.93
GW07	7/16/2007	14.10	14.94
GW07	7/17/2007	14.06	14.95
GW07	7/18/2007	14.15	14.96
GW07	7/19/2007	14.22	14.97
GW07	7/20/2007	14.15	14.98
GW07	7/21/2007	14.04	14.99
GW07	7/22/2007	13.97	15.00
GW07	7/23/2007	14.34	15.01
GW07	7/24/2007	14.66	15.02
GW07	7/25/2007	14.50	15.02
GW07	7/26/2007	14.39	15.03
GW07	7/27/2007	14.35	15.03
GW07	7/28/2007	14.30	15.04
GW07	7/29/2007	14.28	15.04
GW07	7/30/2007	14.30	15.05
GW07	7/31/2007	14.22	15.05
GW07	8/1/2007	14.15	15.06
GW07	8/2/2007	14.10	15.06
GW07	8/3/2007	14.06	15.07
GW07	8/4/2007	14.06	15.07
GW07	8/5/2007	14.02	15.07
GW07	8/6/2007	14.04	15.08
GW07	8/7/2007	14.00	15.08
GW07	8/8/2007	14.76	15.08
GW07	8/9/2007	14.80	15.09
GW07	8/10/2007	15.15	15.09
GW07	8/11/2007	15.17	15.09
GW07	8/12/2007	14.95	15.09
GW07	8/13/2007	14.81	15.10
GW07	8/14/2007	14.67	15.10
GW07	8/15/2007	14.58	15.10
GW07	8/16/2007	14.53	15.10
GW07	8/17/2007	14.50	15.10
GW07	8/18/2007	14.50	15.10
GW07	8/19/2007	14.47	15.11

GW07	8/20/2007	14.50	15.11
GW07	8/21/2007	14.73	15.11
GW07	8/22/2007	14.92	15.11
GW07	8/23/2007	14.81	15.11
GW07	8/24/2007	14.72	15.11
GW07	8/25/2007	14.63	15.11
GW07	8/26/2007	14.55	15.11
GW07	8/27/2007	14.46	15.11
GW07	8/28/2007	14.42	15.11
GW07	8/29/2007	14.38	15.12
GW07	8/30/2007	14.35	15.12
GW07	8/31/2007	14.32	15.12
GW07	9/1/2007	14.25	15.12
GW07	9/2/2007	14.20	15.12
GW07	9/3/2007	14.20	15.11
GW07	9/4/2007	14.15	15.11
GW07	9/5/2007	14.11	15.11
GW07	9/6/2007	14.08	15.11
GW07	9/7/2007	14.08	15.11
GW07	9/8/2007	14.05	15.11
GW07	9/9/2007	14.02	15.11
GW07	9/10/2007	14.04	15.10
GW07	9/11/2007	14.18	15.10
GW07	9/12/2007	14.21	15.10
GW07	9/13/2007	14.12	15.10
GW07	9/14/2007	14.11	15.10
GW07	9/15/2007	14.10	15.10
GW07	9/16/2007	14.03	15.10
GW07	9/17/2007	14.00	15.10
GW07	9/18/2007	13.99	15.10
GW07	9/19/2007	13.98	15.10
GW07	9/20/2007	13.96	15.10
GW07	9/21/2007	13.93	15.10
GW07	9/22/2007	13.97	15.10
GW07	9/23/2007	13.95	15.10
GW07	9/24/2007	13.90	15.10
GW07	9/25/2007	13.89	15.10
GW07	9/26/2007	13.86	15.10
GW07	9/27/2007	13.87	15.10
GW07	9/28/2007	13.88	15.10
GW07	9/29/2007	13.82	15.10
GW07	9/30/2007	13.82	15.10

GW07	10/1/2007	13.86	15.10
GW07	10/2/2007	13.87	15.10
GW07	10/3/2007	13.90	15.10
GW07	10/4/2007	13.86	15.11
GW07	10/5/2007	13.83	15.11
GW07	10/6/2007	13.85	15.11
GW07	10/7/2007	13.82	15.11
GW07	10/8/2007	13.82	15.12
GW07	10/9/2007	13.82	15.12
GW07	10/10/2007	13.98	15.12
GW07	10/11/2007	14.04	15.12
GW07	10/12/2007	14.16	15.12
GW07	10/13/2007	14.08	15.13
GW07	10/14/2007	14.04	15.13
GW07	10/15/2007	14.00	15.13
GW07	10/16/2007	13.97	15.13
GW07	10/17/2007	13.98	15.13
GW07	10/18/2007	14.00	15.13
GW07	10/19/2007	14.04	15.13
GW07	10/20/2007	14.09	15.13
GW07	10/21/2007	13.99	15.14
GW07	10/22/2007	13.98	15.14
GW07	10/23/2007	14.02	15.14
GW07	10/24/2007	14.00	15.14
GW07	10/25/2007	14.00	15.14
GW07	10/26/2007	14.03	15.14
GW07	10/27/2007	14.43	15.14
GW07	10/28/2007	14.51	15.14
GW07	10/29/2007	14.39	15.14
GW07	10/30/2007	14.33	15.14
GW07	10/31/2007	14.31	15.14
GW07	11/1/2007	14.30	15.14
GW07	11/2/2007	14.24	15.14
GW07	11/3/2007	14.29	15.15
GW07	11/4/2007	14.22	15.15
GW07	11/5/2007	14.19	15.15
GW07	11/6/2007	14.28	15.15
GW07	11/7/2007	14.25	15.15
GW07	11/8/2007	14.22	15.15
GW07	11/9/2007	14.24	15.15
GW07	11/10/2007	14.33	15.15
GW07	11/11/2007	14.30	15.15

GW07	11/12/2007	14.30	15.16
GW07	11/13/2007	14.35	15.16
GW07	11/14/2007	14.37	15.16
GW07	11/15/2007	14.43	15.16
GW07	11/16/2007	14.42	15.16
GW07	11/17/2007	14.33	15.16
GW07	11/18/2007	14.28	15.16
GW07	11/19/2007	14.32	15.16
GW07	11/20/2007	14.41	15.16
GW07	11/21/2007	14.43	15.16
GW07	11/22/2007	14.42	15.16
GW07	11/23/2007	14.33	15.16
GW07	11/24/2007	14.29	15.16
GW07	11/25/2007	14.31	15.16
GW07	11/26/2007	14.65	15.16
GW07	11/27/2007	14.83	15.16
GW07	11/28/2007	14.69	15.16
GW07	11/29/2007	14.66	15.16
GW07	11/30/2007	14.59	15.16
GW07	12/1/2007	14.53	15.16
GW07	12/2/2007	14.53	15.18
GW07	12/3/2007	14.82	15.20
GW07	12/4/2007	14.80	15.21
GW07	12/5/2007	14.69	15.23
GW07	12/6/2007	14.59	15.25
GW07	12/7/2007	14.56	15.26
GW07	12/8/2007	14.54	15.28
GW07	12/9/2007	14.53	15.29
GW07	12/10/2007	14.70	15.31
GW07	12/11/2007	14.68	15.32
GW07	12/12/2007	14.66	15.34
GW07	12/13/2007	14.70	15.36
GW07	12/14/2007	15.03	15.37
GW07	12/15/2007	14.98	15.39
GW07	12/16/2007	15.08	15.40
GW07	12/17/2007	15.03	15.42
GW07	12/18/2007	14.88	15.43
GW07	12/19/2007	14.89	15.45
GW07	12/20/2007	14.95	15.46
GW07	12/21/2007	14.94	15.48
GW07	12/22/2007	14.94	15.49
GW07	12/23/2007	15.13	15.51

GW07	12/24/2007	15.23	15.52
GW07	12/25/2007	15.08	15.54
GW07	12/26/2007	15.03	15.55
GW07	12/27/2007	15.24	15.57
GW07	12/28/2007	15.11	15.58
GW07	12/29/2007	15.33	15.59
GW07	12/30/2007	15.26	15.61
GW07	12/31/2007	15.33	15.62
GW08	4/20/2007	13.68	11.28
GW08	4/21/2007	13.51	11.29
GW08	4/22/2007	13.39	11.30
GW08	4/23/2007	13.40	11.31
GW08	4/24/2007	13.47	11.32
GW08	4/25/2007	13.39	11.33
GW08	4/26/2007	13.33	11.34
GW08	4/27/2007	13.65	11.35
GW08	4/28/2007	13.59	11.36
GW08	4/29/2007	13.50	11.37
GW08	4/30/2007	13.43	11.38
GW08	5/1/2007	13.37	11.39
GW08	5/2/2007	13.34	11.40
GW08	5/3/2007	13.27	11.41
GW08	5/4/2007	13.23	11.42
GW08	5/5/2007	13.18	11.43
GW08	5/6/2007	13.12	11.44
GW08	5/7/2007	13.07	11.45
GW08	5/8/2007	13.03	11.46
GW08	5/9/2007	12.60	11.47
GW08	5/10/2007	12.34	11.48
GW08	5/11/2007	12.38	11.49
GW08	5/12/2007	12.43	11.50
GW08	5/13/2007	12.45	11.51
GW08	5/14/2007	12.46	11.52
GW08	5/15/2007	12.43	11.53
GW08	5/16/2007	12.45	11.54
GW08	5/17/2007	12.50	11.54
GW08	5/18/2007	12.49	11.55
GW08	5/19/2007	12.46	11.56
GW08	5/20/2007	12.45	11.57
GW08	5/21/2007	12.43	11.58
GW08	5/22/2007	12.43	11.59
GW08	5/23/2007	12.17	11.60

GW08	5/24/2007	11.93	11.61
GW08	5/25/2007	11.91	11.61
GW08	5/26/2007	11.88	11.62
GW08	5/27/2007	11.86	11.64
GW08	5/28/2007	11.84	11.65
GW08	5/29/2007	11.81	11.66
GW08	5/30/2007	11.78	11.66
GW08	5/31/2007	11.76	11.67
GW08	6/1/2007	11.74	11.68
GW08	6/2/2007	11.72	11.69
GW08	6/3/2007	11.72	11.70
GW08	6/4/2007	11.95	11.72
GW08	6/5/2007	12.01	11.73
GW08	6/6/2007	11.99	11.75
GW08	6/7/2007	11.97	11.76
GW08	6/8/2007	11.96	11.78
GW08	6/9/2007	11.96	11.79
GW08	6/10/2007	11.96	11.80
GW08	6/11/2007	11.96	11.81
GW08	6/12/2007	11.98	11.82
GW08	6/13/2007	12.03	11.83
GW08	6/14/2007	12.11	11.84
GW08	6/15/2007	12.16	11.85
GW08	6/16/2007	12.20	11.86
GW08	6/17/2007	12.24	11.87
GW08	6/18/2007	12.25	11.88
GW08	6/19/2007	12.27	11.89
GW08	6/20/2007	12.31	11.90
GW08	6/21/2007	12.32	11.91
GW08	6/22/2007	12.32	11.93
GW08	6/23/2007	12.31	11.94
GW08	6/24/2007	12.30	11.95
GW08	6/25/2007	12.30	11.96
GW08	6/26/2007	12.31	11.97
GW08	6/27/2007	12.33	11.98
GW08	6/28/2007	12.44	11.99
GW08	6/29/2007	12.53	12.00
GW08	6/30/2007	12.53	12.00
GW08	7/1/2007	12.51	12.01
GW08	7/2/2007	12.49	12.02
GW08	7/3/2007	12.48	12.03
GW08	7/4/2007	12.48	12.03

GW08	7/5/2007	12.64	12.04
GW08	7/6/2007	12.65	12.05
GW08	7/7/2007	12.62	12.06
GW08	7/8/2007	12.59	12.06
GW08	7/9/2007	12.56	12.07
GW08	7/10/2007	12.54	12.08
GW08	7/11/2007	12.59	12.09
GW08	7/12/2007	12.74	12.09
GW08	7/13/2007	12.72	12.10
GW08	7/14/2007	12.70	12.11
GW08	7/15/2007	12.67	12.11
GW08	7/16/2007	12.65	12.12
GW08	7/17/2007	12.64	12.13
GW08	7/18/2007	12.67	12.13
GW08	7/19/2007	12.48	12.14
GW08	7/20/2007	12.32	12.15
GW08	7/21/2007	12.30	12.15
GW08	7/22/2007	12.27	12.16
GW08	7/23/2007	12.40	12.17
GW08	7/24/2007	12.54	12.18
GW08	7/25/2007	12.51	12.19
GW08	7/26/2007	12.48	12.19
GW08	7/27/2007	12.45	12.20
GW08	7/28/2007	12.41	12.21
GW08	7/29/2007	12.38	12.21
GW08	7/30/2007	12.33	12.22
GW08	7/31/2007	12.19	12.22
GW08	8/1/2007	11.89	12.23
GW08	8/17/2007	12.35	12.39
GW08	8/18/2007	12.98	12.40
GW08	8/19/2007	13.08	12.40
GW08	8/20/2007	13.05	12.41
GW08	8/21/2007	13.04	12.42
GW08	8/22/2007	12.98	12.42
GW08	8/23/2007	12.96	12.43
GW08	8/24/2007	13.01	12.43
GW08	8/25/2007	12.96	12.44
GW08	8/26/2007	12.96	12.44
GW08	8/27/2007	12.92	12.45
GW08	8/28/2007	12.89	12.46
GW08	8/29/2007	12.83	12.46
GW08	8/30/2007	12.78	12.47

GW08	8/31/2007	12.70	12.47
GW08	9/1/2007	12.67	12.48
GW08	9/2/2007	12.64	12.48
GW08	9/3/2007	12.57	12.49
GW08	9/4/2007	12.51	12.49
GW08	9/5/2007	12.46	12.50
GW08	9/6/2007	12.43	12.51
GW08	9/7/2007	12.39	12.51
GW08	9/8/2007	12.37	12.52
GW08	9/9/2007	12.36	12.52
GW08	9/10/2007	12.34	12.53
GW08	9/11/2007	12.37	12.53
GW08	9/12/2007	12.39	12.54
GW08	9/13/2007	12.35	12.54
GW08	9/14/2007	12.34	12.55
GW08	9/15/2007	12.30	12.55
GW08	9/16/2007	12.30	12.56
GW08	9/17/2007	12.26	12.57
GW08	9/18/2007	12.24	12.57
GW08	9/19/2007	12.22	12.58
GW08	9/20/2007	12.21	12.58
GW08	9/21/2007	12.18	12.59
GW08	9/22/2007	12.20	12.59
GW08	9/23/2007	12.19	12.60
GW08	9/24/2007	12.17	12.61
GW08	9/25/2007	12.18	12.61
GW08	9/26/2007	12.15	12.62
GW08	9/27/2007	12.15	12.62
GW08	9/28/2007	12.18	12.63
GW08	9/29/2007	12.14	12.64
GW08	9/30/2007	12.13	12.64
GW08	10/1/2007	12.14	12.65
GW08	10/2/2007	12.12	12.65
GW08	10/3/2007	12.12	12.66
GW08	10/4/2007	12.11	12.67
GW08	10/5/2007	12.14	12.67
GW08	10/6/2007	12.11	12.68
GW08	10/7/2007	12.10	12.68
GW08	10/8/2007	12.10	12.69
GW08	10/9/2007	12.10	12.69
GW08	10/10/2007	12.16	12.70
GW08	10/11/2007	12.18	12.70

GW08	10/12/2007	12.27	12.71
GW08	10/13/2007	12.27	12.71
GW08	10/14/2007	12.28	12.71
GW08	10/15/2007	12.29	12.72
GW08	10/16/2007	12.30	12.72
GW08	10/17/2007	12.30	12.73
GW08	10/18/2007	12.31	12.73
GW08	10/19/2007	12.35	12.74
GW08	10/20/2007	12.35	12.74
GW08	10/21/2007	12.28	12.75
GW08	10/22/2007	12.25	12.75
GW08	10/23/2007	12.26	12.75
GW08	10/24/2007	12.26	12.76
GW08	10/25/2007	12.27	12.76
GW08	10/26/2007	12.27	12.77
GW08	10/27/2007	12.39	12.78
GW08	10/28/2007	12.39	12.78
GW08	10/29/2007	12.38	12.79
GW08	10/30/2007	12.37	12.80
GW08	10/31/2007	12.36	12.80
GW08	11/1/2007	12.36	12.81
GW08	11/2/2007	12.35	12.81
GW08	11/3/2007	12.34	12.82
GW08	11/4/2007	12.33	12.82
GW08	11/5/2007	12.33	12.83
GW08	11/6/2007	12.34	12.83
GW08	11/7/2007	12.34	12.84
GW08	11/8/2007	12.33	12.84
GW08	11/9/2007	12.33	12.84
GW08	11/10/2007	12.36	12.85
GW08	11/11/2007	12.36	12.85
GW08	11/12/2007	12.36	12.86
GW08	11/13/2007	12.38	12.86
GW08	11/14/2007	12.38	12.86
GW08	11/15/2007	12.39	12.87
GW08	11/16/2007	12.38	12.87
GW08	11/17/2007	12.38	12.88
GW08	11/18/2007	12.38	12.88
GW08	11/19/2007	12.39	12.88
GW08	11/20/2007	12.40	12.89
GW08	11/21/2007	12.41	12.90
GW08	11/22/2007	12.41	12.90

GW08	11/23/2007	12.39	12.91
GW08	11/24/2007	12.38	12.91
GW08	11/25/2007	12.39	12.92
GW08	11/26/2007	12.49	12.92
GW08	11/27/2007	12.56	12.92
GW08	11/28/2007	12.54	12.93
GW08	11/29/2007	12.54	12.93
GW08	11/30/2007	12.53	12.94
GW08	12/1/2007	12.51	12.94
GW08	12/2/2007	12.52	12.94
GW08	12/3/2007	12.58	12.95
GW08	12/4/2007	12.57	12.95
GW08	12/5/2007	12.57	12.96
GW08	12/6/2007	12.56	12.97
GW08	12/7/2007	12.56	12.97
GW08	12/8/2007	12.55	12.98
GW08	12/9/2007	12.55	12.98
GW08	12/10/2007	12.58	12.99
GW08	12/11/2007	12.58	13.00
GW08	12/12/2007	12.58	13.01
GW08	12/13/2007	12.60	13.01
GW08	12/14/2007	12.70	13.02
GW08	12/15/2007	12.69	13.03
GW08	12/16/2007	12.77	13.04
GW08	12/17/2007	12.81	13.04
GW08	12/18/2007	12.81	13.05
GW08	12/19/2007	12.81	13.06
GW08	12/20/2007	12.81	13.06
GW08	12/21/2007	12.80	13.07
GW08	12/22/2007	12.80	13.08
GW08	12/23/2007	12.87	13.08
GW08	12/24/2007	12.93	13.09
GW08	12/25/2007	12.90	13.10
GW08	12/26/2007	12.88	13.11
GW08	12/27/2007	12.95	13.12
GW08	12/28/2007	12.95	13.13
GW08	12/29/2007	13.03	13.13
GW08	12/30/2007	13.03	13.14
GW08	12/31/2007	13.05	13.15
GW09	4/11/2007	15.52	10.67
GW09	4/12/2007	15.97	10.68
GW09	4/13/2007	16.20	10.70

GW09	4/14/2007	16.02	10.71
GW09	4/15/2007	16.84	10.72
GW09	4/16/2007	17.55	10.73
GW09	4/17/2007	17.43	10.74
GW09	4/18/2007	17.32	10.76
GW09	4/19/2007	17.26	10.77
GW09	4/20/2007	17.15	10.78
GW09	4/21/2007	16.97	10.79
GW09	4/22/2007	16.76	10.80
GW09	4/23/2007	16.62	10.82
GW09	4/24/2007	16.47	10.83
GW09	4/25/2007	16.35	10.84
GW09	4/26/2007	16.27	10.85
GW09	4/27/2007	17.04	10.86
GW09	4/28/2007	17.03	10.87
GW09	4/29/2007	16.79	10.89
GW09	4/30/2007	16.59	10.90
GW09	5/1/2007	16.41	10.91
GW09	5/2/2007	16.48	10.92
GW09	5/3/2007	16.29	10.93
GW09	5/4/2007	16.15	10.95
GW09	5/5/2007	16.06	10.96
GW09	5/6/2007	15.94	10.97
GW09	5/7/2007	15.88	10.98
GW09	5/8/2007	15.84	10.99
GW09	5/9/2007	15.81	11.00
GW09	5/10/2007	15.78	11.02
GW09	5/11/2007	15.78	11.03
GW09	5/12/2007	15.72	11.04
GW09	5/13/2007	15.67	11.05
GW09	5/14/2007	15.61	11.06
GW09	5/15/2007	15.60	11.07
GW09	5/16/2007	15.55	11.08
GW09	5/17/2007	15.55	11.09
GW09	5/18/2007	15.56	11.11
GW09	5/19/2007	15.56	11.12
GW09	5/20/2007	15.54	11.13
GW09	5/21/2007	15.46	11.14
GW09	5/22/2007	15.40	11.15
GW09	5/23/2007	15.28	11.16
GW09	5/24/2007	15.28	11.17
GW09	5/25/2007	15.48	11.19

GW09	5/26/2007	15.42	11.20
GW09	5/27/2007	15.37	11.22
GW09	5/28/2007	15.33	11.23
GW09	5/29/2007	15.27	11.24
GW09	5/30/2007	15.24	11.25
GW09	5/31/2007	15.20	11.26
GW09	6/1/2007	15.17	11.28
GW09	6/2/2007	15.13	11.30
GW09	6/3/2007	15.12	11.31
GW09	6/4/2007	15.34	11.33
GW09	6/5/2007	15.47	11.35
GW09	6/6/2007	15.45	11.38
GW09	6/7/2007	15.44	11.40
GW09	6/8/2007	15.45	11.42
GW09	6/9/2007	15.42	11.43
GW09	6/10/2007	15.39	11.45
GW09	6/11/2007	15.36	11.46
GW09	6/12/2007	15.33	11.47
GW09	6/13/2007	15.34	11.49
GW09	6/14/2007	15.19	11.51
GW09	6/15/2007	15.05	11.52
GW09	6/16/2007	15.05	11.54
GW09	6/17/2007	15.07	11.55
GW09	6/18/2007	15.06	11.57
GW09	6/19/2007	15.07	11.58
GW09	6/20/2007	15.10	11.59
GW09	6/21/2007	15.08	11.61
GW09	6/22/2007	15.06	11.63
GW09	6/23/2007	15.02	11.65
GW09	6/24/2007	14.96	11.67
GW09	6/25/2007	14.93	11.68
GW09	6/26/2007	14.91	11.70
GW09	6/27/2007	14.89	11.71
GW09	6/28/2007	14.91	11.72
GW09	6/29/2007	14.94	11.73
GW09	6/30/2007	14.96	11.75
GW09	7/1/2007	14.93	11.76
GW09	7/2/2007	14.90	11.77
GW09	7/3/2007	14.88	11.78
GW09	7/4/2007	14.89	11.79
GW09	7/5/2007	14.99	11.80
GW09	7/6/2007	15.02	11.81

GW09	7/7/2007	15.03	11.83
GW09	7/8/2007	15.01	11.84
GW09	7/9/2007	14.96	11.85
GW09	7/10/2007	14.92	11.86
GW09	7/11/2007	14.95	11.87
GW09	7/12/2007	15.05	11.88
GW09	7/13/2007	15.09	11.89
GW09	7/14/2007	15.10	11.90
GW09	7/15/2007	15.08	11.91
GW09	7/16/2007	15.03	11.92
GW09	7/17/2007	14.92	11.93
GW09	7/18/2007	14.94	11.94
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GW09	7/21/2007	15.05	11.97
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GW09	7/24/2007	15.33	12.01
GW09	7/25/2007	15.38	12.02
GW09	7/26/2007	15.41	12.03
GW09	7/27/2007	15.42	12.04
GW09	7/28/2007	15.40	12.05
GW09	7/29/2007	15.38	12.06
GW09	7/30/2007	15.38	12.07
GW09	7/31/2007	15.32	12.08
GW09	8/1/2007	15.25	12.09
GW09	8/2/2007	15.18	12.11
GW09	8/3/2007	15.12	12.12
GW09	8/4/2007	15.07	12.14
GW09	8/5/2007	15.01	12.16
GW09	8/6/2007	15.01	12.18
GW09	8/7/2007	14.97	12.20
GW09	8/8/2007	15.36	12.22
GW09	8/9/2007	15.60	12.24
GW09	8/10/2007	15.97	12.26
GW09	8/11/2007	16.29	12.27
GW09	8/12/2007	16.13	12.28
GW09	8/13/2007	16.02	12.29
GW09	8/14/2007	15.89	12.30
GW09	8/15/2007	15.80	12.31
GW09	8/16/2007	15.74	12.32
GW09	8/17/2007	15.68	12.33

GW09	8/18/2007	15.61	12.34
GW09	8/19/2007	15.60	12.35
GW09	8/20/2007	15.60	12.36
GW09	8/21/2007	15.68	12.37
GW09	8/22/2007	15.85	12.37
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GW09	8/24/2007	15.86	12.39
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GW09	8/27/2007	15.65	12.42
GW09	8/28/2007	15.61	12.43
GW09	8/29/2007	15.56	12.43
GW09	8/30/2007	15.51	12.44
GW09	8/31/2007	15.45	12.45
GW09	9/1/2007	15.37	12.46
GW09	9/2/2007	15.32	12.47
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GW09	9/4/2007	15.23	12.49
GW09	9/5/2007	15.17	12.50
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GW09	9/7/2007	15.12	12.51
GW09	9/8/2007	15.07	12.52
GW09	9/9/2007	15.03	12.53
GW09	9/10/2007	15.03	12.54
GW09	9/11/2007	15.08	12.55
GW09	9/12/2007	15.03	12.56
GW09	9/13/2007	15.01	12.57
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GW09	9/26/2007	14.90	12.68
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GW09	10/1/2007	14.96	12.73
GW09	10/2/2007	14.77	12.74
GW09	10/3/2007	14.62	12.75
GW09	10/4/2007	14.65	12.76
GW09	10/5/2007	14.68	12.77
GW09	10/6/2007	14.71	12.77
GW09	10/7/2007	14.68	12.78
GW09	10/8/2007	14.71	12.79
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GW09	11/6/2007	15.84	12.87
GW09	11/7/2007	15.76	12.87
GW09	11/8/2007	15.78	12.87
GW09	11/9/2007	15.81	12.87

GW09	11/10/2007	15.81	12.87
GW09	11/11/2007	15.81	12.87
GW09	11/12/2007	15.85	12.87
GW09	11/13/2007	15.73	12.87
GW09	11/14/2007	15.60	12.87
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GW09	12/2/2007	16.00	12.88
GW09	12/3/2007	16.16	12.89
GW09	12/4/2007	16.20	12.89
GW09	12/5/2007	16.12	12.90
GW09	12/6/2007	16.00	12.91
GW09	12/7/2007	16.02	12.91
GW09	12/8/2007	15.97	12.92
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GW09	12/11/2007	16.06	12.95
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GW09	12/13/2007	16.12	12.96
GW09	12/14/2007	16.37	12.97
GW09	12/15/2007	16.38	12.98
GW09	12/16/2007	16.58	12.99
GW09	12/17/2007	16.37	13.00
GW09	12/18/2007	16.40	13.01
GW09	12/19/2007	16.31	13.02
GW09	12/20/2007	16.40	13.03
GW09	12/21/2007	16.32	13.04

GW09	12/22/2007	16.33	13.04
GW09	12/23/2007	16.61	13.05
GW09	12/24/2007	16.73	13.06
GW09	12/25/2007	16.58	13.08
GW09	12/26/2007	16.52	13.09
GW09	12/27/2007	16.68	13.09
GW09	12/28/2007	16.60	13.10
GW09	12/29/2007	16.86	13.11
GW09	12/30/2007	16.78	13.12
GW09	12/31/2007	16.77	13.13
GW10	4/11/2007	6.90	10.09
GW10	4/12/2007	7.06	10.03
GW10	4/13/2007	7.11	9.98
GW10	4/14/2007	7.08	9.92
GW10	4/15/2007	7.57	9.87
GW10	4/16/2007	8.92	9.81
GW10	4/17/2007	8.91	9.76
GW10	4/18/2007	8.80	9.71
GW10	4/19/2007	8.78	9.65
GW10	4/20/2007	8.63	9.60
GW10	4/21/2007	8.36	9.54
GW10	4/22/2007	8.14	9.49
GW10	4/23/2007	7.97	9.44
GW10	4/24/2007	7.85	9.38
GW10	4/25/2007	7.74	9.33
GW10	4/26/2007	7.67	9.28
GW10	4/27/2007	7.91	9.22
GW10	4/28/2007	7.89	9.17
GW10	4/29/2007	7.80	9.12
GW10	4/30/2007	7.72	9.08
GW10	5/1/2007	7.64	9.04
GW10	5/2/2007	7.63	9.00
GW10	5/3/2007	7.56	8.95
GW10	5/4/2007	7.50	8.92
GW10	5/5/2007	7.45	8.88
GW10	5/6/2007	7.40	8.85
GW10	5/7/2007	7.35	8.82
GW10	5/8/2007	7.30	8.79
GW10	5/9/2007	7.24	8.76
GW10	5/10/2007	7.19	8.73
GW10	5/11/2007	7.19	8.71
GW10	5/12/2007	7.16	8.69

GW10	5/13/2007	7.13	8.67
GW10	5/14/2007	7.08	8.65
GW10	5/15/2007	7.03	8.63
GW10	5/16/2007	7.01	8.62
GW10	5/17/2007	7.04	8.60
GW10	5/18/2007	7.02	8.59
GW10	5/19/2007	7.00	8.58
GW10	5/20/2007	6.98	8.56
GW10	5/21/2007	6.94	8.55
GW10	5/22/2007	6.90	8.54
GW10	5/23/2007	6.88	8.53
GW10	5/24/2007	6.87	8.52
GW10	5/25/2007	6.84	8.52
GW10	5/26/2007	6.82	8.51
GW10	5/27/2007	6.79	8.50
GW10	5/28/2007	6.77	8.49
GW10	5/29/2007	6.74	8.49
GW10	5/30/2007	6.71	8.48
GW10	5/31/2007	6.69	8.48
GW10	6/1/2007	6.69	8.47
GW10	6/2/2007	6.66	8.47
GW10	6/3/2007	6.66	8.47
GW10	6/4/2007	6.96	8.46
GW10	6/5/2007	6.99	8.46
GW10	6/6/2007	6.95	8.46
GW10	6/7/2007	6.92	8.46
GW10	6/8/2007	6.91	8.46
GW10	6/9/2007	6.93	8.46
GW10	6/10/2007	6.93	8.45
GW10	6/11/2007	6.93	8.45
GW10	6/12/2007	6.94	8.45
GW10	6/13/2007	6.97	8.45
GW10	6/14/2007	7.03	8.45
GW10	6/15/2007	7.08	8.45
GW10	6/16/2007	7.10	8.45
GW10	6/17/2007	7.12	8.45
GW10	6/18/2007	7.10	8.45
GW10	6/19/2007	7.08	8.44
GW10	6/20/2007	7.11	8.44
GW10	6/21/2007	7.09	8.44
GW10	6/22/2007	7.08	8.44
GW10	6/23/2007	7.04	8.44

GW10	6/24/2007	7.01	8.44
GW10	6/25/2007	6.98	8.44
GW10	6/26/2007	6.96	8.44
GW10	6/27/2007	6.96	8.44
GW10	6/28/2007	7.01	8.44
GW10	6/29/2007	6.97	8.44
GW10	6/30/2007	6.96	8.44
GW10	7/1/2007	6.95	8.44
GW10	7/2/2007	6.92	8.44
GW10	7/3/2007	6.91	8.43
GW10	7/4/2007	6.90	8.43
GW10	7/5/2007	7.09	8.42
GW10	7/6/2007	7.09	8.42
GW10	7/7/2007	7.05	8.42
GW10	7/8/2007	7.01	8.42
GW10	7/9/2007	6.98	8.41
GW10	7/10/2007	6.95	8.41
GW10	7/11/2007	7.01	8.41
GW10	7/12/2007	7.20	8.41
GW10	7/13/2007	7.14	8.41
GW10	7/14/2007	7.10	8.41
GW10	7/15/2007	7.07	8.40
GW10	7/16/2007	7.04	8.40
GW10	7/17/2007	6.87	8.40
GW10	7/18/2007	6.86	8.40
GW10	7/19/2007	7.02	8.40
GW10	7/20/2007	6.90	8.40
GW10	7/21/2007	6.76	8.40
GW10	7/22/2007	6.73	8.40
GW10	7/23/2007	6.92	8.40
GW10	7/24/2007	7.02	8.40
GW10	7/25/2007	6.97	8.40
GW10	7/26/2007	6.93	8.40
GW10	7/27/2007	6.90	8.39
GW10	7/28/2007	6.87	8.39
GW10	7/29/2007	6.86	8.39
GW10	7/30/2007	6.92	8.39
GW10	7/31/2007	7.01	8.39
GW10	8/1/2007	6.98	8.39
GW10	8/2/2007	6.95	8.39
GW10	8/3/2007	6.91	8.40
GW10	8/4/2007	6.91	8.40

GW10	8/5/2007	6.90	8.40
GW10	8/6/2007	6.88	8.40
GW10	8/7/2007	6.86	8.40
GW10	8/8/2007	7.28	8.40
GW10	8/9/2007	7.29	8.40
GW10	8/10/2007	7.43	8.40
GW10	8/11/2007	7.48	8.40
GW10	8/12/2007	7.44	8.41
GW10	8/13/2007	7.42	8.41
GW10	8/14/2007	7.41	8.41
GW10	8/15/2007	7.37	8.41
GW10	8/16/2007	7.34	8.41
GW10	8/17/2007	7.32	8.41
GW10	8/18/2007	7.32	8.41
GW10	8/19/2007	7.29	8.41
GW10	8/20/2007	7.28	8.41
GW10	8/21/2007	7.37	8.41
GW10	8/22/2007	7.28	8.41
GW10	8/23/2007	7.25	8.41
GW10	8/24/2007	7.31	8.41
GW10	8/25/2007	7.28	8.41
GW10	8/26/2007	7.25	8.41
GW10	8/27/2007	7.22	8.41
GW10	8/28/2007	7.19	8.41
GW10	8/29/2007	7.16	8.41
GW10	8/30/2007	7.12	8.41
GW10	8/31/2007	7.10	8.41
GW10	9/1/2007	7.06	8.41
GW10	9/2/2007	7.03	8.41
GW10	9/3/2007	6.99	8.41
GW10	9/4/2007	6.97	8.41
GW10	9/5/2007	6.94	8.40
GW10	9/6/2007	6.91	8.40
GW10	9/7/2007	6.89	8.40
GW10	9/8/2007	6.86	8.40
GW10	9/9/2007	6.84	8.40
GW10	9/10/2007	6.83	8.40
GW10	9/11/2007	6.89	8.39
GW10	9/12/2007	6.91	8.39
GW10	9/13/2007	6.91	8.39
GW10	9/14/2007	6.92	8.39
GW10	9/15/2007	6.91	8.39

GW10	9/16/2007	6.89	8.39
GW10	9/17/2007	6.88	8.39
GW10	9/18/2007	6.86	8.39
GW10	9/19/2007	6.84	8.39
GW10	9/20/2007	6.83	8.39
GW10	9/21/2007	6.82	8.39
GW10	9/22/2007	6.82	8.39
GW10	9/23/2007	6.82	8.39
GW10	9/24/2007	6.81	8.39
GW10	9/25/2007	6.79	8.39
GW10	9/26/2007	6.62	8.39
GW10	9/27/2007	6.50	8.38
GW10	9/28/2007	6.51	8.38
GW10	9/29/2007	6.51	8.38
GW10	9/30/2007	6.50	8.38
GW10	10/1/2007	6.50	8.38
GW10	10/2/2007	6.46	8.39
GW10	10/3/2007	6.45	8.39
GW10	10/4/2007	6.45	8.39
GW10	10/5/2007	6.50	8.40
GW10	10/6/2007	6.64	8.40
GW10	10/7/2007	6.66	8.40
GW10	10/8/2007	6.65	8.40
GW10	10/9/2007	6.66	8.41
GW10	10/10/2007	6.74	8.41
GW10	10/11/2007	6.77	8.41
GW10	10/12/2007	6.86	8.41
GW10	10/13/2007	6.84	8.41
GW10	10/14/2007	6.83	8.41
GW10	10/15/2007	6.83	8.42
GW10	10/16/2007	6.86	8.42
GW10	10/17/2007	6.89	8.42
GW10	10/18/2007	6.89	8.42
GW10	10/19/2007	6.91	8.42
GW10	10/20/2007	6.94	8.42
GW10	10/21/2007	6.92	8.42
GW10	10/22/2007	6.91	8.42
GW10	10/23/2007	6.91	8.42
GW10	10/24/2007	6.92	8.42
GW10	10/25/2007	6.94	8.43
GW10	10/26/2007	6.79	8.43
GW10	10/27/2007	6.83	8.43

GW10	10/28/2007	6.89	8.43
GW10	10/29/2007	6.87	8.43
GW10	10/30/2007	6.86	8.43
GW10	10/31/2007	6.85	8.43
GW10	11/1/2007	6.84	8.43
GW10	11/2/2007	6.84	8.43
GW10	11/3/2007	6.85	8.43
GW10	11/4/2007	6.83	8.43
GW10	11/5/2007	6.82	8.43
GW10	11/6/2007	6.84	8.44
GW10	11/7/2007	6.84	8.44
GW10	11/8/2007	6.84	8.44
GW10	11/9/2007	6.84	8.44
GW10	11/10/2007	6.87	8.44
GW10	11/11/2007	6.86	8.44
GW10	11/12/2007	6.86	8.44
GW10	11/13/2007	6.87	8.44
GW10	11/14/2007	6.88	8.44
GW10	11/15/2007	6.90	8.44
GW10	11/16/2007	6.91	8.44
GW10	11/17/2007	6.89	8.44
GW10	11/18/2007	6.89	8.44
GW10	11/19/2007	6.91	8.44
GW10	11/20/2007	6.92	8.44
GW10	11/21/2007	6.92	8.45
GW10	11/22/2007	6.92	8.45
GW10	11/23/2007	6.92	8.45
GW10	11/24/2007	6.91	8.45
GW10	11/25/2007	6.90	8.45
GW10	11/26/2007	7.03	8.45
GW10	11/27/2007	7.07	8.45
GW10	11/28/2007	7.06	8.45
GW10	11/29/2007	7.06	8.45
GW10	11/30/2007	7.05	8.45
GW10	12/1/2007	7.05	8.45
GW10	12/2/2007	7.05	8.46
GW10	12/3/2007	7.11	8.48
GW10	12/4/2007	7.10	8.50
GW10	12/5/2007	7.09	8.51
GW10	12/6/2007	7.08	8.53
GW10	12/7/2007	7.07	8.55
GW10	12/8/2007	7.07	8.56

GW10	12/9/2007	7.07	8.58
GW10	12/10/2007	7.10	8.59
GW10	12/11/2007	7.10	8.61
GW10	12/12/2007	7.09	8.63
GW10	12/13/2007	7.14	8.64
GW10	12/14/2007	7.20	8.66
GW10	12/15/2007	7.20	8.67
GW10	12/16/2007	7.27	8.69
GW10	12/17/2007	7.31	8.70
GW10	12/18/2007	7.28	8.72
GW10	12/19/2007	7.27	8.73
GW10	12/20/2007	7.26	8.75
GW10	12/21/2007	7.24	8.77
GW10	12/22/2007	7.23	8.78
GW10	12/23/2007	7.26	8.80
GW10	12/24/2007	7.30	8.81
GW10	12/25/2007	7.28	8.82
GW10	12/26/2007	7.26	8.84
GW10	12/27/2007	7.32	8.85
GW10	12/28/2007	7.30	8.87
GW10	12/29/2007	7.37	8.88
GW10	12/30/2007	7.36	8.90
GW10	12/31/2007	7.39	8.91
GW11	4/10/2007	9.34	6.54
GW11	4/11/2007	9.33	6.51
GW11	4/12/2007	9.45	6.49
GW11	4/13/2007	9.53	6.45
GW11	4/14/2007	9.49	6.42
GW11	4/15/2007	9.89	6.39
GW11	4/16/2007	11.18	6.36
GW11	4/17/2007	11.18	6.33
GW11	4/18/2007	11.09	6.30
GW11	4/19/2007	11.08	6.27
GW11	4/20/2007	10.94	6.24
GW11	4/21/2007	10.71	6.21
GW11	4/22/2007	10.53	6.19
GW11	4/23/2007	10.39	6.17
GW11	4/24/2007	10.22	6.15
GW11	4/25/2007	10.13	6.12
GW11	4/26/2007	10.06	6.11
GW11	4/27/2007	10.28	6.09
GW11	4/28/2007	10.29	6.07

GW11	4/29/2007	10.20	6.06
GW11	4/30/2007	10.13	6.04
GW11	5/1/2007	10.05	6.02
GW11	5/2/2007	10.04	6.01
GW11	5/3/2007	9.97	5.99
GW11	5/4/2007	9.92	5.98
GW11	5/5/2007	9.87	5.96
GW11	5/6/2007	9.81	5.95
GW11	5/7/2007	9.77	5.94
GW11	5/8/2007	9.74	5.93
GW11	5/9/2007	9.65	5.92
GW11	5/10/2007	9.58	5.91
GW11	5/11/2007	9.58	5.90
GW11	5/12/2007	9.54	5.89
GW11	5/13/2007	9.51	5.88
GW11	5/14/2007	9.47	5.87
GW11	5/15/2007	9.45	5.86
GW11	5/16/2007	9.43	5.85
GW11	5/17/2007	9.43	5.84
GW11	5/18/2007	9.42	5.84
GW11	5/19/2007	9.41	5.83
GW11	5/20/2007	9.40	5.82
GW11	5/21/2007	9.35	5.82
GW11	5/22/2007	9.31	5.81
GW11	5/23/2007	9.29	5.80
GW11	5/24/2007	9.28	5.80
GW11	5/25/2007	9.26	5.79
GW11	5/26/2007	9.24	5.79
GW11	5/27/2007	9.21	5.80
GW11	5/28/2007	9.19	5.80
GW11	5/29/2007	9.15	5.79
GW11	5/30/2007	9.13	5.79
GW11	5/31/2007	9.11	5.78
GW11	6/1/2007	9.09	5.79
GW11	6/2/2007	9.07	5.80
GW11	6/3/2007	9.06	5.79
GW11	6/4/2007	9.30	5.81
GW11	6/5/2007	9.35	5.82
GW11	6/6/2007	9.31	5.83
GW11	6/7/2007	9.28	5.85
GW11	6/8/2007	9.27	5.86
GW11	6/9/2007	9.26	5.87

GW11	6/10/2007	9.25	5.88
GW11	6/11/2007	9.24	5.88
GW11	6/12/2007	9.25	5.88
GW11	6/13/2007	9.27	5.90
GW11	6/14/2007	9.32	5.90
GW11	6/15/2007	9.34	5.91
GW11	6/16/2007	9.35	5.91
GW11	6/17/2007	9.36	5.91
GW11	6/18/2007	9.33	5.91
GW11	6/19/2007	9.31	5.92
GW11	6/20/2007	9.34	5.92
GW11	6/21/2007	9.32	5.92
GW11	6/22/2007	9.30	5.94
GW11	6/23/2007	9.26	5.95
GW11	6/24/2007	9.22	5.96
GW11	6/25/2007	9.19	5.97
GW11	6/26/2007	9.17	5.97
GW11	6/27/2007	9.16	5.97
GW11	6/28/2007	9.25	5.97
GW11	6/29/2007	9.24	5.97
GW11	6/30/2007	9.23	5.97
GW11	7/1/2007	9.20	5.97
GW11	7/2/2007	9.17	5.97
GW11	7/3/2007	9.15	5.96
GW11	7/4/2007	9.15	5.96
GW11	7/5/2007	9.30	5.96
GW11	7/6/2007	9.31	5.95
GW11	7/7/2007	9.28	5.95
GW11	7/8/2007	9.24	5.95
GW11	7/9/2007	9.20	5.94
GW11	7/10/2007	9.16	5.94
GW11	7/11/2007	9.19	5.94
GW11	7/12/2007	9.36	5.93
GW11	7/13/2007	9.33	5.93
GW11	7/14/2007	9.30	5.93
GW11	7/15/2007	9.27	5.92
GW11	7/16/2007	9.26	5.92
GW11	7/17/2007	9.29	5.92
GW11	7/18/2007	9.31	5.91
GW11	7/19/2007	9.33	5.91
GW11	7/20/2007	9.18	5.91
GW11	7/21/2007	9.03	5.90

GW11	7/22/2007	8.99	5.91
GW11	7/23/2007	9.12	5.91
GW11	7/24/2007	9.24	5.91
GW11	7/25/2007	9.22	5.91
GW11	7/26/2007	9.20	5.90
GW11	7/27/2007	9.17	5.90
GW11	7/28/2007	9.14	5.90
GW11	7/29/2007	9.13	5.89
GW11	7/30/2007	9.13	5.89
GW11	7/31/2007	9.11	5.89
GW11	8/1/2007	9.07	5.89
GW11	8/2/2007	9.04	5.90
GW11	8/3/2007	9.01	5.91
GW11	8/4/2007	9.00	5.92
GW11	8/5/2007	8.97	5.93
GW11	8/6/2007	8.95	5.95
GW11	8/7/2007	8.93	5.96
GW11	8/8/2007	9.21	5.97
GW11	8/9/2007	9.31	5.99
GW11	8/10/2007	9.44	6.00
GW11	8/11/2007	9.52	6.01
GW11	8/12/2007	9.49	6.03
GW11	8/13/2007	9.46	6.02
GW11	8/14/2007	9.41	6.02
GW11	8/15/2007	9.36	6.02
GW11	8/16/2007	9.32	6.02
GW11	8/17/2007	9.30	6.01
GW11	8/18/2007	9.29	6.01
GW11	8/19/2007	9.26	6.01
GW11	8/20/2007	9.25	6.01
GW11	8/21/2007	9.31	6.00
GW11	8/22/2007	9.37	6.00
GW11	8/23/2007	9.35	5.99
GW11	8/24/2007	9.32	5.99
GW11	8/25/2007	9.29	5.99
GW11	8/26/2007	9.26	5.98
GW11	8/27/2007	9.21	5.98
GW11	8/28/2007	9.19	5.98
GW11	8/29/2007	9.16	5.97
GW11	8/30/2007	9.13	5.97
GW11	8/31/2007	9.10	5.96
GW11	9/1/2007	9.06	5.96

GW11	9/2/2007	9.03	5.96
GW11	9/3/2007	9.01	5.95
GW11	9/4/2007	8.98	5.95
GW11	9/5/2007	8.94	5.95
GW11	9/6/2007	8.92	5.94
GW11	9/7/2007	8.90	5.94
GW11	9/8/2007	8.88	5.94
GW11	9/9/2007	8.86	5.93
GW11	9/10/2007	8.84	5.93
GW11	9/11/2007	8.89	5.92
GW11	9/12/2007	8.91	5.92
GW11	9/13/2007	8.89	5.92
GW11	9/14/2007	8.87	5.92
GW11	9/15/2007	8.87	5.91
GW11	9/16/2007	8.84	5.91
GW11	9/17/2007	8.82	5.91
GW11	9/18/2007	8.81	5.91
GW11	9/19/2007	8.80	5.91
GW11	9/20/2007	8.78	5.91
GW11	9/21/2007	8.77	5.90
GW11	9/22/2007	8.77	5.90
GW11	9/23/2007	8.77	5.90
GW11	9/24/2007	8.75	5.90
GW11	9/25/2007	8.73	5.90
GW11	9/26/2007	8.70	5.90
GW11	9/27/2007	8.70	5.89
GW11	9/28/2007	8.71	5.90
GW11	9/29/2007	8.69	5.90
GW11	9/30/2007	8.68	5.90
GW11	10/1/2007	8.68	5.90
GW11	10/2/2007	8.68	5.90
GW11	10/3/2007	8.68	5.90
GW11	10/4/2007	8.66	5.90
GW11	10/5/2007	8.66	5.90
GW11	10/6/2007	8.67	5.90
GW11	10/7/2007	8.66	5.90
GW11	10/8/2007	8.66	5.90
GW11	10/9/2007	8.65	5.89
GW11	10/10/2007	8.72	5.89
GW11	10/11/2007	8.75	5.89
GW11	10/12/2007	8.83	5.89
GW11	10/13/2007	8.82	5.88

GW11	10/14/2007	8.81	5.88
GW11	10/15/2007	8.80	5.88
GW11	10/16/2007	8.79	5.88
GW11	10/17/2007	8.79	5.88
GW11	10/18/2007	8.79	5.87
GW11	10/19/2007	8.81	5.87
GW11	10/20/2007	8.84	5.87
GW11	10/21/2007	8.81	5.87
GW11	10/22/2007	8.81	5.86
GW11	10/23/2007	8.82	5.86
GW11	10/24/2007	8.80	5.86
GW11	10/25/2007	8.80	5.85
GW11	10/26/2007	8.82	5.85
GW11	10/27/2007	8.98	5.86
GW11	10/28/2007	9.04	5.86
GW11	10/29/2007	9.03	5.88
GW11	10/30/2007	9.02	5.88
GW11	10/31/2007	9.01	5.88
GW11	11/1/2007	9.01	5.88
GW11	11/2/2007	8.99	5.87
GW11	11/3/2007	9.01	5.87
GW11	11/4/2007	8.98	5.87
GW11	11/5/2007	8.97	5.87
GW11	11/6/2007	9.00	5.87
GW11	11/7/2007	8.99	5.87
GW11	11/8/2007	8.99	5.87
GW11	11/9/2007	8.99	5.87
GW11	11/10/2007	9.02	5.86
GW11	11/11/2007	9.01	5.86
GW11	11/12/2007	9.01	5.86
GW11	11/13/2007	9.03	5.85
GW11	11/14/2007	9.03	5.85
GW11	11/15/2007	9.06	5.85
GW11	11/16/2007	9.06	5.85
GW11	11/17/2007	9.03	5.84
GW11	11/18/2007	9.01	5.84
GW11	11/19/2007	9.03	5.84
GW11	11/20/2007	9.06	5.85
GW11	11/21/2007	9.06	5.86
GW11	11/22/2007	9.07	5.86
GW11	11/23/2007	9.04	5.85
GW11	11/24/2007	9.03	5.85

GW11	11/25/2007	9.03	5.85
GW11	11/26/2007	9.14	5.84
GW11	11/27/2007	9.20	5.84
GW11	11/28/2007	9.18	5.84
GW11	11/29/2007	9.20	5.84
GW11	11/30/2007	9.18	5.84
GW11	12/1/2007	9.17	5.84
GW11	12/2/2007	9.18	5.84
GW11	12/3/2007	9.26	5.85
GW11	12/4/2007	9.25	5.85
GW11	12/5/2007	9.23	5.86
GW11	12/6/2007	9.20	5.86
GW11	12/7/2007	9.20	5.87
GW11	12/8/2007	9.19	5.88
GW11	12/9/2007	9.18	5.89
GW11	12/10/2007	9.21	5.89
GW11	12/11/2007	9.18	5.90
GW11	12/12/2007	9.09	5.92
GW11	12/13/2007	9.07	5.92
GW11	12/14/2007	9.12	5.93
GW11	12/15/2007	9.26	5.95
GW11	12/16/2007	9.83	5.96
GW11	12/17/2007	9.83	5.97
GW11	12/18/2007	9.89	5.98
GW11	12/19/2007	9.97	5.99
GW11	12/20/2007	10.18	6.00
GW11	12/21/2007	10.23	6.01
GW11	12/22/2007	10.26	6.02
GW11	12/23/2007	10.42	6.02
GW11	12/24/2007	10.21	6.03
GW11	12/25/2007	9.96	6.05
GW11	12/26/2007	9.94	6.07
GW11	12/27/2007	10.24	6.08
GW11	12/28/2007	10.17	6.09
GW11	12/29/2007	10.29	6.10
GW11	12/30/2007	10.17	6.11
GW11	12/31/2007	10.23	6.12
GW12	4/10/2007	4.66	3.74
GW12	4/11/2007	4.66	3.73
GW12	4/12/2007	4.99	3.72
GW12	4/13/2007	4.88	3.70
GW12	4/14/2007	4.79	3.69

GW12	4/15/2007	5.82	3.67
GW12	4/16/2007	6.76	3.66
GW12	4/17/2007	6.46	3.64
GW12	4/18/2007	6.39	3.63
GW12	4/19/2007	6.39	3.61
GW12	4/20/2007	6.20	3.60
GW12	4/21/2007	5.88	3.59
GW12	4/22/2007	5.66	3.57
GW12	4/23/2007	5.51	3.56
GW12	4/24/2007	5.38	3.55
GW12	4/25/2007	5.26	3.54
GW12	4/26/2007	5.19	3.53
GW12	4/27/2007	5.59	3.52
GW12	4/28/2007	5.44	3.50
GW12	4/29/2007	5.34	3.50
GW12	4/30/2007	5.26	3.49
GW12	5/1/2007	5.18	3.47
GW12	5/2/2007	5.19	3.46
GW12	5/3/2007	5.11	3.45
GW12	5/4/2007	5.06	3.44
GW12	5/5/2007	5.03	3.43
GW12	5/6/2007	4.97	3.42
GW12	5/7/2007	4.93	3.42
GW12	5/8/2007	4.91	3.41
GW12	5/9/2007	4.85	3.40
GW12	5/10/2007	4.79	3.39
GW12	5/11/2007	4.82	3.38
GW12	5/12/2007	4.78	3.37
GW12	5/13/2007	4.76	3.37
GW12	5/14/2007	4.72	3.36
GW12	5/15/2007	4.71	3.35
GW12	5/16/2007	4.74	3.34
GW12	5/17/2007	4.81	3.33
GW12	5/18/2007	4.75	3.32
GW12	5/19/2007	4.71	3.32
GW12	5/20/2007	4.73	3.31
GW12	5/21/2007	4.67	3.30
GW12	5/22/2007	4.62	3.29
GW12	5/23/2007	4.58	3.28
GW12	5/24/2007	4.56	3.28
GW12	5/25/2007	4.56	3.27
GW12	5/26/2007	4.55	3.27

GW12	5/27/2007	4.52	3.29
GW12	5/28/2007	4.51	3.28
GW12	5/29/2007	4.49	3.28
GW12	5/30/2007	4.47	3.28
GW12	5/31/2007	4.46	3.27
GW12	6/1/2007	4.45	3.29
GW12	6/2/2007	4.44	3.29
GW12	6/3/2007	4.45	3.29
GW12	6/4/2007	5.19	3.32
GW12	6/5/2007	4.81	3.34
GW12	6/6/2007	4.69	3.37
GW12	6/7/2007	4.64	3.40
GW12	6/8/2007	4.61	3.42
GW12	6/9/2007	4.60	3.44
GW12	6/10/2007	4.57	3.44
GW12	6/11/2007	4.55	3.45
GW12	6/12/2007	4.57	3.45
GW12	6/13/2007	4.68	3.48
GW12	6/14/2007	4.84	3.49
GW12	6/15/2007	4.74	3.49
GW12	6/16/2007	4.71	3.50
GW12	6/17/2007	4.70	3.50
GW12	6/18/2007	4.67	3.50
GW12	6/19/2007	4.65	3.51
GW12	6/20/2007	4.71	3.52
GW12	6/21/2007	4.70	3.52
GW12	6/22/2007	4.69	3.55
GW12	6/23/2007	4.64	3.58
GW12	6/24/2007	4.59	3.60
GW12	6/25/2007	4.56	3.60
GW12	6/26/2007	4.55	3.60
GW12	6/27/2007	4.54	3.60
GW12	6/28/2007	4.92	3.60
GW12	6/29/2007	4.89	3.60
GW12	6/30/2007	4.85	3.60
GW12	7/1/2007	4.81	3.60
GW12	7/2/2007	4.74	3.60
GW12	7/3/2007	4.70	3.60
GW12	7/4/2007	4.69	3.59
GW12	7/5/2007	5.11	3.59
GW12	7/6/2007	4.99	3.59
GW12	7/7/2007	4.92	3.59

GW12	7/8/2007	4.87	3.58
GW12	7/9/2007	4.81	3.58
GW12	7/10/2007	4.76	3.57
GW12	7/11/2007	4.93	3.57
GW12	7/12/2007	5.15	3.56
GW12	7/13/2007	4.97	3.55
GW12	7/14/2007	4.93	3.55
GW12	7/15/2007	4.88	3.54
GW12	7/16/2007	4.80	3.54
GW12	7/17/2007	4.77	3.54
GW12	7/18/2007	4.89	3.53
GW12	7/19/2007	4.96	3.53
GW12	7/20/2007	4.88	3.53
GW12	7/21/2007	4.83	3.52
GW12	7/22/2007	4.77	3.53
GW12	7/23/2007	5.20	3.53
GW12	7/24/2007	5.13	3.53
GW12	7/25/2007	5.00	3.53
GW12	7/26/2007	4.97	3.52
GW12	7/27/2007	4.94	3.52
GW12	7/28/2007	4.91	3.51
GW12	7/29/2007	4.91	3.50
GW12	7/30/2007	4.96	3.50
GW12	7/31/2007	4.94	3.49
GW12	8/1/2007	4.89	3.51
GW12	8/2/2007	4.84	3.52
GW12	8/3/2007	4.81	3.52
GW12	8/4/2007	4.85	3.55
GW12	8/5/2007	4.82	3.58
GW12	8/6/2007	4.81	3.60
GW12	8/7/2007	4.78	3.63
GW12	8/8/2007	5.39	3.66
GW12	8/9/2007	5.13	3.68
GW12	8/10/2007	5.44	3.71
GW12	8/11/2007	5.26	3.73
GW12	8/12/2007	5.18	3.73
GW12	8/13/2007	5.15	3.73
GW12	8/14/2007	5.10	3.73
GW12	8/15/2007	5.06	3.72
GW12	8/16/2007	5.04	3.71
GW12	8/17/2007	5.06	3.70
GW12	8/18/2007	5.13	3.70

GW12	8/19/2007	5.06	3.70
GW12	8/20/2007	5.05	3.69
GW12	8/21/2007	5.32	3.68
GW12	8/22/2007	5.23	3.67
GW12	8/23/2007	5.15	3.67
GW12	8/24/2007	5.13	3.66
GW12	8/25/2007	5.10	3.66
GW12	8/26/2007	5.06	3.65
GW12	8/27/2007	5.02	3.64
GW12	8/28/2007	4.97	3.63
GW12	8/29/2007	4.94	3.63
GW12	8/30/2007	4.93	3.62
GW12	8/31/2007	4.91	3.61
GW12	9/1/2007	4.87	3.61
GW12	9/2/2007	4.84	3.60
GW12	9/3/2007	4.83	3.60
GW12	9/4/2007	4.81	3.59
GW12	9/5/2007	4.77	3.59
GW12	9/6/2007	4.74	3.58
GW12	9/7/2007	4.74	3.58
GW12	9/8/2007	4.73	3.57
GW12	9/9/2007	4.70	3.57
GW12	9/10/2007	4.71	3.56
GW12	9/11/2007	4.94	3.56
GW12	9/12/2007	5.08	3.55
GW12	9/13/2007	5.00	3.55
GW12	9/14/2007	4.97	3.55
GW12	9/15/2007	4.97	3.54
GW12	9/16/2007	4.91	3.54
GW12	9/17/2007	4.88	3.53
GW12	9/18/2007	4.86	3.53
GW12	9/19/2007	4.86	3.53
GW12	9/20/2007	4.86	3.53
GW12	9/21/2007	4.85	3.52
GW12	9/22/2007	4.88	3.52
GW12	9/23/2007	4.93	3.52
GW12	9/24/2007	4.89	3.52
GW12	9/25/2007	4.93	3.52
GW12	9/26/2007	4.98	3.52
GW12	9/27/2007	4.99	3.51
GW12	9/28/2007	5.03	3.51
GW12	9/29/2007	5.08	3.53

GW12	9/30/2007	5.07	3.53
GW12	10/1/2007	5.09	3.52
GW12	10/2/2007	4.72	3.52
GW12	10/3/2007	4.44	3.52
GW12	10/4/2007	4.45	3.52
GW12	10/5/2007	4.43	3.51
GW12	10/6/2007	4.44	3.50
GW12	10/7/2007	4.42	3.50
GW12	10/8/2007	4.42	3.50
GW12	10/9/2007	4.42	3.49
GW12	10/10/2007	4.68	3.49
GW12	10/11/2007	4.77	3.48
GW12	10/12/2007	4.99	3.47
GW12	10/13/2007	4.85	3.47
GW12	10/14/2007	4.79	3.47
GW12	10/15/2007	4.74	3.46
GW12	10/16/2007	4.70	3.45
GW12	10/17/2007	4.69	3.45
GW12	10/18/2007	4.70	3.44
GW12	10/19/2007	4.73	3.44
GW12	10/20/2007	4.85	3.44
GW12	10/21/2007	4.81	3.43
GW12	10/22/2007	4.79	3.42
GW12	10/23/2007	4.80	3.41
GW12	10/24/2007	4.78	3.41
GW12	10/25/2007	4.78	3.41
GW12	10/26/2007	4.91	3.40
GW12	10/27/2007	5.38	3.42
GW12	10/28/2007	5.13	3.42
GW12	10/29/2007	5.06	3.44
GW12	10/30/2007	5.04	3.45
GW12	10/31/2007	5.02	3.45
GW12	11/1/2007	5.02	3.44
GW12	11/2/2007	4.98	3.44
GW12	11/4/2007	4.98	3.43
GW12	11/5/2007	4.95	3.42
GW12	11/6/2007	5.05	3.43
GW12	11/7/2007	5.04	3.42
GW12	11/8/2007	5.02	3.42
GW12	11/10/2007	5.13	3.41
GW12	11/11/2007	5.10	3.40
GW12	11/13/2007	4.61	3.39

GW12	11/14/2007	4.61	3.39
GW12	11/15/2007	4.65	3.39
GW12	11/16/2007	4.65	3.38
GW12	11/17/2007	4.60	3.37
GW12	11/18/2007	4.56	3.36
GW12	11/19/2007	4.57	3.36
GW12	11/20/2007	4.60	3.39
GW12	11/21/2007	4.62	3.40
GW12	11/22/2007	4.62	3.39
GW12	11/23/2007	4.58	3.39
GW12	11/24/2007	4.55	3.38
GW12	11/25/2007	4.55	3.38
GW12	11/26/2007	4.81	3.37
GW12	11/27/2007	4.75	3.36
GW12	11/28/2007	4.66	3.36
GW12	11/29/2007	4.65	3.36
GW12	11/30/2007	4.62	3.36
GW12	12/1/2007	4.59	3.36
GW12	12/2/2007	4.58	3.35
GW12	12/3/2007	4.78	3.35
GW12	12/4/2007	4.72	3.34
GW12	12/5/2007	4.66	3.34
GW12	12/6/2007	4.62	3.34
GW12	12/7/2007	4.60	3.34
GW12	12/8/2007	4.60	3.34
GW12	12/9/2007	4.58	3.34
GW12	12/10/2007	4.69	3.34
GW12	12/11/2007	4.69	3.34
GW12	12/12/2007	4.71	3.36
GW12	12/13/2007	4.81	3.35
GW12	12/14/2007	5.00	3.36
GW12	12/15/2007	4.85	3.38
GW12	12/16/2007	5.14	3.38
GW12	12/17/2007	4.86	3.39
GW12	12/18/2007	4.75	3.40
GW12	12/19/2007	4.74	3.40
GW12	12/20/2007	4.75	3.40
GW12	12/21/2007	4.73	3.40
GW12	12/22/2007	4.72	3.40
GW12	12/23/2007	4.87	3.41
GW12	12/24/2007	4.91	3.41
GW12	12/25/2007	4.77	3.44

GW12	12/26/2007	4.75	3.45
GW12	12/27/2007	4.96	3.46
GW12	12/28/2007	4.79	3.47
GW12	12/29/2007	5.00	3.47
GW12	12/30/2007	4.85	3.48
GW12	12/31/2007	4.94	3.48

Table 4-9: Model performance statistics comparing predicted versus observed measurements (depth and flow; 2007) for validated Kearny Marsh surface water model (SWMM).

Parameter	***E***	***d***	**RSR**	***r***	**R^2**
Depth	0.81	0.93	0.43	0.92	0.86
Flow	0.52	0.87	0.68	0.78	0.61

Table 4-10: Model performance statistics comparing predicted versus observed head measurements (2007) for validated Kearny Marsh groundwater model (MODFLOW).

Parameter	***E***	***d***	**RSR**	***r***	**R^2**
Head	0.67	0.92	0.57	0.88	0.77

Table 4-11: Predicted hydrologic budgets for Kearny Marsh (SWMM results) for 2006 and 2007.

Water Budget Component (in/yr)	2006	2007
Total Precipitation (P)	48.57	54.32
Evaporation Loss (E)	11.86	12.91
Infiltration Loss (I)	18.50	21.41
Surface Runoff (R)	18.27	19.57

Table 4-12a: Mean predicted flows compared to mean tide heights from 2006 simulation in SWMM.

Mean Predicted Flow (cfs)	Mean Tide Height (ft)
-0.58	4.11
0.34	2.61

Table 4-12b: Mean predicted flows compared to mean tide heights from 2007 simulation in SWMM.

Mean Predicted Flow (cfs)	Mean Tide Height (ft)
-0.72	4.08
0.45	2.49

Table 4-13: Mean groundwater table elevations (feet asl) measured in Kearny Marsh.

Monitoring Well	2006	2007
GW07	3.59	3.90
GW08	3.47	4.05
GW09	3.30	3.64
GW10	3.41	3.64
GW11	3.74	3.72
GW12	3.24	3.54

Table 4-14: Modeled mean, minimum, and maximum groundwater velocities (in ft/day) for Kearny Marsh.

Velocity (ft/day)	**2006**	**2007**
Mean	0.0048	0.0053
Minimum	0.0000	0.0000
Maximum	0.0926	0.0968

5. APPLICATION OF COUPLED MODEL TO EVALUATE HYDROLOGIC IMPACTS OF DEVELOPMENT IN KEARNY MARSH

5.1. Development Changes and Slurry Wall Installation

After validating the coupled models for Kearny Marsh, they were used to predict hydrologic changes due to impacts from proposed development, including additions to the drainage network handling storm runoff, installation of a slurry wall to encircle Keegan Landfill, and development of Keegan Landfill for future use as commercial or industrial property. Expansion of existing drainage networks is proposed to alleviate flooding problems that exist in the Town of Kearny in the vicinity of Kearny Marsh (Neglia 2001). These proposed changes in Kearny Marsh are to take place over several stages or phases (Neglia 2001). Some proposed changes to this drainage system are to expand culverts that carry stormwater out of the marsh and into the Passaic River, construct overflow control structures for flood abatement, and rechannelize Frank's Creek (Neglia 2001). A complete description of proposed changes to the drainage network of Kearny Marsh is available in Neglia (2001).

A slurry wall will be placed around Keegan Landfill and combined with a runoff collection system in order to prevent migration of marsh water onto the site. Slurry walls are used as vertical barriers to control groundwater flow and to contain contaminants as part of waste containment systems (Opdyke and Evans 2005). Slurry walls are generally built in two stages. The first stage involves excavation of a trench to contain the wall while simultaneously filling the excavation with a slurry of bentonite and water (Opdyke and Evans 2005). The second stage involves backfilling the trench with a mixture of soil, a bentonite and water slurry, and/or dry bentonite (Opdyke and Evans 2005). The wall for Kearny Marsh is to be made of a bentonite slurry and backfill material (soil) from the site (T. Marturano, personal communication, March 23, 2008).

Long range plans for Kearny Marsh include possible development of Keegan Landfill so that it may provide light industrial and commercial properties (Hackensack Meadowlands Development Commission [HMDC] 2000). Properties that are permissible under light industrial development include establishments for scientific research and development, automobile service stations, bus terminals, indoor recreation, and/or warehouses or other storage facilities (HMDC 2000). The schedule for these plans is currently unknown.

5.2. SWMM Simulation

For the SWMM model, changes to the model included reducing wetland area including storage capability by the same area as encompassed by the slurry wall. This was accomplished by creating an additional drainage area for the slurry wall and developing the entire site to 100% imperviousness and reducing the Kearny Marsh subcatchment by the same area (Figure 5-1). This has the effect of changing all of the precipitation that lands on this drainage area into runoff, which was diverted into the Kearny Marsh catchment. The collection system was not included in the simulations because all storm water will replace any leachate that currently enters the marsh (T. Marturano, personal communication, June 18, 2008). According to 2002 NJDEP GIS land use/land cover data, many of the current commercial and industrial properties in the

Kearny Marsh area are at about 95% imperviousness. Setting impervious cover this high was done to model the 'worst case scenario' in regard to development impacts. In essence, a piece of the Kearny Marsh subcatchment with the same size as the Keegan Landfill area (100.7 acres) was 'cut out' and created as a separate subcatchment (Figure 5-1). Additionally, all of the proposed changes to Kearny Marsh's drainage network from the Neglia stormwater study (Neglia 2001) were incorporated into the simulation. Additional outfalls, widened channels and other water control structures were added according to proposed plans (Neglia 2001). All data regarding the dimensions, shape, and elevations for these proposed changes are outlined in Neglia (2001).

In order to evaluate the effects of the broken bulkhead connecting Frank's Creek and Kearny Marsh, SWMM was used to simulate the possibility of fixing this broken bulkhead. This was simulated in the model by removing the channel connecting Frank's Creek and the Kearny Marsh subcatchment from the validated 2007 model. The drainage system connecting Kearny Marsh to the Passaic River was maintained in all model simulations. This will also be used to evaluate the impact that additional drainage as outlined in Neglia (2001) will have on marsh hydrology.

5.3. Visual MODFLOW Simulation

As with the coupled model, SWMM-calculated infiltration and evaporation were input as recharge and evapotranspiration, respectively, in Visual MODFLOW. This is to represent the changes due to alterations of the surface (e.g., increased impervious surfaces, re-routing of water from the landfill to Kearny Marsh) and their impact on groundwater.

Slurry walls in MODFLOW are represented using the WALL (HFB) package as a boundary condition in the model (Hsieh and Freckleton 1993). The WALL acts as a horizontal flow barrier (HFB) that simulates a thin, low-permeability feature that impedes the horizontal flow of groundwater (Hsieh and Freckleton 1993). Another method for representing slurry walls is to delineate those cells where the wall is to be located as "no-flow cells" that completely prevent horizontal movement of groundwater (Stewart et al. 1998). The HFB approach, however, has shown good results when used (Gupta and Fox 1999; Harte et al. 2006). The low-conductivity cells designated as part of the slurry wall (HFB cells) restrict flow of water into adjacent cells by dropping the conductivity value in the Darcy equation when calculating groundwater flow (Gupta and Fox 1999). For a complete description of the formulation of the HFB package for MODFLOW, refer to Hsieh and Freckleton (1993).

The HFB boundary was drawn surrounding Keegan Landfill in cells corresponding to the location where the slurry wall is to be built, based upon plans provided by the NJMC (Figure 5-2). Data necessary for the HFB include wall thickness in feet, conductivity of the material that makes up the wall in feet/day, and the direction of the barrier (Hsieh and Freckleton 1993). These data were provided by the NJMC based upon their plans for the Keegan Landfill with the slurry wall thickness to be 3 feet, and the conductivity to be 0.003404 feet/day (converted from the reported 1×10^{-7} centimeter/second) (T. Marturano, personal communication, March 23, 2008). This conductivity value is typical for slurry walls made from a combination of soil and bentonite (Opdyke and Evans 2005).

5.4. Precipitation Scenarios

Simulations were run in both SWMM and Visual MODFLOW using three precipitation scenarios:

- Scenario 1 – 'Dry': Precipitation values, on an hourly basis, taken from a below average precipitation year (2001). Annual precipitation total was 30.51 inches.
- Scenario 2 – 'Average': Hourly precipitation values from an average rainfall year (2002). Annual precipitation totaled 41.59 inches.
- Scenario 3 – 'Wet': Precipitation values from an above average precipitation year (2007). Annual precipitation totaled 54.32 inches.

These three scenarios were chosen to represent hydrologic cycles under a variety of climatological conditions. Mean monthly and annual precipitation totals were reviewed from data located at the New Jersey State Climatologist's Office at Rutgers University (http://climate.rutgers.edu/stateclim/). These data were used to determine which years fall into the 'dry', 'average', and 'wet' categories. Mean annual precipitation from data gathered from 1895 through 2008, is 45.02 inches. Hourly data were downloaded from National Oceanic and Atmospheric Administration's (NOAA's) National Climatic Data Center (NCDC) for each of the chosen years (2001, 2002, and 2007) (http://www.ncdc.noaa.gov/oa/ncdc.html).

Each scenario used the same evaporation rates and tide height data (during the SWMM simulations) so that any differences in calculated runoff values would be due to the amount of rainfall and changes in the subcatchments, better reflecting changing development. The validated 2007 model (without the development changes or inclusion of a slurry wall) also used these three precipitation scenarios as a 'baseline' for comparison with the three precipitation scenarios ('dry', 'average', and 'wet').

5.5. Results

5.5.1. SWMM

A comparison of the results of the hydrologic balance calculated from SWMM shows the impacts of increased developed/impervious area within the wetland (Table 5-1). In each case ('dry', 'average', and 'wet') the following annual changes can be seen: evaporation increases, infiltration decreases, and runoff increases (Table 5-1). Mean evaporation increase was 0.29 inches, mean infiltration loss was 2.33 inches, and mean surface runoff increase was 2.01 inches.

During the 'dry' scenario, evaporation increased 0.28 inches (+3.2% change) from the baseline simulation. Infiltration decreased by 1.70 inches (-16.3% change) and surface runoff increased by 1.43 inches (+13.0% change) (Table 5-1a). The 'average' scenario predicts an evaporation increase of 0.25 inches (+2.9%), a decrease in infiltration of 2.30 inches (-13.9%), and an increase of runoff by 1.94 inches (+12.4%) from the baseline condition (Table 5-1b). Results from the 'wet' simulations predict an increase in evaporation of 0.35 inches (+2.7%), a decrease in infiltration of 2.99 inches (-14.0%), and surface runoff increases by 2.65 inches (+13.5%) from undeveloped conditions ('baseline') (Table 5-1c).

Repairing the broken bulkhead connecting Kearny Marsh and Frank's Creek resulted in no changes in the water budgets before and after repairs. The greatest change was seen in the volume of flooding that occurs with the removal of the drainage provided by the broken bulkhead between Kearny Marsh and Frank's Creek (Table 5-2). During the 'dry' scenarios little additional flooding is predicted to occur with the loss drainage provide by the broken bulkhead (+0.03% change; Table 5-2a). However, both the 'average' and 'wet' scenarios predict large increases in surface flooding. The 'average' precipitation scenario simulates that repairs to the broken bulkhead will increase the flooding in Kearny Marsh from 110.43 million gallons (Mgallons) to 601.21 Mgallons (+444.43% change; Table 5-2a). The 'wet' scenario results in 1,139.70 Mgallons of flooding occurring after the broken bulkhead is repaired as compared to 142.98 Mgallons of flooding if the broken bulkhead remains intact (+697.10% change; Table 5-2a).

Flooding would also increase if the development scenarios outlined in Neglia (2001) were to move forward (Table 5-2b). The volume of flooding, however, is not predicted to be as large, in all precipitation scenarios, as when the broken bulkhead is repaired (Table 5-2a and Table 5-2b).

5.5.2. Visual MODFLOW

Water table elevation was used to evaluate the impact of slurry wall installation because water table levels determine the regularity of baseflow for streams and wetlands (Winter 1999; Sophocleous 2002), and therefore the maintenance of water levels in Kearny Marsh. Comparing the pre- and post-slurry wall installation scenarios, the water table elevations drop in each of the post-slurry wall scenarios (Table 5-3). Mean drop in elevation is 0.72 feet. During 'dry' simulations, the water table dropped 0.24 feet in elevation (-2.1% change) (Table 5-3). For the 'average' and 'wet' simulations, water table elevations dropped 0.87 feet (-6.6%) and 1.05 feet (-8.0%), respectively (Table 5-3).

5.6. Conclusions

Urbanization alters wetlands in urban watersheds, such as the Meadowlands, by clearing vegetation, changing land uses, and fragmenting the landscape with development. Increased runoff, decreased infiltration, increased evaporation, and lowered groundwater tables are all predicted to result due to the installation of the slurry wall and subsequent development (Table 5-1 and Table 5-3). Increasing impervious surfaces associated with urbanization account for many of the alterations to wetland hydrology. Urbanization converts natural habitats to land uses with impervious surfaces (such as asphalt and concrete) that reduce or prevent soil infiltration of precipitation. Impervious surfaces create surface runoff with greater velocities, larger volumes, and shorter times of flow concentration (Brun and Band 2000). These effects are reflected in the results seen from the SWMM simulations.

Flooding has been a recurrent problem in the vicinity of Kearny Marsh. The 2006 and 2007 SWMM simulations indicate a tidal influence on marsh water level and may explain to some degree the area's flooding problems. The connection between Kearny Marsh and Frank's Creek, which currently exists as a broken bulkhead, would be engineered into a channeled drainage system to handle larger volumes and possibly alleviate flooding (Neglia 2001). Results from simulations where the current drainage system to the Passaic River is the sole source of surface water outflows, with the broken bulkhead being repaired, show that flooding would increase (Table 5-2). Flood volumes would be elevated after installation of the slurry wall and inclusion of a drainage network using Frank's Creek in addition to the Passaic River system, but not as large an increase as without such an additional system (Table 5-2).

The drop in groundwater table elevation is in response to the surface water changes seen in hydrologic budgets resulting from the post-development SWMM scenarios: less water is reaching the ground water because more is evaporating from the surface, less water is infiltrating to the groundwater due to increased impervious surfaces, and more is running off into the Passaic River (Table 5-1 and Table 5-3). Increased impervious surfaces, including the Keegan Landfill developed areas, contribute to decreased groundwater recharge by reducing available groundwater recharge area (Rose and Peters 2001). This is reflected in both the decrease in infiltration amounts from the SWMM simulations (Table 5-1) and in lowered water table elevations that result from the Visual MODFLOW model runs (Table 5-3). A hydrologic model of northwestern New Jersey showed similar results, as development alters land use by reducing water infiltration to the unconfined aquifer below (Shirinian-Orlando and Uchrin 2007). Rapid routing of water to urban streams reduces surface and shallow subsurface storage, which results in lower long-term groundwater recharge, and subsequently, reduced groundwater discharge during the period of baseflow (Rose and Peters 2001). MODFLOW models simulating pre- and post-development conditions for the northern Coastal Plain in New Jersey showed a decrease in groundwater discharge to adjacent streams (Pucci, Jr. and Pope 1995). Decreasing baseflow discharged to Kearny Marsh may lead to a reduction in wetland water levels and possible drying out of many portions of the marsh.

Figure 5-1: SWMM map of Kearny Marsh with development, additional drainage networks, and slurry wall included to represent future water control efforts.

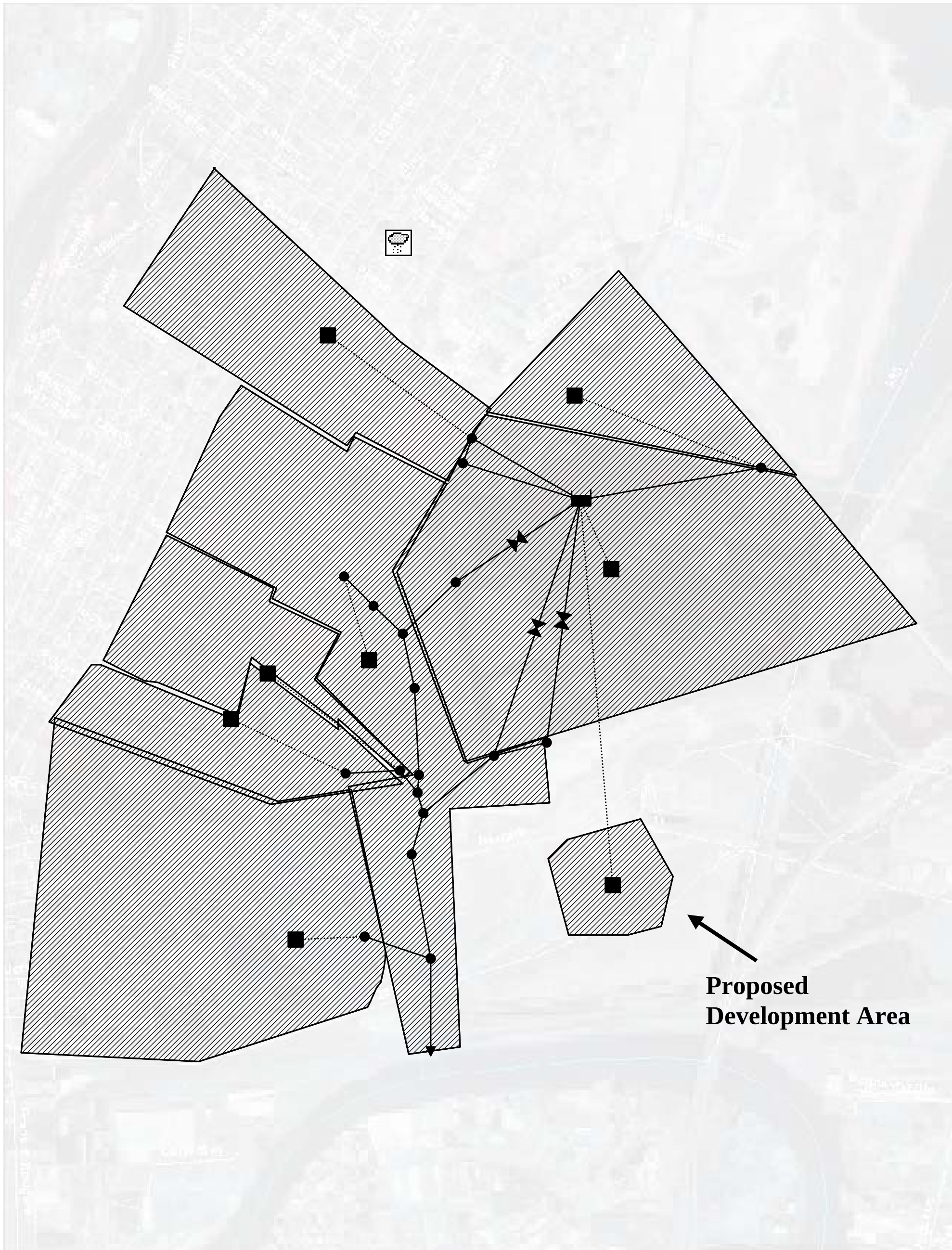

Figure 5-2: Visual MODFLOW map of Kearny Marsh with slurry wall cells (denoted with brown lines on top face) and drain designated cells (in gray).

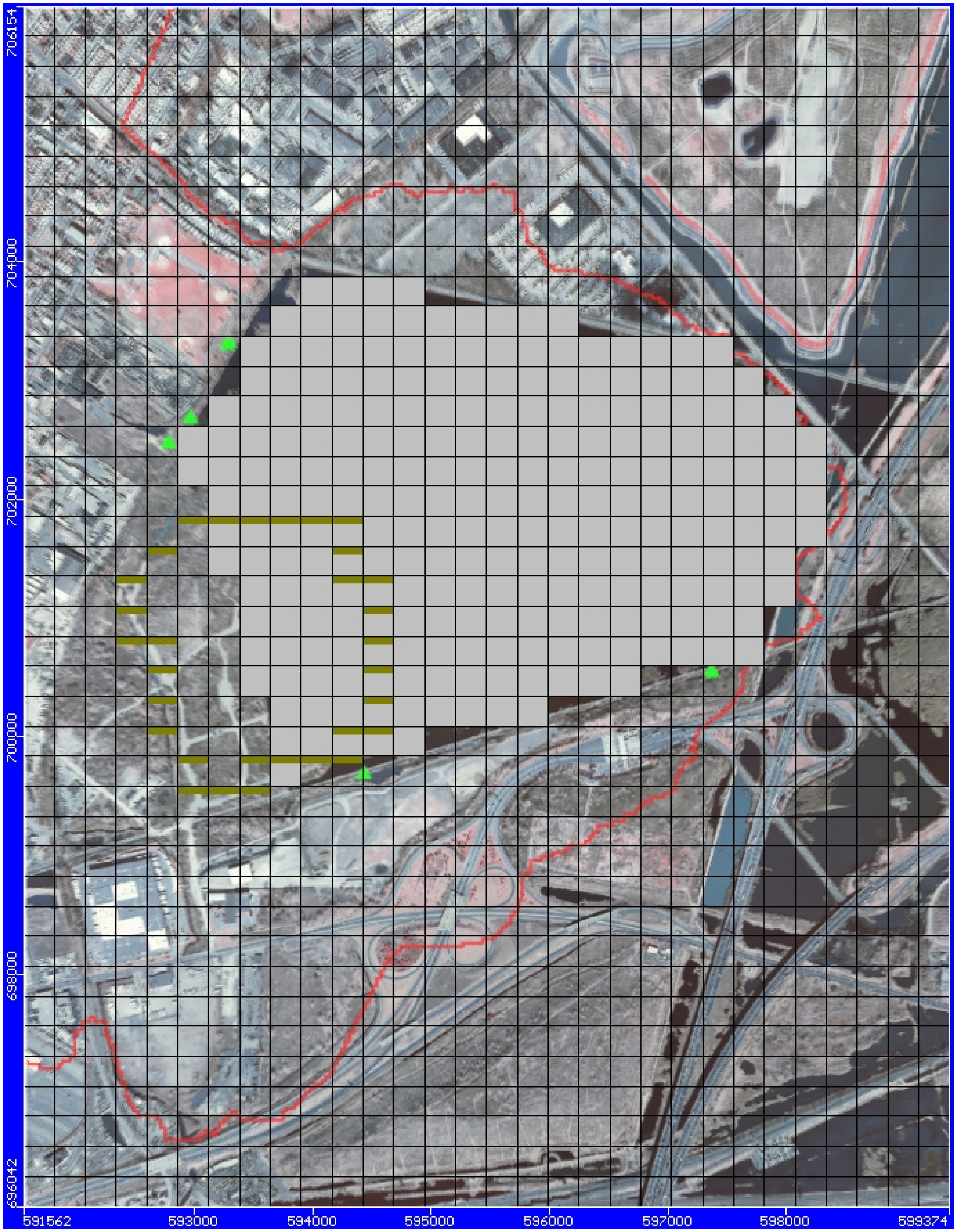

Table 5-1a: SWMM calculated water budgets for 'dry' precipitation scenario before installation of the slurry wall ('baseline') and after ('slurry wall').

Water Budget Component (inches/year)	Baseline	Slurry Wall	Difference	% Difference
Total Precipitation	30.51	30.51	0.00	0.0%
Evaporation Loss	8.86	9.14	+0.28	+3.2%
Infiltration Loss	10.46	8.76	-1.70	-16.3%
Surface Runoff	11.02	12.45	+1.43	+13.0%
Surface Storage	0.19	0.19	0.00	0.0%

Table 5-1b: SWMM calculated water budgets for 'average' precipitation scenario before installation of the slurry wall ('baseline') and after ('slurry wall').

Water Budget Component (inches/year)	Baseline	Slurry Wall	Difference	% Difference
Total Precipitation	41.59	41.59	0.00	0.0%
Evaporation Loss	8.73	8.98	+0.25	+2.9%
Infiltration Loss	16.57	14.27	-2.30	-13.9%
Surface Runoff	15.65	17.59	+1.94	+12.4%
Surface Storage	0.68	0.67	-0.01	-1.5%

Table 5-1c: SWMM calculated water budgets for 'wet' precipitation scenario before installation of the slurry wall ('baseline') and after ('slurry wall').

Water Budget Component (inches/year)	Baseline	Slurry Wall	Difference	% Difference
Total Precipitation	54.32	54.32	0.00	0.0%
Evaporation Loss	12.91	13.26	+0.35	+2.7%
Infiltration Loss	21.41	18.42	-2.99	-14.0%
Surface Runoff	19.57	22.22	+2.65	+13.5%
Surface Storage	0.50	0.51	+0.01	+2.0%

Table 5-2a: SWMM flooding volumes (as million gallons) before ('broken') and after ('repaired') repairing the broken bulkhead between Frank's Creek and Kearny Marsh for all precipitation scenarios.

	Dry		Average		Wet	
	Broken	Repaired	Broken	Repaired	Broken	Repaired
Surface Flooding (Mgallons)	53.51	53.53	110.43	601.21	142.98	1,139.70
Difference (Mgallons)	+0.02		+490.78		+996.72	
% Difference (Mgallons)	+0.03%		+444.43%		+697.10%	

Table 5-2b: SWMM flooding volumes (as million gallons) before repairing the broken bulkhead between Frank's Creek and Kearny Marsh ('broken') and after installation of the slurry wall ('slurry wall') for all precipitation scenarios.

	Dry		Average		Wet	
	Broken	Slurry Wall	Broken	Slurry Wall	Broken	Slurry Wall
Surface Flooding (Mgallons)	53.51	65.64	110.43	125.26	142.98	162.60
Difference (Mgallons)	+12.13		+14.83		+19.62	
% Difference (Mgallons)	+22.67%		+13.43%		+13.72%	

Table 5-3: Visual MODFLOW modeled average water table elevation for each precipitation scenario (dry, average, wet) before installation of the slurry wall ('baseline') and after ('slurry wall').

	Dry		Average		Wet	
	Baseline	Slurry Wall	Baseline	Slurry Wall	Baseline	Slurry Wall
Average Water Table Elevation (feet)	11.57	11.33	13.24	12.37	13.15	12.10
Difference (feet)	-0.24		-0.87		-1.05	
% Difference (feet)	-2.1%		-6.6%		-8.0%	

6. SUMMARY

A coupled surface water and groundwater model for Kearny Marsh was able to successfully describe the complex hydrology for this urban wetland. Modeled surface water, in SWMM, was linked to groundwater, in MODFLOW. This was accomplished by using output from SWMM (specifically infiltration losses and evaporation) as boundary conditions in MODFLOW (as recharge and evapotranspiration, respectively). Linkage between SWMM and MODFLOW has been accomplished previously (Rowan 2001), but was not specifically performed in an urban wetland. In addition, a third computer program, the Multiple Model Broker, was required in order to accomplish the coupling (Rowan 2001). While the coupling of SWMM and MODFLOW for Kearny Marsh was accomplished simplistically, a calibrated and validated model was developed that provided insight into the hydrology of this urban marsh. Increased capabilities of newer versions of SWMM and MODFLOW have lessened the need for such a third party program and increased the ability to facilitate interaction between them.

The hydrology of Kearny Marsh is a mixture of stormwater/runoff dynamics, discharge from groundwater, and tidal influences that combine to sustain this urban wetland. Precipitation and stormwater runoff are the primary inputs to surface water and infiltration is the primary input into groundwater. Groundwater is also discharging into Kearny Marsh, maintaining water levels. Tides influence the hydrology of Kearny Marsh via a broken bulkhead connecting Frank’s Creek to Kearny Marsh. During low tide, Frank’s Creek drains water out of the marsh from both the broken bulkhead area and the designed drainage system connecting to the Passaic River. During high tide, however, the break in the bulkhead upstream of the tide gates allows flows to short-circuit Frank’s

Creek and flow through the bulkhead directly into Kearny Marsh. This additional water flow could be responsible for flooding that occurs in nearby portions of the Town of Kearny. This data could be helpful to alleviate flooding problems for area residents.

The goal of this research was to develop a model as a tool to aid in the management and restoration of Kearny Marsh. Development scenarios, both planned and hypothetical were modeled to determine the impacts of such management on this resource. Negative impacts to water quantity associated with urbanization were simulated to occur both currently and in the future if proposed engineering changes were to proceed. Increased runoff, decreased infiltration, increased evaporation, and lowered groundwater tables are all predicted to result due to the installation of the slurry wall and subsequent development. Increasing impervious surfaces associated with urbanization account for many of the alterations to wetland hydrology. Impervious surfaces create surface runoff with greater velocities, larger volumes, shorter times of flow concentration, and reduce areas where infiltration to groundwater can occur.

Future efforts should take into account hydrologic information, such as water budget information and simulated responses to management scenarios, in order to increase the likelihood of successful restoration. In Tennessee (Morgan and Roberts 2003), Massachusetts (Brown and Veneman 2001), New Jersey (NJDEP 2002), and other areas of the United States (Minkin and Ladd 2003), the results of ignoring such information have resulted in failed restoration of wetlands. Kearny Marsh represents an opportunity to learn from such failures and provide for successful enhancement of this ecosystem.

7. REFERENCES

Amatya, D.M., R.W. Skaggs, and J.D. Gregory. 1995. Comparison of Methods for Estimating REF-ET. *Journal of Irrigation and Drainage Engineering*. 121(6): 427-435.

Arnold, J.G. and N. Fohrer. 2005. SWAT2000: Current Capabilities and Research Opportunities in Applied Watershed Modelling. *Hydrological Processes*. 19: 563-572.

Barco, J., K.M. Wong, and M.K. Stenstrom. 2008. Automatic Calibration of the U.S. EPA SWMM Model for a Large Urban Catchment. *Journal of Hydraulic Engineering*. 134(4):466-474.

Barrett, K.R. and M.A. McBrien. 2007. Chemical and Biological Assessment of an Urban, Estuarine Marsh in Northeastern New Jersey, USA. *Environmental Monitoring & Assessment*. 124:63-88.

Batelaan, O. and F. De Smedt. 2004. SEEPAGE, a New MODFLOW DRAIN Package. *Ground Water*. 42(4): 576-588.

Batelaan, O., F. De Smedt, and L. Triest. 2003. Regional Groundwater Discharge: Phreatophyte Mapping, Groundwater Modelling and Impact Analysis of Land-Use Change. *Journal of Hydrology*. 275: 86-108.

Bedford, B.L. 1996. The Need to Define Hydrologic Equivalence at the Landscape Scale for Freshwater Wetland Mitigation. *Ecological Applications*. 6(1): 57-68.

Bentivegna, C.S., J-E. Alfano, S.M. Bugel, and K. Czechowicz. 2004. Influence of Sediment Characteristics on Heavy Metal Toxicity in an Urban Marsh. *Urban Habitats*. 2(1): 91-111.

Bidlake, W.R., W.M. Woodham, and M.A. Lopez. 1995. Evapotranspiration from Areas of Native Vegetation in West-Central Florida. U.S. Geological Survey Water Supply Paper 2340.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells. *Water Resources Research*. 12(3): 423-428.

Bradford, R.B. and M.C. Acreman. 2003. Applying MODFLOW to Wet Grassland In-Field Habitats: A Case Study from Pevensey Levels, UK. *Hydrology and Earth System Sciences*. 7(1): 43-55.

Bradley, C. 1996. Transient Modelling of Water-Table Variation in a Floodplain Wetland, Narborough Bog, Leicestershire. *Journal of Hydrology*. 185: 87-114.

Bradley, C. 1997. The Hydrological Basis for Conservation of Floodplain Wetlands: Implications of Work at Narborough Bog, UK. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 7: 41-62.

Bradley, C. 2002. Simulation of the Annual Water Table Dynamics of a Floodplain Wetland, Narborough Bog, UK. *Journal of Hydrology*. 261: 150-172.

Brennan, K.E., D.J. O'Leary, and S.P. Buckley. 2001. Hydrologic Analysis of the Wetland Habitat of the Federally Threatened Bog Turtle. Proceedings of the International Conference on Ecology and Transportation. Keystone, CO. September 24-28, 2001. 51-64.

Brown, S.C. and P.L.M. Veneman. 2001. Effectiveness of Compensatory Wetland Mitigation in Massachusetts, USA. *Wetlands*. 21(4):508-518.

Brun, S.E. and L.E. Band. 2000. Simulating Runoff Behavior in an Urbanizing Watershed. *Computers, Environment and Urban Systems*. 24:5-22.

Bullock, A. and M. Acreman. 2003. The Role of Wetlands in the Hydrologic Cycle. *Hydrology and Earth Systems Sciences*. 7(3):358-389.

Burba, G.G., S.B. Verma, and J. Kim. 1999. Surface Energy Fluxes of Phragmites australis in a Prairie Wetland. *Agricultural and Forest Meteorology*. 94:31-51.

Camp Dresser and McKee, Inc. 1998. Land Use Feasibility Study: Keegan Landfill, Kearny, New Jersey. Camp Dresser and McKee, Inc. Edison, NJ.

Campbell Scientific, Inc. 2006. Open Path Eddy Covariance System Operator's Manual: CSAT3, LI-7500, and KH20. Campbell Scientific, Inc. Logan, UT.

Chang, J-H. 1959. An Evaluation of the 1948 Thornthwaite Classification. *Annals of the Association of American Geographers*. 49(1): 24-30.

Chen, D., G. Gao, C. Xu, J. Guo, and G. Ren. 2005. Comparison of the Thornthwaite Method and Pan Evaporation with the Standard Penman-Monteith Estimates of Reference Evapotranspiration in China. *Climate Research*. 28: 123-132.

Clark, S., R. Pitt, S. Burian, R. Field, E. Fan, J. Heaney, and L. Wright. 2007. Annotated Bibliography of Urban Wet Weather Flow Literature From 1996 Through 2006. Retrieved March 2006 from, http://rpitt.eng.ua.edu/Publications/Wetweatherlit/1996%20to%202006%20WEF%20lit%20reviews.pdf.

Clymo, R.S. 2004. Hydraulic Conductivity of Peat at Ellergower Moss, Scotland. *Hydrological Processes*. 18: 261-274.

Dadaser-Celik. F., H.G. Stefan, and P.L. Brezonik. 2006. Dynamic Hydrologic Model of the Örtülüakar Marsh in Turkey. *Wetlands*. 26(4): 1089-1102.

Deliman, P.N., R.H. Glick, and C.E. Ruiz. 1999. Review of Watershed Water Quality Models. U.S. Army Corps of Engineers, Water Quality Research Program. Washington, DC. Technical Report W-99-1.

Drexler, J.Z., R.L. Snyder, D. Spano, and K.T. Paw. 2004. A Review of Model and Micrometeorological Methods Used to Estimate Wetland Evapotranspiration. *Hydrological Processes*. 18: 2071-2101.

Dunne, T. and L.B. Leopold. 1978. *Water in Environmental Planning*. W. H. Freeman and Company. San Francisco, CA.

Ehrenfeld, J.G. 2000. Evaluating Wetlands within an Urban Context. *Urban Ecosystems*. 4:69-85.

Ehrenfeld, J.G., H.B Cutway, R. Hamilton IV, and E. Stander. 2003. Hydrologic Description of Forested Wetlands in Northeastern New Jersey, NJ – An Urban/Suburban Region. *Wetlands*. 23(4):685-7000.

Elkiran, G. and M. Ergil. 2006. The Assessment of a Water Budget of North Cyprus. *Building and Environment*. 41:1671-1677.

Farahani, H.J., T.A. Howell, W.J. Shuttleworth, and W.C. Bausch. 2007. Evapotranspiration: Progress in Measurement and Modeling in Agriculture. *Transactions of the ASABE*. 50(5): 1627-1638.

Favero, L., E. Mattiuzzo, and D. Franco. 2007. Practical Results of a Water Budget Estimation for a Constructed Wetland. *Wetlands*. 27(2): 230-239.

Fermor, P.M., P.D. Hedges, J.C. Gilbert, and D.J.G. Gowing. 2001. Reedbed Evapotranspiration Rates in England. *Hydrological Processes*. 15: 621-631.

Fetter, C.W. 1999. *Contaminant Hydrogeology, 2nd edition*. Prentice Hall, Inc. Englewood Cliffs, NJ.

Fowler J., L. Cohen, and P. Jarvis. 1999. *Practical Statistics for Field Biology: 2nd Edition*. John Wiley & Sons Ltd. New York, NY.

Freeze, R.A. and J.A. Cherry. 1979. *Groundwater*. Prentice Hall, Inc. Englewood Cliffs, NJ.

Furman, A. 2008. Modeling Coupled Surface-Subsurface Flow Processes: A Review. *Vadose Zone Journal*. 7: 741-756.

Garcia, M., D. Raes, R. Allen, and C. Herbas. 2004. Dynamics of Reference Evapotranspiration in the Bolivian Highlands (Altiplano). *Agricultural and Forest Meteorology*. 125: 67-82.

Gerla, P.J. and R.K. Matheney. 1996. Seasonal Variability and Simulation of Groundwater Flow in a Prairie Wetland. *Hydrological Processes*. 10: 903-920.

Grapes, T.R., Bradley, C., and G.E. Petty. 2006. Hydrodynamics of Floodplain Wetlands in a Chalk Catchment: The River Lambourn, UK. *Journal of Hydrology*. 320: 324-341.

Gupta, N. and T.C. Fox. 1999. Hydrogeologic Modeling for Permeable Reactive Barriers. *Journal of Hazardous Materials*. 68: 19-39.

Hackensack Meadowlands Development Commission (HMDC). 2000. Kearny Area Redevelopment Plan. Hackensack Meadowlands Development Commission. Lyndhurst, NJ.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald. 2000. MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model – User Guide to Modularization Concepts and the Ground-Water Flow Process. U.S. Geological Survey. Reston, VA. Open-File Report 00-92.

Harrelson, C.C., C.L. Rawlins, and J.P. Potyondy. 1994. Stream Channel Reference Sites: An Illustrated Guide to Field Technique. USDA Forest Service, Fort Collins, CO. General Technical Report RM-245.

Harte, P.T., L.F. Konikow, and G.Z. Hornberger. 2006. Simulation of Solute Transport Across Low-Permeability Barrier Wall. *Journal of Contaminant Hydrology*. 85: 247-270.

Hasse, J.E. and R.G. Lathrop. 2003. Land Resource Impact Indicators of Urban Sprawl. *Applied Geography*. 23:159-175.

Hsieh, P.A. and J.R. Freckleton. 1993. Documentation of a Computer Program to Simulate Horizontal-Flow Barriers Using the U.S. Geological Survey's Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. U.S. Geological Survey. Sacramento, CA. Open-File Report 92-477.

Hughes, C.E., P. Binning, and G.R. Willgoose. 1998. Characterisation of the Hydrology of an Estuarine Wetland. *Journal of Hydrology*. 211:34-49.

Jang, S., M. Cho, J. Yoon, Y. Yoon, S. Kim, G. Kim, L. Kim, and H. Aksoy. 2007. Using SWMM as a Tool for Hydrologic Impact Assessment. *Desalination*. 212: 344-356.

Kazezyilmaz-Alhan, C.M. and M.A. Medina, Jr. 2007. Kinematic and Diffusion Waves: Analytical and Numerical Solutions to Overland and Channel Flow. *Journal of Hydraulic Engineering*. 133(2): 217-228.

Kazezyilmaz-Alhan, C.M., and M.A. Medina, Jr. 2008. The Effect of Surface/Ground Water Interactions on Wetland Sites with Different Characteristics. *Desalination*. 226:298-305.

Kazezyilmaz-Alhan, C.M., M.A. Medina, Jr., and C.J. Richardson. 2007. A Wetland Hydrology and Water Quality Model Incorporating Surface Water/Groundwater Interactions. *Water Resources Research*. 43(W04434): 1-16.

Keeland, B.D., J.F. Dowd, and W.S. Hardegree. 1997. Use of Inexpensive Pressure Transducers for Measuring Water Levels in Wells. *Wetlands Ecology and Management*. 5: 121-129.

Kentula, M.E., S.E. Gwin, and S.M. Pierson. 2004. Tracking Changes in Wetlands with Urbanization: Sixteen Years of Experience in Portland, Oregon, USA. *Wetlands*. 24(4):734-743.

Kim, N.W., I.M. Chung, Y.S. Won, and J.G. Arnold. 2008. Development and Application of the Integrated SWAT-MODFLOW Model. *Journal of Hydrology*. 356: 1-16.

Kiviat, E. and K. MacDonald. 2004. Biodiversity Patterns and Conservation in the Hackensack Meadowlands, New Jersey. *Urban Habitats*. 2(1):28-61.

Kiviat, E. and K. MacDonald-Beyers. 2006. The Hackensack Meadowlands, a Metropolitan Wildlife Refuge. Meadowlands Conservation Trust. Lyndhurst, NJ.

Kocis, J.M. 1982. The Kearny Freshwater Marsh: The Dynamics of a Young Freshwater Marsh in the Hackensack Meadowlands, a Basin Management Plan. Hackensack Meadowlands Development Commission. Lyndhurst, NJ.

Krause, P., D.P. Boyle, and F. Bäse. 2005. Comparison of Different Efficiency Criteria for Hydrological Model Assessment. *Advances in Geosciences*. 5:89-97.

Krause, S. and A. Bronstert. 2007. The Impact of Groundwater-Surface Water Interactions on the Water Balance of a Mesoscale Lowland River Catchment in Northeastern Germany. *Hydrological Processes*. 21: 169-185.

Kreiser, G.S. 2003. A Wetland Restoration Project: Water Budget and Nutrient Analysis of a Drained Carolina Bay. M.S. Thesis. North Carolina State University, Raleigh, NC, USA.

Kumar, C.P. no date. Groundwater Flow Models. Retrieved September 2005 from, http://www.angelfire.com/nh/cpkumar/publication/flowmodels.pdf.

Kuser, J.E. and G. Zimmermann. 1995. Restoring Atlantic White-Cedar Swamps: Techniques for Propagation and Establishment. *Tree Planters Notes*. 46(3): 78-85.

LaBaugh, J.W. and T.C. Winter. 1984. The Impact of Uncertainties in Hydrologic Measurement on Phosphorus Budgets and Empirical Models for Two Colorado Reservoirs. *Limnology and Oceanography*. 29(2):322-339.

Langan Engineering and Environmental Services, Inc. (Langan). 1999. Sediment and Water Sampling Report: Kearny Marsh, Kearny, New Jersey. Langan. Elmwood Park, NJ.

Lott, R.B. and R.J. Hunt. 2001. Estimating Evapotranspiration in Natural and Constructed Wetlands. *Wetlands*. 21(4): 614-628.

Lu, J., G. Sun, S.G. McNulty, and D.M. Amatya. 2005. A Comparison of Six Potential Evapotranspiration Methods for Regional Use in the Southeastern United States. *Journal of the American Water Resources Association*. 41(3): 621-633.

Mansell, R.S., S.A. Bloom, and G. Sun. 2000. A Model for Wetland Hydrology: Description and Validation. *Soil Science*. 165(5): 384-397.

Mansoor, N. and L. Slater. 2007. Aquatic Electrical Resistivity Imaging of Shallow-Water Wetlands. *Geophysics*. 72(5): F211-F221.

Mansoor, N., L. Slater, F. Artigas, and E. Auken. 2006. Case History: High-Resolution Geophysical Characterization of Shallow-Water Wetlands. *Geophysics*. 71(4): B101-B109.

Marshall, S. 2004. The Meadowlands Before the Commission: Three Centuries of Human Use and Alterations of the Newark and Hackensack Meadowlands. *Urban Habitats*. 2(1): 4-27.

Marsh-McBirney, Inc. 1990. Flo-Mate Model 2000 Portable Flowmeter Instruction Manual. Marsh-McBirney, Inc. Frederick, MD.

Matthews, J.W. and A.G. Endress. 2008. Performance Criteria, Compliance Success, and Vegetation Development in Compensatory Mitigation Wetlands. *Environmental Management*. 41:130-141.

McCuen, R.H., Z. Knight, and A.G. Cutter. 2006. Evaluation of the Nash-Sutcliffe Efficiency Index. *Journal of Hydrologic Engineering*. 11(6):597-602.

Minkin, P. and R. Ladd. 2003. Success of Corps-Required Wetland Mitigation in New England. U.S. Army Corps of Engineers; New England District.

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

Montalto, F.A. and T.S. Steenhuis. 2004. The Link Between Hydrology and Restoration of Tidal Marshes in the New York/New Jersey Estuary. *Wetlands*. 24(2):414-425.

Morgan, K.L. and T.H. Roberts. 2003. Characterization of Wetland Mitigation Projects in Tennessee, USA. *Wetlands*. 23(1):65-69.

Moriasi, D.N., J.G. Arnold, M.W. Van Liew, R.L. Bingner, R.D. Harmel, and T.L. Veith. 2007. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Transactions of the American Society of Agricultural and Biological Engineers*. 50(3): 885-900.

National Research Council. 1995. *Wetlands: Characteristics and Boundaries*. National Academy Press. Washington, DC.

Neglia Engineering Associates (Neglia). 2001. Storm Water Evaluation Drainage Study. Neglia. Lyndhurst, NJ.

New Jersey Department of Environmental Protection (NJDEP). 2002. Creating Indicators of Wetland Status (Quantity and Quality): Freshwater Wetland Mitigation in New Jersey. New Jersey Department of Environmental Protection, Division of Science, Research, & Technology. Trenton, NJ.

New Jersey Meadowlands Commission (NJMC). 2005. Hackensack Meadowlands Floodplain Management Plan (DRAFT). New Jersey Meadowlands Commission. Lyndhurst, NJ.

New Jersey Meadowlands Commission (NJMC). 2004. Master Plan. Retrieved May 9, 2008, from http://www.meadowlands.state.nj.us/about/NJMC%20Doc%20Archive/NJMC%20Master%20Plan.pdf.

Niemczynowicz, J. 1999. Urban Hydrology and Water Management – Present and Future Challenges. *Urban Water*. 1:1-14.

Obropta, C., P. Kallin., M. Mak, and B. Ravit. 2008. Modeling Urban Wetland Hydrology for the Restoration of a Forested Riparian Wetland Ecosystem. *Urban Habitats*. 5(1): 183-198.

Obropta, C.C. and J.S. Kardos. 2007. Review of Urban Stormwater Quality Models: Deterministic, Stochastic, and Hybrid Approaches. *Journal of the American Water Resources Association*. 43(6): 1508-1523.

Opdyke, S.M. and J.C. Evans. 2005. Slag-Cement-Bentonite Slurry Walls. *Journal of Geotechnical and Geoenvironmental Engineering*. 131(6): 673-681.

Owen, C.R. 1995. Water Budget and Flow Patterns in an Urban Wetland. *Journal of Hydrology*. 169: 171-187.

Pati, S. 2006. Effects of Subsurface Flows on Wetland Restoration at Juniper Bay and Surrounding Area. Ph.D. Dissertation. North Carolina State University. Raleigh, NC.

Pereira, A.R. and W.O. Pruitt. 2004. Adaptation of the Thornthwaite Scheme for Estimating Daily Reference Evapotranspiration. *Agricultural Water Management*. 66: 251-257.

Perkins, D.F. 1999. Use and Construction of a Lysimeter to Measure Evapotranspiration. http://www.llansadwrn-wx.co.uk/lysim.html.

Prueger, J.H., J.L. Hatfield, J.K. Aase, and J.L. Pikul, Jr. 1997. Bowen-Ratio Comparisons with Lysimeter Evapotranspiration. *Agronomy Journal*. 89(5): 730-736.

Pucci, Jr., A.A. and D.A. Pope. 1995. Simulated Effects of Development on Regional Ground-Water/Surface-Water Interactions in the Northern Coastal Plain of New Jersey. *Journal of Hydrology*. 167: 241-262.

Raisin, G., J. Bartley, and R. Croome. 1999. Groundwater Influence on the Water Balance and Nutrient Budget of a Small Natural Wetland in Northeastern Victoria, Australia. *Ecological Engineering*. 12:133-147.

Rana, G. and N. Katerji. 2000. Measurement and Estimation of Actual Evapotranspiration in the Filed Under Mediterranean Climate: A Review. *European Journal of Agronomy*. 13: 125-153.

Reilly, T.E. 2001. System and Boundary Conceptualization in Ground-Water Flow Simulation. U.S. Geological Survey. Reston, VA. Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 3, Application of Hydraulics, Chapter B8.

Reinelt, L.E. and R.R. Horner. 1995. Pollutant Removal from Stormwater Runoff by Palustrine Wetlands Based on Comprehensive Budgets. *Ecological Engineering*. 4:77-97.

Restrepo, J.I., A.M. Montoya, and J. Obeysekera. 1998. A Wetland Simulation Module for the MODFLOW Ground Water Model. *Ground Water*. 36(5): 764-770.

Restrepo, J.I., D.G.A. Montoya, N. Restrepo, and J. Giddings. 2006. Simulation of Water Levels and Water Diversions in a Subtropical Coastal Wetland. *Journal of Coastal Research*. 22(1): 339-349.

Rice, D., J. Rooth, and J.C. Stevenson. 2000. Colonization and Expansion of Phragmites australis in Upper Chesapeake Bay Tidal Marshes. *Wetlands*. 20(2): 280-299.

Rose, S. and N.E. Peters. 2001. Effects of Urbanization on Streamflow in the Atlanta area (Georgia, USA): A Comparative Approach. *Hydrologic Processes*. 15:1441-1457.

Rosenberry, D.O., D.I. Stannard, T.C. Winter, and M.L. Martinez. 2004. Comparison of 13 Equations for Determining Evapotranspiration from a Prairie Wetland, Cottonwood Lake Area, North Dakota, USA. *Wetlands*. 24(3): 483-497.

Rosenberry, D.O., T.C. Winter, D.C. Buso, and G.E. Likens. 2007. Comparison of 15 Evaporation Methods Applied to a Small Mountain Lake in the Northeastern USA. *Journal of Hydrology*. 340: 149-166.

Rossman, L.A. 2005. Storm Water Management Model User's Manual Version 5.0. U.S. Environmental Protection Agency, Office of Research and Development. Cincinnati, OH. EPA/600/R-05/040.

Rowan, A.T. 2001. Development of the Multiple Model Broker, a System Integrating Stormwater and Groundwater Models of Different Spatial and Temporal Scales Using Embedded GIS Functionality. Ph.D. Dissertation. Rutgers, The State University of New Jersey, New Brunswick, NJ, USA.

Sample, D.J. and J.P. Heaney. 2006. Integrated Management of Irrigation and Urban Storm-Water Infiltration. *Journal of Water Resources Planning and Management*. 132(5): 362-373.

Schaefli, B. and H.V. Gupta. 2007. Do Nash Values Have Value? *Hydrological Processes*. 21:2075-2080.

Schnoor, J.L. 1996. *Environmental Modeling: Fate and Transport of Pollutants in Water, Air, and Soil*. John Wiley & Sons, Inc., New York, NY.

Schot, P. and T. Winter. 2006. Preface: Groundwater-Surface Water Interactions in Wetlands for Integrated Water Resources Management. *Journal of Hydrology*. 320: 261-263.

Shaw, E.M. 1994. *Hydrology in Practice, 3rd edition*. Chapman & Hall, London, England.

Shirinian-Orlando, A.A. and C.G. Uchrin. 2007. Modeling the Hydrology and Water Quality Using BASINS/HSPF for the Upper Maurice Watershed, New Jersey. *Journal of Environmental Science & Health, Part A: Toxic/Hazardous Substances & Environmental Engineering*. 42: 289-303.

Shoemaker, W.B., S. Huddleston, C.L. Boudreau, and A.M. O'Reilly. 2008. Sensitivity of Wetland Saturated Hydraulic Heads and Water Budgets to Evapotranspiration. *Wetlands*. 28(4): 1040-1047.

Skaggs, R.W. 1980. Methods for Design and Evaluation of Drainage-Water Management Systems for Soils with High Water Tables. U.S. Department of Agriculture Soil Conservation Service, South National Technical Center. Fort Worth, TX.

Sophocleous, M. 2002. Interactions Between Groundwater and Surface Water: The State of the Science. *Hydrogeology Journal*. 10: 52-67.

Sophocleous, M. and S.P. Perkins. 2000. Methodology and Application of Combined Watershed and Ground-Water Models in Kansas. *Journal of Hydrology*. 236: 185-201.

Sophocleous, M.A., J.K. Koelliker, R.S. Govindaraju, T. Birdie, S.R. Ramireddygari, and S.P. Perkins. 1999. Integrated Numerical Modeling for Basin-Wide Water Management: The Case of the Rattlesnake Creek Basin in South-Central Kansas. *Journal of Hydrology*. 214: 179-196.

Stewart, L.K., P.F. Hudak, and R.D. Doyle. 1998. Modeling Hydrologic Alterations to a Developing Wetland in an Abandoned Borrow Pit. *Journal of Environmental Management*. 53: 231-239.

Sun, G., H. Riekerk, and N.B. Comerford. 1998a. Modeling the Forest Hydrology of Wetland-Upland Ecosystems in Florida. *Journal of the American Water Resources Association*. 34(4): 827-841.

Sun, G., H. Riekerk, and N.B. Comerford. 1998b. Modeling the Hydrologic Impacts of Forest Harvesting on Florida Flatwoods. *Journal of the American Water Resources Association*. 34(4): 843-854.

Sun, G., S.G. McNulty, D.M. Amatya, R.W. Skaggs, L.W. Swift Jr., J.P. Shepard, and H. Riekerk. 2002. A Comparison of the Watershed Hydrology of Coastal Forested Wetlands and the Mountainous Uplands in the Southern US. *Journal of Hydrology*. 263:92-104.

Sun, G., T.J. Callahan, J.E. Pyzola, and C.C. Trettin. 2006. Modeling the Climatic and Subsurface Stratigraphy Controls on the Hydrology of a Carolina Bay Wetland in South Carolina, USA. *Wetlands*. 26(2): 567-580.

Tan, S.B.K., E.B. Shuy, and L.H.C. Chua. 2007. Modelling Hourly and Daily Open-Water Evaporation Rates in Areas with an Equatorial Climate. *Hydrological Processes*. 21: 486-499.

Tanner, B.D. 1988. Use Requirements for Bowen Ratio and Eddy Correlation Determination of Evapotranspiration, in Specialty Conference of the Irrigation and Drainage Division, Lincoln, NE. July 19–21, 1988. Proceedings: New York, American Society of Civil Engineers.

Thornthwaite, C.W. 1948. An Approach Toward a Rational Classification of Climate. *Geographical Review*. 38(1): 55-94.

Tiner, R.W. J.Q. Swords, and B.J. McClain. 2002. Wetland Status and Trends for the Hackensack Meadowlands. An Assessment Report from the U.S. Fish and Wildlife Service's National Wetlands Inventory Program. U.S. Fish and Wildlife Service, Northeast Region. Hadley, MA. 29 pp.

Tsihrintzis, V.A. and R. Hamid. 1997. Modeling and Management of Urban Stormwater Runoff Quality: A Review. *Water Resources Management*. 11: 137-164.

Tsihrintzis, V.A. and R. Hamid. 1998. Runoff Quality Prediction from Small Urban Catchments Using SWMM. *Hydrological Processes*. 12: 311-329.

Tsihrintzis, V.A., D.L. John, and P.J. Tremblay. 1998. Hydrodynamic Modeling of Wetlands for Flood Detention. *Water Resources Management*. 12: 251-269.

Twilley, R.R. and R. Chen. 1998. A Water Budget and Hydrology Model of a Basin Mangrove Forest in Rookery Bay, Florida. *Marine and Freshwater Research*. 1998. 49:309-323.

United States Army Corps of Engineers. 1987. Corps of Engineers Wetlands Delineation Manual. Wetlands Research Program Technical Report Y-87-1. USACE Waterways Experiment Station, Vicksburg, MS.

United States Army Corps of Engineers, South Florida Water Management District, and Kimley-Horn and Associates, Inc. 2002. B.2 Hydraulics Final Model Evaluation Report, EAA Storage Reservoirs – Phase 1. Comprehensive Everglades Restoration Plan.

van der Kamp, G. 2001. Methods for Determining the In Situ Hydraulic Conductivity of Shallow Aquitards – An Overview. *Hydrogeology Journal*. 9: 5-16.

Vepraskas, M.J., R.L. Huffman, and G.S. Kreiser. 2006. Hydrologic Models for Altered Landscapes. *Geoderma*. 131:287-298.

Villagra, M.M., O.O.S. Bacchi, R.L. Tuon, and K. Reichardt. 1995. Difficulties of Estimating Evapotranspiration from the Water Balance Equation. *Agricultural and Forest Meteorology*. 72: 317-325.

Waddington, J.M. and N.T. Roulet. 1997. Groundwater Flow and Dissolved Carbon Movement in a Boreal Peatland. *Journal of Hydrology*. 191: 122-138.

Warwick, J.J. and P. Tadepalli. 1991. Efficacy of SWMM Applications. *Journal of Water Resources Planning and Management*. 117(3): 352-366.

Watson, V.J., O.L. Loucks, and W. Wojner. 1981. The Impacts of Urbanization on Seasonal Hydrologic and Nutrient Budgets of a Small North American Watershed. *Hydrobiologica*. 77:87-96.

Weis, J.S., J. Skurnick, and P. Weis. 2004. Studies of a Contaminated Brackish Marsh in the Hackensack Meadowlands of Northeastern New Jersey: Benthic Communities and Metal Contamination. *Marine Pollution Bulletin*. 49:1025-1035.

Willmott, C.J. 1982. Some Comments on the Evaluation of Model Performance. *Bulletin of the American Meteorological Society*. 63(11):1309-1313.

Wilsnack, M.M., D.E. Welter, A.M. Montoya, J.I. Restrepo, and J. Obeysekera. 2001. Simulating Flow in Regional Wetlands with the MODFLOW Wetlands Package. *Journal of the American Water Resources Association*. 37(3): 655-674.

Winston, R.B. 1996. Design of an Urban, Ground-Water Dominated Wetland. *Wetlands*. 16(4): 524-531.

Winter, T.C. 1981. Uncertainties in Estimating the Water Balance of Lakes. *Water Resources Bulletin*. 17:82-115.

Winter, T.C. 1999. Relation of Streams, Lakes, and Wetlands to Groundwater Flow Systems. *Hydrogeology Journal*. 7: 28-45.

Xiong, Y. and C.S. Melching. 2005. Comparison of Kinematic-Wave and Nonlinear Reservoir Routing of Urban Watershed Runoff. *Journal of Hydrologic Engineering*. 10(1): 39-49.

Xu, C.-Y. and V.P. Singh. 2001. Evaluation and Generalization of Temperature-Based Methods for Calculating Evaporation. *Hydrological Processes*. 15: 305-319.

Yan, J and K.R. Smith. 1994. Simulation of Integrated Surface Water and Ground Water Systems – Model Formulation. *Water Resources Bulletin*. 30(5): 879-890.

Zhang, L. and W.J. Mitsch. 2005. Modelling Hydrologic Processes in Created Freshwater Wetlands: An Integrated System Approach. *Environmental Modelling & Software*. 20:935-946.

Zoppou, C. 2001. Review of Urban Storm Water Models. *Environmental Modelling & Software*. 16: 195-231.

APPENDIX A: SWMM Reports

```
EPA STORM WATER MANAGEMENT MODEL - VERSION 5.0 (Build 5.0.005b)
---------------------------------------------------------------


****************
Analysis Options
****************
Flow Units ............... CFS
Infiltration Method ...... GREEN_AMPT
Flow Routing Method ...... DYNWAVE
Starting Date ............ JAN-01-2006 00:00:00
Ending Date .............. JAN-01-2007 00:00:00
Report Time Step ......... 00:15:00
Wet Time Step ............ 00:15:00
Dry Time Step ............ 00:15:00
Routing Time Step ........ 30.00 sec


*************
Element Count
*************
Number of rain gages ...... 1
Number of subcatchments ... 7
Number of nodes ........... 18
Number of links ........... 18
Number of pollutants ...... 0
Number of land uses ....... 5


***************
Landuse Summary
***************
                      Sweeping   Maximum      Last
Name                  Interval   Removal     Swept
---------------------------------------------------
Developed/Urban           0.00      0.00      0.00
Wetlands                  0.00      0.00      0.00
Forest                    0.00      0.00      0.00
BarrenLand                0.00      0.00      0.00
Water                     0.00      0.00      0.00


****************
Raingage Summary
****************
                                          Data        Interval
Name                Data Source           Type          hours
--------------------------------------------------------------
KMStormGage         2006HourlyPpt         VOLUME         1.00


********************
Subcatchment Summary
********************
Name                          Area     Width   %Imperv    %Slope    Rain Gage
-----------------------------------------------------------------------------
BellevilleTpk                40.36   1909.00     25.42    0.0005    KMStormGage
BergenAvenue                 95.99   1384.32     45.22    3.4500    KMStormGage
DeadHorseCreek              108.42   1491.30     50.94    3.9200    KMStormGage
FranksCreek                 318.06   2101.11     42.64    0.4700    KMStormGage
GunnelOval                  186.83   2396.16     49.43    0.0005    KMStormGage
HarrisonAvenue              364.45   4126.08     63.76    2.4800    KMStormGage
KearnyMarsh                 456.07   4264.56      2.48    0.2900    KMStormGage


************
Node Summary
************
Name                Type                Invert     Depth
--------------------------------------------------------
BTOutlet            JUNCTION              1.27      4.25
DHCulvertA          JUNCTION             -2.00     15.00
DHHeadwater         JUNCTION             -2.00     15.00
FCBulkhead          JUNCTION              0.24     15.50
```

FCCulvertC	JUNCTION	1.23	15.00
FCCulvertD	JUNCTION	0.74	15.00
FCDHConfluence	JUNCTION	0.74	15.00
FCHeadwater	JUNCTION	3.00	15.00
FCKeeganCulvA	JUNCTION	0.97	15.00
FCKeeganCulvB	JUNCTION	0.74	15.00
FCRailroadCulv	JUNCTION	1.00	15.00
GOOutlet	JUNCTION	-0.71	3.50
HAFCConfluence	JUNCTION	0.74	15.00
HAHeadwater	JUNCTION	1.23	15.00
KMOutlet	JUNCTION	-0.55	15.00
KMtoFC	JUNCTION	0.00	15.00
PassaicOutfall	OUTFALL	-2.54	15.00
KMWetland	STORAGE	0.00	15.00

****
Link Summary
****

Name	From Node	To Node	Type	Length	%Slope	N
BTtoKM	BTOutlet	KMWetland	CONDUIT	87	2.9011	0.0170
DHStreamSeg1	DHHeadwater	DHCulvertA	CONDUIT	717	0.0001	0.0110
DHStreamSeg2	FCDHConfluence	DHCulvertA	CONDUIT	336	0.8144	0.0110
FC&DHSegment	FCCulvertC	FCDHConfluence	CONDUIT	157	0.3111	0.0110
FCStreamSeg1A	FCHeadwater	FCRailroadCulv	CONDUIT	724	0.2762	15.0000
FCStreamSeg1B	FCRailroadCulv	FCBulkhead	CONDUIT	237	0.3209	15.0000
FCStreamSeg2	FCKeeganCulvA	FCBulkhead	CONDUIT	766	0.0300	0.0110
FCStreamSeg3	FCKeeganCulvA	FCKeeganCulvB	CONDUIT	1149	0.0200	0.0110
FCStreamSeg4	FCKeeganCulvB	FCDHConfluence	CONDUIT	331	0.0003	0.0110
FCStreamSeg6	FCCulvertC	FCCulvertD	CONDUIT	650	0.0754	0.0110
FCStreamSeg7	FCCulvertD	HAFCConfluence	CONDUIT	2162	0.0000	0.0100
FCStreamSeg8	HAFCConfluence	PassaicOutfall	CONDUIT	1203	0.2727	0.0130
GOtoKMWetland	KMWetland	GOOutlet	CONDUIT	212	0.0972	0.0170
HAStreamSeg1	HAHeadwater	HAFCConfluence	CONDUIT	944	0.0519	0.0130
KMStreamSeg1	FCCulvertC	KMOutlet	CONDUIT	1297	0.1369	0.0750
KMtoFCSegment	FCBulkhead	KMtoFC	CONDUIT	708	0.0339	1.5000
FCOutlet	KMWetland	KMtoFC	OUTLET			
PassaicOutlet	KMWetland	KMOutlet	OUTLET			

****
Cross Section Summary
****

Conduit	Shape	Full Depth	Full Area	Hyd. Rad.	Max. Width	Full Flow
BTtoKM	RECT_CLOSED	3.00	16.71	0.97	5.57	244.61
DHStreamSeg1	TRAPEZOIDAL	15.00	1050.00	9.81	100.00	767.24
DHStreamSeg2	TRAPEZOIDAL	15.00	1050.00	9.81	100.00	58641.59
FC&DHSegment	RECT_OPEN	15.00	120.00	3.16	8.00	1946.28
FCStreamSeg1A	RECT_OPEN	15.00	165.00	4.02	11.00	2.17
FCStreamSeg1B	RECT_CLOSED	8.00	88.00	2.32	11.00	0.86
FCStreamSeg2	RECT_OPEN	15.00	165.00	4.02	11.00	977.45
FCStreamSeg3	RECT_OPEN	15.00	165.00	4.02	11.00	797.88
FCStreamSeg4	RECT_OPEN	11.00	121.00	3.67	11.00	67.54
FCStreamSeg6	TRAPEZOIDAL	15.00	750.00	8.61	80.00	11688.10
FCStreamSeg7	TRAPEZOIDAL	15.00	750.00	8.61	80.00	318.45
FCStreamSeg8	TRAPEZOIDAL	15.00	750.00	8.61	80.00	18809.01
GOtoKMWetland	CIRCULAR	3.00	7.07	0.75	3.00	15.90
HAStreamSeg1	TRAPEZOIDAL	15.00	750.00	8.61	80.00	8204.62
KMStreamSeg1	RECT_OPEN	15.00	120.00	3.16	8.00	189.38
KMtoFCSegment	RECT_OPEN	15.00	225.00	5.00	15.00	12.00

****
Transect Summary
****

Transect KM2SeptFlows
Area:

0.0008	0.0032	0.0073	0.0130	0.0227
0.0373	0.0567	0.0818	0.1126	0.1483
0.1856	0.2240	0.2727	0.3263	0.3831
0.4419	0.5013	0.5614	0.6221	0.6834

```
            0.7455     0.8081     0.8714     0.9354     1.0000
Hrad:
            0.0325     0.0651     0.0976     0.1302     0.1179
            0.1555     0.1869     0.2190     0.2494     0.2682
            0.3251     0.3287     0.3521     0.3971     0.4409
            0.5009     0.5600     0.6180     0.6751     0.7313
            0.7867     0.8412     0.8949     0.9478     1.0000
Width:
            0.0250     0.0500     0.0750     0.1000     0.2000
            0.2500     0.3452     0.4305     0.5157     0.5667
            0.5833     0.7000     0.8000     0.8500     0.9000
            0.9100     0.9200     0.9300     0.9400     0.9500
            0.9600     0.9700     0.9800     0.9900     1.0000


**************************        Volume         Depth
Runoff Quantity Continuity     acre-feet        inches
**************************     ---------       -------
Total Precipitation ......      6355.315        48.570
Evaporation Loss .........      1551.168        11.855
Infiltration Loss ........      2421.233        18.504
Surface Runoff ...........      2391.105        18.274
Final Surface Storage ....         0.000         0.000
Continuity Error (%) .....        -0.129


**************************        Volume        Volume
Flow Routing Continuity        acre-feet      Mgallons
**************************     ---------     ---------
Dry Weather Inflow .......         0.000         0.000
Wet Weather Inflow .......      2391.760       779.391
Groundwater Inflow .......         0.000         0.000
RDII Inflow ..............         0.000         0.000
External Inflow ..........         0.000         0.000
External Outflow .........      1976.954       644.220
Surface Flooding .........       436.790       142.335
Evaporation Loss .........         0.000         0.000
Initial Stored Volume ....       118.730        38.690
Final Stored Volume ......        84.310        27.474
Continuity Error (%) .....         0.495


***************************
Subcatchment Runoff Summary
***************************

-----------------------------------------------------------------------------
                      Total      Total      Total      Total      Total    Runoff
                     Precip      Runon       Evap      Infil     Runoff     Coeff
Subcatchment             in         in         in         in         in
-----------------------------------------------------------------------------
BellevilleTpk        48.570      0.000      6.452     32.161      9.969     0.205
BergenAvenue         48.570      0.000      7.997     10.454     30.264     0.623
DeadHorseCreek       48.570      0.000      7.971      9.291     31.461     0.648
FranksCreek          48.570      0.000     10.263     13.365     24.988     0.514
GunnelOval           48.570      0.000     41.205      5.257      2.113     0.044
HarrisonAvenue       48.570      0.000      8.510      6.936     33.256     0.685
KearnyMarsh          48.570      0.000      5.829     39.435      3.316     0.068
-----------------------------------------------------------------------------
Totals               48.570      0.000     11.855     18.504     18.274     0.376


******************
Node Depth Summary
******************

------------------------------------------------------------------------------
                 Average  Maximum  Maximum  Time of Max    Total    Total
                   Depth    Depth      HGL   Occurrence  Flooding  Minutes
Node                Feet     Feet     Feet  days hr:min   in/acre  Flooded
------------------------------------------------------------------------------
BTOutlet            1.25     1.67     2.94   201  16:00         0        0
DHCulvertA          3.26     7.26     5.26   201  16:03         0        0
DHHeadwater         3.26     7.27     5.27   201  16:03         0        0
FCBulkhead          1.10     5.08     5.32   201  16:00         0        0
```

FCCulvertC	0.09	3.54	4.77	201	16:05	0	0
FCCulvertD	0.23	3.98	4.72	201	16:05	0	0
FCDHConfluence	0.59	4.50	5.24	201	16:02	0	0
FCHeadwater	2.31	15.00	18.00	13	18:55	5241.26	25000
FCKeeganCulvA	0.37	4.34	5.31	201	16:00	0	0
FCKeeganCulvB	0.59	4.52	5.26	201	16:01	0	0
FCRailroadCulv	2.27	14.74	15.74	154	01:00	0	0
GOOutlet	2.61	3.50	2.79	0	00:00	0.13	1
HAFCConfluence	0.15	3.98	4.72	42	07:59	0	0
HAHeadwater	0.06	4.22	5.45	201	16:00	0	0
KMOutlet	1.87	5.33	4.78	201	16:05	0	0
KMtoFC	1.52	4.28	4.28	201	16:32	0	0
PassaicOutfall	2.65	7.79	5.25	30	09:59	0	0
KMWetland	1.91	2.43	2.43	313	04:46	0	0

****
Conduit Flow Summary
****

Conduit	Maximum Flow CFS	Time of Max Occurrence days	hr:min	Maximum Velocity ft/sec	Length Factor	Maximum /Design Flow	Total Minutes Surcharged
BTtoKM	17.71	201	16:00	3.04	1.00	0.07	0
DHStreamSeg1	224.23	201	15:57	0.58	1.00	0.29	0
DHStreamSeg2	401.34	201	15:56	1.35	1.00	0.01	0
FC&DHSegment	380.81	201	16:02	11.88	1.00	0.20	0
FCStreamSeg1A	3.36	22	10:11	0.03	1.00	1.54	32823
FCStreamSeg1B	2.61	300	12:56	0.04	1.00	3.02	68506
FCStreamSeg2	34.77	201	15:22	2.16	1.00	0.04	0
FCStreamSeg3	61.64	201	15:24	2.86	1.00	0.08	0
FCStreamSeg4	71.67	201	15:25	2.81	1.00	1.06	5
FCStreamSeg6	373.12	201	16:03	4.21	1.00	0.03	0
FCStreamSeg7	384.50	201	16:09	3.93	1.00	1.21	30
FCStreamSeg8	1131.87	201	16:01	8.94	1.00	0.06	0
GOtoKMWetland	21.24	0	00:00	3.81	1.00	1.34	1
HAStreamSeg1	790.59	201	16:00	7.70	1.00	0.10	0
KMStreamSeg1	14.55	201	15:35	0.62	1.00	0.08	0
KMtoFCSegment	6.48	201	15:59	0.11	1.00	0.54	0

****
Flow Classification Summary
****

	--- Fraction of Time in Flow Class ----								
Conduit	Dry	Up Dry	Down Dry	Sub Crit	Sup Crit	Up Crit	Down Crit	Avg. Froude Number	Avg. Flow Change
BTtoKM	0.00	0.83	0.00	0.17	0.00	0.00	0.00	0.00	0.0000
DHStreamSeg1	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.0000
DHStreamSeg2	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.0000
FC&DHSegment	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.07	0.0000
FCStreamSeg1A	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.0001
FCStreamSeg1B	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.0002
FCStreamSeg2	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.02	0.0000
FCStreamSeg3	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.03	0.0000
FCStreamSeg4	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.02	0.0001
FCStreamSeg6	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.06	0.0000
FCStreamSeg7	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.05	0.0000
FCStreamSeg8	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.03	0.0000
GOtoKMWetland	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.0000
HAStreamSeg1	0.00	0.56	0.00	0.44	0.00	0.00	0.00	0.02	0.0000
KMStreamSeg1	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.0000
KMtoFCSegment	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.0000

****
Highest Continuity Errors
****

Node KMWetland (2.77%)
Node FCCulvertD (0.13%)

```
Node HAFCConfluence (0.12%)
Node FCBulkhead (0.05%)
Node FCKeeganCulvB (0.03%)


***************************
Time-Step Critical Elements
***************************
Link FC&DHSegment (0.28%)
Link FCStreamSeg4 (0.21%)
Link GOtoKMWetland (0.00%)
Node GOOutlet (0.00%)


*************************
Routing Time Step Summary
*************************
Minimum Time Step           :     1.22 sec
Average Time Step           :    29.93 sec
Maximum Time Step           :    30.00 sec
Percent in Steady State     :     0.00
Average Iterations per Step :     2.00


Analysis begun on:  Tue Jun 09 11:26:51 2009
Total elapsed time: 00:01:28
```

```
EPA STORM WATER MANAGEMENT MODEL - VERSION 5.0 (Build 5.0.005b)
---------------------------------------------------------------


****************
Analysis Options
****************
Flow Units ............... CFS
Infiltration Method ...... GREEN_AMPT
Flow Routing Method ...... DYNWAVE
Starting Date ............ JAN-01-2007 00:00:00
Ending Date .............. JAN-01-2008 00:00:00
Report Time Step ......... 00:15:00
Wet Time Step ............ 00:15:00
Dry Time Step ............ 00:15:00
Routing Time Step ........ 30.00 sec


*************
Element Count
*************
Number of rain gages ...... 1
Number of subcatchments ... 7
Number of nodes ........... 18
Number of links ........... 18
Number of pollutants ...... 0
Number of land uses ....... 5


***************
Landuse Summary
***************
                      Sweeping   Maximum      Last
Name                  Interval   Removal     Swept
--------------------------------------------------
Developed/Urban           0.00      0.00      0.00
Wetlands                  0.00      0.00      0.00
Forest                    0.00      0.00      0.00
BarrenLand                0.00      0.00      0.00
Water                     0.00      0.00      0.00


****************
Raingage Summary
****************
                                        Data        Interval
Name                Data Source         Type           hours
------------------------------------------------------------
KMStormGage         2007HourlyPpt       VOLUME          1.00


********************
Subcatchment Summary
********************
Name                          Area     Width   %Imperv    %Slope    Rain Gage
-----------------------------------------------------------------------------
BellevilleTpk                40.36   1909.00     25.42    0.0005    KMStormGage
BergenAvenue                 95.99   1384.32     45.22    3.4500    KMStormGage
DeadHorseCreek              108.42   1491.30     50.94    3.9200    KMStormGage
FranksCreek                 318.06   2101.11     42.64    0.4700    KMStormGage
GunnelOval                  186.83   2396.16     49.43    0.0005    KMStormGage
HarrisonAvenue              364.45   4126.08     63.76    2.4800    KMStormGage
KearnyMarsh                 456.07   4264.56      2.48    0.2900    KMStormGage


************
Node Summary
************
Name                Type                Invert     Depth
--------------------------------------------------------
BTOutlet            JUNCTION              1.27      4.25
DHCulvertA          JUNCTION             -2.00     15.00
DHHeadwater         JUNCTION             -2.00     15.00
FCBulkhead          JUNCTION              0.24     15.50
```

FCCulvertC	JUNCTION	1.23	15.00
FCCulvertD	JUNCTION	0.74	15.00
FCDHConfluence	JUNCTION	0.74	15.00
FCHeadwater	JUNCTION	3.00	15.00
FCKeeganCulvA	JUNCTION	0.97	15.00
FCKeeganCulvB	JUNCTION	0.74	15.00
FCRailroadCulv	JUNCTION	1.00	15.00
GOOutlet	JUNCTION	-0.71	3.50
HAFCConfluence	JUNCTION	0.74	15.00
HAHeadwater	JUNCTION	1.23	15.00
KMOutlet	JUNCTION	-0.55	15.00
KMtoFC	JUNCTION	0.00	15.00
PassaicOutfall	OUTFALL	-2.54	15.00
KMWetland	STORAGE	0.00	15.00

****
Link Summary
****

Name	From Node	To Node	Type	Length	%Slope	N
BTtoKM	BTOutlet	KMWetland	CONDUIT	87	2.9011	0.0170
DHStreamSeg1	DHHeadwater	DHCulvertA	CONDUIT	717	0.0001	0.0110
DHStreamSeg2	FCDHConfluence	DHCulvertA	CONDUIT	336	0.8144	0.0110
FC&DHSegment	FCCulvertC	FCDHConfluence	CONDUIT	157	0.3111	0.0110
FCStreamSeg1A	FCHeadwater	FCRailroadCulv	CONDUIT	724	0.2762	15.0000
FCStreamSeg1B	FCRailroadCulv	FCBulkhead	CONDUIT	237	0.3209	15.0000
FCStreamSeg2	FCKeeganCulvA	FCBulkhead	CONDUIT	766	0.0300	0.0110
FCStreamSeg3	FCKeeganCulvA	FCKeeganCulvB	CONDUIT	1149	0.0200	0.0110
FCStreamSeg4	FCKeeganCulvB	FCDHConfluence	CONDUIT	331	0.0003	0.0110
FCStreamSeg6	FCCulvertC	FCCulvertD	CONDUIT	650	0.0754	0.0110
FCStreamSeg7	FCCulvertD	HAFCConfluence	CONDUIT	2162	0.0000	0.0100
FCStreamSeg8	HAFCConfluence	PassaicOutfall	CONDUIT	1203	0.2727	0.0130
GOtoKMWetland	KMWetland	GOOutlet	CONDUIT	212	0.0972	0.0170
HAStreamSeg1	HAHeadwater	HAFCConfluence	CONDUIT	944	0.0519	0.0130
KMStreamSeg1	FCCulvertC	KMOutlet	CONDUIT	1297	0.1369	0.0750
KMtoFCSegment	FCBulkhead	KMtoFC	CONDUIT	708	0.0339	1.5000
FCOutlet	KMWetland	KMtoFC	OUTLET			
PassaicOutlet	KMWetland	KMOutlet	OUTLET			

****
Cross Section Summary
****

Conduit	Shape	Full Depth	Full Area	Hyd. Rad.	Max. Width	Full Flow
BTtoKM	RECT_CLOSED	3.00	16.71	0.97	5.57	244.61
DHStreamSeg1	TRAPEZOIDAL	15.00	1050.00	9.81	100.00	767.24
DHStreamSeg2	TRAPEZOIDAL	15.00	1050.00	9.81	100.00	58641.59
FC&DHSegment	RECT_OPEN	15.00	120.00	3.16	8.00	1946.28
FCStreamSeg1A	RECT_OPEN	15.00	165.00	4.02	11.00	2.17
FCStreamSeg1B	RECT_CLOSED	8.00	88.00	2.32	11.00	0.86
FCStreamSeg2	RECT_OPEN	15.00	165.00	4.02	11.00	977.45
FCStreamSeg3	RECT_OPEN	15.00	165.00	4.02	11.00	797.88
FCStreamSeg4	RECT_OPEN	11.00	121.00	3.67	11.00	67.54
FCStreamSeg6	TRAPEZOIDAL	15.00	750.00	8.61	80.00	11688.10
FCStreamSeg7	TRAPEZOIDAL	15.00	750.00	8.61	80.00	318.45
FCStreamSeg8	TRAPEZOIDAL	15.00	750.00	8.61	80.00	18809.01
GOtoKMWetland	CIRCULAR	3.00	7.07	0.75	3.00	15.90
HAStreamSeg1	TRAPEZOIDAL	15.00	750.00	8.61	80.00	8204.62
KMStreamSeg1	RECT_OPEN	15.00	120.00	3.16	8.00	189.38
KMtoFCSegment	RECT_OPEN	15.00	225.00	5.00	15.00	12.00

****
Transect Summary
****

Transect KM2SeptFlows
Area:

0.0008	0.0032	0.0073	0.0130	0.0227
0.0373	0.0567	0.0818	0.1126	0.1483
0.1856	0.2240	0.2727	0.3263	0.3831
0.4419	0.5013	0.5614	0.6221	0.6834

```
             0.7455     0.8081     0.8714     0.9354     1.0000
Hrad:
             0.0325     0.0651     0.0976     0.1302     0.1179
             0.1555     0.1869     0.2190     0.2494     0.2682
             0.3251     0.3287     0.3521     0.3971     0.4409
             0.5009     0.5600     0.6180     0.6751     0.7313
             0.7867     0.8412     0.8949     0.9478     1.0000
Width:
             0.0250     0.0500     0.0750     0.1000     0.2000
             0.2500     0.3452     0.4305     0.5157     0.5667
             0.5833     0.7000     0.8000     0.8500     0.9000
             0.9100     0.9200     0.9300     0.9400     0.9500
             0.9600     0.9700     0.9800     0.9900     1.0000


**************************        Volume         Depth
Runoff Quantity Continuity     acre-feet        inches
**************************     ---------       -------
Total Precipitation ......      7107.694        54.320
Evaporation Loss .........      1689.635        12.913
Infiltration Loss ........      2801.106        21.407
Surface Runoff ...........      2560.199        19.566
Final Surface Storage ....        65.595         0.501
Continuity Error (%) .....        -0.124


**************************        Volume        Volume
Flow Routing Continuity        acre-feet      Mgallons
**************************     ---------     ---------
Dry Weather Inflow .......         0.000         0.000
Wet Weather Inflow .......      2560.945       834.522
Groundwater Inflow .......         0.000         0.000
RDII Inflow ..............         0.000         0.000
External Inflow ..........         0.000         0.000
External Outflow .........      2134.884       695.684
Surface Flooding .........       438.785       142.985
Evaporation Loss .........         0.000         0.000
Initial Stored Volume ....        90.764        29.577
Final Stored Volume ......        69.442        22.629
Continuity Error (%) .....         0.324


***************************
Subcatchment Runoff Summary
***************************

----------------------------------------------------------------------------
                       Total      Total      Total      Total      Total     Runoff
                      Precip      Runon       Evap      Infil     Runoff      Coeff
Subcatchment              in         in         in         in         in
----------------------------------------------------------------------------
BellevilleTpk         54.321      0.000      7.044     36.757     10.532      0.194
BergenAvenue          54.321      0.000      8.922     13.453     32.103      0.591
DeadHorseCreek        54.321      0.000      8.980     11.949     33.560      0.618
FranksCreek           54.321      0.000     11.247     16.146     26.975      0.497
GunnelOval            54.321      0.000     44.081      0.710      5.315      0.098
HarrisonAvenue        54.321      0.000      9.748      8.896     35.818      0.659
KearnyMarsh           54.321      0.000      6.130     46.117      2.085      0.038
----------------------------------------------------------------------------
Totals                54.321      0.000     12.913     21.407     19.566      0.360


******************
Node Depth Summary
******************

-----------------------------------------------------------------------------
                    Average    Maximum    Maximum    Time of Max      Total      Total
                      Depth      Depth        HGL     Occurrence   Flooding    Minutes
Node                   Feet       Feet       Feet    days hr:min    in/acre    Flooded
-----------------------------------------------------------------------------
BTOutlet               1.25       1.57       2.84     215  16:00          0          0
DHCulvertA             3.31       6.60       4.60     215  16:05          0          0
DHHeadwater            3.31       6.61       4.61     215  16:06          0          0
FCBulkhead             1.10       4.39       4.63     215  16:09          0          0
```

FCCulvertC	0.09	2.85	4.08	215	16:00	0	0
FCCulvertD	0.23	3.33	4.07	215	16:01	0	0
FCDHConfluence	0.59	3.84	4.58	215	16:05	0	0
FCHeadwater	2.78	15.00	18.00	0	15:11	5265.35	29958
FCKeeganCulvA	0.37	3.65	4.62	215	16:08	0	0
FCKeeganCulvB	0.59	3.86	4.60	215	16:06	0	0
FCRailroadCulv	2.68	14.74	15.74	155	13:10	0	0
GOOutlet	2.74	3.50	2.79	0	00:00	0.11	1
HAFCConfluence	0.13	3.22	3.96	221	18:02	0	0
HAHeadwater	0.06	3.52	4.75	215	16:00	0	0
KMOutlet	1.86	4.66	4.11	215	16:01	0	0
KMtoFC	1.50	3.70	3.70	215	16:42	0	0
PassaicOutfall	2.52	7.88	5.34	105	06:00	0	0
KMWetland	2.04	2.36	2.36	221	21:07	0	0

****
Conduit Flow Summary
****

Conduit	Maximum Flow CFS	Time of Max Occurrence days	hr:min	Maximum Velocity ft/sec	Length Factor	Maximum /Design Flow	Total Minutes Surcharged
BTtoKM	11.34	215	16:00	1.67	1.00	0.05	0
DHStreamSeg1	164.48	215	15:58	0.48	1.00	0.21	0
DHStreamSeg2	286.51	215	15:58	1.11	1.00	0.00	0
FC&DHSegment	271.09	215	15:58	10.32	1.00	0.14	0
FCStreamSeg1A	3.36	47	14:27	0.03	1.00	1.54	40807
FCStreamSeg1B	2.73	154	21:40	0.04	1.00	3.16	85449
FCStreamSeg2	26.30	215	15:25	1.79	1.00	0.03	0
FCStreamSeg3	45.68	215	15:27	2.45	1.00	0.06	0
FCStreamSeg4	53.42	215	15:27	2.40	1.00	0.79	0
FCStreamSeg6	266.76	215	16:11	3.60	1.00	0.02	0
FCStreamSeg7	266.53	215	16:14	3.56	1.00	0.84	0
FCStreamSeg8	794.29	215	16:03	10.40	1.00	0.04	0
GOtoKMWetland	17.53	0	00:00	3.97	1.00	1.10	1
HAStreamSeg1	553.27	215	16:00	6.68	1.00	0.07	0
KMStreamSeg1	10.57	215	15:39	0.60	1.00	0.06	0
KMtoFCSegment	4.78	215	16:06	0.09	1.00	0.40	0

****
Flow Classification Summary
****

	--- Fraction of Time in Flow Class ----							Avg.	Avg.
Conduit	Dry	Up Dry	Down Dry	Sub Crit	Sup Crit	Up Crit	Down Crit	Froude Number	Flow Change
BTtoKM	0.00	0.74	0.00	0.26	0.00	0.00	0.00	0.00	0.0000
DHStreamSeg1	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.0000
DHStreamSeg2	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.0000
FC&DHSegment	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.08	0.0000
FCStreamSeg1A	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.0002
FCStreamSeg1B	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.0002
FCStreamSeg2	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.03	0.0000
FCStreamSeg3	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.03	0.0000
FCStreamSeg4	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.02	0.0001
FCStreamSeg6	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.06	0.0000
FCStreamSeg7	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.06	0.0000
FCStreamSeg8	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.04	0.0000
GOtoKMWetland	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.0000
HAStreamSeg1	0.00	0.42	0.00	0.58	0.00	0.00	0.00	0.03	0.0000
KMStreamSeg1	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.0000
KMtoFCSegment	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.0000

****
Highest Continuity Errors
****

Node KMWetland (2.06%)
Node HAFCConfluence (0.12%)

```
Node FCCulvertD (0.09%)
Node FCBulkhead (0.05%)
Node FCKeeganCulvB (0.03%)


***************************
Time-Step Critical Elements
***************************
Link FCStreamSeg4 (0.13%)
Link FC&DHSegment (0.09%)
Link GOtoKMWetland (0.00%)
Node GOOutlet (0.00%)


*************************
Routing Time Step Summary
*************************
Minimum Time Step           :     3.85 sec
Average Time Step           :    29.98 sec
Maximum Time Step           :    30.00 sec
Percent in Steady State     :     0.00
Average Iterations per Step :     2.00


Analysis begun on:  Thu Jun 11 16:05:30 2009
Total elapsed time: 00:01:18
```

CURRICULUM VITA
STEVEN E. YERGEAU

EDUCATION:

2010	Ph.D. in Environmental Sciences Rutgers, The State University of New Jersey – New Brunswick, NJ
2004	M.S. in Biology Southern Connecticut State University – New Haven, CT
1993	B.S. in Biology University of Massachusetts, Dartmouth – North Dartmouth, MA

EMPLOYMENT:

2005 – 2009	Research Assistant, Graduate Assistant Water Resources Program, Rutgers – New Brunswick, NJ
2008	Lecturer Holy Family University – Philadelphia, PA
1999 – 2005	Senior Watershed Specialist Stony Brook-Millstone Watershed Association – Pennington, NJ
1995 – 1999	Director of Research Save the Sound, Inc. – Stamford, CT
1995	Assistant Director Woodcock Nature Center – Wilton, CT
1995	Environmental Instructor Honey Creek Environmental Education Center – Waverly, GA
1994	Intern Lloyd Center for Environmental Studies – South Dartmouth, MA
1993 – 1994	Quality Assurance Assistant Findley Research, Inc. – Fall River, MA

PUBLICATIONS:

Yergeau, S.E., D.G. Smith, and T. Bosakowski. 2006. *Avian Utilization of Created Wetlands in New Jersey*. New Jersey Birds. 32(3): 61-63.

Yergeau, S. 2004. *Vertebrate Utilization, Emphasizing Birds, of Created Wetlands in New Jersey*. M.S. Thesis. Southern Connecticut State University, New Haven, CT.

Yergeau, S. 2000. *Warm Season Algal Blooms in Four Long Island Sound Harbors*. In: Proceedings of the 1998 Long Island Sound Research Conference. Connecticut Sea Grant, Groton, CT. 15 p.

Yergeau, S. 1998. *Warm Season Algal Populations in Four Long Island Sound Harbors*. In: Proceedings of the National Water Quality Monitoring Council Conference. NWQMC, Oklahoma City, OK. 13 p.

Yergeau, S., A. Lang, and R. Teeters. 1997. *Assessment of Phytoplankton Diversity as an Indicator of Water Quality.* In: Proceedings of the National Association of Environmental Professionals Conference. NAEP, Orlando, FL. 7 p.