



New Jersey
Meadowlands



KEARNY MARSH HYDROLOGY STUDY

*PREPARED BY
RUTGERS UNIVERSITY*

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CONFIDENTIAL



Final Report

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Executive Summary

Background

The New Jersey Meadowlands Commission (NJMC) has determined that remediation and restoration of the 350-acre freshwater Kearny Marsh ecosystem is a high priority. The marsh is located in the Town of Kearny and is included in the New Jersey Meadowlands District. Since the marsh was formed almost forty years ago, it 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). Contamination of the marsh sediments with heavy metals, PAHs, and PCBs has been well documented ([www.erc.rutgers.edu/Kearny Marsh/Publications](http://www.erc.rutgers.edu/Kearny_Marsh/Publications)). The NJMC initiated this study to determine the extent of current contaminant movement into the marsh via surface and groundwater transport.

The two year Kearny Marsh hydrology study was completed in May 2008. The primary goals of this project were to characterize the existing hydrology of the Kearny Marsh, evaluate current transport of contaminants into the marsh from the highly urbanized surrounding land use, to project effects on the marsh hydrology of proposals to redevelop and reuse the site, and to project future marsh water levels under drought and high precipitation conditions. We also utilized the data collected as an aide to provide insight as to the amount and potential source of current pollutant loadings, and to recommend Best Management Practices (BMPs) to reduce existing water quality impairments.

A total of eight sets of groundwater samples and five sets of stormwater samples were collected and analyzed during 2006-2007. Stormwater samples were collected from three input locations: adjacent to the Gunnell Oval ball fields, at the broken Frank's Creek bulkhead, and adjacent to the railroad tracks opposite the 1-E landfill. Groundwater samples were collected from six locations surrounding the marsh perimeter: adjacent to the Gunnell Oval ball fields, on the western boundary of the marsh, adjacent to the Keegan landfill, adjacent to the Town of Kearny landfill, adjacent to the NJ Turnpike exit 15W, and on the northern boundary of the marsh opposite the 1-E landfill.

Water quality parameters (nutrients, dissolved oxygen, temperature, pH, and turbidity) exhibited by both storm and ground waters were characterized and compared to State of NJ water quality standards. Contaminants of concern, including heavy metals, polyaromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and volatile organics that continue to enter the Kearny Marsh were identified, and the annual loading rates of these compounds were estimated through the use of hydrologic models.

Kearny Marsh Hydrologic Models

Hydrologic models describing surface and ground water movements into and through the marsh were developed, calibrated, integrated, and field verified. The USEPA Storm Water Management Model (SWMM) v.5.0 was used to describe surface water flows; the USGS Visual MODFLOW v.4.1 model was used to describe groundwater movement. We integrated the SWMM and MODFLOW models to describe the linkage and interactions between surface water flow and the underlying groundwater system. Using the results of the SWMM and MODFLOW models after calibration and validation, a water budget was developed for this urban system that describes the current hydrologic inputs and outputs of the marsh.

Because very little peer-reviewed literature is available that described the Kearny Marsh groundwater movement, urban water budgets, or hydrologic modeling of urban wetland systems, a number of empirical field measurements were made in an effort to increase the accuracy of our hydrologic models. Groundwater height was determined through the use of pressure transducers placed in one groundwater well in each of the six well clusters. Evapotranspiration (ET) was calculated using the traditional Thornwaithe equation, and then field verified through the installation of lysimeters and through direct field measurement of latent heat fluxes. Our findings confirmed the hypothesis that the Thornwaithe equation underestimates evapotranspiration losses from the Kearny Marsh urban wetland system.

Our data show that although surface water inputs are the main water source for the Kearny Marsh, the system is a discharge wetland, whose water levels are also supported by groundwater that flows in an easterly direction. Groundwater enters the marsh on the western perimeter and flows through the marsh toward the Hackensack River. A broken bulkhead connection between

Frank's Creek and the Kearny Marsh produces a variable water flow, which is under the influence of the Passaic River tidal cycle. When a precipitation event occurs in conjunction with a high tidal cycle, water flows from the creek and into the marsh due to the closure of downstream tide gates. When the tide gates are open, water flows out of Kearny Marsh. Due to the complexity of modeling changes in water flows into and out of the Frank's Creek/Kearny Marsh broken bulkhead, we recommend that further data collection occur at this location to refine the hydrologic model calculations.

The MODFLOW groundwater model is a unique addition to information known about the Kearny Marsh ecosystem, because very little data existed prior to this study that described groundwater movement related to this system. The integrated models that have been developed can be used as a predictive tool to describe potential changes to the marsh water budget as a result of planned restoration activities.

Kearny Marsh Contaminant Inputs

To estimate ongoing pollution inputs to Kearny Marsh, event mean concentrations of each contaminant and nutrients were averaged over the two year study period. These concentrations were incorporated into the hydrologic models, which then estimated the annual loading of the various compounds at each sampling location based on modeled flow data.

Stormwater concentrations of heavy metals, including arsenic, mercury, lead, and manganese are above the State of NJ water quality standards. Concentrations of arsenic, iron, manganese, and mercury were also above the State of NJ ground water quality standards. Based on the hydrologic model estimates, over 500,000 pounds of metals are entering the Kearny Marsh annually, and approximately 70% of this load enters the marsh through groundwater movement on the western perimeter of the marsh.

Organic contaminants also continue to enter Kearny Marsh, primarily through the groundwater. PCB mean concentrations are above the State of NJ water quality standards for both surface stormwater and groundwater at all locations sampled. The mean benzene concentration is above the State of NJ stormwater standard at two of the three stormwater sampling locations. The

estimated annual loading of polycyclic aromatic hydrocarbons (PAHs) is in excess of 3,000 pounds annually, with 69% estimated to be entering through the shallow groundwater on the western perimeter of the marsh. PAH sources appear to be both pyrolytic (derived as a result of combustion) and petrogenic (derived from oil and coal tar sources). PAH ‘fingerprints’ from the various sampling locations differ, suggesting that different sources are contributing to the overall PAH contamination. Based on the PAH composition in the western wells and standing surface waters, there appears to be movement of surface water contaminants into the shallow groundwater.

Water quality analysis shows mean concentrations of total phosphorus are above the State of NJ surface water quality standards, and mean concentrations of ammonia are above the State of NJ groundwater quality standards. Hydrologic model estimates of annual groundwater ammonia inputs are over 460,000 pounds. Estimates of stormwater total phosphorus are in excess of 29,000 pounds. These nutrient inputs have the potential to support rapid eutrophication of the marsh ecosystem. Turbidity was above NJ water quality standards in all stormwater samples. Groundwater pH was below NJ water quality standards, and groundwater dissolved oxygen was consistently below 3 mg/L.

The majority of the Kearny Marsh stormwater contaminant loadings appear to be occurring at the Frank’s Creek interface; the majority of groundwater contaminate loadings appear to be occurring along the western perimeter of the marsh; the majority of water quality impairment loadings appear to be occurring adjacent to the Town of Kearny and the Keegan Landfills.

Best Management Practice (BMP) Recommendations

Due to the impairments being caused as a result of water flowing into the marsh from Frank’s Creek, we recommend that this connection be severed. Should the connection remain, it needs to be physically controlled, so that water can drain out of the marsh, while water flow into the marsh is restricted during storm events that coincide with the high tidal cycle. If severing this connection is not feasible, we recommend that water flowing through Frank’s Creek be treated in an engineered environment, such as a natural wetland system constructed on a portion of the

Keegan Landfill, or in a small engineered treatment facility. The CSO that currently discharges into Frank's Creek should be disconnected from the storm sewer system.

Groundwater originating on the western perimeter of the marsh should be collected and treated prior to discharge to remove the contamination that is present. We recommend constructing a leachate collection system that operates in conjunction with the proposed Keegan Landfill slurry wall. We recommend the installation of additional groundwater monitoring wells up gradient to assist in identification of the source of the groundwater contamination.

Projected Hydrologic Changes

The validated SWMM and MODFLOW models were utilized to project the effects that construction of a slurry wall around the Keegan Landfill will have on the overall Kearny Marsh hydrology. While a wall will prevent leachate from entering the marsh, potentially reducing contaminate inputs, the model does project hydrologic changes after construction of the slurry wall. Because approximately 100 acres of wetlands will be capped and redeveloped, it is estimated that: 1) surface runoff from the impervious surface area will increase; 2) the water levels in the marsh will increase; 3) the marsh water table elevations will decrease; and 4) marsh flood waters will increase.

Study Conclusions

A comprehensive restoration plan that takes into account effects produced by installation of the slurry wall needs to be developed. Contaminant loadings in surface stormwater runoff must be removed. Groundwater contaminant sources must be identified and treatment options developed. To fully realize the NJMC goal of restoring the Kearny Marsh ecosystem, and utilize its waters for recreational activities, the current contaminate loadings going into the marsh must be remediated.

Background

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 350-acre freshwater marsh ecosystem. This freshwater marsh is affected by historical and current contaminant inputs from improperly closed landfills, combined sewer overflows, municipal stormwater discharges, and regional atmospheric deposition. The hydrologic conditions of the marsh are characterized by human alterations, including: (1) creation of mosquito drainage ditches that traverse the original marsh surface; (2) channeling of marsh drainage to a partially clogged 60” pipe in the Belleville Turnpike/NJ Turnpike northeastern corner of the site; and (3) municipal stormwater inputs as a result of development within the Town of Kearny. Due to the surrounding urban land use and the adjacent Keegan and Town of Kearny Landfills, significant negative affects were 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 valuable ecosystem is a high priority. One aspect of the proposed restoration is the installation of a bentonite slurry wall that will enclose the 100-acre Keegan Landfill and stop the flow of contaminated leachate from the landfill into the marsh. It is anticipated that once contained, in January, 2009, the Keegan Landfill adjacent to the marsh will commence accepting approximately 10,000 tons of dry waste weekly, until reaching a final maximum elevation of 60 feet ngvd (NJMC 2008).

Urban Wetland Restoration

Wetlands are dynamic ecosystems, which are controlled by environmental factors that affect their structure and function. Important wetland functions include providing: critical habitat for many species of plants and animals, water control through storage and retention of floodwaters, water quality protection, a sink for anthropogenic contaminants, and recreational opportunities for surrounding residents (Ehrenfeld et al. 2003). Hydrology plays a critical role in wetland development, structure, and function, and basic hydrologic information, including seasonal water balance and groundwater table dynamics, is needed to understand wetland ecosystem functions

(Sun et al. 2002). Wetland functions can be impaired by the surrounding watershed, especially if an area is highly urbanized (Ehrenfeld 2000). Because of the intimate relationship between hydrology and the ability of a wetland to provide important ecological functions, an in-depth understanding of the wetland's hydrology is critical if efforts to conserve and restore a system are to be effective (Montalto & Steenhuis 2004).

The wetland hydroperiod is the seasonal water level pattern that describes the rise and fall of surface and subsurface water. In the case of Kearny Marsh, the difference in height of the water surface can vary by up to two feet in any given year (Mansoor et al., 2006). If the watershed's impact on a wetland hydroperiod can be characterized and quantified, it is possible to mitigate the effects of urbanization through improved watershed controls, stormwater management efforts, or development regulations (Faulkner 2004).

Water Budget and Hydrologic Models

The most significant issue associated with wetland restoration planning is the lack of calculations or estimates of water availability that suggest a restoration is likely to produce a system capable of supporting wetland vegetation (Morgan & Roberts 2003). It is essential to develop a water budget that is more detailed than just identifying the water source and its movement. The water budget must account for each component of the hydrologic cycle in order to quantify its contribution in a particular system (Figure 1). A water budget is commonly calculated using a mass balance approach where the 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).

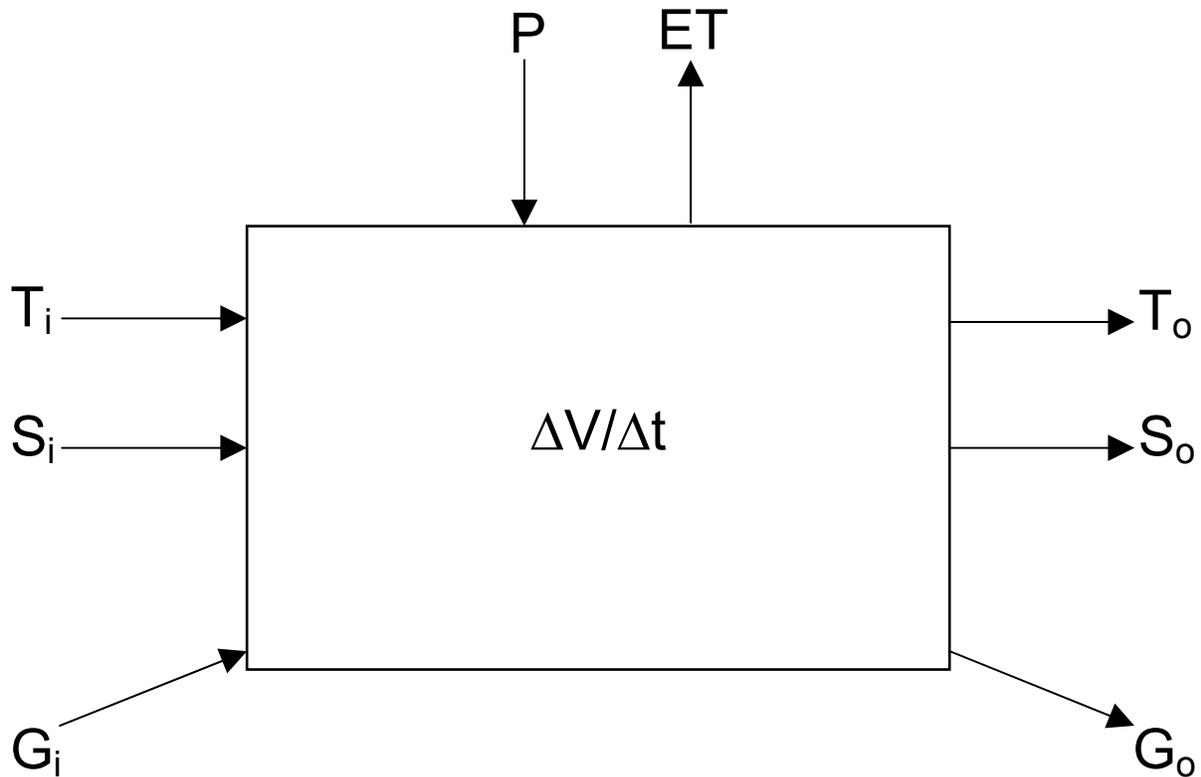


Figure 1: Schematic of generalized water budget (terms correspond to those given in Equation 1).

A common water budget equation is described by Mitsch & Gosselink (2000):

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

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

There is a need to better document the hydrological characteristics of New Jersey's coastal wetlands, including the Kearny Marsh system, in order to improve hydrological modeling capabilities, and to link hydrological characterization with ecological structure and functional capabilities (Montalto & Steenhuis 2004). While many studies have calculated water budgets in a variety of areas at multiple scales, only Owen (1995) and Reinelt & Horner (1995) determined

comprehensive water budgets for wetlands located within urban settings. This lack of data related to comprehensive hydrologic budgets in urban wetlands may be due partially to the complexity of hydrologic changes brought about by urbanization (Table 1).

Table 1: Effects of Urbanization on Wetland Hydrology (adapted from Ehrenfeld 2000).

Urban Feature	Immediate Effect	Effect on Wetland(s)
Decrease in surface storage of stormwater	Increase in surface runoff	Increase surface water input to wetland
Increase in stormwater discharge relative to baseflow discharge	Increase in erosive force within stream channels	Increased sediment inputs to receiving coastal wetland systems
Lower water quality	Increase in turbidity, nutrients, metals, organic pollutants Decrease in oxygen concentrations	Eutrophication, changes in biogeochemical cycles, concentration of contaminants of concern in the wetland sediments
Culverts, engineered outfalls replace low-order streams	More variable baseflow and low-flow conditions	Atypical wetland hydrologic patterns
Decrease in groundwater recharge	Decrease in groundwater flow	Reduction in baseflow and potential elimination of dry season streamflow
Increase in flood frequency and magnitude	Increased scour and inundation of wetland surface	Physical disturbance of wetland vegetation
Increase in range of flow rates (low flows are diminished; high flows are augmented)	Wetland deprived of water during dry periods	Wetland hydrology incapable of supporting native plant species Conditions supportive of invasive species including <i>Phragmites australis</i>
Flows are more highly regulated	Magnitude of spring flush is diminished	Atypical wetland hydrologic patterns

Although the water budget equation (Eq. 1) is straightforward, consideration needs to be given to the accuracy in determining the various components in any model. In an urban watershed, all hydrologic processes must be considered at much smaller temporal (usually a single storm event) and spatial scales (Niemczynowicz 1999). Urban hydrologists often 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). Direct measurements are

typically obtained for data related to precipitation and surface water flows; indirect measurements or calculations are typically used in determining evapotranspiration (ET) and groundwater flows.

The problems created when attempting to characterize altered urban hydrology using short-term measurements of water levels can be overcome with hydrologic models (Vepraskas et al. 2006). Because models are simplified approximations of reality they will always contain some margin of error, which can include: (1) model error; (2) errors in the state variables (dependent variables and initial conditions); (3) errors in the input data used to drive the model; and (4) parameter error (rate constants, coefficients, and independent variables) (Schnoor 1996). Any hydrologic budget should include error analysis in order to allow for realistic use (Winter 1981). Few studies analyzing model error have been performed, especially in urban wetlands, and those studies do not agree on the error associated with various components of the water budget. Studies that have included error analysis cite literature values of error derived for lakes (Kreiser 2003), which are quite probably inappropriate for urban wetlands.

The error range in certain parameters, particularly precipitation and ET, is currently known or assumed (usually on the order of 5-10%), whereas error associated with other parameters, particularly groundwater and tidal flows, is currently unknown. Vepraskas et al. (2006) found that the two largest components of their water budget for a bay in North Carolina (USA) were precipitation and ET, and that these components were the most difficult to measure accurately. Owen (1995) presents one of the few urban wetland water budgets to perform an error analysis, determined as the remainder of $[(\text{inputs} - \text{outputs}) - (\text{change in storage})]$. A total seasonal error for the ET estimate alone was calculated to be 43% for the first year of the study, and 60% for the second year (Owen 1995). Methods to measure individual components of a hydrologic budget have been reviewed and suggestions to increase accuracy have been proposed (Berne et al. 2004; Drexler et al. 2004; Rosenberry et al. 2004). For example, no universal model or measurement technique for urban ET has yet been identified, and empirical methods need site-specific calibration (Drexler et al. 2004).

The importance of ET as a major pathway of loss in wetland systems dictates increasing the accuracy in its estimation under urban conditions. It has been suggested that the best way to improve urban 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). In our efforts to reduce the potential error associated with ET, we decided to collect empirical field data to determine the most accurate ET rate possible for the urban Kearny Marsh system.

In addition to modeling hydrology, water budgets have been useful in determining nutrient budgets for wetlands (LaBaugh & Winter 1984; Reinelt & Horner 1995; Raisin et al. 1999), and determining the impact(s) of wetland restoration on existing hydrology (Kreiser 2003; Vepraskas et al. 2006). Improved water balance models that accurately predict changes in hydrology could provide a large benefit in planning urban wetland restorations such as the restoration proposed for the Kearny Marsh ecosystem.

Kearny Marsh Hydrology Study

The primary goals of this project were to characterize the existing hydrology of the Kearny Marsh, evaluate current transport of contaminants into the marsh from the highly urbanized surrounding land use, to project effects on the marsh hydrology of proposals to redevelop and reuse the site, and to project future marsh water levels under drought and high precipitation conditions. We also utilized the data collected as an aide to provide insight as to the amount and potential source of current pollutant loadings, and to recommend Best Management Practices (BMPs) to reduce existing water quality impairments. The specific objectives of this study were to:

- 1) Characterize Kearny Marsh groundwater and surface water hydrology,
- 2) Determine present contaminant loadings into the Kearny Marsh via surface and ground water inputs,
- 3) Calibrate and field verify water quantity and quality models for the Kearny Marsh wetland system,
- 4) Where possible, characterize potential sources of current Kearny Marsh contaminants, and
- 5) Identify BMPs that can be implemented to mitigate negative environmental impacts on the Kearny Marsh ecosystem.

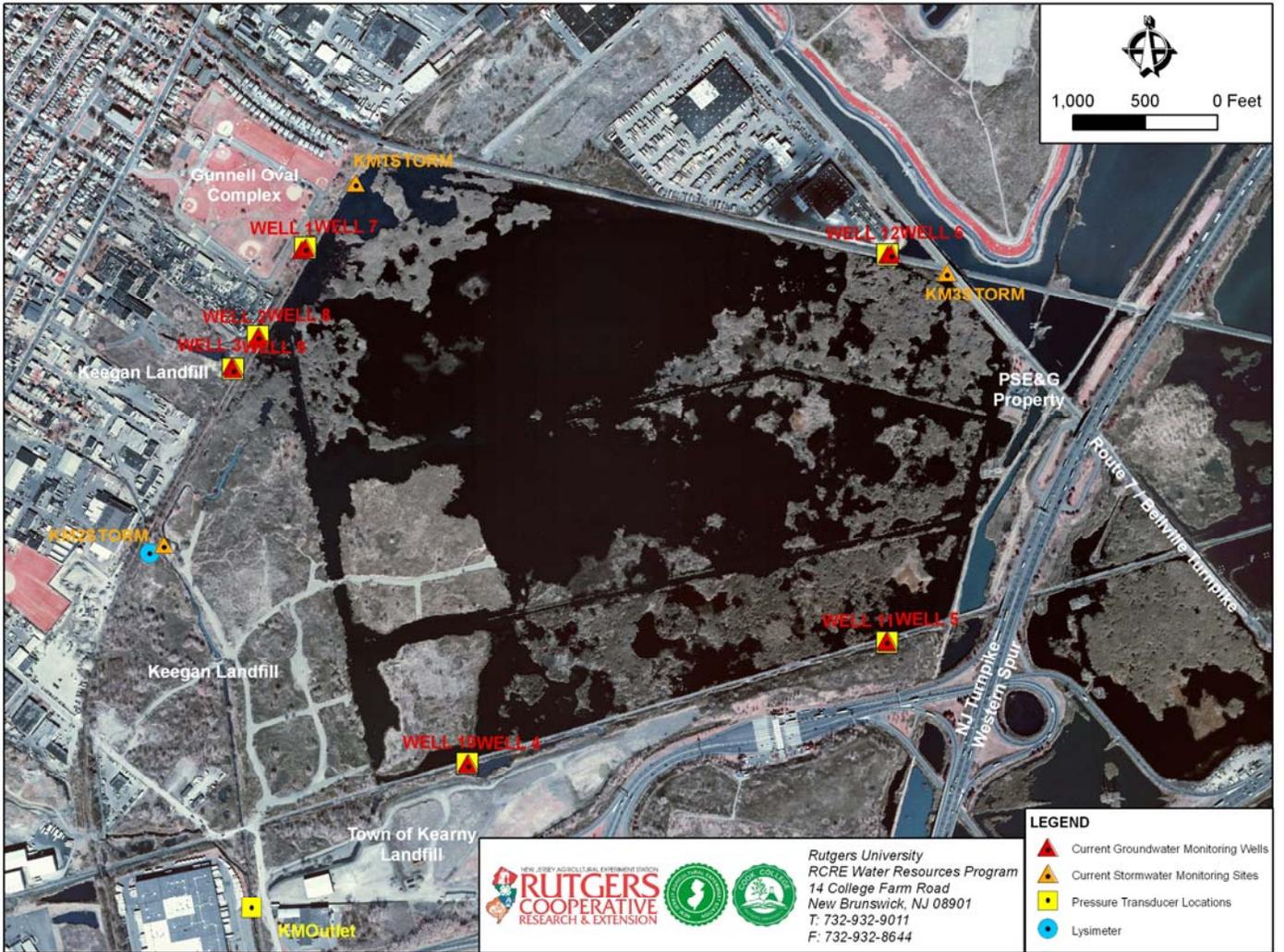


Figure 1. Kearny Marsh water sample collection sites.

Sample Collection Methods

Stormwater: Locations of stormwater inputs to Kearny Marsh were jointly identified by NJMC staff and Rutgers researchers in late 2005. A third stormwater input location (KM3) was subsequently identified during sample collection activities in July 2006. Sampling at this location commenced during September 2006. Stormwater samples were collected during 2006-2007 from the three Kearny Marsh input locations (Figure 1) during five storm events. To properly capture an appropriate ‘first flush’ of pollutants, samples were collected during storm events that occurred after a minimum of three consecutive days without rainfall. Samples were collected over the period of the hydrograph and the flow-weighted concentration means were calculated for the individual storm events. It was determined that the first set of samples, collected from KM1 and KM2 in May 2006, did not capture the ‘first flush,’ and so the data from this event were not included in the statistical analyses. For a complete description of the stormwater sampling protocols see Appendix II.

Groundwater: Six clusters of groundwater wells (Figure 1) were installed around the perimeter of Kearny Marsh in February, 2006. Each well cluster contained a shallow (15 ft.) and a deep (25 ft.) well. Eight sets of groundwater samples were collected quarterly during 2006-2007 from the twelve sampling wells. The first groundwater samples collected in March 2006 exhibited a high level of turbidity. Because of the potential for certain contaminants to sorb to sediment particles, the metal and PAH data from this first groundwater sampling were excluded from the statistical analyses. To reduce subsequent sample turbidity, a low flow pump (200 ml min^{-1}) was utilized to first purge the wells and then draw up the ground water samples. Samples were not collected from wells 1 and 7 during the spring 2007 sampling event due to flooding from the nor’easter on April 14-15, 2007. For a complete description of the groundwater sampling protocols see Appendix II.

During sample collection, and on additional site visits, depth to the water level in the groundwater wells was measured to the nearest $\frac{1}{4}$ inch. 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. Elevations surveyed were referenced to a NOAA elevation station located at stormwater sampling site KM3 (Figure 1).

Hydraulic conductivity estimates were measured in six of the groundwater wells. One well in each cluster was tested using the ‘transducer method’ (Bouwer & Rice 1976). A transducer is placed in the well below the water-level at a sufficient depth to permit testing by removing a ‘slug’ of water. The sample ‘slug’ is removed suddenly by pumping water out of the well rapidly, and a series of water-level versus time measurements are made as the water-level returns to its original depth. A data-logger records water-depth above the transducer before, during, and after the ‘slug’ is removed. The measurements are collected automatically by the transducer and data-logger, at pre-programmed time intervals. Hydraulic conductivity was calculated using change in time versus change in water depth. This measurement was used to calculate the magnitude of groundwater flows and to estimate the associated pollutant loadings to the marsh on an annual basis.

Volatile organic compounds (VOCs) were collected from the groundwater wells during sampling events conducted in 2007. The samples were collected using disposable Teflon® bailers. A rope was attached to the bailer to lower and retrieve the bailer in each groundwater well. Bailers were drained into 1 L amber bottles ensuring that no head space was left within the bottle. Care was taken to reduce disturbance of the sample as much as possible. One bailer was used at each well to eliminate cross-contamination between well samples.

Transducers: To determine the water table elevation six pressure transducers collecting ‘real time’ hourly depth measurements were installed in the six shallow wells (GW07 through GW12) during the spring groundwater sampling event in 2007. These transducers were left in the wells through February 2008. Data was downloaded from the transducers semimonthly to ensure proper functioning, and this data was incorporated into the water budget model to determine groundwater flow direction and velocity. Water table elevations were referenced to the elevations surveyed on December 20, 2006 and January 3, 2007.

In July, 2007, a pressure transducer was also placed at the Kearny Marsh drainage outlet (KMO, Figure 1) located at the broken Frank's Creek bulkhead, and the water depth was recorded hourly. This transducer was installed to determine the magnitude of water flow entering or exiting the marsh drainage system due to water exchanges with Frank's Creek, and to determine the extent of any tidal influence on the marsh. Data was downloaded semimonthly and was used to refine and verify the water budget, and to develop a rating curve for estimating water flows at this location. The pressure transducer was surveyed on July 30, 2007, with elevations referenced to wells GW04 and GW10.

Lysimeters: To measure evapotranspiration (ET) from the marsh, a non-weighing lysimeter was constructed and installed in Kearny Marsh (near the break in the bulkhead at Frank's Creek; Figure 1) in May, 2007. Measurements were taken from the lysimeter semimonthly to ensure proper functioning. A second lysimeter was installed in fall 2007 adjacent to the Gunnell Oval ballfields. Evapotranspiration was also measured using open water latent heat flux data collected during September and December, 2007. These latent heat flux measurements allowed us to calculate ET from both open water and vegetated marsh areas, and to combine these calculations to produce a more accurate ET calculation for the total marsh ecosystem. This field ET measurement was used to refine the water budget.

Sample Analyses

All storm and ground water samples were analyzed to determine water quality parameters (temperature, dissolved oxygen, conductivity, turbidity, pH) and nutrient (nitrogen and phosphorus species) concentrations. Samples were also analyzed to determine the concentrations and loadings of various contaminants of concern, including heavy metals (Ag, As, Ba, Be, Bi, Cd, Co, Cr, Cs, Cu, Ga, Hg, In, Li, Mn, Ni, Pb, Rb, Se, Sr, Ti, U, V), PAHs (anthracene, benzo[a]anthracene, benzo[a]pyrene, benzo[b]fluorine, benzo[b]naphtho[2,1-d]thiophene, benzo[b+k]fluoranthene, benzo[e]pyrene, benzo[g,h,i]perylene, chrysene, coronene, cyclopenta[cd]pyrene, dibenzo[a,h+a,c]anthracene, dibenzothiophene, fluoranthene, fluorine, indeno[1,2,3-cd]pyrene, methylphenanthrenes, naphthacene, perylene, phenanthrene, pyrene), PCBs (49 congeners), dioxin, and semi-volatile organic compounds (MTBE, benzene, toluene, m-, p-, and o-xylene, ethylbenzene). Samples exhibiting high concentrations of the

analytic standard PAHs were subsequently analyzed to identify all PAH peaks observed in the GC-MS chromatograph. This complete PAH ‘fingerprint’ was employed to characterize the potential sources of the PAH compounds (Brodskaa et al., 2002). See Appendix I for a description of analytic protocols.

Stormwater event mean concentrations were calculated as flow weighted averages, using the concentrations and flows measured at different periods across the storm event hydrograph. Averages were obtained by taking the sum of the product of the concentration multiplied by the flow, divided by the total flow (Equation 2). Annual stormwater loadings were estimated using the SWMM and MODFLOW hydrologic model data (see below). Briefly, the event mean concentration was applied to the water volume within the sampling point drainage basin to obtain the total storm event loadings. Groundwater annual loading rates were obtained by using the MODFLOW groundwater flow rate multiplied by concentrations in the collected groundwater samples.

$$EMC = \Sigma(Q_i * C_i) / \Sigma Q_T \quad (Eq.2)$$

Where, EMC = Event Mean Concentration
Q_i = Flow at time of sampling
C_i = Sample concentration
Q_T = Total storm event flow

Hydrologic Model Development

Certain assumptions related to Kearny Marsh hydrology were developed. We described the hydrology of the system utilizing the USEPA Storm Water Management Model (SWMM) v.5.0, and the USGS Visual MODFLOW v.4.1 model to simulate water movement into and through Kearny Marsh. MODFLOW was used to simulate the groundwater system that underlies the marsh, while SWMM was used to simulate the surface water inputs to the marsh, including inflows from both stormwater discharges and overland flows. Our goal was to link the MODFLOW and SWMM models to better describe the interaction between the marsh and the underlying groundwater system. Using the results of the SWMM and MODFLOW models after calibration and validation, a water budget was developed for this urban system that describes the current hydrologic inputs and outputs of the marsh.

The MODFLOW groundwater model is a unique addition to information known about the Kearny Marsh ecosystem, because very little data existed that described groundwater movements related to this system. Empirical field data was collected by Rutgers that describes hydraulic conductivity, accurate groundwater levels based upon elevation surveys, data from the pressure transducers installed in each well cluster, and groundwater quality. The Rutgers model will be useful in evaluating the long term plans to restore Kearny Marsh. The model can also be used as a predictive tool to describe potential changes to the marsh water budget as a result of planned restoration activities.

Water Budget Calculation

We first computed the Kearny Marsh water budget based on data derived from existing sources. This initial water budget calculation used a mass balance approach (inputs – outputs = change in storage), and was constructed for the years 2000 through 2006 (see paper presented at the May 2007 MERI Meadowlands Symposium, Appendix III). We then collected additional empirical data over the course of the study, which was analyzed and incorporated into the water budget in an effort to increase its accuracy. The original inputs for the mass balance were precipitation and runoff, while ET and surface outflows were estimated. However, the empirical data showed that groundwater inflows and outflows, tidal influences determining water exchanges between Frank's Creek and Kearny Marsh, and urban ET were all affecting the overall water budget of the system.

Evapotranspiration (ET) Characterization

ET in the initial water budget was calculated using the Thornthwaite equation, which takes into account only air temperature. The Thornthwaite equation was chosen because it is relatively simple, frequently used, and is thought to do a fairly good job estimating ET, especially for areas in the eastern United States (Palmer & Havens 1958, Rosenberry et al., 2004). However, there are few published ET values obtained empirically in highly urbanized systems, and one problem with the Thornthwaite equation is that it tends to underestimate ET values. Because of these weaknesses, we measured actual Kearny Marsh ET using a non-weighing lysimeter that was installed in 2007. ET measurements from the lysimeter were collected semimonthly, and were

used in combination with the latent heat flux measurements taken in summer and winter 2007 to more accurately characterize ET rates from this urban wetland.

Thornthwaite equation

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

$$PET_i = 16(10T_i/I)^a \tag{Eq. 3}$$

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

T_i = mean monthly temperature (in °C)

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 converted from millimeters per month (mm/mo) to inches per month (in/mo) to correlate with other measurements used in this study.

The Thornthwaite equation relies on monthly air temperatures, which were obtained for 2006 and 2007 from the Newark Liberty International Airport in Newark, NJ via web download from http://climate.rutgers.edu/stateclim_v1/monthlydata/index.html. The weather station at the airport is approximately 5.5 miles away from Kearny Marsh. Since the 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 in degrees Fahrenheit and were converted to degrees Celsius prior to PET calculation. This resulted in some of the mean monthly temperatures becoming negative (during winter months). In the few cases where this occurred, equation values (for a , I , and PET) were assumed to be equal to 0.00 in/mo.

The Thornthwaite equation (Eq. 3) results in PET; actual evapotranspiration (AET) was calculated by multiplying the resulting PET by a correction factor to account for the duration of sunshine during each month, based on latitude (Table 1). Monthly AET values were converted to daily values (inches per day; in/day) by dividing the AET for each month by the number of days in that particular month.

Table 1. Correction Factors for Monthly Sunshine Duration (Dunne & 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

One problem often cited with the Thornthwaite equation is that it tends to underestimate ET values; underestimation has been demonstrated to be the case for arid areas (Chen et al. 2005) or equatorial areas with high humidity (Tan et al. 2007, Lu et al. 2005). We did not know if underestimation was occurring when using the Thornthwaite equation to calculate ET in an urban marsh located in a temperate climate.

Lysimeters

Lysimeters are considered to be suitable for the measurement of evapotranspiration in wetlands (Lott & Hunt 2001). These devices are used to determine the net input from precipitation minus outputs due to evaporation and vegetation transpiration. Two non-weighing Lysimeters (Figure 2), constructed following Perkins (1999) and Lott & Hunt (2001), were placed in Kearny Marsh in May and September 2007. A 2-gallon plastic bucket (the “tank”) was connected, using 10 feet of ¾-inch PVC pipe, to a 5-gallon plastic bucket (the “receiver”), which was capped with a sealed lid (Perkins 1999). A trench was dug to accommodate the lysimeter, ensuring that the receiver was at a lower 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 eliminate any exchange with ground and surface waters (Lott & Hunt 2001). This was done to ensure the data collected reflected the effects of precipitation and evapotranspiration only. 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 soils and plants during this process. To provide time for the plants to reestablish and the lysimeter to stabilize (Perkins 1999), ET readings commenced approximately two (2) weeks after lysimeter placement in Kearny Marsh.

ET measurements were taken by removing the water that collected in the receiver (the “percolate”) and measuring the water volume in a graduated cylinder. ET was measured semimonthly, and was determined 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 measured volume of water was added to the tank, and several minutes (10-15) were allowed to pass to ensure adequate seepage from the tank to the receiver. This added water was 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 was added to the previous time period rainfall to obtain the total water added to the lysimeter (Perkins 1999). 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. 4; Perkins 1999). ET was divided by the number of days in the time period to get a daily ET value (inches/day).

$$\text{Water Added (inches) + Rainfall (inches) - Percolate (inches) = PE (inches)} \quad (\text{Eq. 4})$$

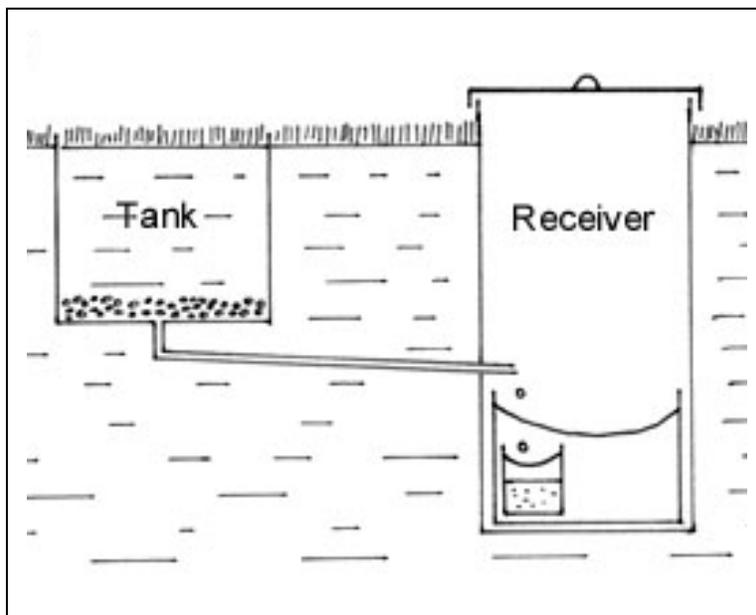


Figure 2. Schematic diagram of the non-weighing lysimeter installed in Kearny Marsh.

The second lysimeter installed in fall 2007 near the Gunnell Oval Recreation Complex did not function properly. Due to the high water table at this location, groundwater infiltrated the lysimeter, adding excess water to the receiver and making the data unusable. Results from the second lysimeter were not included in this analysis.

Eddy Correlation Measurement

To better account for surface variation, it has been suggested that the best way to improve wetland ET estimates is by improving the measurement and relative weighting of net radiation and conductive (ground or water) heat flux density (Drexler et al. 2004). Latent heat flux was measured following the procedures outlined by Bidlake et al. (1995). In brief, a Campbell Scientific 3-dimensional anemometer (measuring wind speed in 3 dimensions) and hygrometer were placed 2 meters off the ground along the train tracks in the southeastern portion of Kearny Marsh (Figure 3). This location provided enough open water surface over which wind could pass and be measured. ET rates were calculated from the latent heat measurements, which were divided by the product of the density of water (1000 kg/m^3) multiplied by water's latent heat of vaporization ($2.5 \times 10^6 \text{ J/kg}$).

Figure 3. Measuring Kearny Marsh latent heat flux with a Campbell Scientific anemometer (measuring wind speed in 3 dimensions) and hygrometer.



To balance the hydrologic budget, surface water outflows were calculated as equal to the balance remaining after ET was subtracted from all inflows. The routes for this outflow are the stormwater system in the southern portion of the marsh and, during low tide, the broken bulkhead connection between Frank's Creek and the southwestern corner of the Marsh (Neglia 2001). A rating curve was developed based on data collected from the pressure transducer placed at the Frank's Creek bulkhead in summer 2007 (Figure 1). Water flow velocities were used with the water depth data to develop the rating curve, which determined current surface

outflows from this location in the marsh. This information was subsequently incorporated into the water budget.

SWMM Model Development

The Kearny Marsh SWMM model was built using the delineated drainage basins from Neglia Engineering's storm water study (Neglia 2001). These drainage systems, which were designed to collect stormwater, were utilized to develop the model because it appears that the majority of the surface flows entering Kearny Marsh are from runoff. Data used in the construction of the model (i.e., channel dimensions, subbasin sizes, etc.) were from the Neglia report. Land use data, lengths of subbasins, and distances were obtained using ArcGIS 9.0, and incorporated into the model. Daily rainfall information for 2005 and 2006 was obtained from the MERI weather monitoring station in Lyndhurst, NJ (<http://merigis.njmeadowlands.gov/vdv/index.php>), and this information was used to determine runoff values for each drainage basin. Precipitation values from each of the storm events sampled during 2006 and 2007 were also added to the model, and used to determine flooding potential in the streams or stormwater channels draining the marsh. Additional parameters calculated in the SWMM model were storage volume, evaporation, runoff, and maximum flows for each stream channel for each storm event modeled.

An additional drainage area for the Belleville Turnpike was added after the input at KM3 was discovered. 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 using ArcGIS 9 (ArcMap v.9.2) and compared to the 'Neglia-delineated' drainage areas. We determined that these two descriptions corresponded, and so utilized the basins described in the Neglia (2001) stormwater study, supplemented with the Belleville Turnpike basin Rutgers identified.

Much of the data used in the construction of the model (i.e., channel dimensions, subbasin sizes, etc.) were taken from the Neglia report. Data that was not available in the Neglia Report (2001) (i.e. land use data, lengths of subbasins, distances) were obtained in GIS using ArcGIS 9 (ArcMap v.9.2) and incorporated into the model. Additionally, elevations of selected structures within Kearny Marsh, (outfall pipes, culverts and channels) were surveyed in October 2007 in

order to accurately model the Kearny Marsh surface water flows. Daily rainfall information for 2006 and 2007 was obtained from the MERI weather monitoring station located in Lyndhurst, NJ (<http://merigis.njmeadowlands.gov/vdv/index.php>); this data was supplemented with precipitation data from Newark Liberty International Airport (<http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwDI~StnSrch~StnID~20018901#ONLINE>). Additional parameters calculated in the SWMM model were storage volume, evaporation (determined by measuring latent heat flux as described above), runoff, flooding and maximum flows for each stream channel for each storm event modeled.

SWMM Model Calibration

Stormwater flows and depths were taken in February, May and September, 2006, at the stormwater sampling locations (KM1, KM2 and KM3). This data was used to calibrate the Kearny Marsh surface water model. (**Note:** Because a ‘first flush’ was not captured during the May 2006 sampling event, the analytical results from these samples were **not** used in the water quality analysis of the Kearny Marsh system. However, the water flows and depths measured during this storm were used in the model calibration.) The measured parameters were compared to the model output through the Nash-Sutcliffe Efficiency Coefficient (Eq. 3). The coefficient, E , is used to compare the 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” (Krause et al. 2005):

$$E = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad \text{Eq. 3}$$

This equation produces a range of E from $-\infty$ (infinity) to E equals 1; values closer to 1 indicate greater agreement between the model predictions and the observed values (Krause et al. 2005). An E value equal to 0 indicates that the model is predicting no better than using the average of the observed data (Evans et al. 2002). Therefore, any positive value ($E > 0$) suggests that the model has some utility, with higher values indicating better model performance (Evans et al.

2002). Other data analyses, including correlation analysis and ANOVA, were used to compare the model predictions to the field measurements.

Different versions of the Kearny Marsh SWMM model were run, and each model's output (depths and flows) were compared to the measured values using the Nash-Sutcliffe Efficiency Coefficient. Model parameters were changed to obtain a better fit (i.e., to make E closer to 1) between each model simulation. The parameters most often changed were the Manning's roughness coefficient (n), of the drainage area, or the slope of the drainage area. The objective was to increase or decrease flows through the system, so that they better matched the observed values. After running several iterations of the surface water model, final E values calculated for 2006 depths were equal to 0.885, and for flows were equal to an E value of 0.582. Additional analyses of the observed and predicted values were conducted. Correlations between the observed values and the predicted values in 2006 were strong for both depths ($R = 0.94$) and flows ($R = 0.80$). Residuals (the observed value minus the predicted value) were calculated for both depths and flows. The average 2006 depth residual was 0.05 feet, and the average flow residual was 0.12 cubic feet per second (cfs). ANOVA tests of the 2006 depths and flows showed no statistically significant difference between the observed and the predicted values (depths: $F(1,28) = 0.04$, $p = 0.84$; flows: $F(1,28) = 0.16$, $p = 0.69$). We then concluded that the SWMM model was calibrated for 2006 and we could therefore move to model validation.

SWMM Model Validation

The model was validated by taking the calibrated model, entering precipitation, evaporation, and tide height data for 2007, and then running the model. The Nash-Sutcliffe Efficiency Coefficient was calculated for water depths and flows as measured at KM1, KM2 and KM3 during the March and October 2007 sampling events. Correlation of the observed depths and model predicted depths (2007) were strongly correlated ($R = 0.91$). The resulting E for depths was 0.787; however the flows correlation E value was 0.094. Even though a lower E value was calculated for the 2007 flows, the observed flows measured during the storm sampling events and the flows predicted in the SWMM simulation showed a moderate correlation ($R = 0.61$). The average residual for 2007 depths was -0.05 feet, and the flow average residual was 0.15 cfs. ANOVA analysis of the 2007 depths and flows showed no statistically significant difference

between the observed and the predicted values (depths: $F(1.34) = 0.02$, $p = 0.88$; flows: $F(1.34) = 0.31$, $p = 0.58$). Therefore, it was concluded that the model was valid for 2007.

Possibly due to the complexity of the Kearny Marsh system, comparison of the observed and predicted flows using the Nash-Sutcliffe Coefficient is producing lower than optimal results. The largest disadvantage of the Nash-Sutcliffe efficiency is the fact that the differences between the observed and predicted values are calculated as squared values, and as a result, larger values are strongly overestimated whereas lower values are neglected (Krause et al. 2005). When the 2007 observed values were compared to predicted values for the KM2 site alone, the estimated Nash-Sutcliffe Coefficient drops to -0.172. The model may be under-predicting maximum flows and over-predicting minimum flows due to the backwater effect at the connection between Kearny Marsh and Frank's Creek (where during a high tide the water from Frank's Creek will short circuit the creek and enter Kearny Marsh). **For this reason, we have not include the KM2 results in our estimate of Kearny Marsh stormwater loadings because the loads were estimated using the modeled flows.**

MODFLOW

MODFLOW Model Development

Due to a lack of groundwater and hydrogeologic data for Hudson County and the Kearny Marsh area, our MODFLOW model was created from data primarily collected from the field, supplemented with information gathered from literature sources. We kept the Kearny Marsh groundwater MODFLOW model 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 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 wells drilled for this study. Also, it was at or close to this depth that a clay layer was observed during the drilling of the 12 groundwater wells. This clay layer was assumed to be the bottom layer of our modeled aquifer. Our assumption, based upon the information available, is 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 the soil logs obtained at that time. Ground surface elevation for the area was imported into

Visual MODFLOW using the State's 10 meter Digital Elevation Grid for Watershed Management Area 4.

During the groundwater sampling events in 2006 and 2007, and on additional site visits during the study period, depth to water level in the groundwater wells was measured to the nearest $\frac{1}{4}$ 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. Elevations surveyed were referenced to a NOAA elevation station located at stormwater sampling site KM3 (Figure 1). Hydraulic conductivity estimates were measured in six of the groundwater wells on February 28, May 30, and June 28, 2007, when one well in each cluster was tested using the 'transducer method.' The measurements are collected automatically by the transducer and data-logger, at pre-programmed time intervals. Hydraulic conductivity was calculated using change in time versus change in water depth. The average conductivity was calculated and used in all directions (X, Y and Z). This assumes that the aquifer being modeled is isotropic.

To determine the water table elevation, the six pressure transducers collecting 'real time' depth data were installed during the spring groundwater sampling event (April 11, 12 & 20, 2007) and hourly depth measurements were recorded. These transducers were left in the wells until March 17, 2008. Data was downloaded from the transducers semimonthly to ensure proper functioning. This data was incorporated into the model to determine groundwater flow direction and groundwater velocity. Water table elevations were referenced to the Digital Elevation Grid.

Based upon the water table elevations calculated from the pressure transducers in each well, it was determined that Kearny Marsh is a groundwater discharge wetland (i.e., groundwater is discharging into the marsh, which helps to maintain marsh water levels) since the water table elevation is generally higher than the marsh water surface elevation. Because of this characteristic, it was determined that the best boundary condition to place in Visual MODFLOW was the Drain (DRN) function. 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. The DRN package assumes the drain has no effect if the head in the aquifer falls

below the fixed head of the drain. 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 the marsh's surface water, which then flows out to the Passaic River. Additional boundary conditions for the MODFLOW model were Recharge (REC) and Evapotranspiration (EVT). The REC values for 2006 and 2007 were taken from the 2006 and 2007 SWMM models; the infiltration loss from SWMM is REC input (calculated in inches/year) in Visual MODFLOW. The same was done for EVT; the evaporation loss from SWMM in 2006 and 2007 was used as the EVT (in inches/year) in Visual MODFLOW. We note that a possible weakness in this approach is that using an ET rate derived above the marsh surface may result in an overestimation of groundwater ET.

MODFLOW Model Calibration

MODFLOW contains a calibration graph that compares the modeled groundwater head values to the observed heads, taken from the depth to water measurements in Kearny Marsh groundwater wells. Statistics used to determine the model performance included standard error in feet and correlation coefficients. The groundwater model was run and these values were graphed. When the standard error and correlation coefficient were outside of acceptable values (i.e., large errors or correlation coefficients below 0.7) then selected parameters were changed to obtain a better fit in these statistics. Most often the parameter selected was the elevation of the DRN underlying the Kearny Marsh model. After several runs of the Kearny Marsh groundwater model, the standard error for 2006 was finally calculated as 0.21 feet and the correlation coefficient was 0.869. These were judged acceptable, and the model was then validated.

MODFLOW Model Validation

As with the SWMM model, the MODFLOW model was validated by taking the 2006 calibrated model, entering 2007 values for recharge, evapotranspiration (both taken from the 2007 SWMM model), and groundwater head data (obtained from the pressure transducers), and then running the model. Calibration graphs for the groundwater head were viewed to determine the standard error and the correlation coefficient between the observed and predicted groundwater heads. The resulting standard error for 2007 was 0.05 ft and the correlation coefficient was 0.876. These correlations were well within accepted values and the model was deemed valid. The 2007 model (with a lower standard error and a higher correlation coefficient) may have performed better than

the 2006 model due to the fact that there was a much larger set of groundwater head data (hourly readings from six wells during April through December, 2007).

RESEARCH RESULTS

Due to the heterogeneity of sampling results by date, the variability of sampling results by location, and ultimately the need to identify contaminant loadings from specific input sources, we are reporting the data for each surface water input or groundwater well cluster as the mean concentration based on the average of all sampling events. *Names of these sampling points do not imply a source of contamination, but merely serve to identify the individual storm or groundwater sampling locations.* Due to a failure to capture the ‘first flush,’ the stormwater data collected during the May 2006 sampling event is not included in the following graphs and tables.

Stormwater Sampling Locations

Gunnell Oval Storm Drains (KM1): Placed at the eastern end of the dead end street (East Midland Avenue), this storm drain discharges directly into the northwestern corner of Kearny Marsh.

Frank’s Creek Broken Bulkhead (KM2): The water movement into and out of the marsh at this location is currently being influenced by the presence of functional tide gates downstream of the sampling point. When a precipitation event occurs during high tide and the tide gates are closed, water in Frank’s Creek rises, and then flows into Kearny Marsh. When a precipitation event occurs during low tide and the tide gates are open, the water flow changes direction, moving out of Kearny Marsh, into Frank’s Creek, and downstream to the Passaic River. We note that the current connection between Kearny Marsh and Frank’s Creek is a broken bulkhead. Loadings from this location are contributing to contaminant inputs to the marsh, and so we have retained this connection in the hydrologic model.

Railroad Culvert (KM3): This culvert drains stormwater into the northeastern corner of Kearny Marsh adjacent to the unused rail bed, opposite the 1E Landfill.

Contaminant concentrations were calculated as the mean of all samples collected over the two years of the study. Mean arsenic concentrations were above the NJ water quality standards at all stormwater input locations; mercury was above the NJ surface water quality standards at KM1

and KM2 (Figure 4a). Mean concentrations of manganese and lead were above the NJ surface water quality standards at locations KM2 and KM3 (Figure 4). Mean PAH concentrations were highest at the KM1 and KM2 sampling locations on the western perimeter of the marsh (Figure 6a), and concentrations of benzene in these samples exceeded the NJ surface water quality standards (Figure 8). ΣPCB mean concentrations were also above the NJ surface water quality standard at all stormwater sampling locations (Figure 7a). Any dioxins present were below our analytic detection limit (0.05 µg/L). Average total phosphorus concentrations were above the NJ surface water quality standards at all sampling locations (Figure 10), and mean sample turbidity exceeded the NJ surface water quality standards at all sampling locations (Figure 9).

Estimated stormwater annual loading rates are highest at the KM2 sampling location (Figure 5). However, due to the difficulties in modeling the flows at this location as a result of the directional changes in water movement, we hesitate to draw conclusions about annual loads without additional data. Based on the limited data collected, the SWMM model projects that over 1,000 lbs/yr of metals are entering the marsh at this location (Table 2). We note that this number is an order of magnitude lower than loadings attributed to the various groundwater sampling locations (see below).

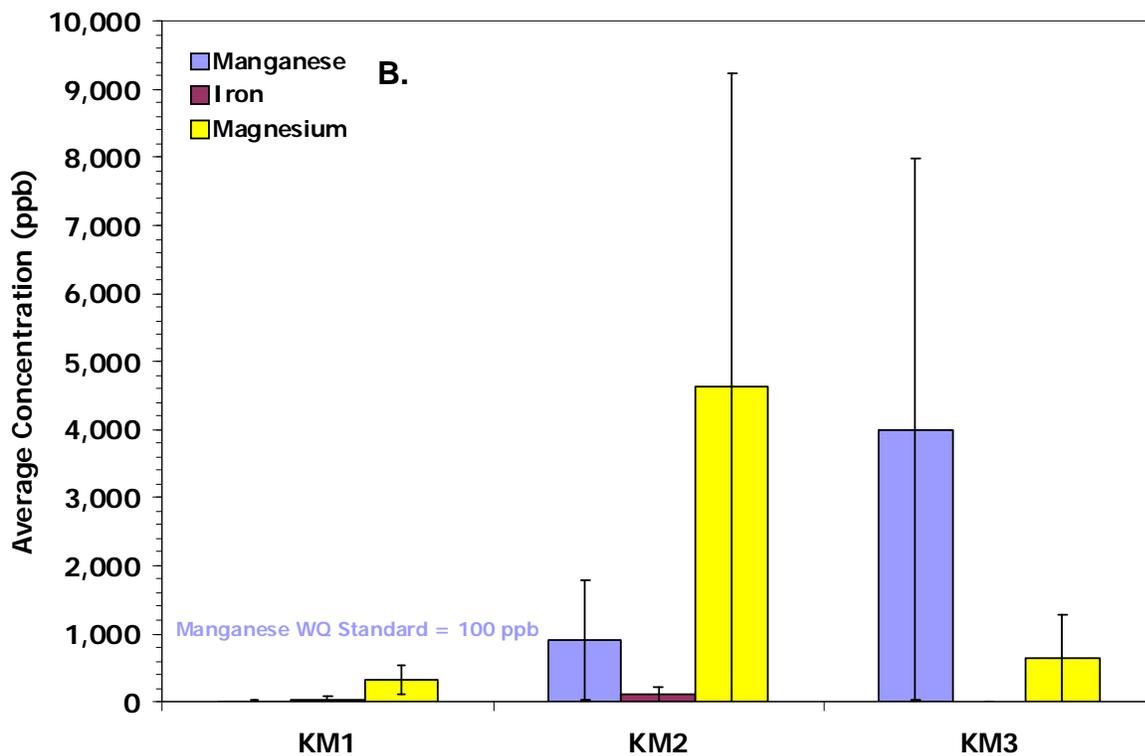
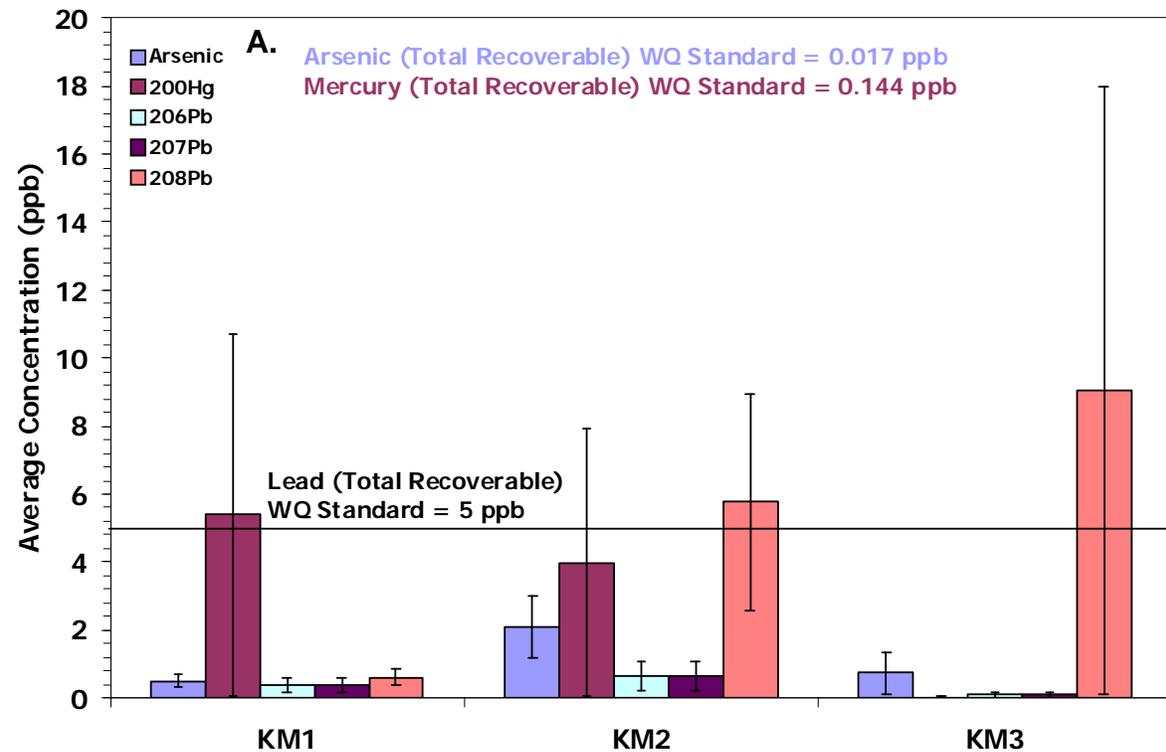


Figure 4. Flow weighted average of select heavy metal concentrations in Kearny Marsh stormwater samples collected during 2006-2007.

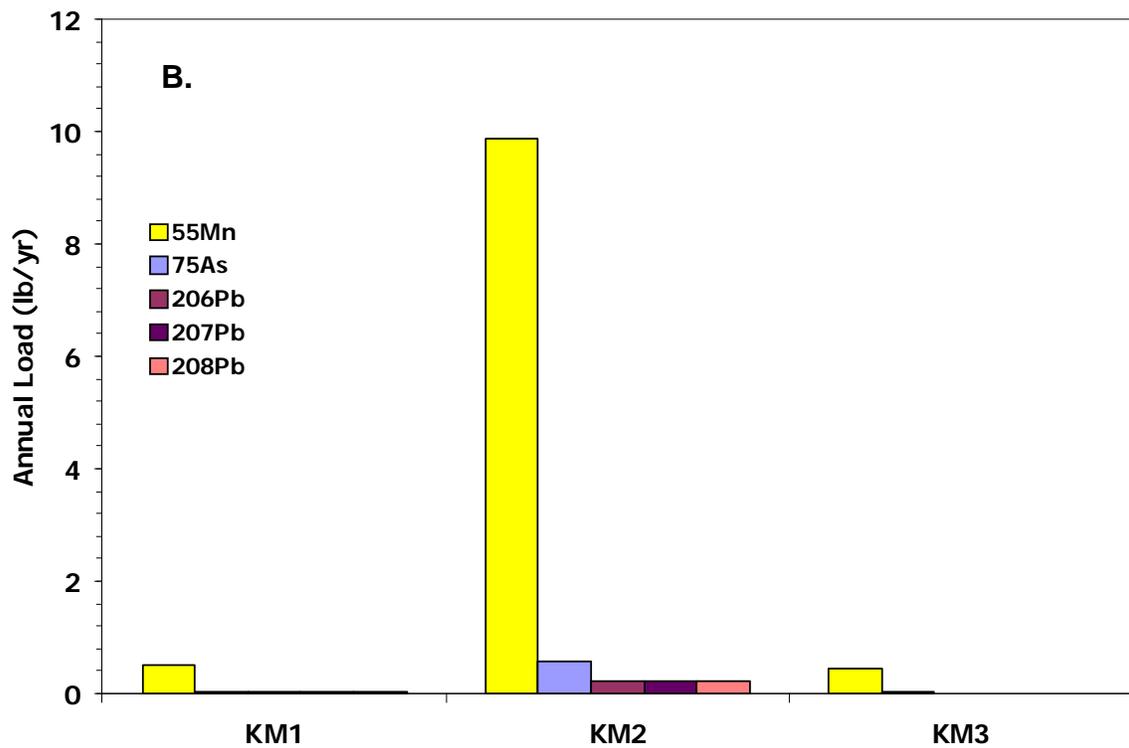
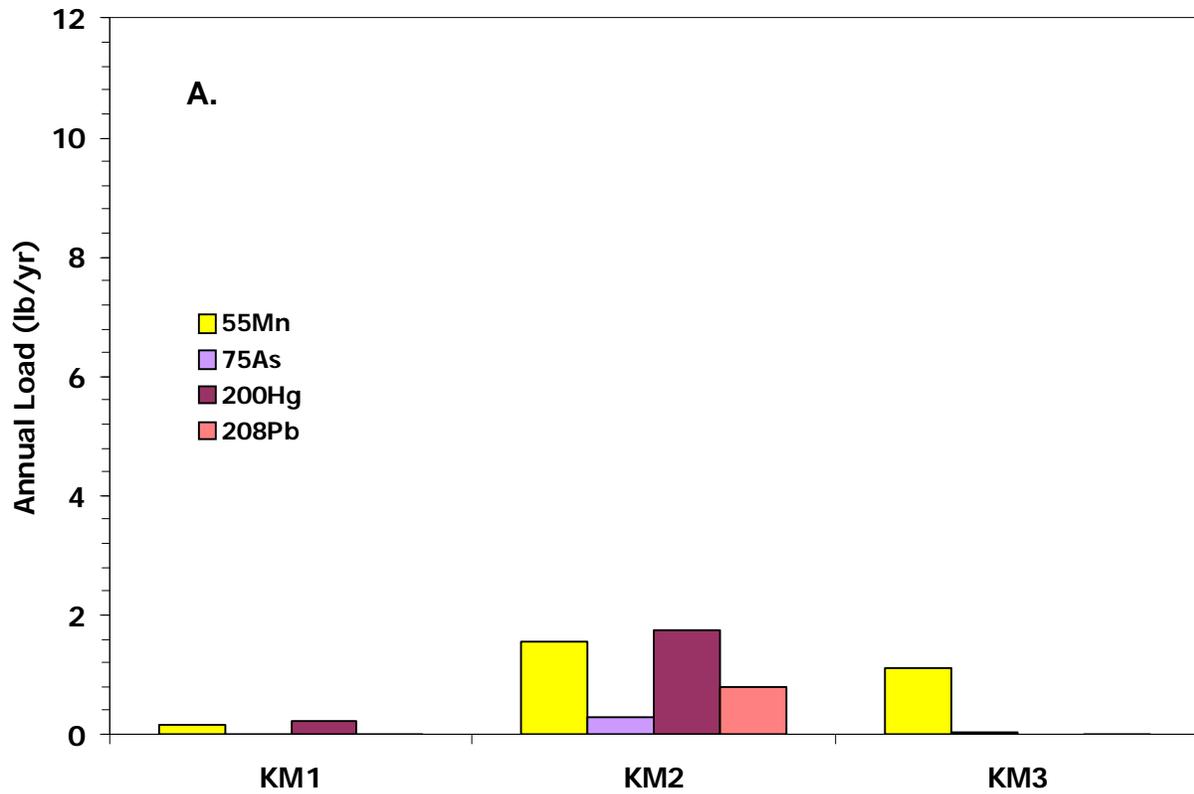


Figure 5. Model estimates of annual heavy metal loadings in Kearny Marsh stormwater based on samples collected during 2006 (a) and 2007 (b).

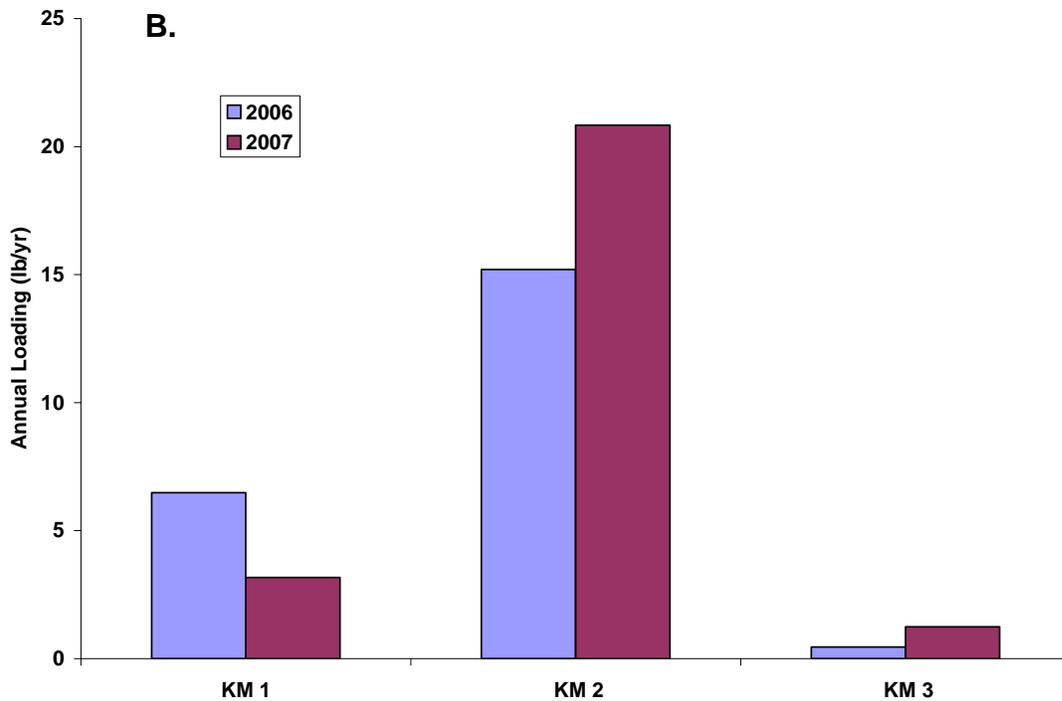
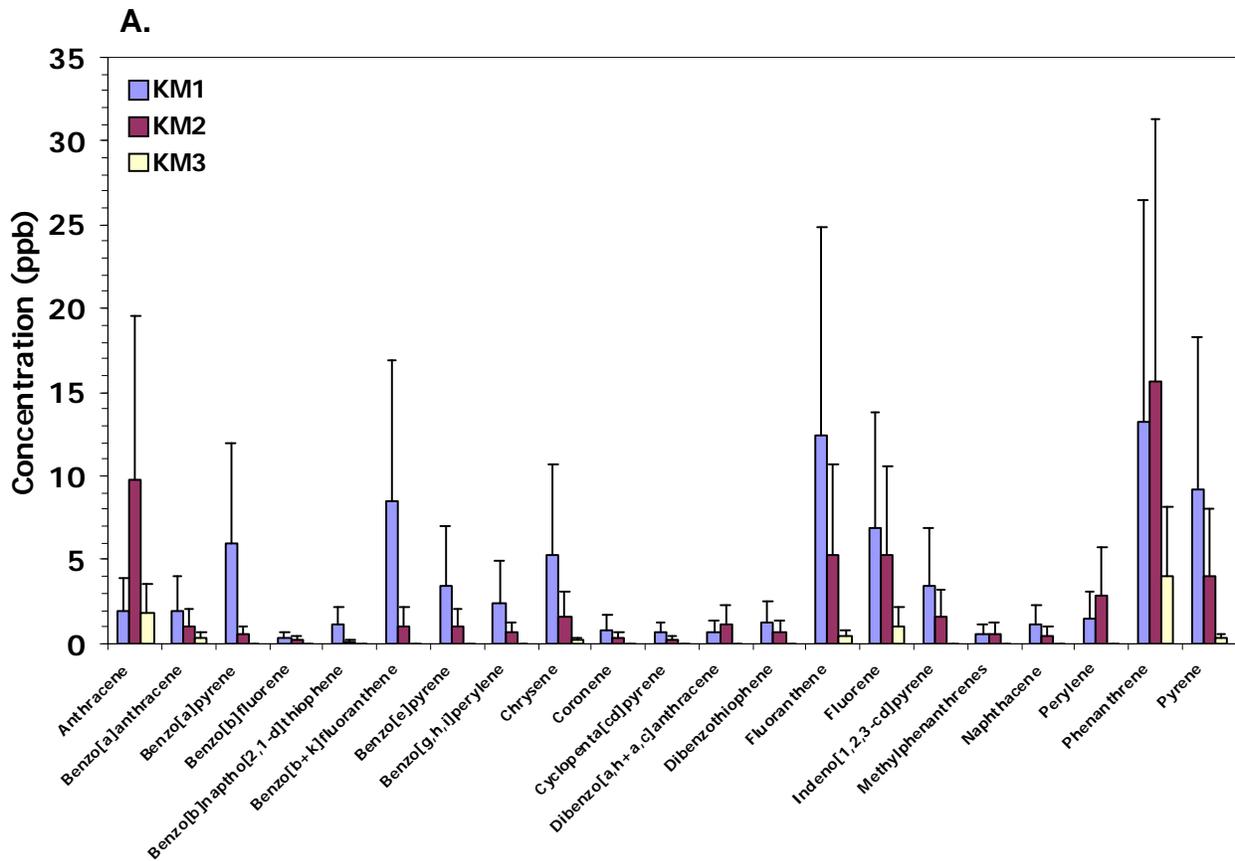


Figure 6. Flow weighted average concentrations of a suite of 21 PAH contaminants (a), and model estimated annual PAH loading in pounds per year (b) based on Kearny Marsh stormwater samples collected during 2006-2007.

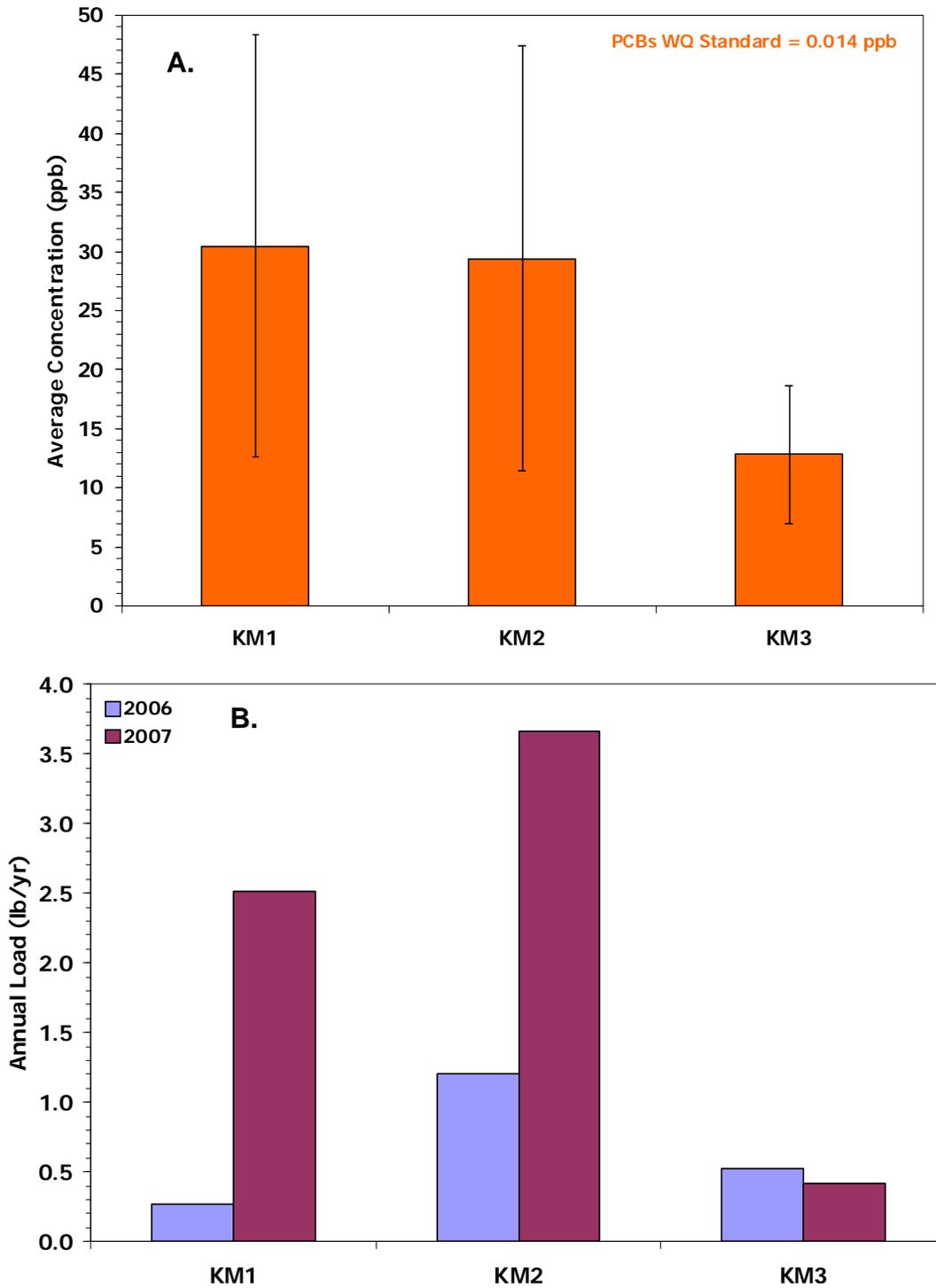


Figure 7. Average Σ PCB concentrations (a) and model estimated annual Σ PCB loadings in Kearny Marsh stormwater samples collected during 2006-2007.

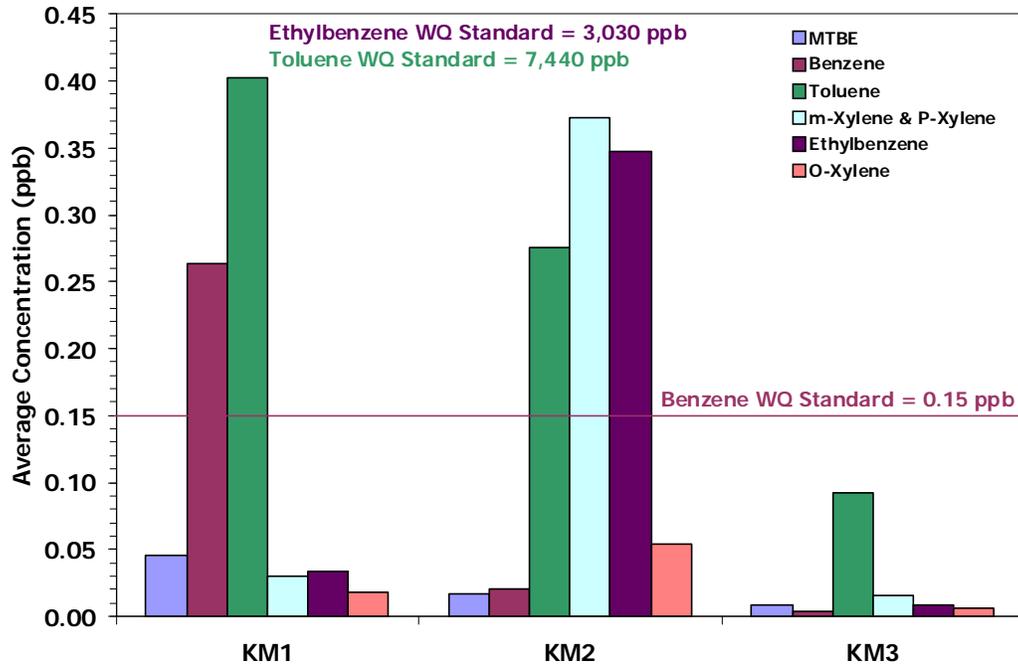


Figure 8. Concentrations of volatile organic compounds (VOCs) in Kearny Marsh stormwater samples collected in 2007.

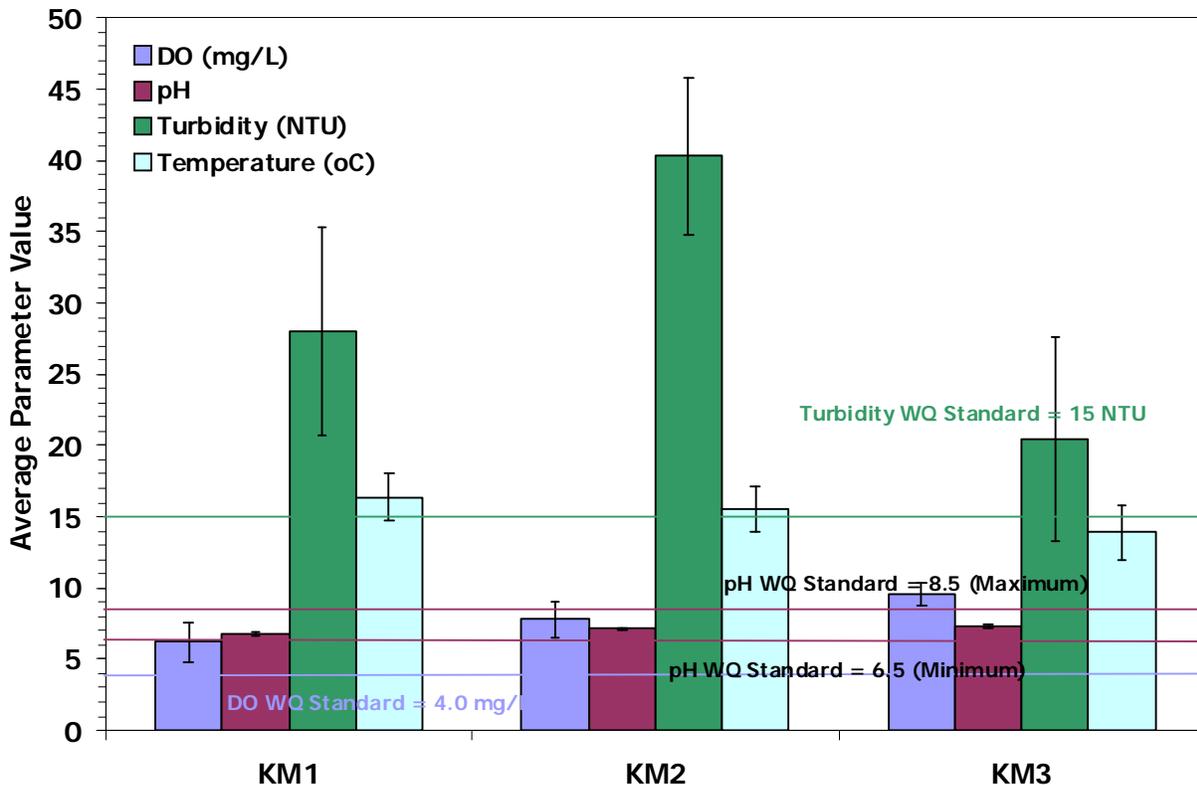


Figure 9. Mean of water quality parameters measured during Kearny Marsh stormwater sampling events in 2006 – 2007. DO = dissolved oxygen.

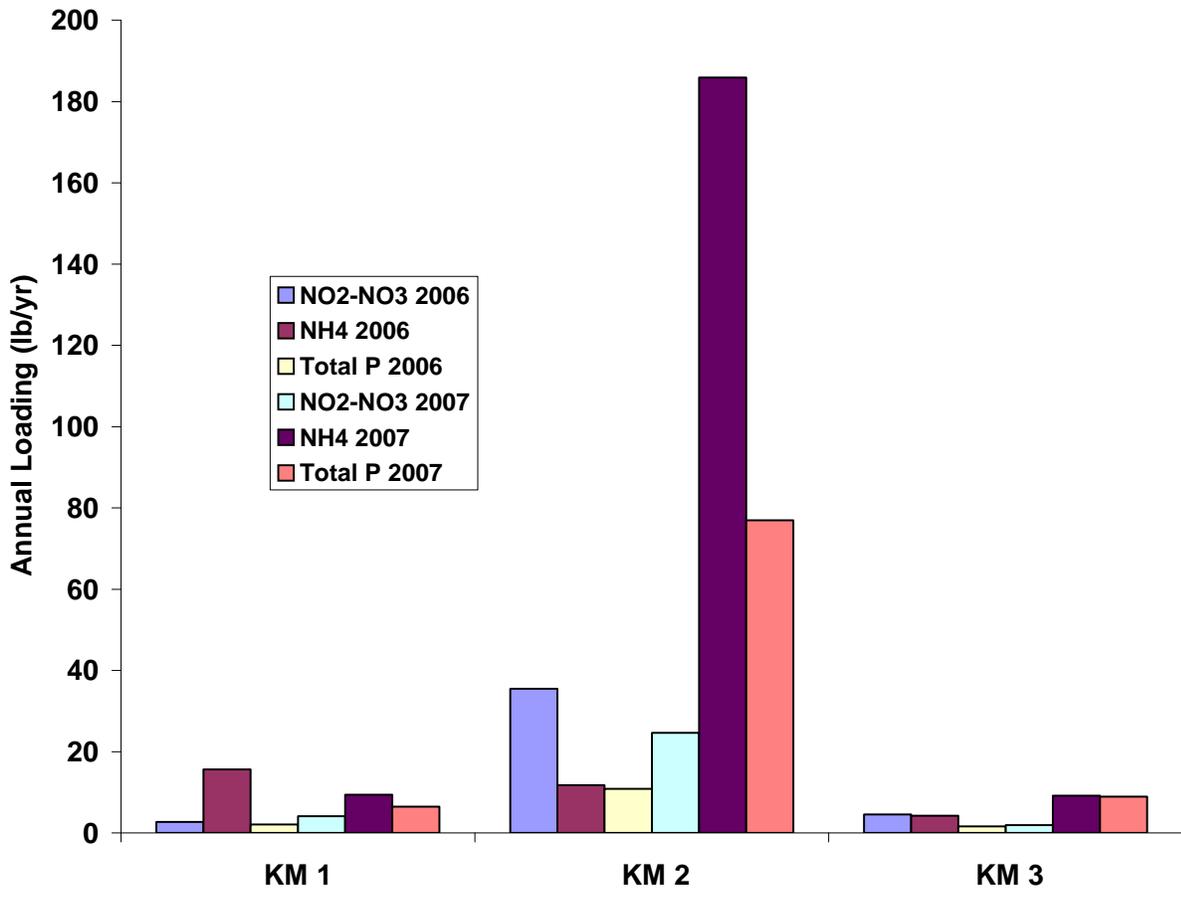
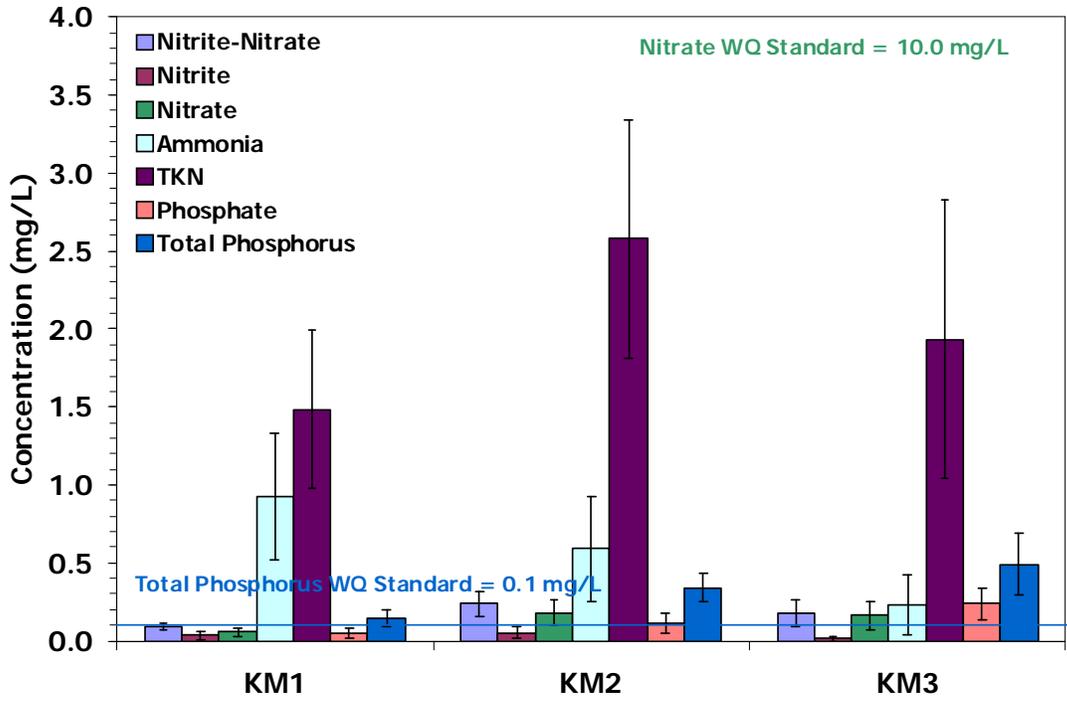


Figure 10. Average nitrogen and phosphorus concentrations (a) and model estimated annual loadings (b) in Kearny Marsh stormwater samples collected during 2006-2007.

GROUNDWATER SAMPLING LOCATIONS

Six clusters of groundwater wells were installed on the western, eastern, and southern perimeter of the marsh. Each cluster contained a 25 ft. deep well (D) and a 15 ft. shallow well (S). *The name given to each location is for identification purposes only, and is not meant to imply a specific source of groundwater contamination.* Due to excess turbidity, data from the March 2006 sampling event is excluded from the following graphs and tables.

Gunnell Oval (GWs 1-deep and 7-shallow): Placed between the eastern perimeter of the Gunnell Oval roadway and the marsh, these wells collected groundwater that flowed into the northwestern corner of Kearny Marsh.

Auto Body (GWs 2-deep and 8-shallow): Placed between the ditch that flows behind the light industrial area located immediately south of the entrance to Gunnell Oval, these wells collected groundwater that flowed in a southerly direction through the ditch and into the western perimeter of Kearny Marsh.

Keegan Landfill (GWs 3-deep and 9-shallow): Placed between the ponded water south of the light industrial area and west of the Keegan landfill, these wells collected groundwater that flowed south through the ditch, west through the unlined Keegan landfill, and into the southwestern corner of Kearny Marsh.

Town of Kearny Landfill (GWs 4-deep and 10-shallow): Placed between the unused rail bed and the closed, but unlined Town of Kearny Landfill, these wells collected groundwater that flowed northeast from the landfill and into the southern perimeter of Kearny Marsh.

NJ Turnpike (GWs 5-deep and 11-shallow): Placed in the southeastern corner of Kearny Marsh adjacent to the unused rail bed, these wells collected groundwater that may be subject to runoff from the NJ Turnpike at the 15W interchange.

PSE&G (GWs 6-deep and 12-shallow): Placed between an unused rail bed and the Kearny Marsh, opposite the working 1-E Landfill, these wells collected groundwater that flowed into the northeastern corner of Kearny Marsh.

After analyzing the groundwater well data, it appears that there are significant differences between the groundwater in wells on the western perimeter of the marsh versus waters in the eastern, southern, and northern wells. For this reason, we have formatted the following graphs so the western groundwater patterns are more easily observed.

In general, mean groundwater concentrations of heavy metals were highest in the wells located on the western perimeter of Kearny Marsh (Figures 11 - 14). Mean arsenic concentrations were above the NJ groundwater quality standards in all the wells sampled (Figure 11); iron and manganese were above the groundwater standard in all wells (Figures 12, 13) **except** the shallow wells at PSEG (GW12 - iron) and at Gunnell Oval (GW07 - manganese), respectively. Mean mercury concentration was above the NJ groundwater standards in the shallow well GW09 adjacent to the Keegan Landfill (Figure 14). The mean Σ PCBs were above the NJ groundwater standard in all wells (Figure 19a). PAHs were found to be highest in two shallow wells (Figure 20a) located south of Gunnell Oval (GW08) and adjacent to the Town of Kearny landfill (GW10). Volatile organic compounds (Figure 21a) were highest in the shallow well adjacent to Gunnell Oval (GW7), the shallow well adjacent to the Keegan landfill (GW9), and the deep well adjacent to the Town of Kearny landfill (GW10). Any dioxins present were below our detection limits (0.05 $\mu\text{g/L}$).

Ammonia was the dominant nitrogen species found in groundwater, and the mean concentrations exceeded NJ's groundwater quality standards at all sampling locations **except** in shallow wells GW08 and GW12 and deep well GW3; mean nitrate-nitrite concentrations were not found to exceed NJ water quality standards (Figure 22). The mean pH in five of the groundwater wells (four of which are located on the western perimeter of the marsh) was below NJ groundwater quality standards (Figure 27). Mean dissolved oxygen was consistently below 3 mg/L in all groundwater sampling locations (Figure 28).

The vast majority of the estimated contaminant and nutrient loadings that enter Kearny Marsh annually are coming from groundwater inputs (Tables 2, 3, 4), versus from stormwater inputs. Based on the model estimates, over 4,400 pounds of organic contaminants (PAHs, PCBs) and over 500,000 pounds of metals continue to enter Kearny Marsh annually via the groundwater. The locations estimated to contribute PAH loadings of over 1,000 lbs/yr are both located on the western marsh perimeter (shallow wells GW08 and GW10); these two wells contribute an estimated 69% of the annual PAH model loadings. These same locations accounted for the highest estimated metal loadings (Table 4). In conjunction with the other two western wells, these six wells accounted for an estimated 375,440 lbs/yr of metals, equal to 70% of the estimated annual groundwater metal inputs into Kearny Marsh.

Table 2. Annual Mean of Selected Metal Contaminant Loadings to Kearny Marsh Based on Average 2006-2007 Estimated Loadings.

Site	Location	7Li	24Mg	27Al	52Cr	55Mn	56Fe	69Ga	75As	88Sr	111Cd
KM1	Stormwater outlet East Midland	0.11	17.01	0.01	0.02	0.33	2.15	0.12	0.02	2.07	0.00
KM2	Broken Frank's Creek bulkhead	0.83	1455.58	0.80	0.33	5.70	22.81	0.37	0.42	31.96	0.01
KM3	Inlet at Belleville Turnpike	0.15	117.22	0.00	0.01	0.78	0.00	0.05	0.03	5.92	0.00
GW01-D	Gunnel Oval	123	13,059	12	2.75	3,730	865	7	3	1,031	4
GW07-S	Gunnel Oval	313	13,961	0	2.30	77	7,316	187	1	1,667	715
GW02-D	Behind Automobile Scrap Yard	12	32,151	0	4.16	13,569	24,835	6	5	1,231	48
GW08-S	Behind Automobile Scrap Yard	8	15,709	78	6.67	8,234	22,161	13	5	1,053	3
GW03-D	Keegan Landfill	11	25,612	4	2.28	13,626	10,531	12	4	1,153	116
GW09-S	Keegan Landfill	7	12,833	292	5.47	12,248	18,461	2	1	1,373	21
GW04-D	Town of Kearny Landfill	12	84,826	14	7.55	2,809	643	41	9	1,018	260
GW10-S	Town of Kearny Landfill	24	61,855	28	7.04	773	3,037	19	9	906	119
GW05-D	New Jersey Turnpike	51	26,568	0	6.45	1,099	1,286	41	9	688	1
GW11-S	New Jersey Turnpike	54	25,659	6	4.99	2,562	1,046	40	15	632	1
GW06-D	Belleville Turnpike	24	37,050	19	4.42	2,257	3,440	53	18	1,054	1
GW12-S	Belleville Turnpike	3	4,389	3	0.85	419	19	8	1	286	6
	TOTAL ESTIMATED ANNUAL LOAD	644	355,260	457	55.28	61,408	93,665	430	80	12,132	1,296

Table 2 Continued. Annual Mean of Selected Metal Contaminant Loadings to Kearny Marsh Based on Average 2006-2007 Estimated Loadings.

Site	Location	137Ba	200Hg	202Hg	206Pb	207Pb	208Pb	Total All Metals
KM1	Stormwater outlet East Midland	2.47	0.12	0.01	0.02	0.02	0.02	26
KM2	Broken Frank's Creek bulkhead	9.24	0.88	0.02	0.13	0.13	0.52	1,536
KM3	Inlet at Belleville Turnpike	1.59	0.00	0.00	0.00	0.00	0.00	126
GW01-D	Gunnel Oval	373	0.32	0.15	0.64	0.65	1.48	19,226
GW07-S	Gunnel Oval	3,775	0.18	0.17	0.32	0.32	0.32	28,070
GW02-D	Behind Automobile Scrap Yard	163	0.22	0.16	0.26	0.26	0.50	72,041
GW08-S	Behind Automobile Scrap Yard	505	0.51	0.13	0.80	0.80	1.82	47,805
GW03-D	Keegan Landfill	588	0.22	0.20	0.42	0.43	0.64	51,676
GW09-S	Keegan Landfill	45	4.04	0.20	0.42	0.42	5.90	45,318
GW04-D	Town of Kearny Landfill	1,434	0.32	0.18	0.44	0.43	0.61	91,132
GW10-S	Town of Kearny Landfill	652	0.61	0.17	0.69	0.71	0.92	67,471
GW05-D	New Jersey Turnpike	1,443	0.11	0.08	0.37	0.37	0.49	31,253
GW11-S	New Jersey Turnpike	1,580	0.14	0.10	0.40	0.40	0.67	31,660
GW06-D	Belleville Turnpike	1,953	0.32	0.19	0.50	0.49	0.72	45,917
GW12-S	Belleville Turnpike	333	0.32	0.31	0.30	0.30	0.30	5,472
	TOTAL ESTIMATED ANNUAL LOAD	12,858	8.32	2.07	5.70	5.72	14.91	538,728

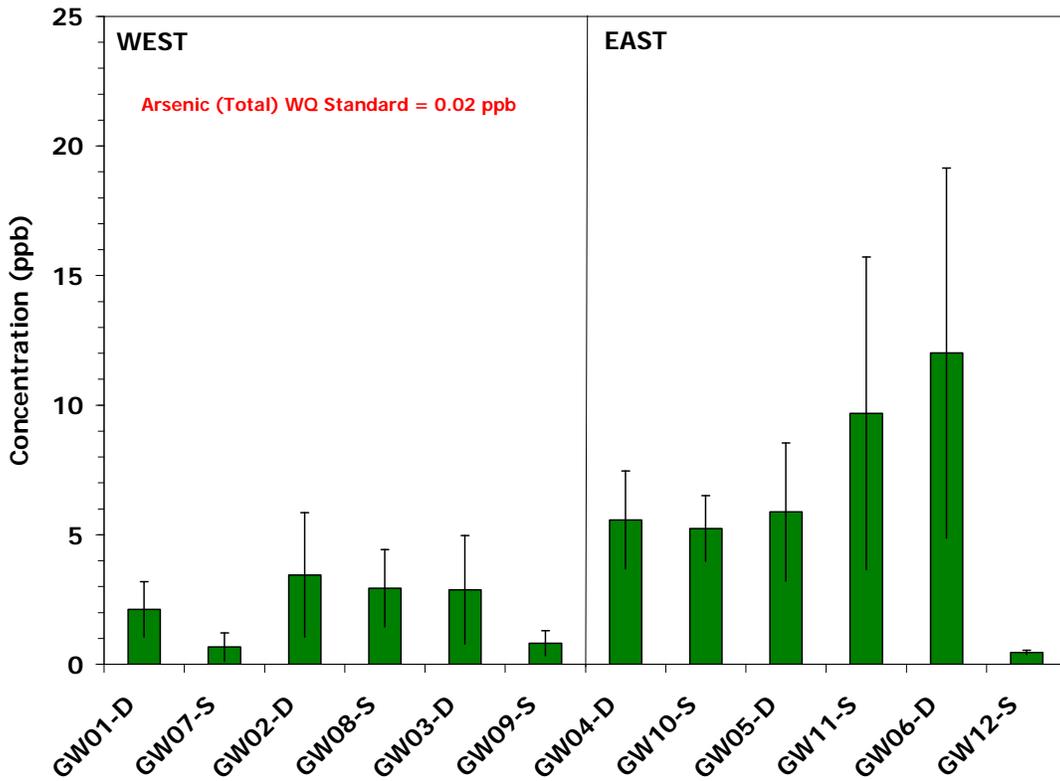


Figure 11. Mean Kearny Marsh groundwater arsenic concentrations in samples collected during 2006 - 2007. D = deep well; S = shallow well.

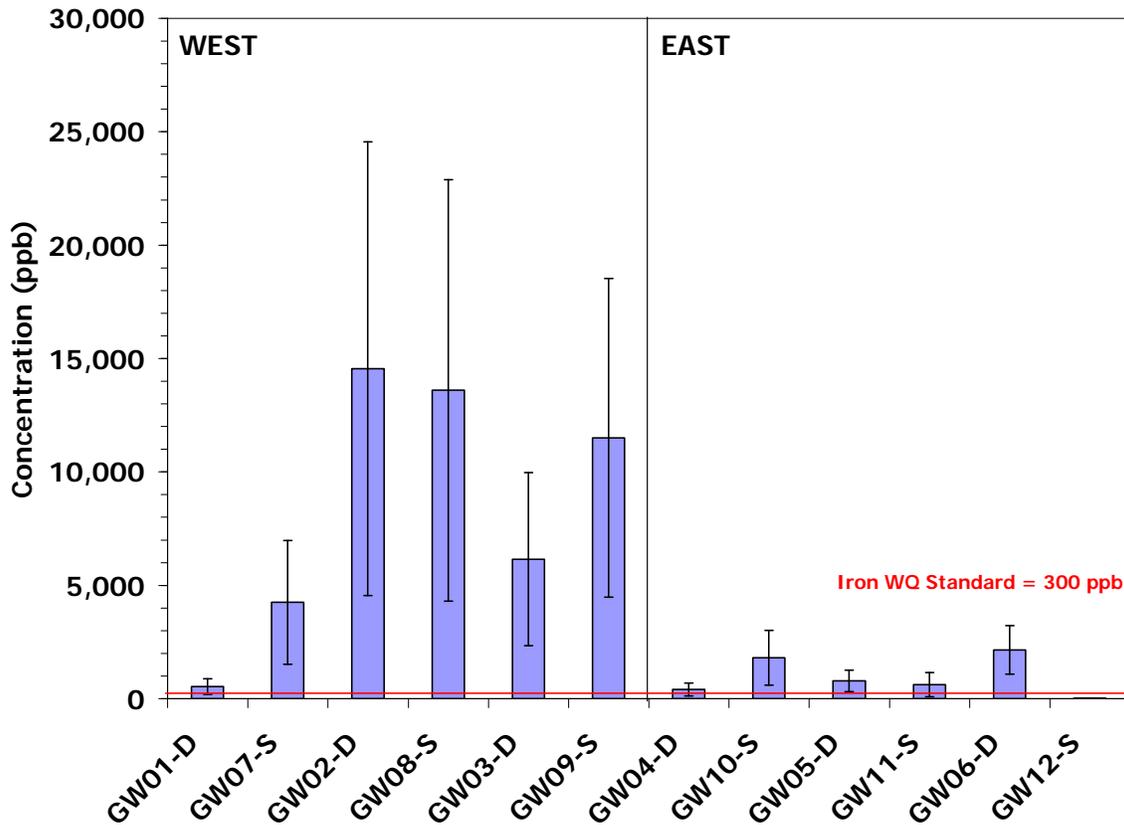


Figure 12. Mean Kearny Marsh groundwater iron concentrations in samples collected during 2006 - 2007. D = deep well; S = shallow well.

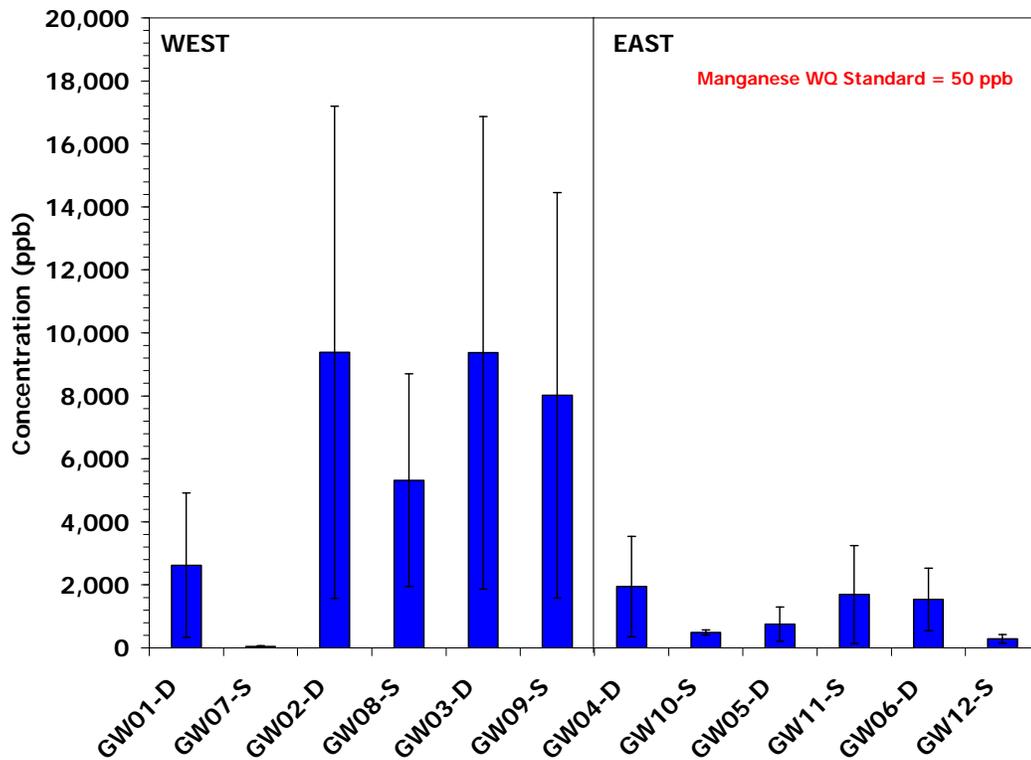


Figure 13. Mean Kearny Marsh groundwater manganese concentrations in samples collected during 2006 - 2007. D = deep well; S = shallow well.

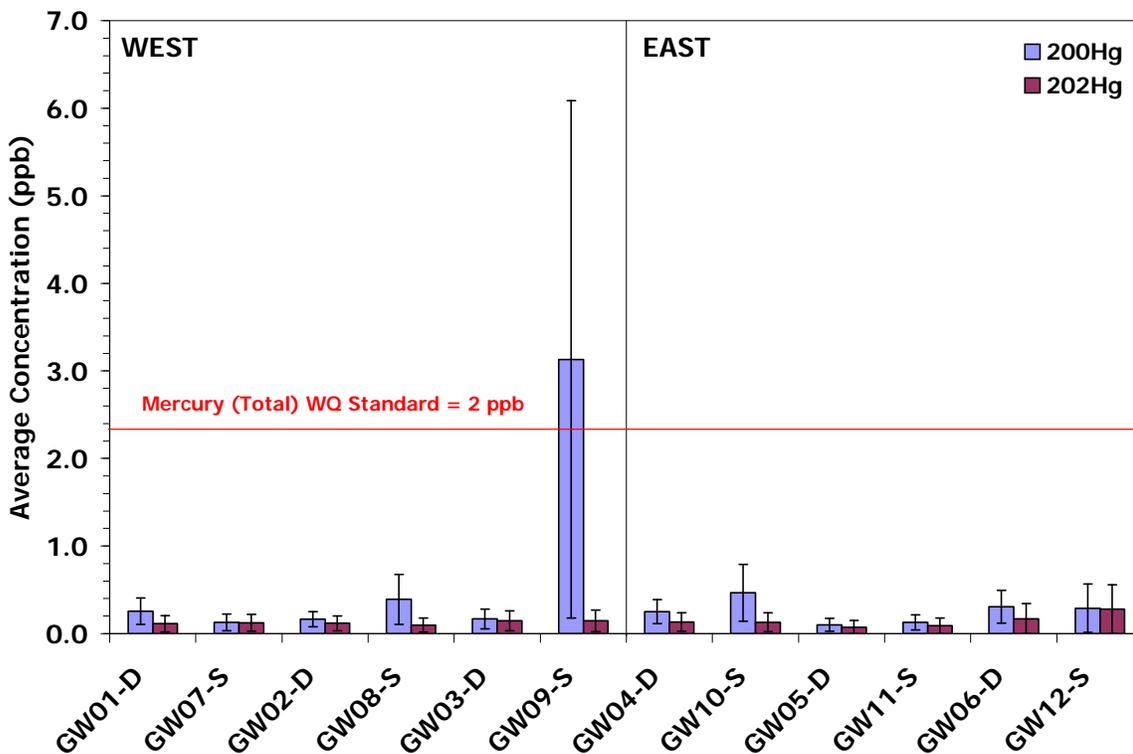


Figure 14. Mean Kearny Marsh groundwater mercury concentrations in samples collected during 2006 - 2007. D = deep well; S = shallow well.

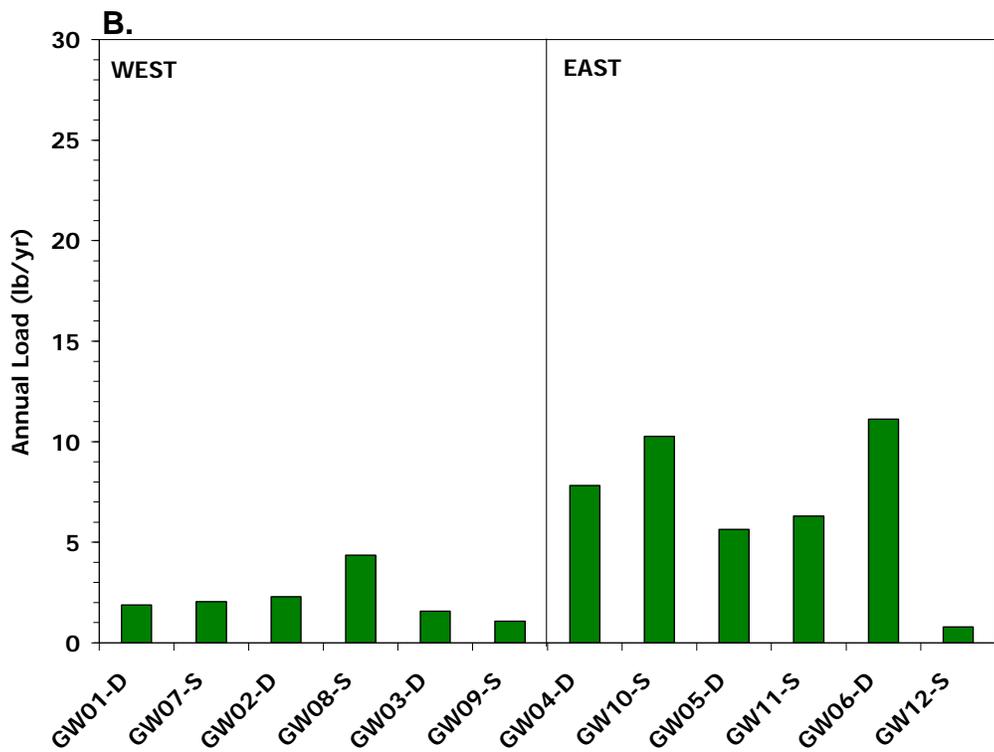
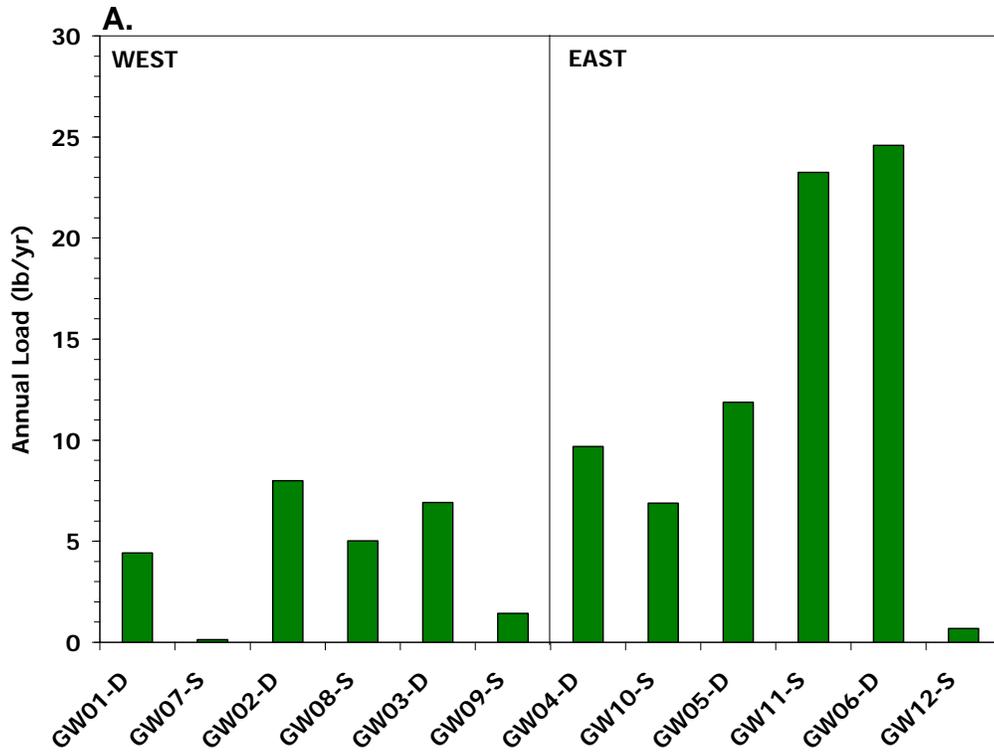


Figure 15. Estimated Kearny Marsh groundwater arsenic loadings in samples collected during (a) 2006 and (b) 2007. D = deep well; S = shallow well.

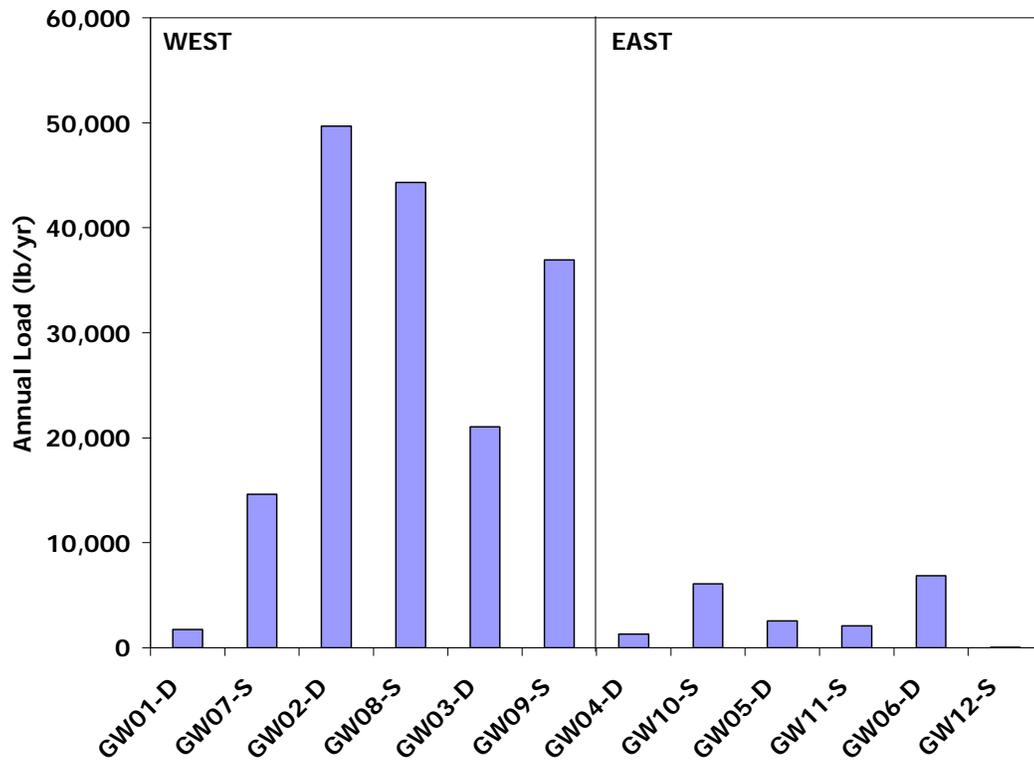


Figure 16. Estimated Kearny Marsh groundwater iron loadings in samples collected during 2007. D = deep well; S = shallow well.

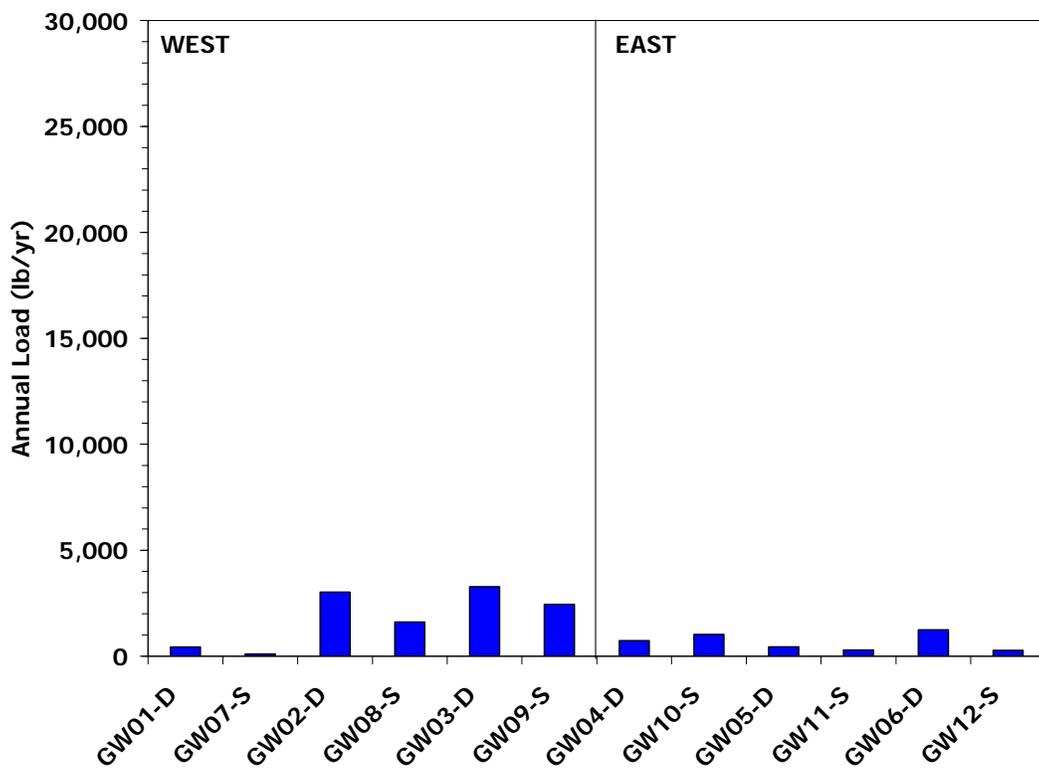
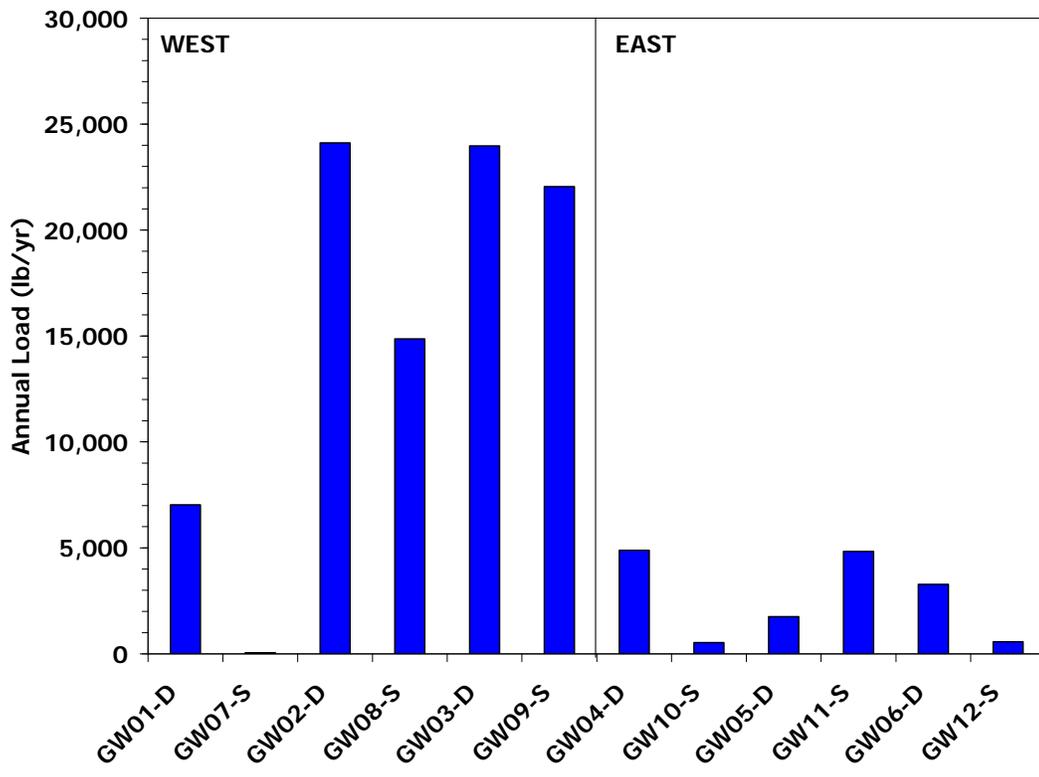


Figure 17. Estimated Kearny Marsh groundwater manganese loadings in samples collected during (a) 2006 and (b) 2007. D = deep well; S = shallow well.

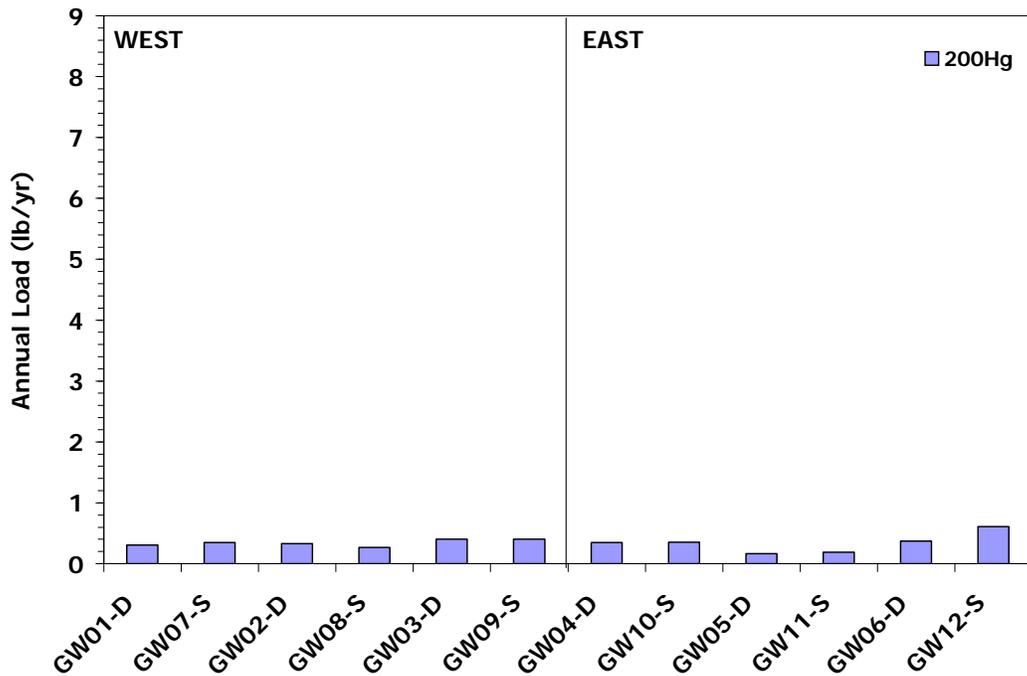
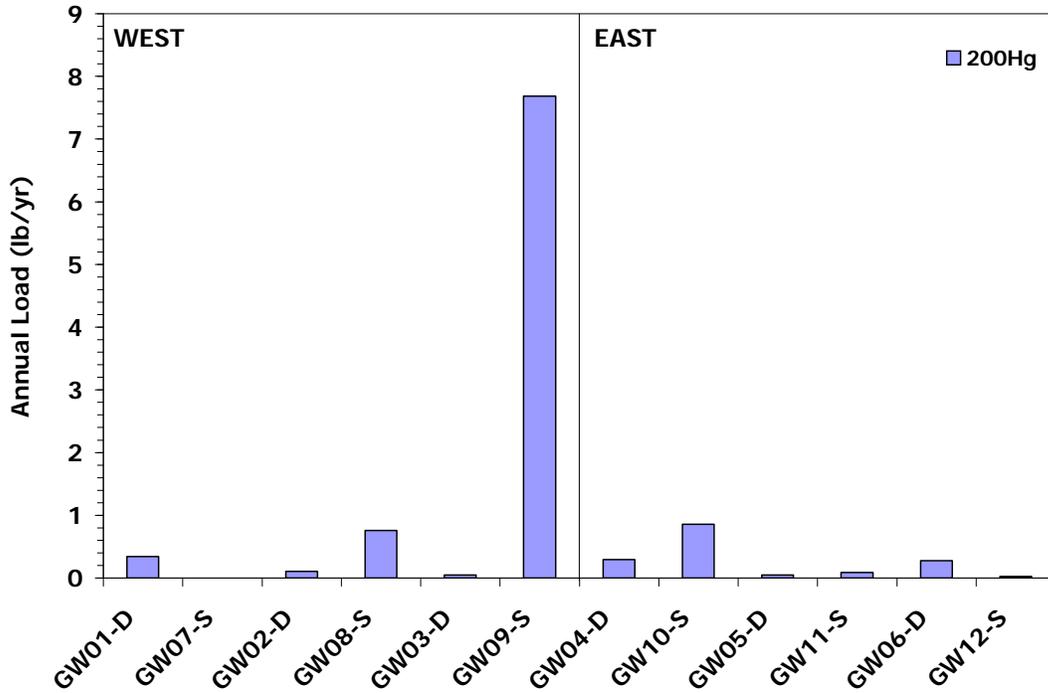


Figure 17. Estimated Kearny Marsh groundwater manganese loadings in samples collected during (a) 2006 and (b) 2007. D = deep well; S = shallow well.

Table 3. Annual Organic Contaminant Loadings to Kearny Marsh Based on Average 2006-2007 Estimated Loadings.

Site	Location	Total PAHs	Total PCBs	MTBE
KM1	Stormwater outlet base of East Midland Avenue	4.82	1.39	0.00
KM2	Broken Frank's Creek bulkhead	18.01	2.43	0.00
KM3	Inlet at Belleville Turnpike	0.85	0.46	0.00
GW01-D	Gunnel Oval	63	19	0.04
GW07-S	Gunnel Oval	285	34	9.54
GW02-D	Behind Automobile Scrap Yard	98	82	0.02
GW08-S	Behind Automobile Scrap Yard	1,547	27	0.22
GW03-D	Keegan Landfill	113	84	0.02
GW09-S	Keegan Landfill	720	113	0.19
GW04-D	Town of Kearny Landfill	55	69	5.72
GW10-S	Town of Kearny Landfill	1,574	21	0.24
GW05-D	New Jersey Turnpike	118	77	0.06
GW11-S	New Jersey Turnpike	8,328	46	0.26
GW06-D	Belleville Turnpike	110	47	0.01
GW12-S	Belleville Turnpike	76	29	0.00
TOTAL ESTIMATED ANNUAL LOAD		13,112	652	16.32

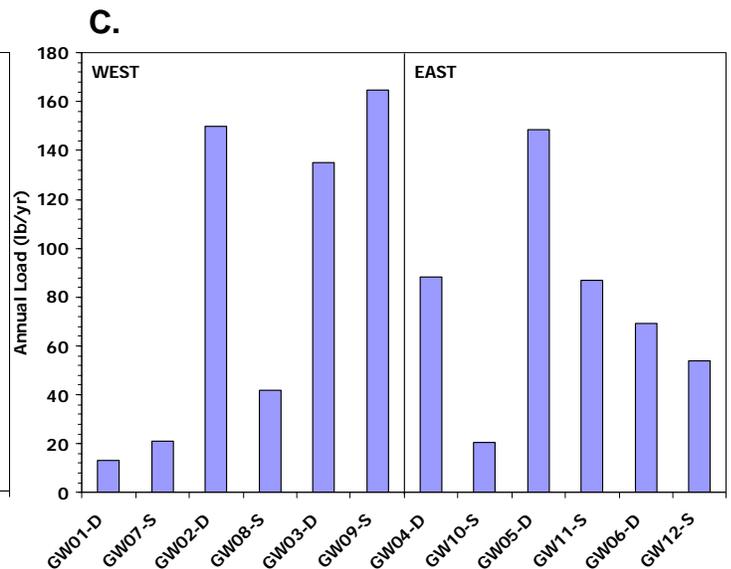
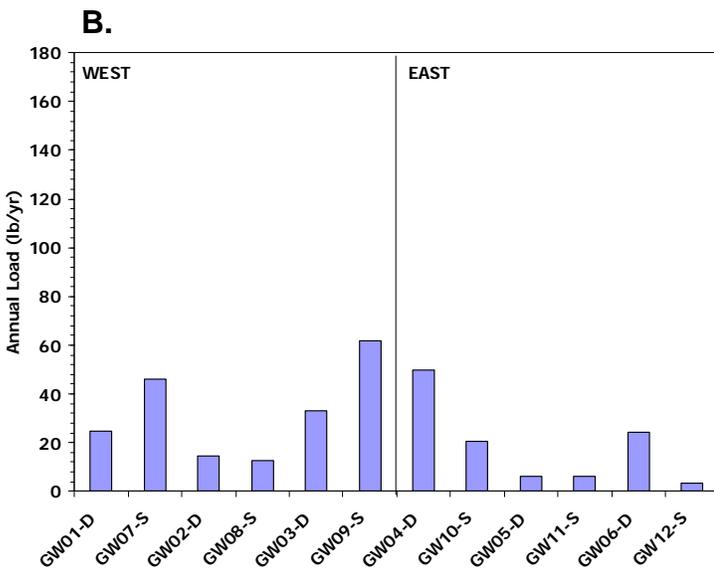
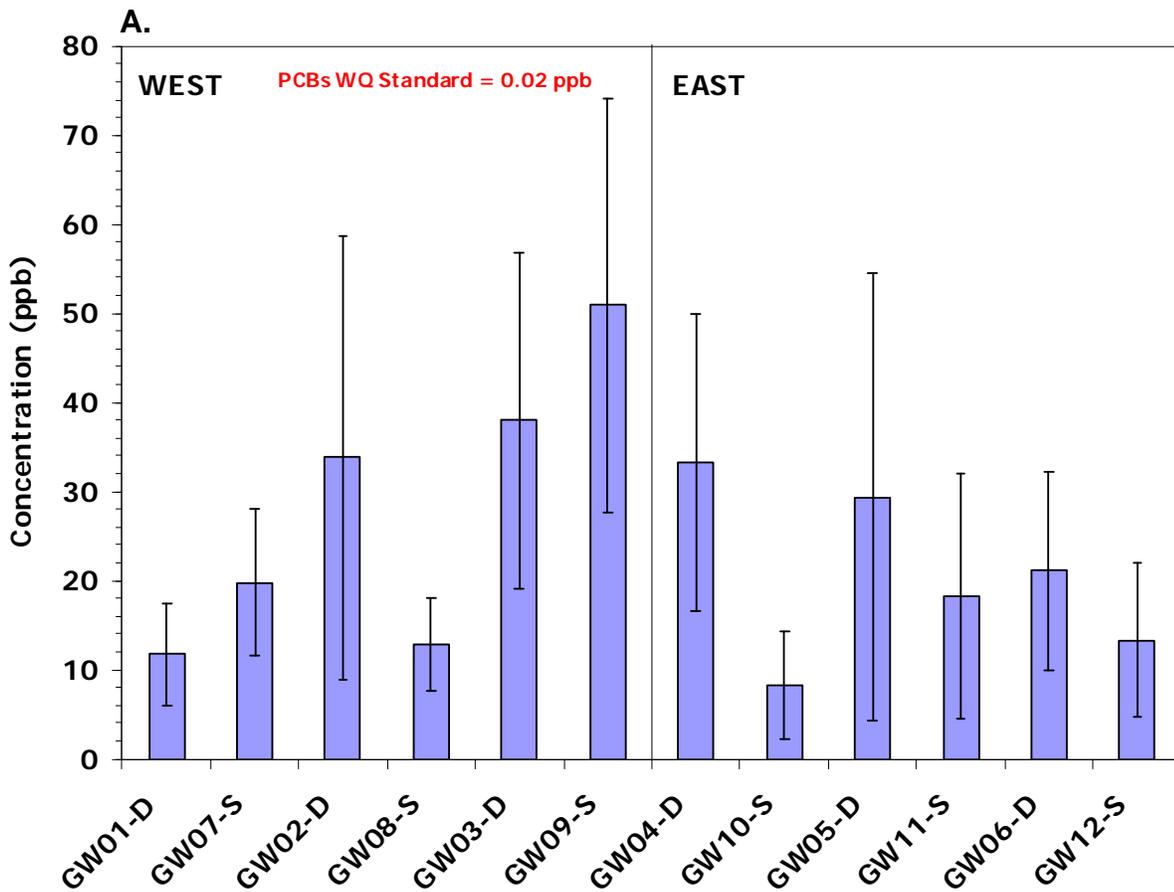


Figure 19. Mean Σ PCB concentrations (a) and estimated annual Σ PCB loadings 2006 (b) and 2007 (c) in Kearny Marsh groundwater samples collected during 2006 - 2007. D = deep well; S = shallow well.

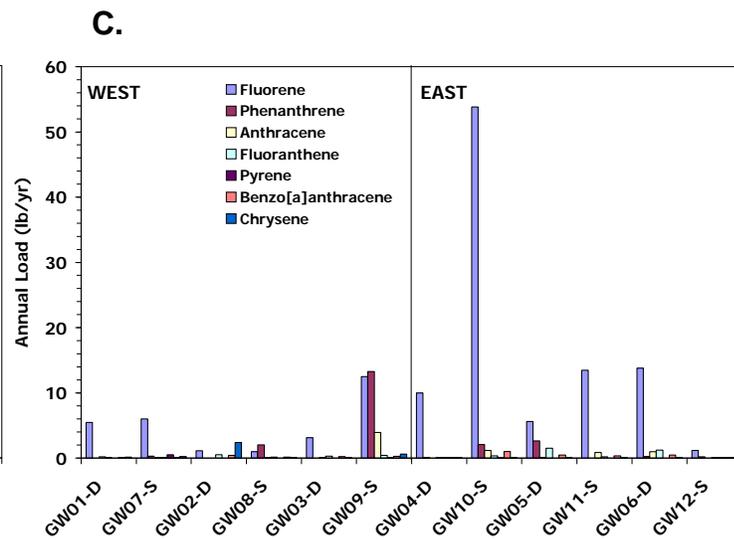
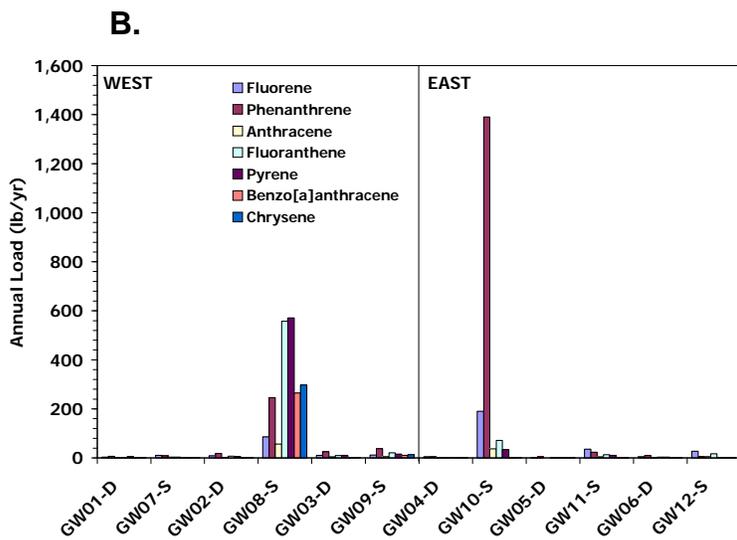
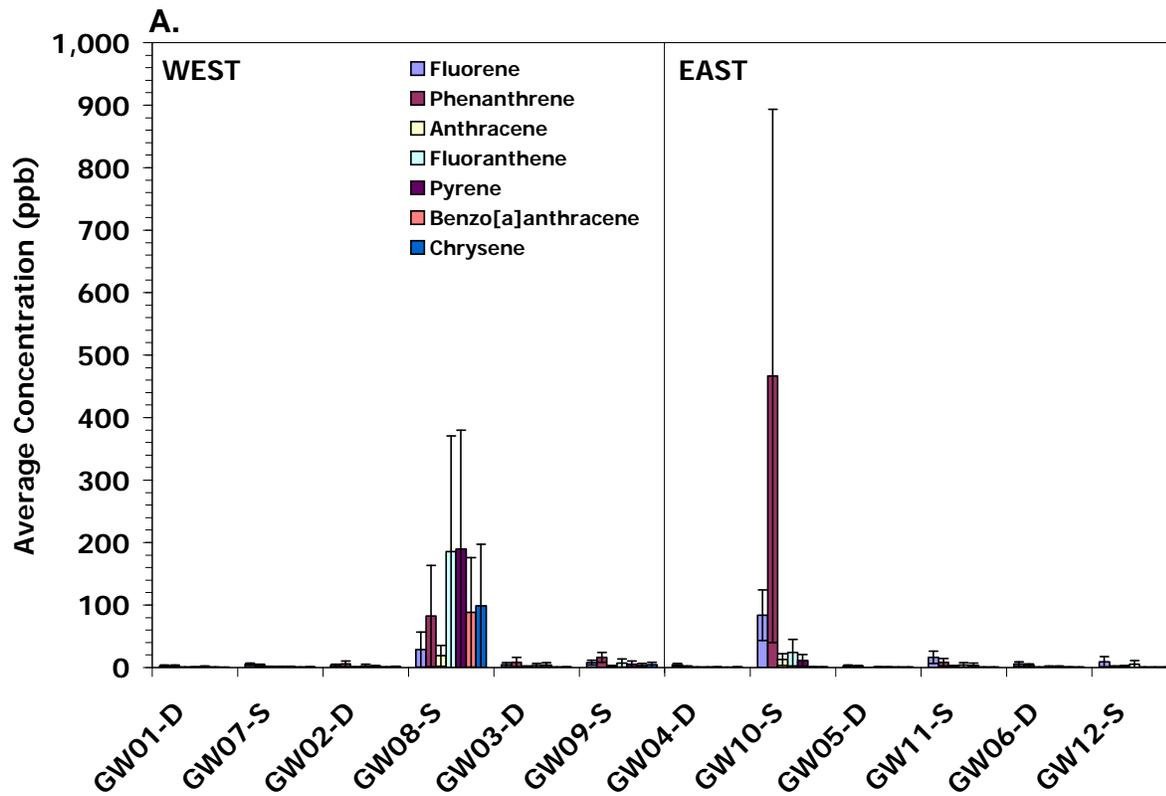


Figure 20. Mean PAH concentrations (a), estimated 2006 (b), and 2007 (c) annual PAH loadings in Kearny Marsh groundwater samples collected during 2007 - 2008. D = deep well; S = shallow well.

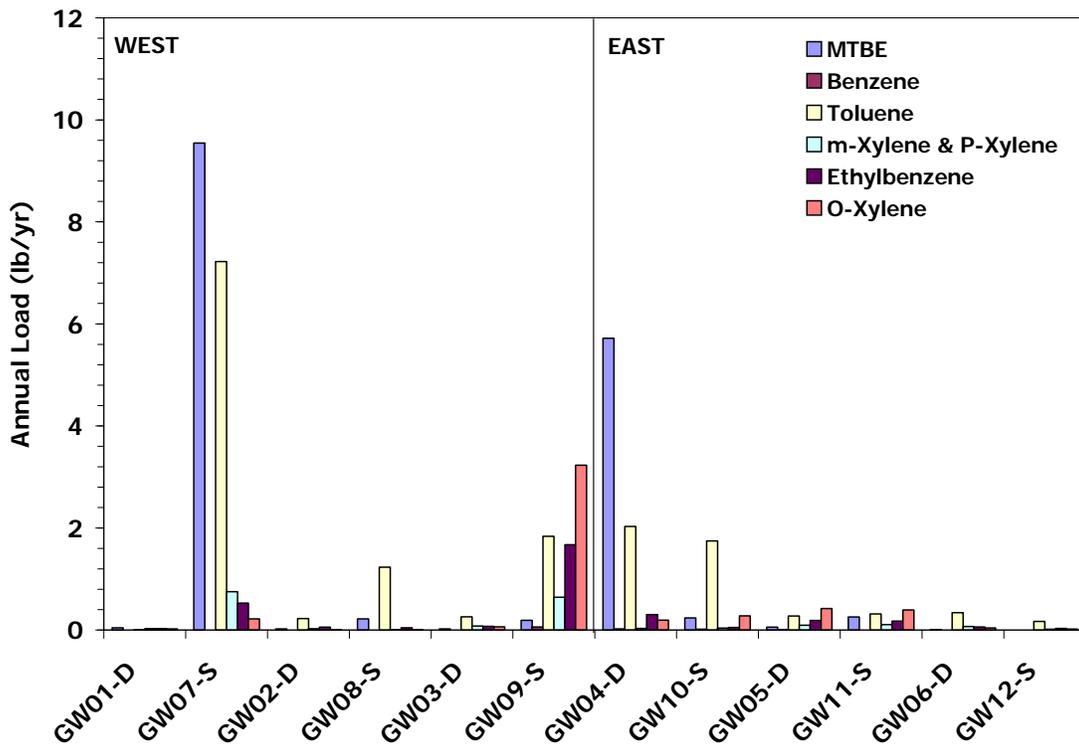
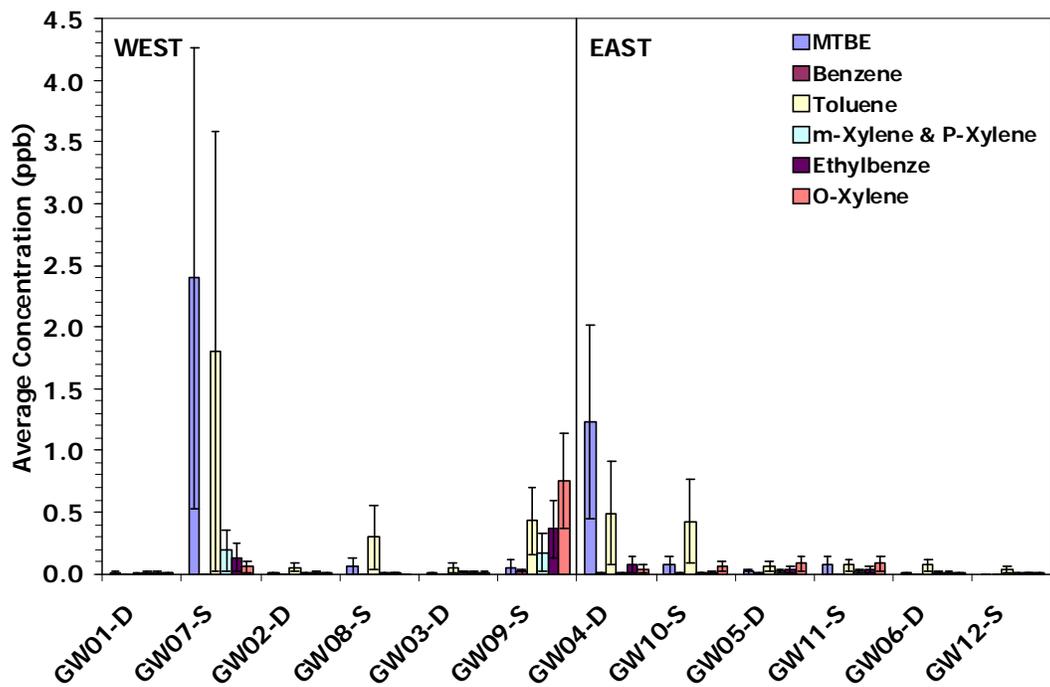


Figure 21. Semi-volatile organic (VOC) concentrations (a) and estimated annual VOC loadings (b) in Kearny Marsh groundwater samples collected during 2007. D = deep well; S = shallow well.

Table 4. Annual Nutrient Loadings to Kearny Marsh Based on Average 2006-2007 Estimated Loadings.

Site	Location	Nitrite-Nitrate	Ammonia	Total Phosphorus
KM1	Stormwater outlet base of East Midland Avenue	3.44	12.53	4.27
KM2	Broken Frank's Creek bulkhead	30.08	98.81	43.90
KM3	Inlet at Belleville Turnpike	3.25	6.73	5.28
GW01-D	Gunnel Oval	299	24,741	532
GW07-S	Gunnel Oval	273	22,189	920
GW02-D	Behind Automobile Scrap Yard	838	8,396	1,441
GW08-S	Behind Automobile Scrap Yard	598	5,424	2,379
GW03-D	Keegan Landfill	500	4,593	2,081
GW09-S	Keegan Landfill	260	14,918	7,720
GW04-D	Town of Kearny Landfill	389	51,538	2,449
GW10-S	Town of Kearny Landfill	441	58,831	2,437
GW05-D	New Jersey Turnpike	189	98,510	2,509
GW11-S	New Jersey Turnpike	174	103,439	2,531
GW06-D	Belleville Turnpike	401	70,134	3,529
GW12-S	Belleville Turnpike	646	837	582
TOTAL ESTIMATED ANNUAL LOAD		5,046	463,669	29,163

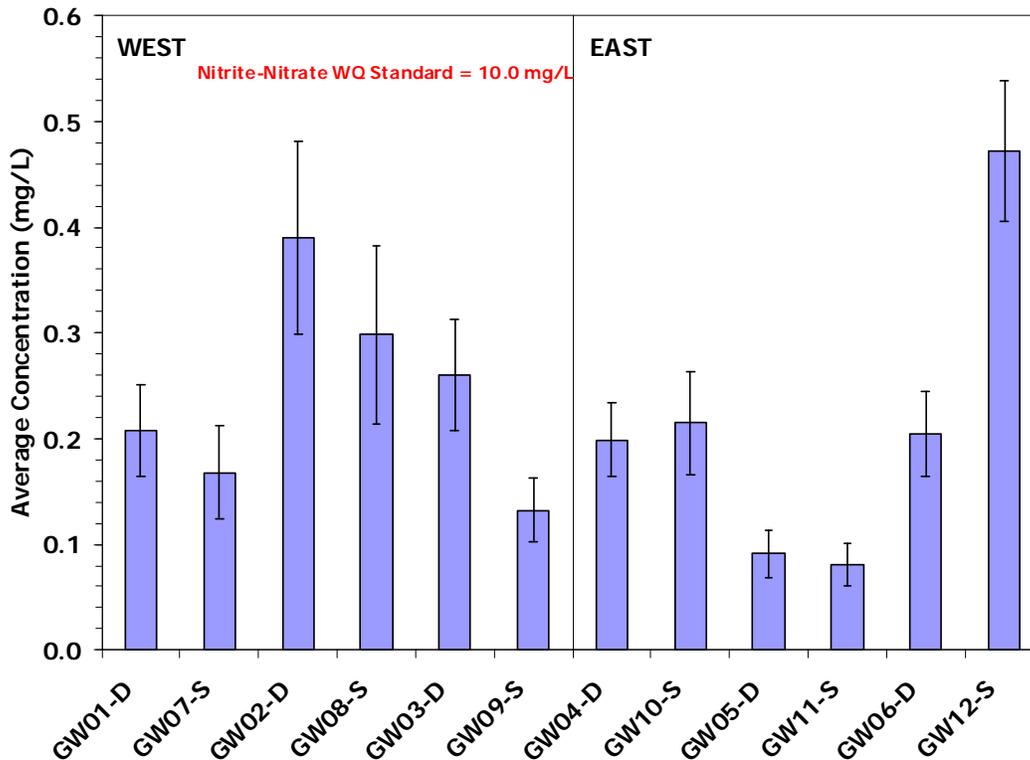
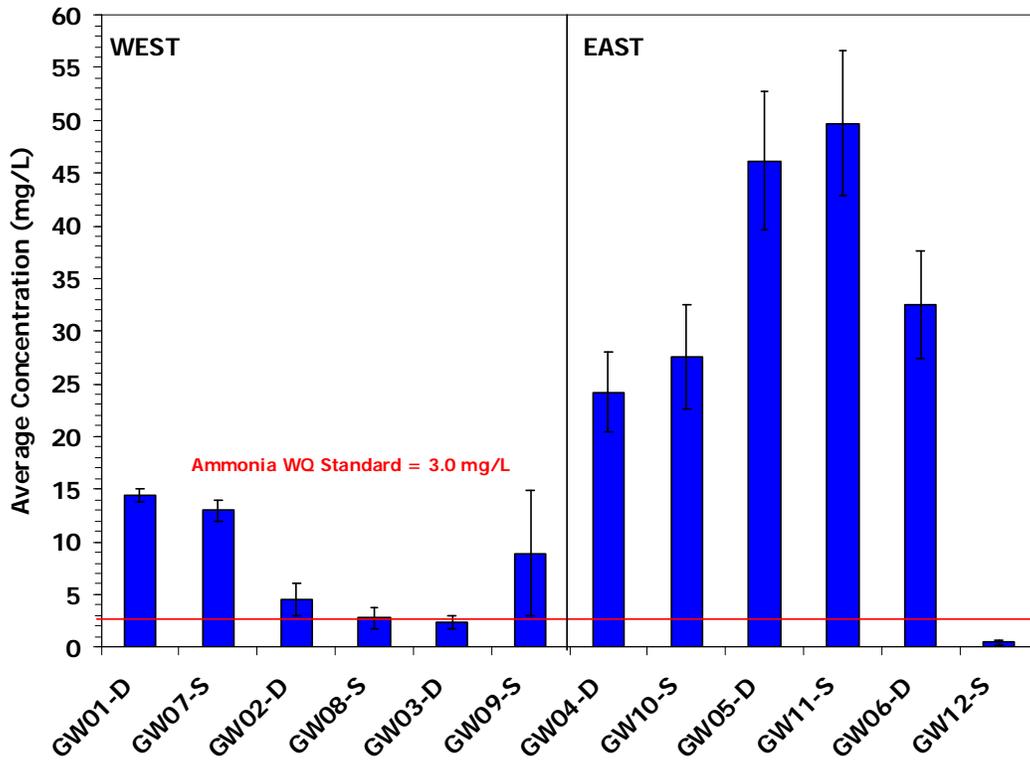


Figure 22. Mean ammonia (a) and nitrate-nitrite (b) concentrations in Kearny Marsh groundwater samples collected during 2006 - 2007. D = deep well; S = shallow well.

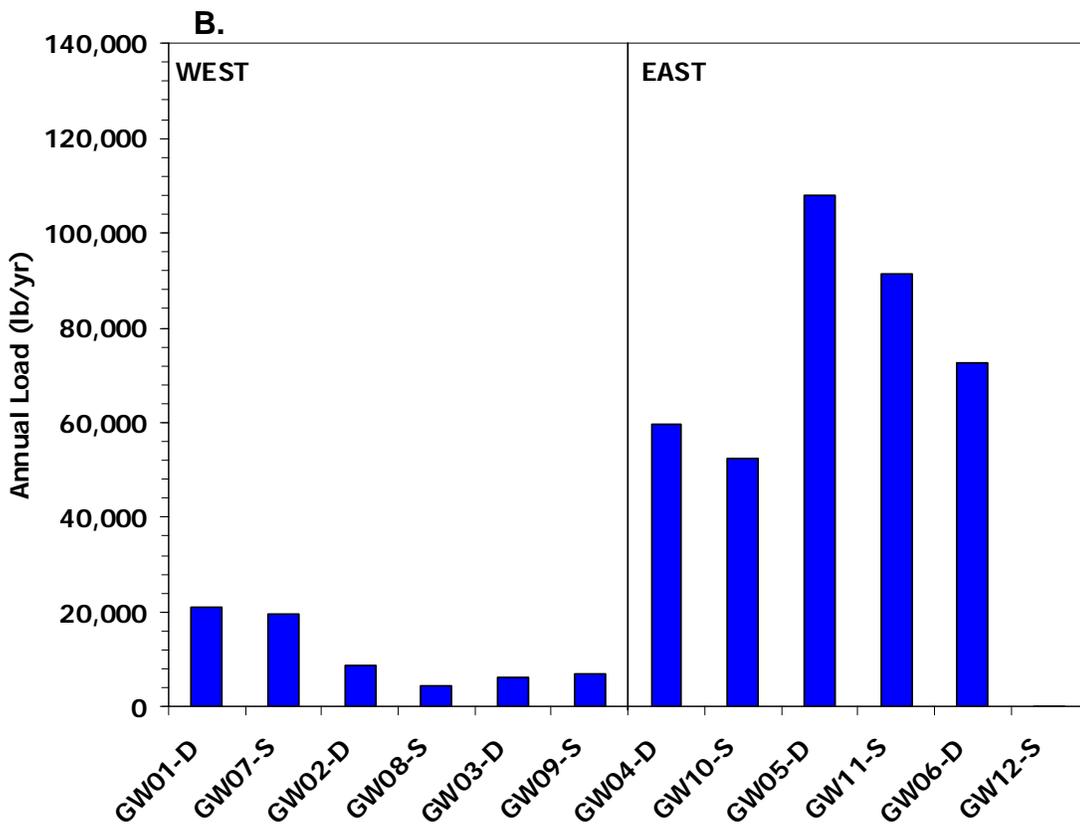
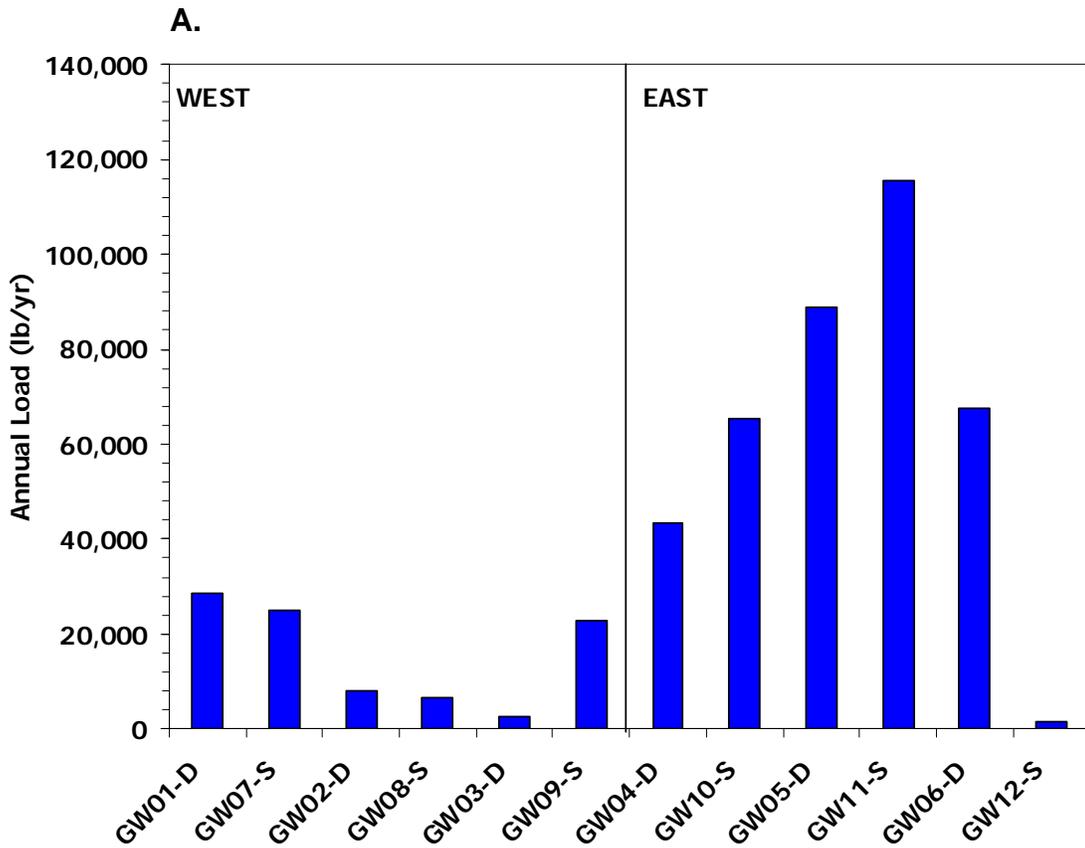


Figure 23. Estimated mean ammonia loadings in Kearny Marsh groundwater during 2006 (a) and 2007 (b).

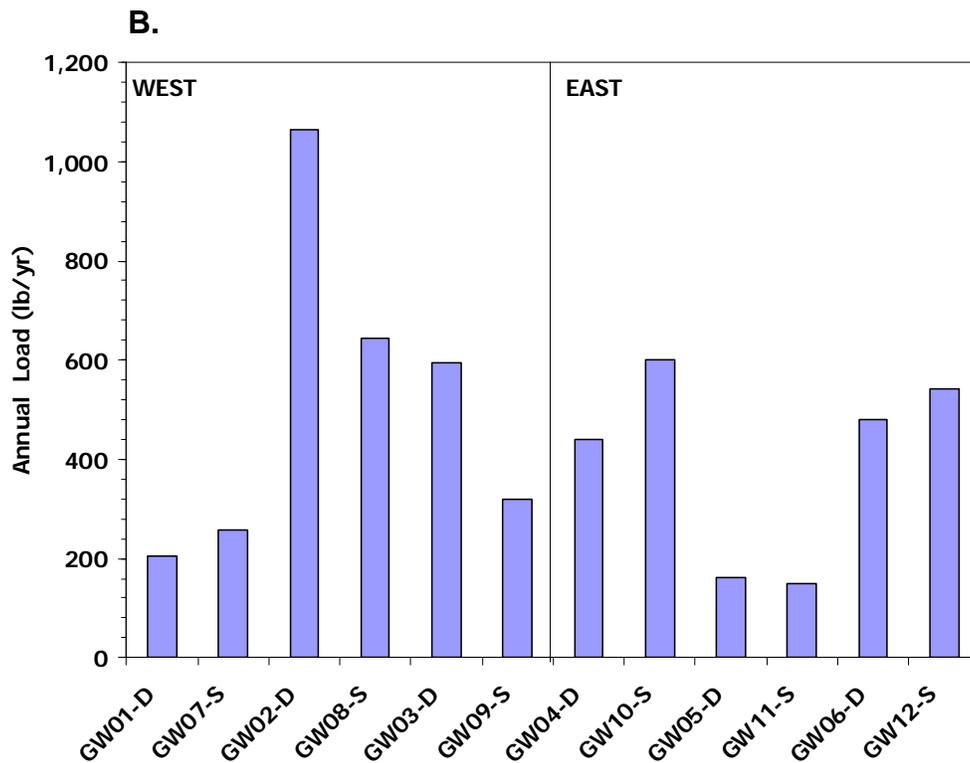
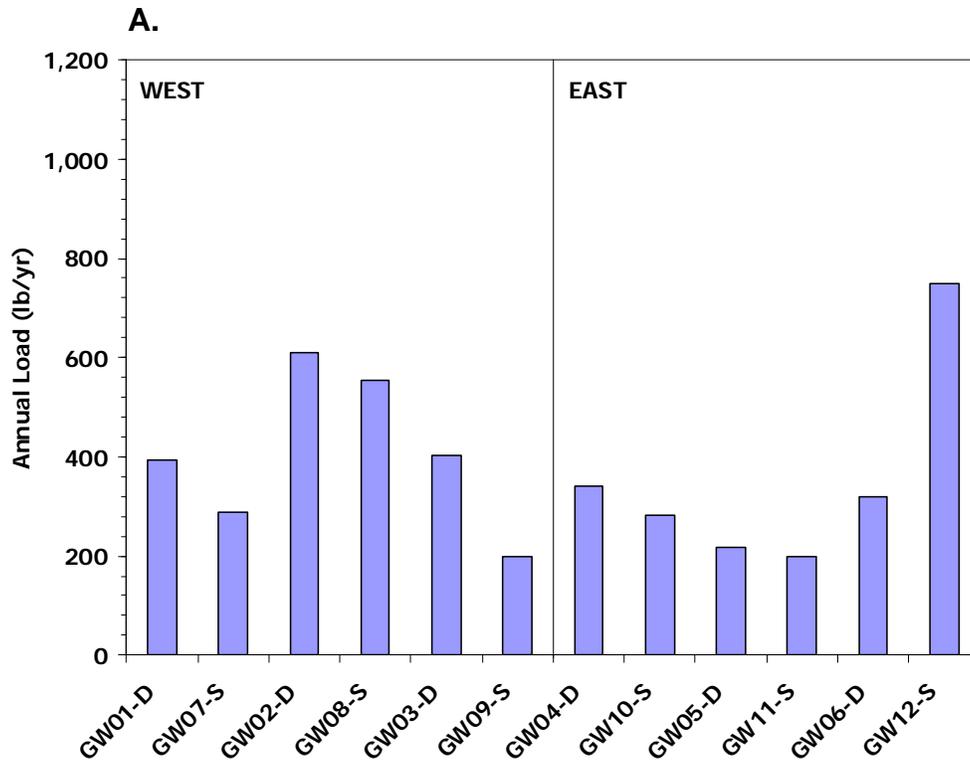
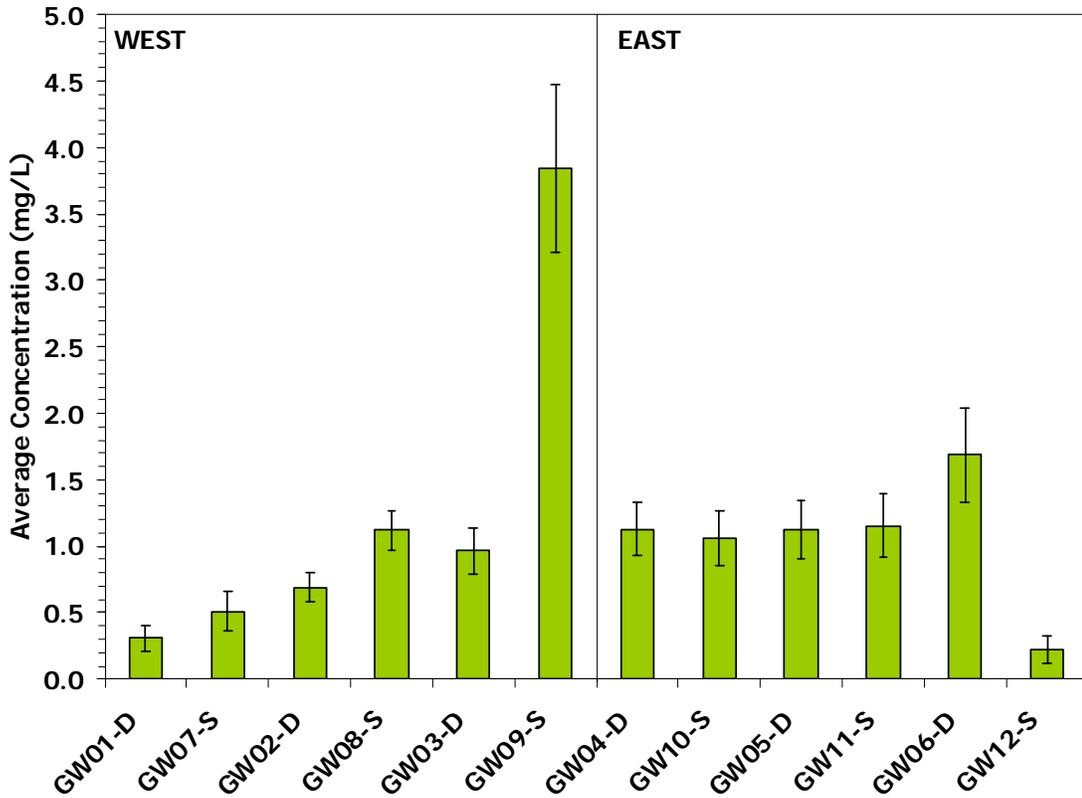


Figure 24. Estimated mean nitrite-nitrate loadings in Kearny Marsh groundwater during 2006 (a) and 2007(b).



**Figure 25. Mean total phosphorus concentrations in Kearny Marsh groundwater samples collected during 2006 - 2007.
D = deep well; S = shallow well.**

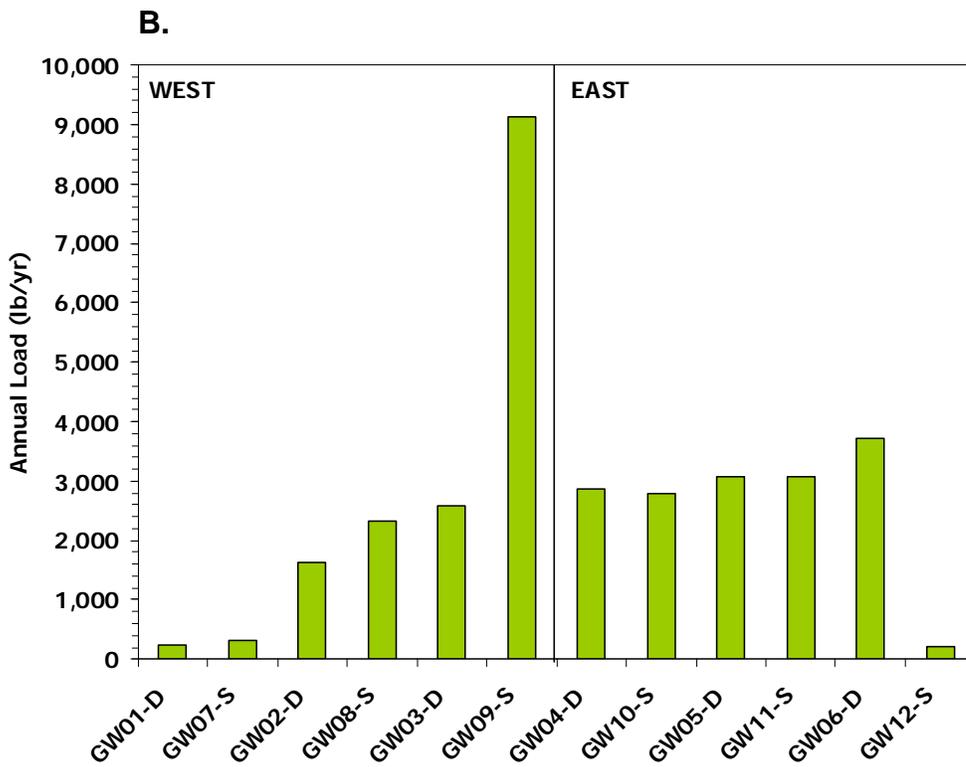
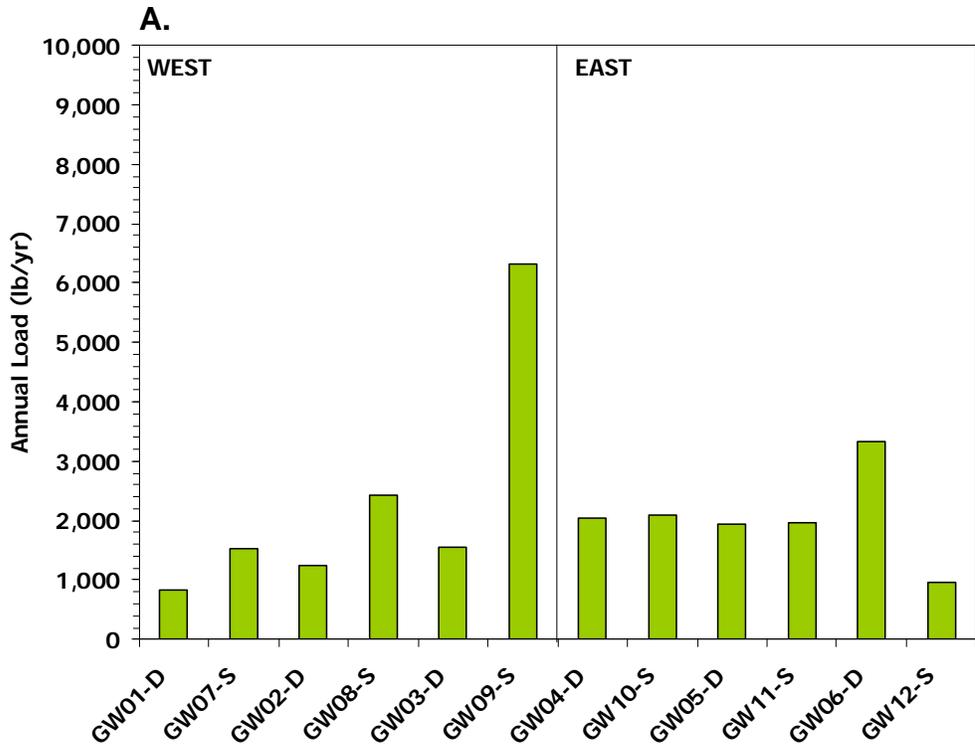


Figure 26. Estimated mean total phosphorus loadings in Kearny Marsh groundwater during 2006 (a) and 2007).

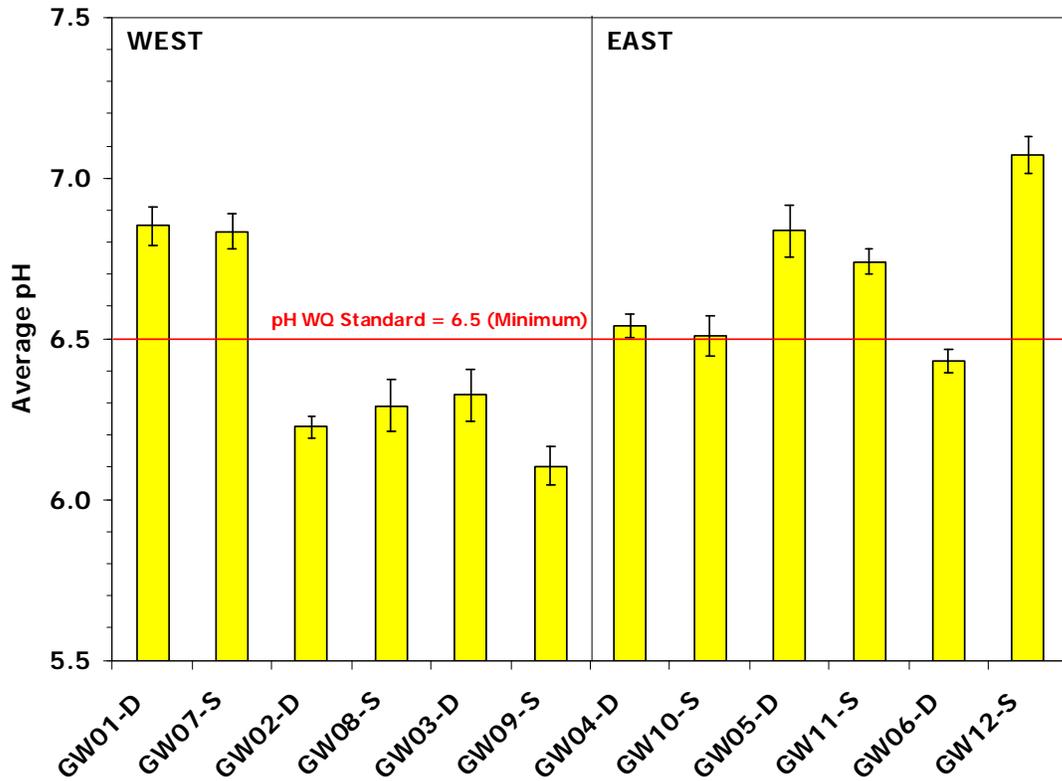


Figure 27. Mean pH in Kearny Marsh groundwater samples collected during 2007 – 2008.

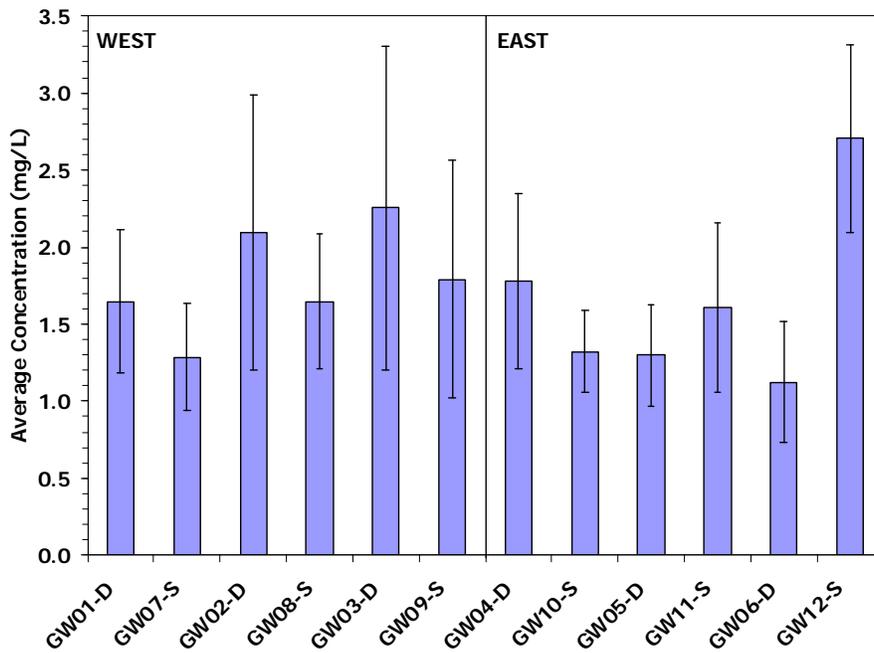


Figure 28. Mean dissolved oxygen in Kearny Marsh groundwater samples collected during 2007 – 2008.

HYDROLOGIC MODEL DEVELOPMENT

Evapotranspiration Calculations

ET rates, no matter how they were measured/calculated, followed a seasonal pattern, with higher summer rates and lower rates in the fall and winter (Figure 29). This is due to the increased temperature and plant growth in spring and summer. The lowest ET rates for May – December 2007 were obtained using the Thornthwaite equation (average ET = 0.113 in/day). The highest rates were observed using the lysimeter measurements (0.260 in/day), which were more than double the ET rate predicted by the Thornthwaite calculation. The eddy correlation data (0.176 in/day) fell between Thornthwaite and the lysimeter data. The eddy correlation method was chosen for use in the SWMM and MODFLOW models since it had the lowest standard error and is currently considered the best method with which to accurately estimate ET rates. *However, we note that two factors may still be contributing to an underestimation of ET using this method: 1) days with precipitation are calculated as contributing zero ET; and 2) empirical data was collected in September and December, when plant transpiration is below the summer peak.*

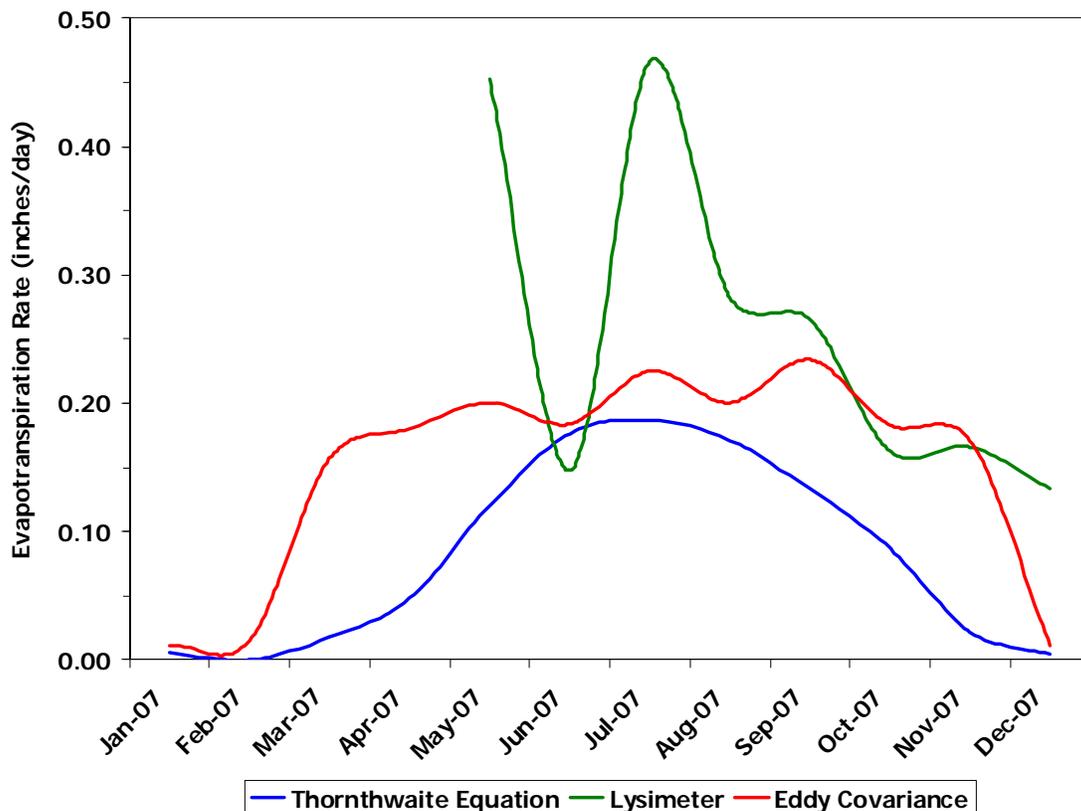


Figure 29. Comparison of calculated ET using the Thornthwaite Equation and empirically determined ET using lysimeter measurements versus eddy covariance measurements.

SWMM SURFACE WATER

Water budgets for 2006 and 2007 show that precipitation was the largest water input to Kearny Marsh in both years modeled, and the largest water loss was from infiltration into the ground (Table 5). Precipitation in 2006 was equal to the average for New Jersey (2006 = 48.57 in/yr; NJ average = 44.99 in/yr); in 2007 precipitation was higher than the NJ average (54.32 in/yr). Infiltration into the ground accounted for a loss of 18.50 in/yr in 2006 and 21.41 in/yr in 2007. More water evaporated, infiltrated, and ran off in 2007 versus 2006 due to the higher amount of precipitation (and therefore available water).

Table 5: Annual water budgets for Kearny Marsh calculated using USEPA SWMM.

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

From the model, it was predicted that flooding occurred in both 2006 and 2007 at two locations: the area adjacent to Gunnell Oval and the headwaters of Frank’s Creek. 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 14, 2005, 5.6 inches of rain fell in Kearny, resulting in flooding in the Keegan Landfill in the western portion of Kearny Marsh (Figure 30). This area is near 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 east of the Kearny Marsh boundary, and so was not included in the surface water model.

From the SWMM model we were able to determine that the broken bulkhead connecting Kearny Marsh to Frank’s Creek is affecting surface flows in this system. During low tide, the Frank’s Creek system drains water out of the marsh from both the broken bulkhead area and the designed drainage system in the southwestern section of Kearny Marsh. This situation changes, however, during high tide. The tide gates located along Frank’s Creek and its tributaries are in working order (N. Agnoli, *personal communication*) and are closed during a high tide. This causes water

to build up behind the tide gates, and allows water flowing from upstream of the broken bulkhead to leave Frank's Creek and flow into Kearny Marsh (Figure 31).



Figure 30. Flooding in the Keegan Landfill south of the Gunnell Oval (photo taken 10/14/05).

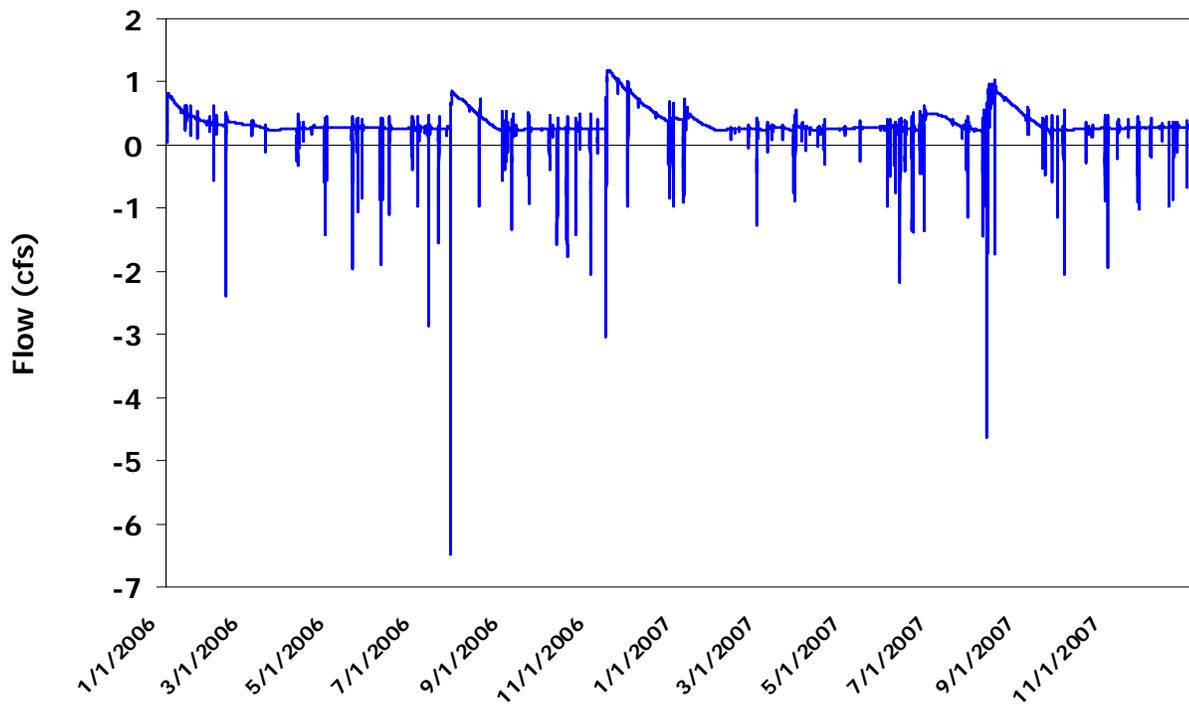


Figure 31: Predicted flows between Kearny Marsh and Frank's Creek (positive flow moves from Kearny Marsh into Frank's Creek; negative flows move into Kearny Marsh).

MODFLOW Groundwater

The Visual MODFLOW model was able to predict groundwater flow direction and velocity based on our input data. The general groundwater flow direction is from west to east, towards the Hackensack River (Figure 32). This flow prediction coincides with the direction of groundwater movement observed by Mansoor et al. (2006), as well as the direction determined using data obtained from the groundwater well transducers. This means that the water quality of the western perimeter groundwater can impact the marsh groundwater as it flows towards the eastern portion of the marsh. In addition, data from the well pressure transducers indicate a shallow water table that responds to precipitation.

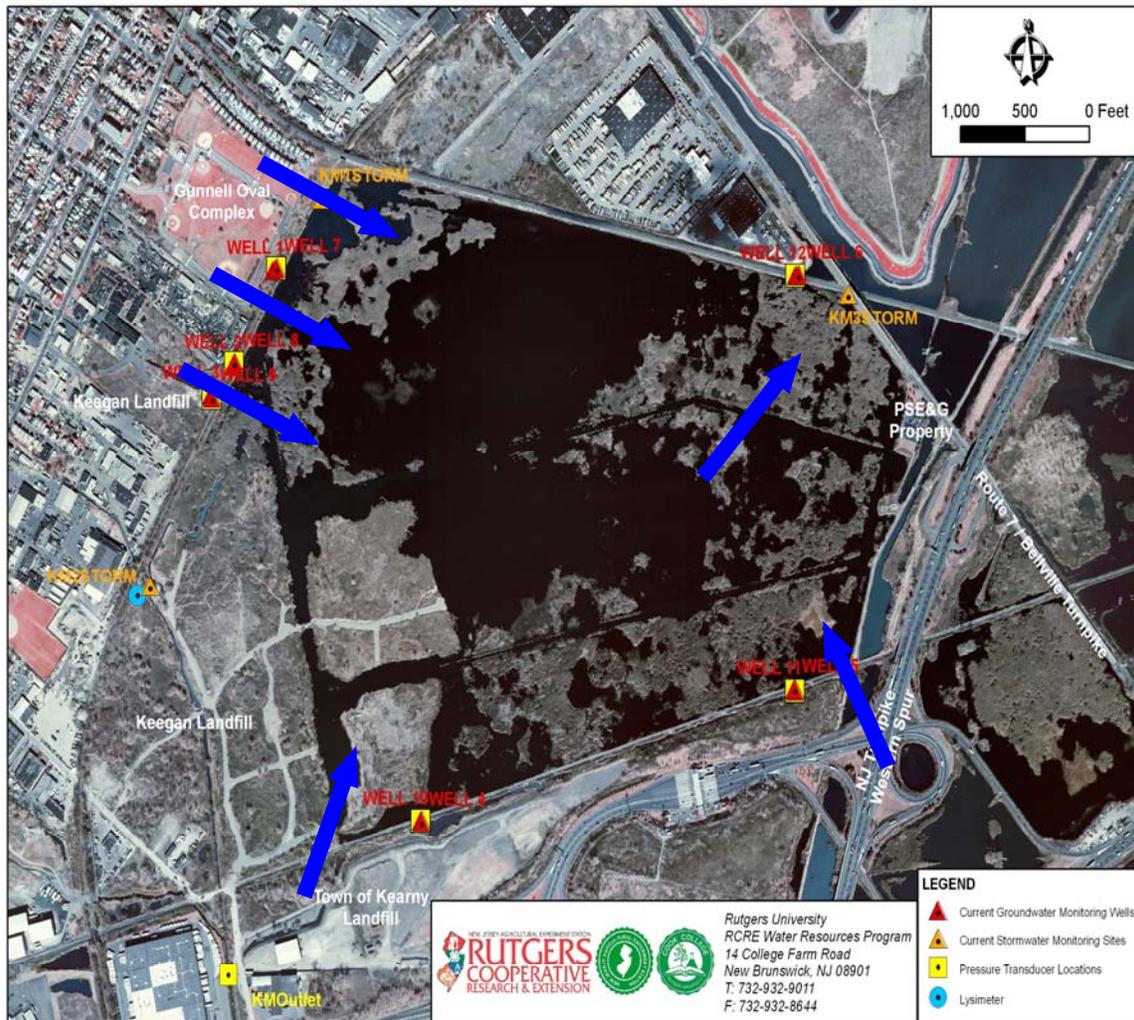


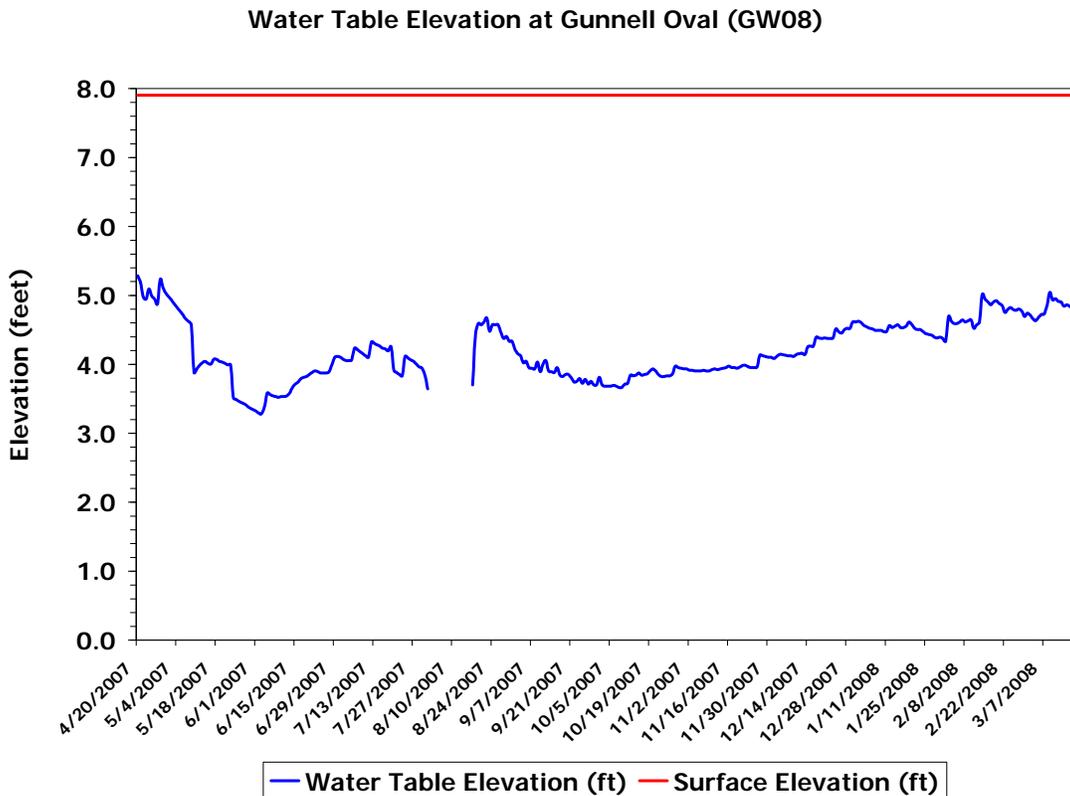
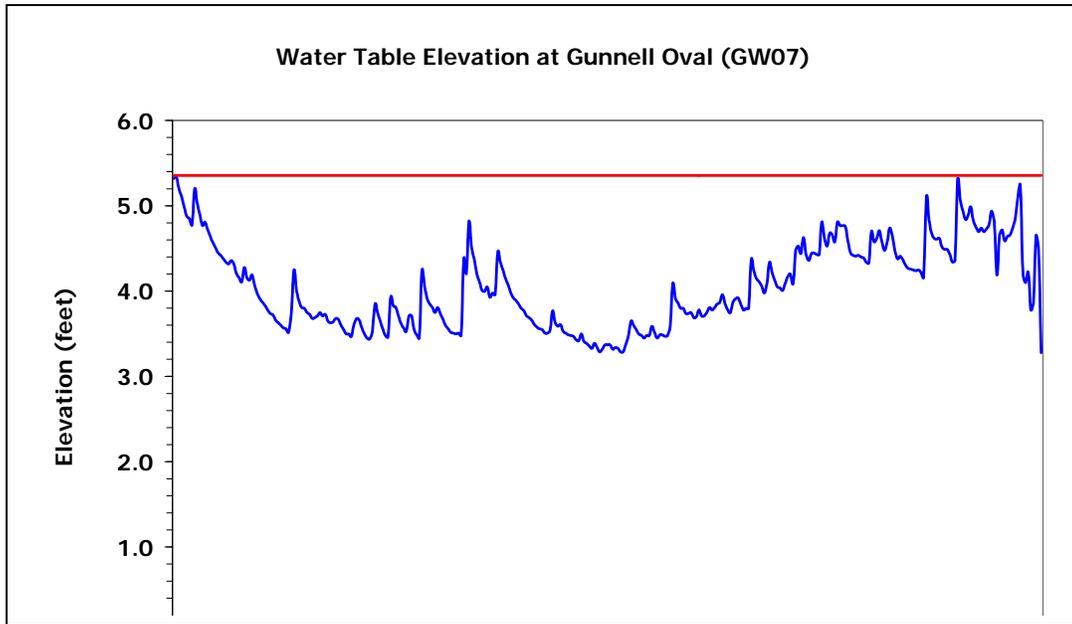
Figure 32. Direction of groundwater flow into and through the Kearny Marsh.

Groundwater velocities were variable throughout the year, depending on the amount of recharge and evaporation occurring in Kearny Marsh. Between years, however, the groundwater velocities were similar (Table 6). Groundwater may be draining into Kearny Marsh at a regular rate and flowing out to the Passaic River. Groundwater velocities were predicted to be higher in areas adjacent to the DRN due to changes in the groundwater head elevation and possible changes in marsh water depths. Since previously, little was known about groundwater resources in the vicinity of Kearny Marsh, this model has provided some valuable information on the possible hydrologic dynamics of this system.

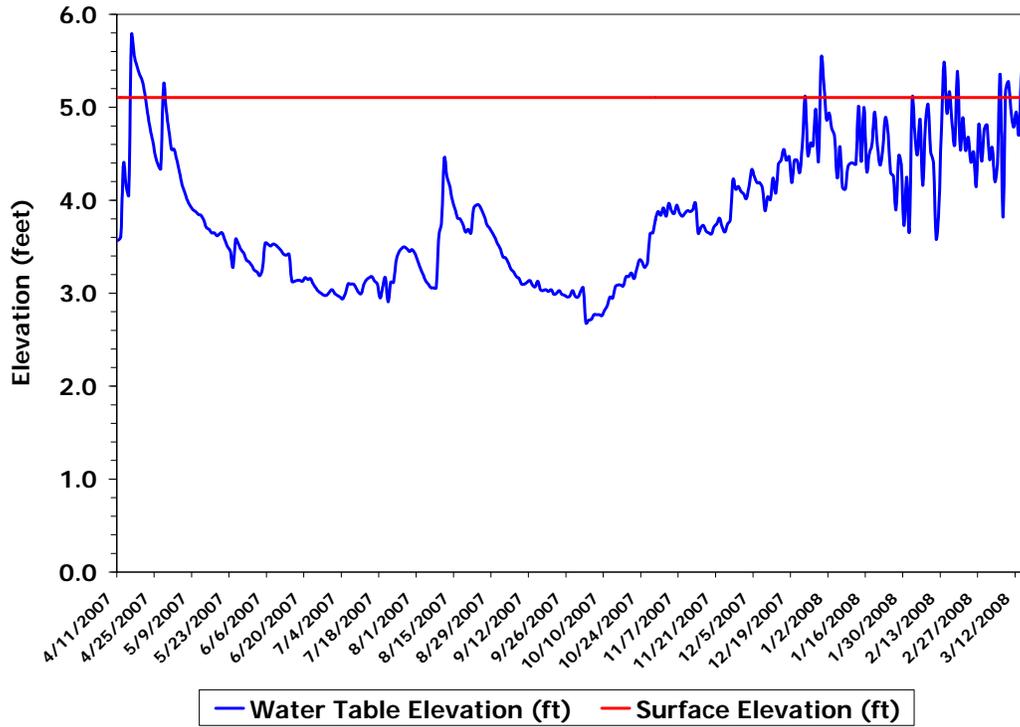
Table 6: Modeled average, minimum, and maximum groundwater velocities (feet/day) in Kearny Marsh.

VELOCITY (feet/day)	2006	2007
Average	0.0099	0.0106
Minimum	0.0000	0.0000
Maximum	0.1426	0.1412

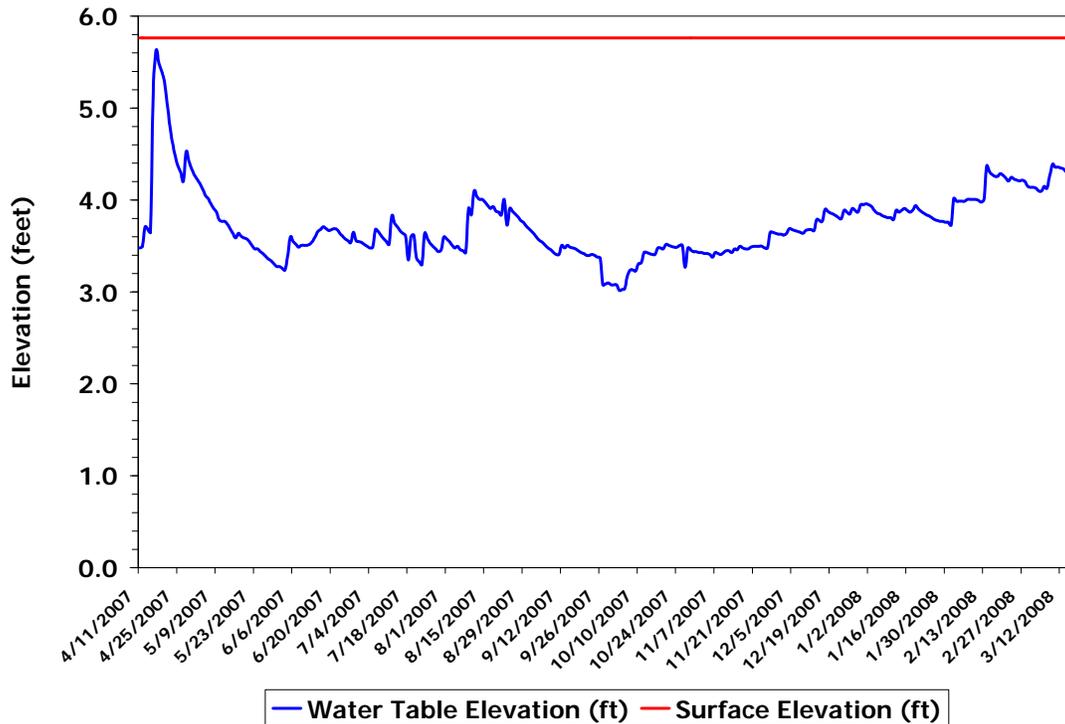
Figures 33 - 38: Water table elevations as recorded by pressure transducers in the six shallow groundwater wells. Water table elevations above ground surface elevations indicate the water above the soil surface (flooding).



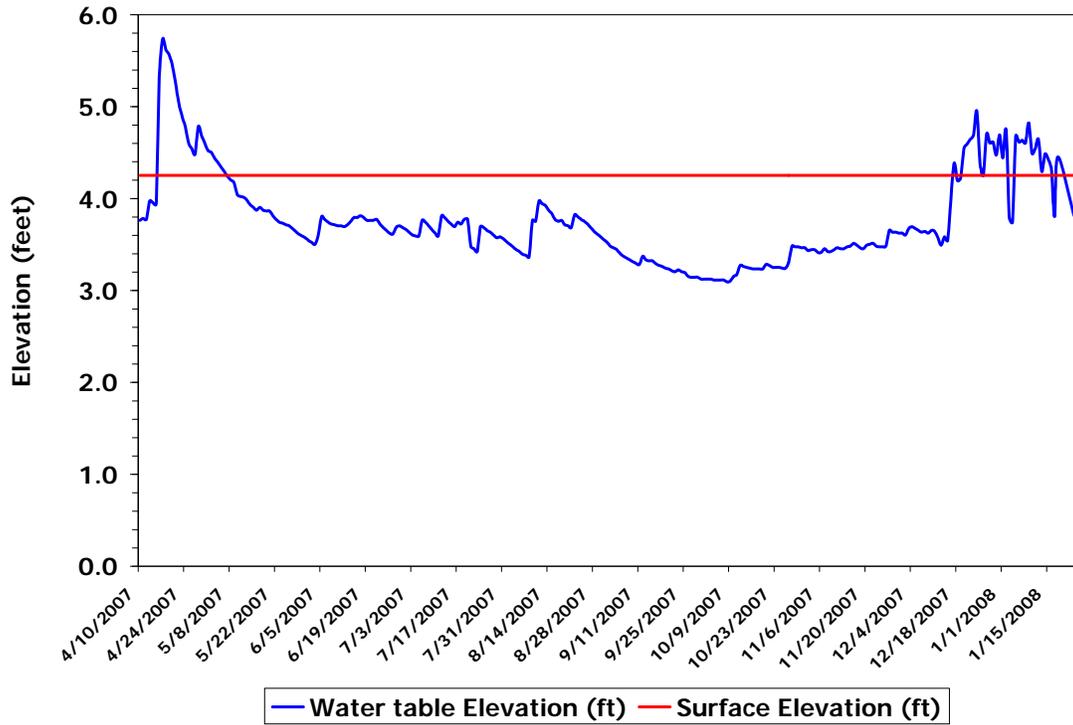
Water Table Elevation at Keegan Landfill (GW09)



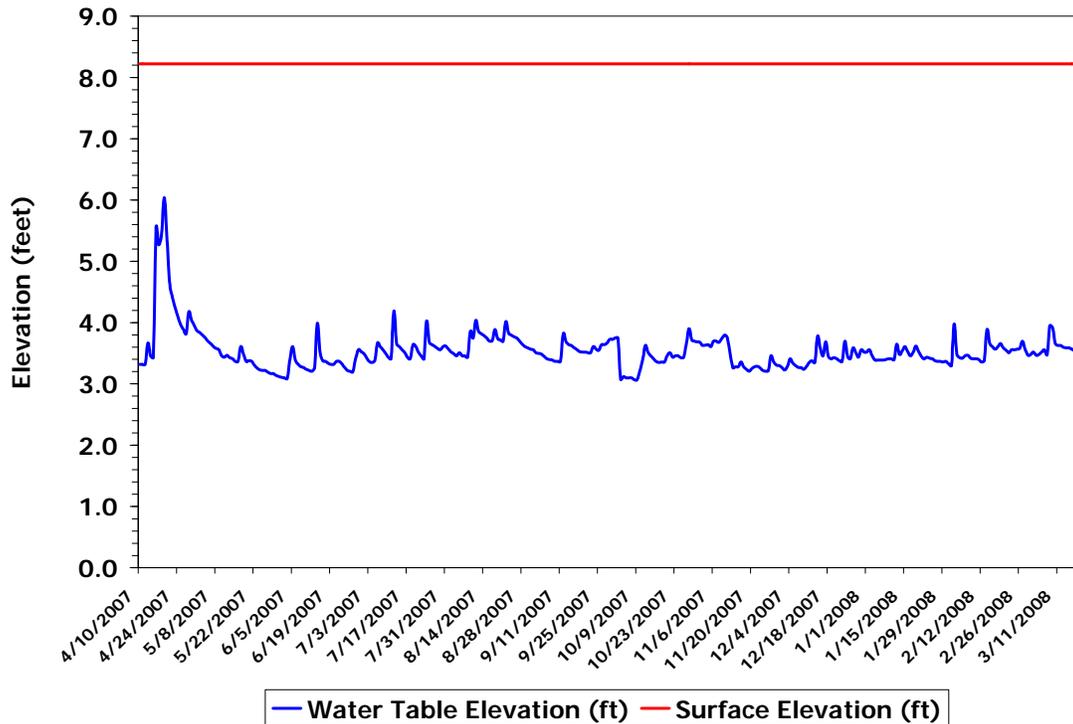
Water Table Elevation at Bergen Avenue (GW10)



Water Table Elevation at New Jersey Turnpike (GW11)



Water Table Elevation at Belleville Turnpike (GW12)



STUDY CONCLUSIONS

HYDROLOGY

The hydrology of the Kearny Marsh is due to a complicated interaction between storm-driven surface waters, an engineered tide gate system, and groundwater that is discharging into the marsh. General conclusions about the system's overall hydrology that can be derived from the study field work and the models are as follows:

1. Kearny Marsh is a groundwater discharge wetland, gaining water in the marsh surface from groundwater, which helps to maintain water levels in the marsh.
2. Groundwater flow is in an easterly direction, with water moving from the Town of Kearny towards the Hackensack River.
3. The broken bulkhead between Kearny Marsh and Frank's Creek allows for additional water inputs into the marsh when high tides occur. If the high tidal cycle coincides with a storm event, then marsh water depths can be increased to the point where flooding occurs in surrounding areas. This effect was both predicted by the SWMM model and observed in the field.
4. Flooding is occurring in areas of the marsh due a combination of the shallow water table that becomes elevated during storm events, impermeable urban development that reduces the area available for infiltration of stormwater, and drainage through 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 NJMC reports and field observations show flooding occurs in areas adjacent to the marsh, but outside the SWMM model boundaries.

Stormwater Related Issues

1. More extensive data collection is needed to characterize the stormwater runoff flows and contaminant loadings entering Kearny Marsh, specifically the runoff entering through the Frank's Creek connection.
2. Nutrients are a major problem in runoff entering Kearny Marsh. The nutrient data show that this freshwater marsh system is phosphorus limited, yet total phosphorus concentrations are higher than the NJ State water quality standard. These results suggest

the potential for rapid eutrophication of Kearny Marsh due to the limiting nutrient entering the system in higher than regulated concentrations.

3. Monitoring of the quality of the open waters found **within** Kearny Marsh should be conducted to determine what processes (if any) are affecting contaminant transformation or sequestration during residence time within the marsh.

Groundwater Related Issues

1. Groundwater water quality at discrete locations surrounding Kearny Marsh was determined. However, to more fully characterize the sources and amount of ongoing groundwater contamination inputs, it is recommended that additional groundwater wells be placed up gradient of the existing monitoring wells (i.e., to the west of the marsh in the Town of Kearny and south of the Kearny Marsh between the marsh and the Passaic River).
2. Ammonia, possibly due to landfill leachate, is a problem in the groundwater, especially in the eastern portion of the marsh down gradient from the unlined Keegan and Town of Kearny Landfills. Previous research in Kearny Marsh found an average ammonia concentration of 54.8 mg/L in the Hackensack River surface water to the east of Kearny Marsh, which was hypothesized to be due to the influence from the adjacent landfill (Konsevick et al. 1994). The Kearny Marsh groundwater concentrations observed during this study are similar in value to the concentrations reported over a decade ago, indicating that possible leachate contamination of the groundwater is a continuing issue.
3. PAHs are a problem along the western edge of Kearny Marsh. Source tracking indicates that the groundwater PAHs are pyrolytic (combustion-based) in origin, and that potential contamination sources are located behind GW08 and possibly GW10.

Hydrologic Model Related Issues

1. Although empirical measurements of ET were conducted for this study, we believe that ET in this highly urbanized system may still be underestimated, especially during the summer plant growing season. Therefore, the model projections of surface water levels may be overstated and projected runoff may be understated, and so we suggest continued

refinement of these models, and additional field verification of critical parameters, particularly groundwater flows and ET measurements.

SLURRY WALL SIMULATION(S):

Once the models were validated, they were used to predict changes to Kearny Marsh hydrology after construction of the proposed slurry wall that will close off the Keegan Landfill from Kearny Marsh. Model assumptions related to the slurry wall include:

1. Surface water flow changes to the SWMM model post-wall included:
 - a. Reducing wetland area storage capability by the amount of area encompassed by the slurry wall. This was accomplished by creating an additional drainage area bounded by the slurry wall, and treating the entire area as 100% impervious.
 - b. These modifications change all the precipitation that lands on the redeveloped drainage area to runoff, which the model then input into Kearny Marsh.
2. As per the NJMC (Thomas Marturano, *personal communication*) and the Town of Kearny restoration plans (Neglia 2001), the connection between Frank's Creek and Kearny Marsh was retained in the SWMM model simulations.
3. In Visual MODFLOW, a Wall (HFB) boundary was drawn around the Keegan Landfill in the location (Thomas Marturano, *personal communication*) where the slurry wall is planned; data for the HFB wall (thickness and permeability) were obtained from the NJMC (Thomas Marturano, *personal communication*). The reduced permeability was incorporated into the MODFLOW to model groundwater flow.
4. Proposed changes to the Kearny Marsh drainage network, taken from the Town of Kearny study (Neglia 2001), were incorporated into the model (additional outfalls, widened channels and other water control structures).

Simulations were then run for both SWMM and MODFLOW under the following precipitation scenarios:

1. Dry – precipitation values taken from a drought year (2001).
2. Average – precipitation values from an average rainfall year (2002).
3. Wet – precipitation values from a wet year (2007).

Each scenario used the same evaporation and tide height data so that any differences would be due solely to the amount of rainfall. The validated 2007 model (without the slurry wall) used the same precipitation scenarios to provide a ‘baseline’ for comparison.

Model Projections

A comparison of the water budgets for the above conditions, as calculated by SWMM, shows an effect of increasing the developed/impervious area within the existing Kearny Marsh wetland system (Table 7). Under each precipitation scenario the following can be expected after construction of the slurry wall: evaporation increases, infiltration decreases, and runoff increases. These hydrologic impacts have been related to increased urbanization (Table 1). In the Kearny Marsh case, approximately 100 acres of impervious area would be added after construction of the slurry wall if the site is fully re-developed. The projected water table elevations (in relation to the surface elevations from the Digital Elevation Grid) drop in each of the precipitation scenarios (Table 8). This is in response to the surface water changes seen in the SWMM budget: less water is reaching the ground water because more is evaporating from the surface, less water is infiltrating to the groundwater, and more is running off into the Passaic River. The model also projects that the average depth of water in the marsh will increase after construction of the slurry wall (Table 9), and that surface flooding will increase under all three precipitation scenarios (Table 10). Installation of the slurry wall, followed by closure of the Keegan Landfill, and subsequent development of the 100 acres is projected by the models to result in hydrologic changes typically observed after urbanization/development.

Table 7: SWMM calculated water budgets for dry, average, and wet precipitation scenarios before ('baseline') and after installation of the slurry wall ('slurry wall').

Water Budget Component (inches/year)	Dry – Baseline	Dry – Slurry Wall	Average - Baseline	Average – Slurry Wall	Wet - Baseline	Wet – Slurry Wall
Total Precipitation	30.51	30.51	41.59	41.59	54.32	54.32
Evaporation Loss	8.86	9.14	8.73	8.98	12.91	13.26
Infiltration Loss	10.46	8.76	16.57	14.27	21.41	18.42
Surface Runoff	11.02	12.45	15.65	17.59	19.57	22.22

Table 8: Visual MODFLOW modeled average water table elevations for dry, average, and wet precipitation scenarios before ('baseline') and after installation of the slurry wall ('slurry wall').

	Dry - Baseline	Dry – Slurry Wall	Average - Baseline	Average – Slurry Wall	Wet - Baseline	Wet – 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	

Table 9. Model Estimated Change in Average Marsh Water Depth for Dry, Average, and Wet Precipitation Scenarios Before ('Baseline') and After Installation of the Slurry Wall ('Slurry Wall').

	Dry - Baseline	Dry - Slurry Wall	Average - Baseline	Average - Slurry Wall	Wet - Baseline	Wet - Slurry Wall
Average Marsh Depth (feet)	1.72	2.09	1.89	2.27	2.03	2.38
Difference (feet)	0.37		0.38		0.35	

Table 10. Model Estimated Change in Surface Flooding for Dry, Average, and Wet Precipitation Scenarios Before ('Baseline') and After Installation of the Slurry Wall ('Slurry Wall').

	Dry - Baseline	Dry - Slurry Wall	Average - Baseline	Average - Slurry Wall	Wet - Baseline	Wet - Slurry Wall
Annual Surface Flooding (million gallons)	53.51	65.64	110.43	125.26	142.99	162.60
Difference (Mgallons)	12.125		14.83		19.616	

POLYCYCLIC AROMATIC HYDROCARBON (PAH) SOURCE TRACKING

Polycyclic aromatic hydrocarbons (PAHs) are produced anthropogenically when organic material is combusted (pyrolytic), or when petroleum products (petrogenic) are released into the environment. Pyrolytic PAHs form as a consequence of incomplete fuel combustion, whereas petrogenic PAHs are derived from crude oil or unburned fuel and their refined products. An indicator of an anthropogenic versus natural PAH source is an increase in the proportion of thermodynamically less stable PAH isomers relative to the stable isomers: anthracene relative to phenanthrene, fluoranthene relative to pyrene, benzo[a]anthracene relative to chrysene (Vrana et al. 2001). Numerous sources contribute to environmental release of PAHs in the northern NJ/NY metropolitan region, including combustion of fossil fuels, petroleum spills or dumping, and PAH release from products containing petroleum or coal, such as coal tar sealants and creosote (Valle et al., 2007). Based on the surrounding land use, possible sources contributing to current PAH inputs into Kearny Marsh may include vehicle emissions, tire wear, creosote railroad ties on the northern, western, and southern marsh perimeter, oil products on the auto body sites adjacent to Gunnell Oval, leaking underground storage tanks, pavement sealants, and landfills leaking leachate, as well as regional atmospheric deposition (Valle et al., 2007).

PAH Fingerprint Analysis

In order to further characterize potential sources of PAH contamination, a PAH ‘fingerprint’ analysis was conducted. PAH ‘fingerprints’ for each sample were created by dividing the individual PAH concentrations by the sum of the site’s total PAHs (Kimbrough & Dickhut 2006). These fingerprints were compared to determine the similarities or differences in potential PAH sources at the various sampling locations.

PAH Ratios

Another method used to evaluate the potential source of environmental PAHs is to calculate specific PAH/PAH ratios in order to determine whether a suite of PAHs is from pyrolytic or petrogenic sources. PAH/PAH ratios have a history of usage in identifying PAH sources (Budzinski et al. 1997; Ghosh et al. 2000; Webster et al. 2000; Vrana et al. 2001; Sanders et al. 2002; De Luca et al. 2005). We analyzed the ratios of phenanthrene/anthracene, fluoranthene/pyrene, and chrysene/benzo(a)anthracene because samples were tested for these

compounds throughout the two year study period. A phenanthrene/anthracene ratio of <10 indicates a combustion source (Sanders et al. 2002; De Luca et al. 2005); a fluoranthene/pyrene ratio >1 indicates a combustion source (Sanders et al. 2002; De Luca et al. 2005); a chrysene/benzo(a)anthracene ratio <1 indicates a combustion source (Sanders et al. 2002).

PAH Characterization utilizing Principal Component Analysis

Principal Component Analysis (PCA) was employed to determine if there were specific PAH patterns among the various stormwater sampling points and the groundwater well locations. PCA is a multivariate statistical procedure that transforms a large number of variables into a small number of uncorrelated variables (Principal Components). The first Principal Component accounts for the highest possible variance in the dataset, and each succeeding Component explains as much of the remaining variability as possible. In a plot of Principal Components, samples that are similar will form a 'cluster' (Kim et al. 2006), and PCA is often used to compare different environmental samples (Burns et al., 1997). PCA was used to analyze Kearny Marsh PAH fingerprints because it has proven to be a robust method in determining PAH sources (Burns et al. 1997; Page et al. 1999; Golobocanin et al. 2004; Walker et al. 2005; Hwang and Foster 2006; Kim et al. 2006; Qiao et al. 2006).

PAH SOURCE TRACKING RESULTS

Stormwater

Stormwater PAH loading plots (Figure 39) show a clear separation between PAHs that originate from combustion sources (pyrolytic) versus non-combustion sources (petrogenic). These clusters are consistent with PAH patterns seen in urban stormwater runoff in Washington, DC (Hwang & Foster 2006). Pyrolytic PAHs include 3-, 4-, and 5-ring compounds such as fluoranthene and pyrene, and high molecular weight PAHs; PAHs from petrogenic sources include low molecular weight PAHs with one to three rings, such as fluorine, phenanthrene, and anthracene (Valle et al., 2007).

Kearny Marsh stormwater PAH ratios indicate that the source material is pyrolytic (combustion) in nature. Typical pyrolytic PAH sources are vehicular and other exhaust emissions, crankcase oil, asphalt, coal tar (a roofing and sealant material), creosote (a wood preservative), and wood

burning (Sanders et al. 2002). Possible sources of the pyrolytic PAHs in Kearny Marsh stormwater include deposition of exhaust from local and regional vehicular traffic, discharges from local industry, non-point source pavement runoff, and regional inputs from the greater metropolitan area

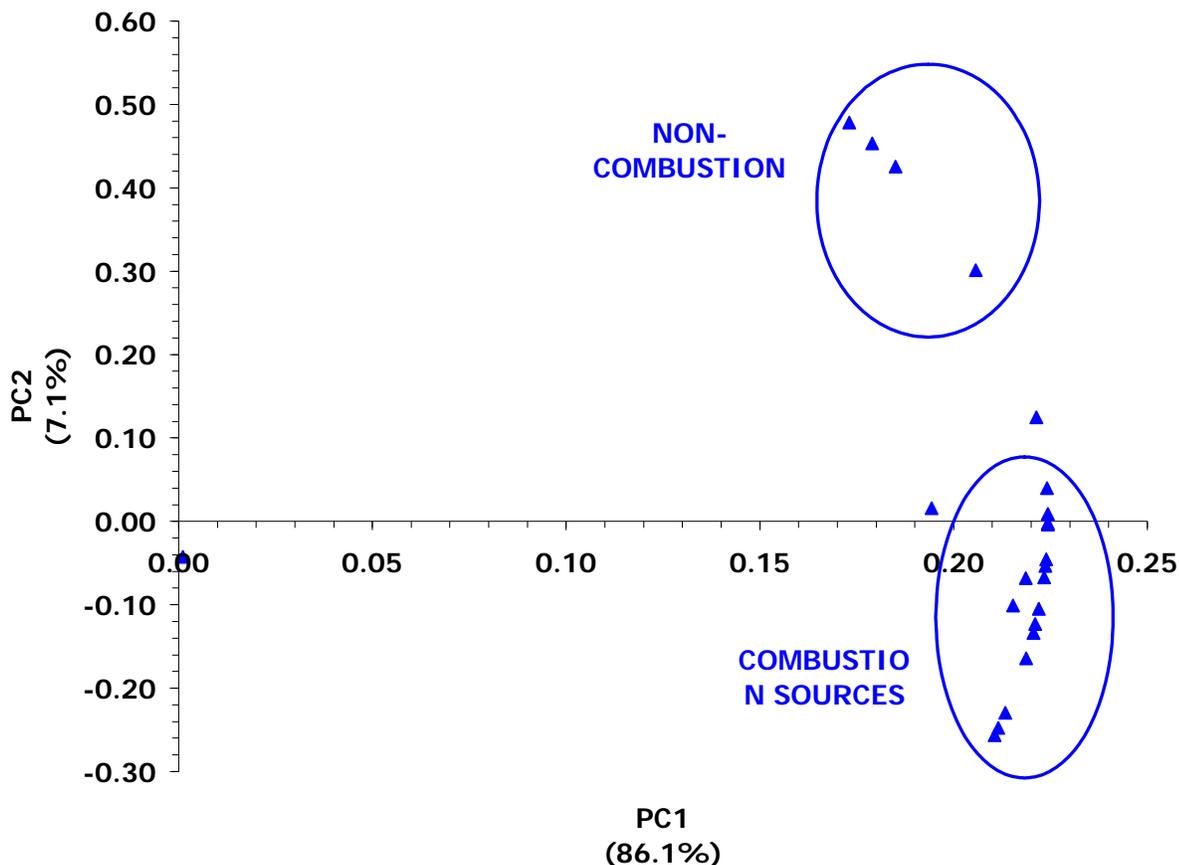


Figure 39: Principal Component Loading Plot of Kearny Marsh stormwater PAHs.

The clustering of KM2 and KM3 PAHs in the PCA ordination space (Figure 40), indicates a strong similarity in PAH composition at these two stormwater sampling locations, a composition that is quite different from the proportion of the various PAHs in KM1 stormwater. In general, concentrations of individual PAHs are also higher at KM 1 (Figure 6a). KM1 exhibits a larger proportion of high molecular weight (HMW) PAHs (benzo[a]pyrene, benzo[b+k]fluoranthene, benzo[e]pyrene, and indeno[1,2,3-cd]pyrene); KM2 and KM3 show a higher proportion of low molecular weight (LMW) PAHs (Figure 41). This indicates that KM1 has a different PAH source than the other two locations. Due to the high heat required for formation of these

compounds, HMW PAHs are more prevalent in pyrogenic sources (Kimbrough & Dickhut 2006), and so PAHs originating from a fuel source may be more common at this location.

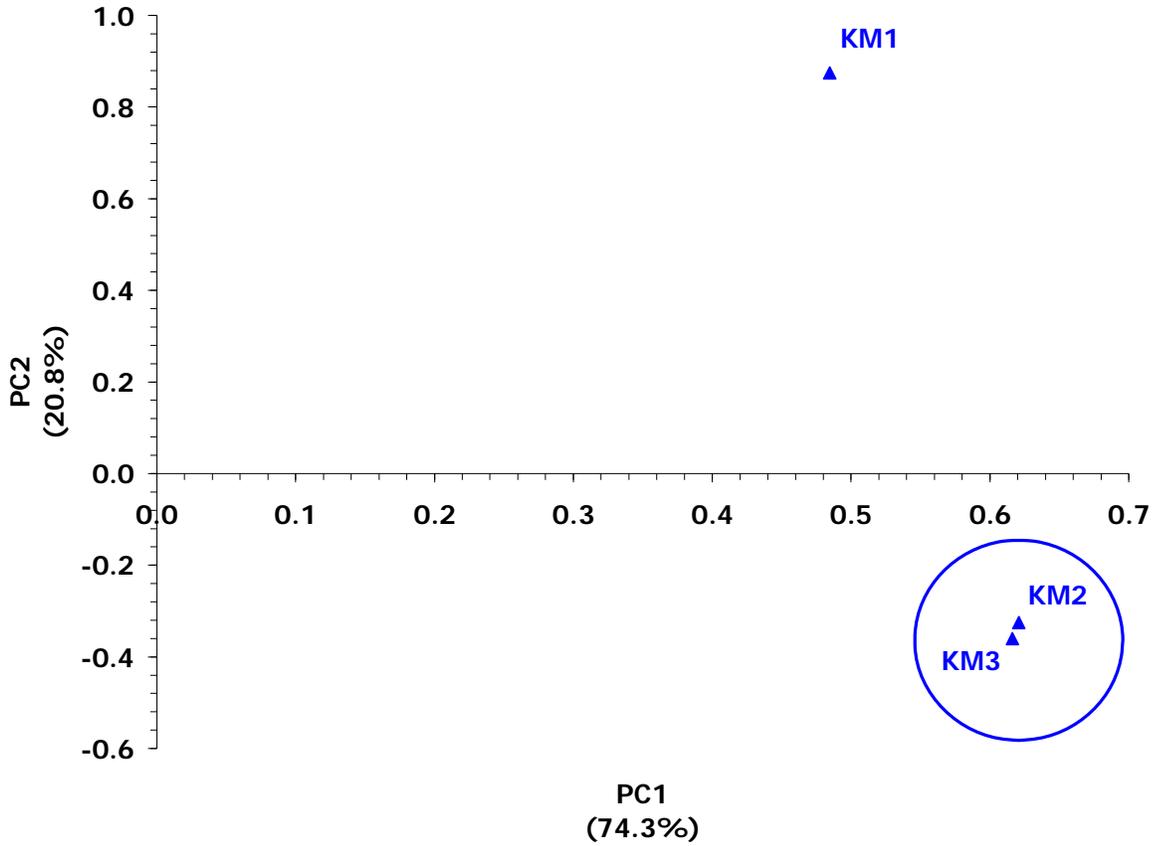


Figure 40: Principal Component plot of Kearny Marsh stormwater PAH composition by sampling location.

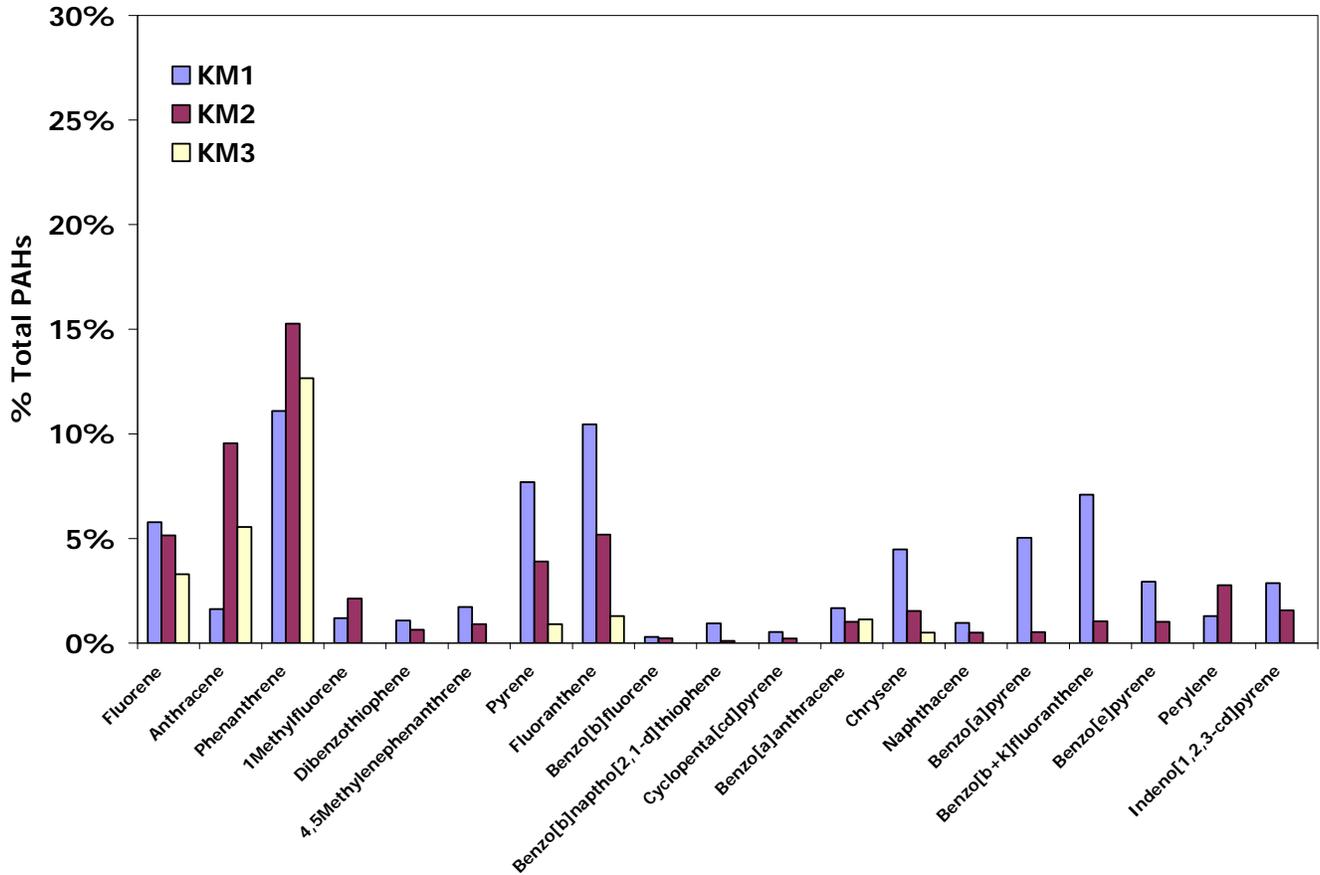


Figure 41: Proportion of component PAHs in Kearny Marsh stormwater in order of increasing molecular weight (left to right).

Groundwater

The PCA loading plot suggest that like stormwater PAHs, the groundwater PAHs come from both combustion (pyrolytic), and non-combustion (petrogenic) sources (Figure 42). However, only the groundwater pyrolytic PAHs form a cluster within the ordination space, indicating greater diversity in groundwater petrogenic PAHs that that seen in the stormwater samples.

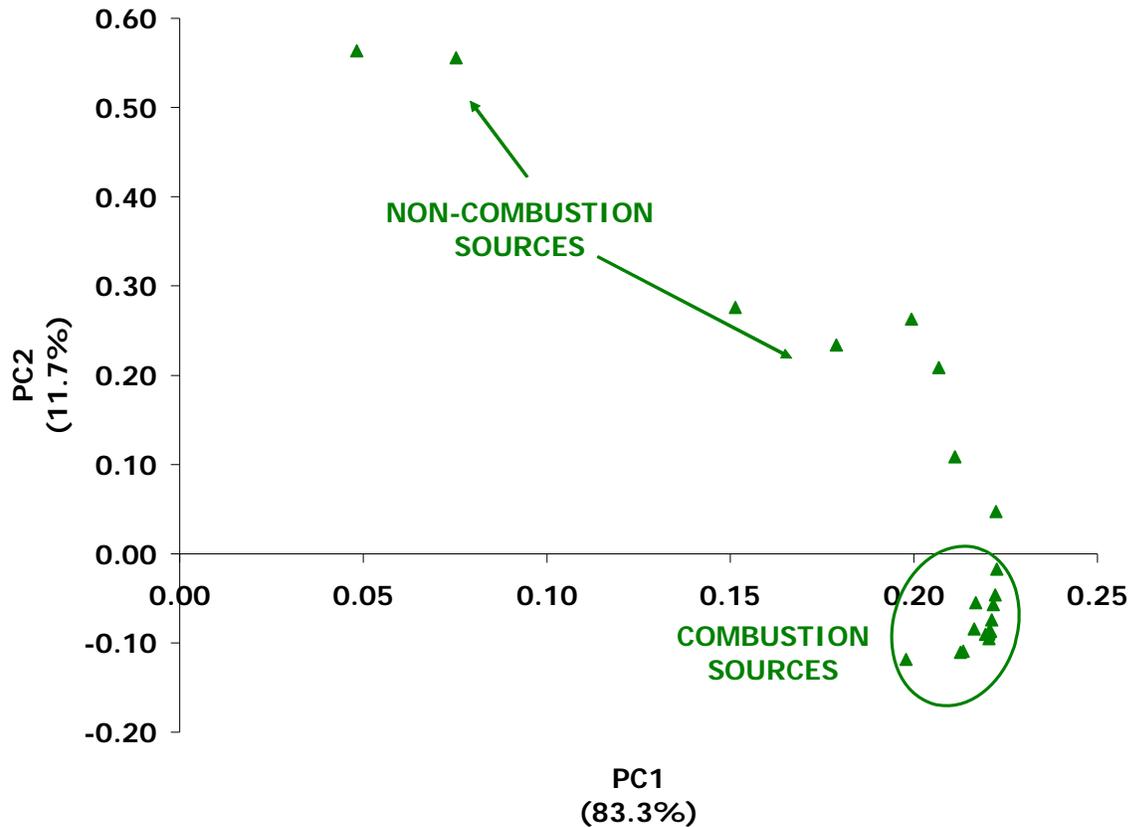


Figure 42: Principal Component groundwater Loading Plot of Kearny marsh PAH composition.

Principal Components analysis of groundwater PAHs by location (Figure 43) found the six deep groundwater wells (GW01, GW02, GW03, GW04, GW05, GW06) clustering within the ordination space, which suggests that the PAH composition in the deep groundwater may be more homogeneous. Shallow wells GW10 and GW11 were also within this cluster. However, four shallow wells (GW07, GW08, and GW09 on the western perimeter, and GW12) occupy

other positions within the ordination space, indicating a different source of shallow groundwater PAHs.

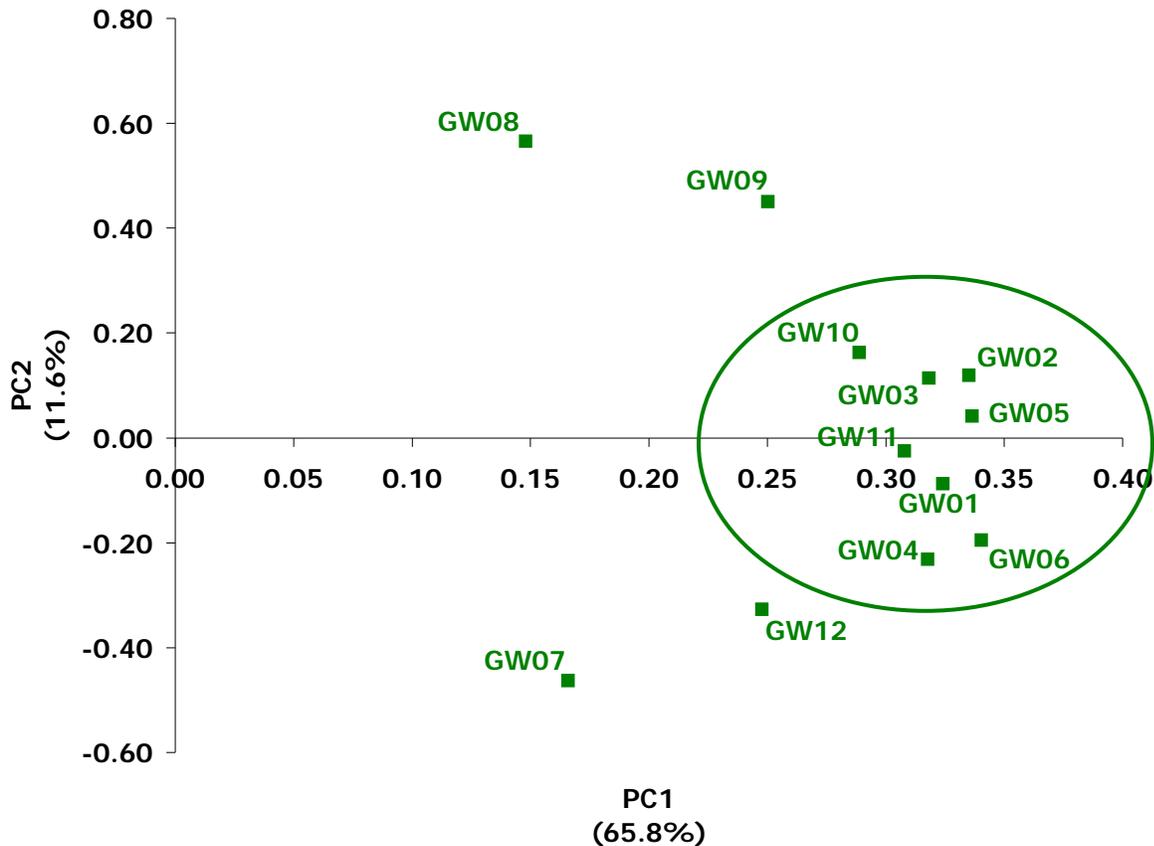


Figure 43: Principal Components plot of Kearny Marsh groundwater PAH by well location.

The concentrations of PAHs characteristic of a combustion source (fluoranthene, pyrene, and chrysene) are highest at GW08 (Figure 20). As predicted by the hydrologic models, and as observed in the groundwater well pressure transducers, groundwater flow is from the ditch and ponded areas on the western perimeter of the marsh, past GW08, and westward into the marsh (Figure 32). Stormwater runoff carrying PAHs from pyrolytic sources (vehicular and other exhaust emissions, crankcase oil, asphalt, coal tar (a roofing and sealant material), creosote), washing off roads, industrial lots, parking areas and the railroad beds, could collect in these areas, and subsequently flow into the groundwater.

In order to determine if groundwater PAH concentration and composition was being affected by surface water movement, in March 2008, samples were obtained from the ditch behind GW08 and the ponded area where surface water collects behind GW09. PAH concentrations in these surface water samples were analyzed, and the PAH composition of both surface and ground waters on the western marsh perimeter were compared using PCA. The PCA ordination (figure 44) shows a cluster that includes GW08, the ditch surface water, and GW09, suggesting a possible connection between the ditch surface waters and the shallow groundwater. Similarly, there appears to be a correlation between the PAH composition of GW07 and the ponded surface water (Figure 44), suggesting a common PAH source, possibly runoff from the highly developed Town of Kearny. PAHs in the deeper groundwater are forming a separate cluster (Figure 44), suggesting that the surface water/runoff is having a greater influence on the shallower groundwater PAH composition than on the deeper groundwater PAH composition.

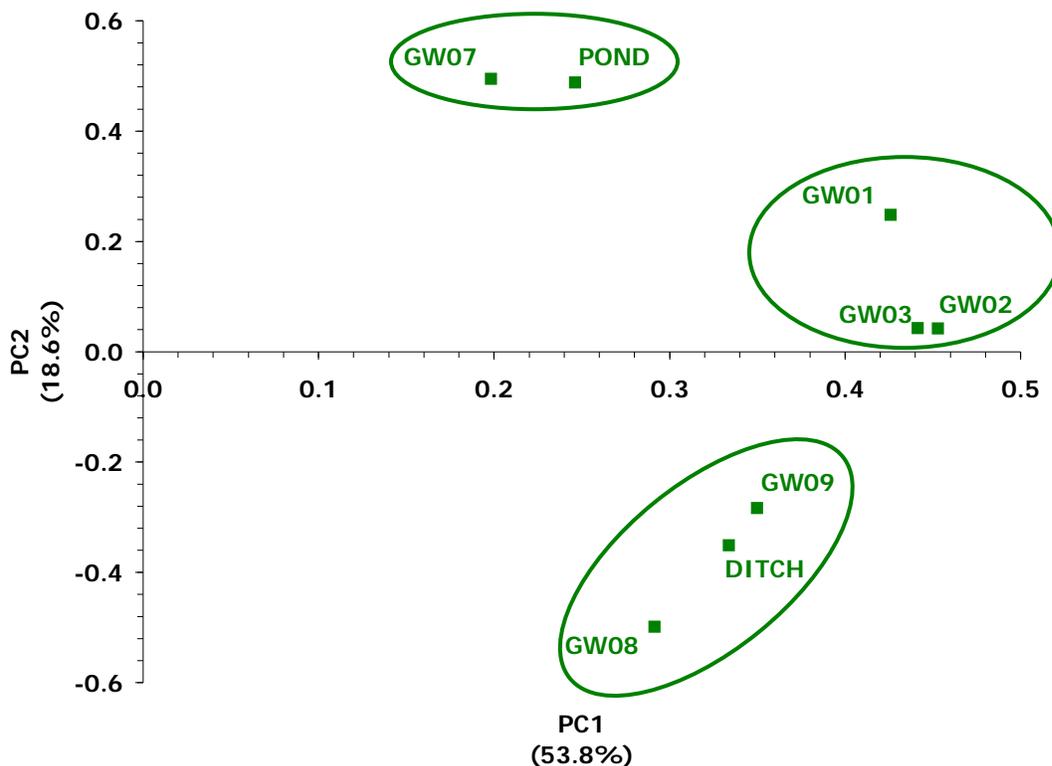


Figure 44: Principal Components plot of stormwater and groundwater PAHs comparing sampling locations on the western perimeter of Kearny Marsh.

‘Fingerprint’ analysis of PAHs in groundwater well GW08 and the ditched surface water behind GW08 support the similarity observed in the PCA. However, the fingerprint analysis (Figure 45) suggests that it is the proportion of phenanthrene, anthracene and pyrene that is contributing to the similarities between these surface and groundwater samples.

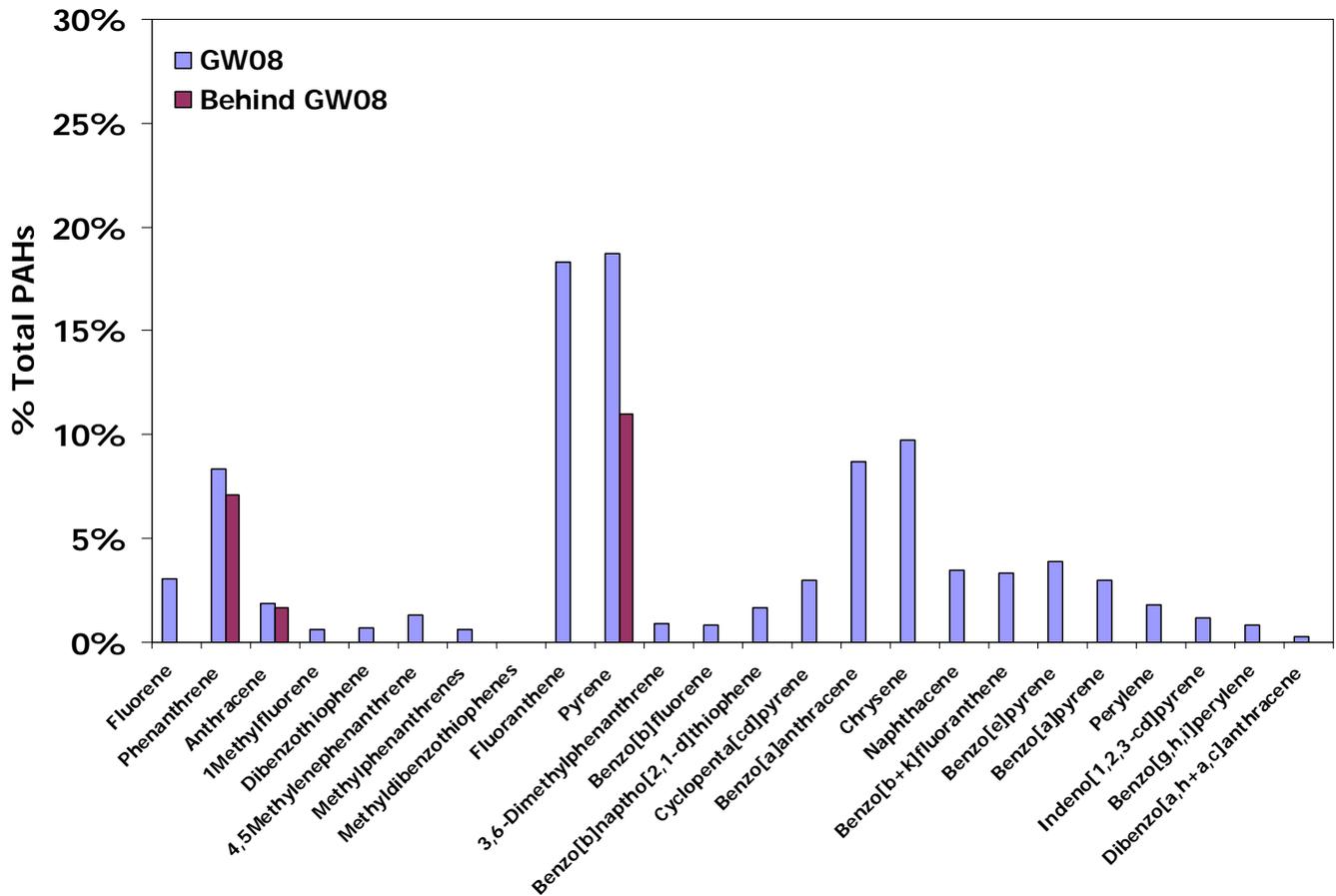


Figure 45: Plot of PAH ‘fingerprints’ for groundwater monitoring well GW08 and the sample from the surface water body behind GW08.

‘Fingerprint’ analyses for all groundwater wells were completed and tested using correlation analysis (Table 9). The analysis supports the conclusion that there is a strong correlation between PAH fingerprints among the deep groundwater wells. Correlation analysis comparing the wells on the western perimeter shows a moderate correlation between GW01 and the ponded area, and between the ditch, GW08 and GW09 (Table 10).

Table 9. Correlation analysis comparing PAH composition of Kearny Marsh groundwater wells. Bold red typeface indicates significant correlation at the $r \geq 0.70$ level; bold black typeface indicates significant correlation at the $r \geq 0.60$ level.

	GW01-D	GW07-S	GW02-D	GW08-S	GW03-D	GW09-S	GW04-D	GW10-S	GW05-D	GW11-S	GW06-D	GW12-S
GW01-D		0.40	0.80	0.28	0.85	0.53	0.88	0.70	0.88	0.75	0.89	0.60
GW07-S	0.40		0.44	-0.02	0.32	0.13	0.39	0.26	0.41	0.39	0.50	0.43
GW02-D	0.80	0.44		0.50	0.91	0.67	0.76	0.89	0.86	0.74	0.86	0.57
GW08-S	0.28	-0.02	0.50		0.43	0.60	0.24	0.21	0.39	0.18	0.26	0.26
GW03-D	0.85	0.32	0.91	0.43		0.55	0.77	0.84	0.86	0.64	0.80	0.46
GW09-S	0.53	0.13	0.67	0.60	0.55		0.43	0.61	0.71	0.77	0.53	0.32
GW04-D	0.88	0.39	0.76	0.24	0.77	0.43		0.60	0.82	0.74	0.96	0.80
GW10-S	0.70	0.26	0.89	0.21	0.84	0.61	0.60		0.75	0.72	0.72	0.27
GW05-D	0.88	0.41	0.86	0.39	0.86	0.71	0.82	0.75		0.79	0.87	0.62
GW11-S	0.75	0.39	0.74	0.18	0.64	0.77	0.74	0.72	0.79		0.84	0.58
GW06-D	0.89	0.50	0.86	0.26	0.80	0.53	0.96	0.72	0.87	0.84		0.79
GW12-S	0.60	0.43	0.57	0.26	0.46	0.32	0.80	0.27	0.62	0.58	0.79	

Table 10. Correlation analysis comparing PAH composition of the western Kearny Marsh groundwater wells and two surface water bodies on the western marsh perimeter. Bold red typeface indicates significant correlation at the $r \geq 0.70$ level; bold black typeface indicates significant correlation at the $r \geq 0.60$ level.

	GW01-D	GW07-S	GW02-D	GW08-S	GW03-D	GW09-S	DITCH	POND
GW01-D		0.40	0.80	0.28	0.85	0.53	0.49	0.65
GW07-S	0.40		0.44	-0.02	0.32	0.13	0.07	0.33
GW02-D	0.80	0.44		0.50	0.91	0.67	0.55	0.41
GW08-S	0.28	-0.02	0.50		0.43	0.60	0.60	0.08
GW03-D	0.85	0.32	0.91	0.43		0.55	0.61	0.40
GW09-S	0.53	0.13	0.67	0.60	0.55		0.45	0.14
DITCH	0.49	0.07	0.55	0.60	0.61	0.45		0.11
POND	0.65	0.33	0.41	0.08	0.40	0.14	0.11	

BEST MANAGEMENT PRACTICES (BMPs)& RECOMMENDATIONS

Stormwater

The overall goals of stormwater best management practices are to both reduce the volume of water entering a system, and to improving the quality of the water that does enter. For example, a reduction of the volume, and therefore flows, entering a wetland will reduce the amount of soil disturbance that could release contaminants attached to soil particles; slower flows could also result in increased infiltration to groundwater due to the longer residence time of water flowing over pervious surfaces. For more information on the BMPs listed below, please refer to the NJDEP's NJ Stormwater Best Management Practices Manual which is available for download at: http://www.njstormwater.org/bmp_manual2.htm. Additional information can also be found at http://water.rutgers.edu/Fact_Sheets/Default.htm, a fact sheet available through the Rutgers University Water Resources Program web site.

1. **Fix the broken bulkhead between Frank's Creek and Kearny Marsh:** Due to the backwater effect seen at Frank's Creek, and the subsequent discharge into Kearny Marsh, fixing the broken bulkhead between the two water bodies would likely resolve a few of the problems observed:
 - a. Flooding may be reduced due to the loss of the additional water volume added to the marsh during high tide and precipitation events,
 - b. Discharge from the CSO located along Frank's Creek will overcome the back water effect and discharge to the Passaic River, eliminating the loads to Kearny Marsh and reducing the volume of water flooding the headwaters of the creek,
 - c. Water quality would be improved as the CSO discharge is diverted downstream to the Passaic River.
2. **Treatment systems for Frank's Creek:** An engineered system needs to be created in order to treat pollutants from Frank's Creek. A 'pocket treatment facility' could be built in order to mechanically and/or chemically treat pollutants from the creek. A second option is a created wetland, possibly located on a portion of the Keegan Landfill, which could filter pollutants and store floodwaters. This type of treatment option could also be used to educate visitors to Kearny Marsh about the importance of wetland functions.

3. **Separate the CSO:** Separation of the stormwater drainage system from the wastewater systems is an option that would reduce the quantity of water entering Kearny marsh, while improving water quality by reducing discharge of untreated wastewater during storm events.
4. **Community stormwater controls:** Since the pollution observed at the Gunnell Oval storm sampling site (KM1) is from a stormwater collection system, the source of this pollution is the general watershed over which the stormwater flows. This non-point source pollution could be managed by placing stormwater controls throughout the community. Small engineered systems could be located throughout the Town of Kearny to help reduce the quantity of water entering the existing collection systems (like the CSO on Frank's Creek) and to improve the quality of the water entering Kearny Marsh. These controls could include vegetated detention/retention basins such as rain gardens and green roofs. Successful use of this type of control has been demonstrated in urban areas such as Philadelphia and Chicago. These controls provide possible benefits, including infiltration of precipitation that would normally create runoff that carries contamination; flow reduction that could lead to fewer flooding/inundation events; reduction of nutrients as vegetation takes them up to support growth; and containment of sediments that may carry bound contaminants.

Groundwater

1. **Additional monitoring wells:** This study has expanded the knowledge of the hydrologic characteristics and quality of the groundwater system underlying Kearny Marsh, and demonstrated that groundwater is an important factor in determining new contaminant inputs to the system. The contaminant concentrations have been determined and certain contaminants (PAHs) have been characterized. However, these results are most applicable to the discrete locations from which they were obtained. Additional monitoring wells in areas up-gradient of the groundwater wells that were installed as part of this study would help to further elucidate the original sources of groundwater contamination. For example, additional wells placed to the west of our 'western' wells (deep wells GW01, GW02, GW03 and shallow wells GW07, GW08, and GW09) would

help to determine the extent of PAHs contamination seen in that vicinity and help pinpoint the source(s).

2. **Pump and Treat:** Pumping the groundwater and treating it before discharged to another waterway is one option to remove many of the contaminants detected during this study. Options for discharge include discharge to surface water systems (either natural or engineered) or back into the groundwater from which it was drawn. Pump-and-treat systems remove groundwater contaminated with a variety of dissolved materials, including VOCs, SVOCs, fuels, and dissolved metals.
3. **Cap Keegan Landfill:** An impervious cap over the Keegan Landfill during its redevelopment will help to reduce the amount of leachate created by reducing the volume of water percolating through the landfill.
4. **Install slurry wall:** The slurry wall planned for installation in preparation for resuming operation of the Keegan Landfill needs to be implemented. This wall will act as a physical barrier to stop leachate from entering Kearny Marsh groundwater. In combination with a leachate collection system (see below), a slurry wall will help to sequester the contamination while either natural attenuation is occurring (for some organic contaminants), or prior to treatment and eventual disposal.
5. **Leachate collection:** Plans for the operation of the Keegan Landfill need to maintain a leachate collection system to remove the groundwater contaminants observed in this study. Such a system would remove a volume of contaminated water from the landfill operation that would otherwise enter Kearny Marsh's groundwater. The leachate collection system would also help to reduce pressure on the slurry wall, helping to prevent leakage into the marsh.

STUDY CONCLUSIONS

The NJMC is investing major financial resources to restore the Kearny Marsh. These initiatives currently include plans to construct a slurry wall around the Keegan Landfill, and potentially capping the marsh sediments to sequester historic contamination. The results of this study indicate that without addressing ongoing contamination, found primarily in Frank's Creek surface waters and the groundwater discharging into the marsh, these restoration efforts will be impeded by the continuing inputs of heavy metal, PAH, and PCB contamination to the marsh.

The restoration will also be impeded by the large nitrogen and phosphorus inputs, which will contribute to rapid anthropogenic eutrophication of the system. We urge the NJMC and the Town of Kearny to consider implementing BMPs that will reduce the groundwater contaminant and nutrient loadings to protect the valuable Kearny Marsh ecosystem.

REFERENCES

1. Berne, A., G. Delrieu, J.D. Creutin, and C. Obled. 2004. Temporal and Spatial Resolution of Rainfall Measurements Required for Urban Hydrology. *Journal of Hydrology*. 299:166-179.
2. 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 2430. 35 pp.
3. 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.
4. Budzinski, H., I. Jones, J. Bellocq, C. Pierard, and P. Garrigues. 1997. Evaluation of Sediment Contamination by Polycyclic Aromatic Hydrocarbons in the Gironde Estuary. *Marine Chemistry*. 58:85-97.
5. Burns, W.A., P.J. Mankiewicz, A.E. Bence, D.S. Page, and K.R. Parker. 1997. A Principal-Component and Least-Squares Methods for Allocating Polycyclic Aromatic Hydrocarbons in Sediment to Multiple Sources. *Environmental Toxicology and Chemistry*. 16(6):1119-1131.
6. 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.
7. De Luca, G., A. Furesi, G. Micera, A. Panzanelli, P.C. Piu, M.I. Pilo, N. Spano, and G. Sanna. 2005. Nature, Distribution and Origin of Polycyclic Aromatic Hydrocarbons (PAHs) in the Sediments of Olbia Harbor (Northern Sardinia, Italy). *Marine Pollution Bulletin*. 50:1223-1232.
8. Drexler, J.Z., R.L. Snyder, D. Spano, and K.T Paw. 2004. *A Review of Models and Micrometeorological Methods Used to Estimate Wetland Evapotranspiration*. Hydrologic Processes. 18:2071-2101.
9. Ehrenfeld, J.G. 2000. Evaluating wetlands within an urban context. *Urban Ecosystems* 4:69-85.
10. 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.
11. Evans, B.M., D.W. Lehning, K.J. Corradini, G.W. Petersen, E. Nizeyimana, J.M. Hamlett, P.D. Robillard, and R.L. Day. A Comprehensive GIS-Based Modeling Approach for Predicting Nutrient Loads in Watersheds. *Journal of Spatial Hydrology*. 2(2):1-18.
12. Faulkner, S. 2004. Urbanization impacts on the structure and function of forested wetlands. *Urban Ecosystems* 7:89-106.
13. Ghosh, U., J.S. Gillette, R.G. Luthy, and R.N. Zare. 2000. Microscale Location, Characterization, and Association of Polycyclic Aromatic Hydrocarbons on Harbor Sediment Particles. *Environmental Science and Technology*. 34:1729-1736.
14. Golobocanin, D.D., B.D. Skrbic, and N.R. Miljevic. 2004. Principal Component Analysis for Soil Contamination with PAHs. *Chemometrics and Intelligent Laboratory Systems*. 72:219-223.

15. Hwang, H-M., and G.D. Foster. 2006. Characterization of Polycyclic Aromatic Hydrocarbons in Urban Stormwater Runoff Flowing into the Tidal Anacostia River, Washington, DC, USA. *Environmental Pollution*. 140:416-426.
16. Kim, M., M.C. Kennicutt II, and Y. Qian. 2006. Molecular and Stable Isotope Characterization of PAH Contaminants at McMurdo Station, Antarctica. *Marine Pollution Bulletin*. 52:1585-1590.
17. Kimbrough, K.L. and R.M. Dickhut. 2006. Assessment of Polycyclic Aromatic Hydrocarbon Input to Urban Wetlands in Relation to Adjacent Land Use. *Marine Pollution Bulletin*. 52:1355-1363.
18. Konsevick, E., C.C. Hobbie, and P. Lupini. 1994. Monitoring Effects of Urban Land Use on Estuarine Water Quality, Hackensack Meadowlands District, New Jersey. Presented at the 30th Annual American Water Resource Association Conference, National Symposium on Water Quality.
19. Krause, P., D.P. Boyle, F. Bäse. 2005. Comparison of Different Efficiency Criteria for Hydrological Model Assessment. *Advances in Geosciences*. 5:89-97.
20. 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.
21. 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.
22. Lott, R.B. and R.J. Hunt. 2001. Estimating Evapotranspiration in Natural and Constructed Wetlands. *Wetlands*. 21(4): 614-628.
23. 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.
24. 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.
25. Mitsch, W.J., Gosselink, J.G. 2000. Wetlands, 3rd edition. John Wiley and Sons, Inc. New York, NY.
26. Montalto, F.A., Steenhuis, T.S. 2004. The Link Between Hydrology and Restoration of Tidal Marshes in the New York/New Jersey Estuary. *Wetlands* 24(2):414-425.
27. Morgan, K.L., Roberts, T.H. 2003. Characterization of wetland mitigation projects in Tennessee, USA. *Wetlands* 23(1):65-69.
28. Neglia Engineering Associates (Neglia). 2001. Storm Water Evaluation Study. Neglia Engineering Project 10129. Lyndhurst, NJ.
29. Niemczynowicz, J. 1999. Urban hydrology and water management – Present and future challenges. *Urban Water* 1:1-14.
30. NJDEP. 2005a. Surface Water Quality Standards (N.J.A.C. 7:9B). Trenton, NJ. 127 pp.
31. NJDEP. 2005b. Ground Water Quality Standards. Chapter 7:9C. Trenton, NJ. 26 pp.
32. NJMC. 2005. Hackensack Meadowlands Floodplain Management Plan (DRAFT). New Jersey Meadowlands Commission. Lyndhurst, NJ. 215pp.
33. NJMC. 2008. Solicitation for Expression of Interest NJMC Keegan Landfill Operational, Management, and Maintenance Services. April 7, 2008.

34. Owen, C.R. 1995. Water budget and flow patters in an urban wetland. *Journal of Hydrology* 169: 171-187.
35. Page, D.S., P.D. Boehm, G.S. Douglas, A.E. Bence, W.A. Burns, and P.J. Mankiewicz. 1999. Pyrogenic Polycyclic Aromatic Hydrocarbons in Sediments Record Past Human Activity: A Case Study in Prince William Sound, Alaska. *Marine Pollution Bulletin*. 38(4):247-260.
36. Palmer, W.C. and A.V. Havens. 1958. A graphical technique for determining evapotranspiration by the Thornthwaite equation. *Monthly Weather Review*, April: 123-128.
37. Perkins, D.F. 1999. Use and construction of a lysimeter to measure evapotranspiration. <http://www.llansadwrn-wx.co.uk/lysim.html>.
38. Qiao, M., C. Wang, S. Huang, D. Wang, and Z. Wang. 2006. Composition, Sources, and Potential Toxicological Significance of PAHs in the Surface Sediments of the Meiliang Bay, Taihu Lake, China. *Environment International*. 32:28-33.
39. 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.
40. Reinelt, L.E., Horner, R.R. 1995. Pollutant removal from stormwater runoff by palustrine wetlands based on comprehensive budgets. *Ecological Engineering* 4:77-97.
41. Rosenberry, D.O., Stannard, D.I., Winter, T.C., Martinez, M.L. 2004. Comparison of 13 equations for determining evapotranspiration from a prairie wetland, Cottonwood Lake Area, North Dakota, USA. *Wetlands* 24(3): 483-497.
42. Sanders. M., S. Silvertsen, and G. Scott. 2002. Origin and Distribution of Polycyclic Aromatic Hydrocarbons in Surficial Sediments from the Savannah River. *Environmental Contamination and Toxicology*. 43:438-448.
43. Schnoor, J.L. 1996. *Environmental Modeling: Fate and Transport of Pollutants in Water, Air, and Soil*. John Wiley & Sons, Inc., New York, NY.
44. Sun, G., McNulty, S.G., Amatya, D.M., Skaggs, R.W., Swift, L.W. Jr., Shepard, J.P., Riekerk, H. 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.
45. 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.
46. USEPA & USACE. 1997. Phase 2 Report – Further Site Characterization and Analysis Volume 2C – Data evaluation and interpretation report Hudson River PCB reassessment RI/FS. Tams consultants, T.C.G., Inc. Gradient Corporation.
47. Valle, S., Panero, M.A., Shor, L. 2007. Pollution prevention and management for polycyclic aromatic hydrocarbons in the New York/New Jersey harbor. New York Academy of Sciences Report., New York, NY.
48. Vepraskas, M.J., Huffman, R.L., Kreiser, G.S. 2006. Hydrologic models for altered landscapes. *Geoderma* 131:287-298.
49. Vrana, B., A. Paschke, and P. Popp. 2001. Polyaromatic Hydrocarbon Concentrations and Patterns in Sediments and Surface Water of the Mansfeld Region, Saxony-Anhalt, Germany. *Journal of Environmental Monitoring*. 3:602-609.

50. Walker, S.E., R.M. Dickhut, C. Chisholm-Brause, S. Sylva, and C.M. Reddy. 2005. Molecular and Isotopic Identification of PAH Sources in a Highly Industrialized Urban Estuary. *Organic Chemistry*. 32:619-632.
51. Webster, L., A.D. McIntosh, C.F. Moffat, E.J. Dalgarno, N.A. Brown, and R.J. Fryer. 2000. Analysis of Sediments from Shetland Island Voes for Polycyclic Aromatic Hydrocarbons, Steranes and Triterpanes. *Journal of Environmental Monitoring*. 2:29-38.
52. Winter, T.C. 1981. Uncertainties in Estimating the Water Balance of Lakes. *Water Resources Bulletin*. 17:82-115.

Appendix I.
Analytical Protocols

EOHSI Methods Summary

The analysis protocols were based GC/ Ion Trap Mass Spec (MSⁿ) analysis of all analytes. The Ion Trap MSⁿ analytical capabilities enhanced both the selectivity and sensitivity of the overall analytical method. The nature of these samples suggested that contamination from multiple contaminant sources be considered, and therefore the compound classes were expected to be varied. Using a non-selective detector for the identification of possible analytes means that only the retention time of the compound is used for its identification. This can lead to an erroneous over prediction of the amount of a specific contaminant. Multiple MS with known fragmentation patterns can increase sensitivity because even though the compound's signal is lost with each successive Ion trapping (IT) MS program, the background signal decreases much more rapidly. We have used this methodology to improve water samples analyses as part of a study for the NJDEP. Using multistage Ion Trap MS programs, we were able to increase the sensitivity by as many as four orders of magnitude over conventional quadrupole detection for both PCBs and PAHs. We utilized this expertise in adaptation of standard GC/MS EPA methods for the analysis of BTEX, PCBs PAHs Dioxins and chlorinated and/or OP pesticides.

Quantitation of each analyte was performed by calibration curve using commercial standards and the most reliable second stage ion. Internal standards were used for quality control and blank samples were included in each sample set.

BTEX/MTBE

A new method developed by USEPA Las Vegas utilizes direct injection of water samples for the analysis of MTBE and BTEX. A source programmable injector is used to selectively inject the MTBE Benzene and the others without significant water interference. The method worked reasonably well, but was not as sensitive as solid phase microextraction (SPME). Houghton and Hall utilized SPME with GC/MS detection for the same suite of compounds. This method worked well for the MTBE, but they were less successful with the other analytes. We have the capability to utilize both technologies to monitor these analytes. From previous work in our laboratory we have found compromise fiber loading conditions using a 10% NaCl solution to load the seven MTBE/BTEX analytes. We compared the SPME method with an SPI of the analytes with subsequent GC/ITMS² detection. We used the newer mixed mode divinylbenzen (DVB)/carboxene/PDMS fiber for analyte isolation.

PCBs

EPA method 1668 utilizes GC/ITMS for detection of all 209 PCB congeners. We utilized the standard mix to precisely quantify congeners including those found in highest concentration in the original analysis. An MS² or MS³ method was utilized to isolate each of the PCBs focusing on the 18 most important PCBs for quantification. Since we have already used this method to identify a coeluting compound that was not a PCB, we are confident that this methodology can be used to eliminate false positives. Mixes one and two, which represent 137 of the congeners, were injected and the retention time index was used to identify any coeluting PCB congeners. These congeners were reported together. This optimized chromatographic/mass spectrometric

approach has been validated independently and recognized as one of top two column systems from 17 different GC column systems tested by PCB standard vendors.

PAHs

The PAHs were analyzed using the multistage IT MS method. This method follows EPA method 525.1 in analysis instrumentation, but the multistage MS gives much better sensitivity and a subsequent lowering of the method detection limit. We used a Carbowax/DVB SPME fiber for preconcentration of the PAHs that we used for the BTEX/MTBE. This method was optimized by Dr. Robert Stiles as part of his dissertation work in the EOHSI laboratory.

Pesticides

The OPs and organo-chlorine analysis methods were based on EPA method 525.1. An adaptation of a solid phase extraction was made to convert analyte isolation and preconcentration from solid phase to SPME. We followed this protocol for organochlorine pesticides in another study. Ops that do not lend themselves to SPME were preconcentrated using solid phase extraction (SPE), and the GC/MS techniques were as described above. Twelve organochlorine and 10 OP pesticides were quantitated using this method.

Dioxin Analysis

The analysis for dioxins was performed by GC/ITMS using a multi-step MS method. The samples were preconcentrated using a solid phase extraction of the water, followed by blow down of the solvent. An SPI allowed for a large volume injection of the sample and yielded a detection limit of 0.05 µg/l. We also concentrated further by sampling the preconcentrate with SPME.

Semivolatile Analysis

EPA method 8270 is a performance based GC/MS method for a general scan of semivolatile organic chemicals. It is the method we have been using over eight years to identify semivolatile unknown contaminants in source water and drinking water samples. Using this method we have identified more than 600 compounds in various water systems throughout New Jersey. We used this method for all general scan analysis of the water samples collected. Our user libraries were critical for screening unknowns and removing background organic chemicals, and reducing false positive IDs when comparing TICs to the NIST Library.

Metals

All metal analyses were performed using ICP/MS. The detection limits for all toxic metals are less than 1 ppb. For Fe, Zn, and Mg the limit is well below 1 ppm, which is much lower than the concentration of these elements in the samples analyzed to date.

EPA method 200.8 is a trace metals method for water samples that uses ICPMS for metals quantitation. The principal difficulty with using this method for mercury is the carryover

(memory effects) seen when mercury contacts quartz or glass surfaces. We have overcome these memory affects using a 2% gold rinse solution, which amalgamates the mercury. We have previously used this method for the validation of a new EPA mercury speciation method 3200 and in validation proof of principal studies for the NJDEP using EPA method 6800. In addition, NIST or NIST traceable quality control (QC) samples were included with each sample run. Recoveries of >80% were required for an analysis run to be classified as acceptable.

Rutgers EcoComplex Methods Summary

Standard Operating Procedure: Ammonia

Approved Method:

EPA Method 350.1

Matrix:

Water

Scope:

In water systems a main source of ammonia is excrement from organisms and decomposition of debris. Additional ammonia sources in these systems can be from leaky septic systems, and run off from agriculture fields and lawns. High ammonia levels in water can be toxic to fish, causing conditions such as gill disease, dropsy, and finrot. It is important to aquatic diversity and health to monitor ammonia in water systems.

Application:

Ambient waters

Detection Limit:

0.004 to 5.0 mg N/L of NH₃

Method Detection Limit = 0.004 mg N/L

Summary of Test Method:

This method detects ammonia concentrations by using the Berthelot reaction. The sample is combined with alkaline phenol and then sodium hypochlorite which produces indophenol blue. Sodium nitroprusside is added and the solution is heated to 60°C to enhance sensitivity. A spectrophotometer with a filter of 630 nm is used to measure the nitrogen concentration in the sample.

Standard Operating Procedure: Nitrite and/or Nitrate&Nitrite

Approved Method:

EPA Method 353.2

Matrix:

Water

Scope:

Nitrate and nitrite are considered pollutants in water systems when detected at high levels (excess of 10 mg/L under state and federal law). Excess nitrite/nitrate in natural water systems can lead to algal blooms. High nitrite/nitrate levels in drinking water also pose a risk for people, especially infants. It inhibits the blood from carrying oxygen, and in infants has led to “blue baby syndrome.” It is important to monitor nitrite/nitrate levels in water systems to manage natural systems and reduce its impact on human health.

Application:

Ambient waters

Detection Limit:

0.017 to 8.0 mg N/L of NO₂-N Method Detection Limit = 0.017 mg N/L

0.01 to 20.0 mg N/L of NO₂/NO₃-N Method Detection Limit = 0.01 mg N/L

Summary of Test Method:

This method uses copper cadmium as a reduction agent to convert nitrate into nitrite in a sample. The combined nitrate + nitrite (in the form of nitrite) is diazotized with sulfanilamide and coupled with N-(1-naphthyl)-ethylenediamine dihydrochloride creating a magenta colored product. The final product is passed through a spectrophotometer at a wavelength of 520nm. Separate nitrite values can be obtained by running the sample through this process without the copper cadmium reducing agent.

Standard Operating Procedure: Kjeldahl Nitrogen - Total**Approved Method:**

EPA Method 351.2

Matrix:

Water

Scope:

Nitrogen can be found in water systems in a variety of different forms. Most common inorganic forms are nitrate, nitrite, and ammonia. There are analytical methods to measure the amounts of inorganic nitrogen. However, organic nitrogen can also be found in water bodies. In order to determine organic nitrogen amounts, total Kjeldahl nitrogen must first be determined. Total Kjeldahl nitrogen (TKN) represents the total organic nitrogen and ammonia. Performing TKN measurements along with the other inorganic nitrogen forms, gives a better understanding of the nitrogen distribution in water bodies. This information is vital to any management and/or remediation projects.

Application:

Ambient waters

Detection Limit:

0.08 to 25.0 mg N/L

Method Detection Limit = 0.08 mg N/L

Summary of Test Method:

The sample is digested in the presence of sulfuric acid, potassium sulfate, and copper sulfate for approximately four hours during which all organic nitrogen is converted to ammonium. The sample is re-suspended to its original volume with deionized water. The sample is analyzed for ammonia and combined with salicylate and sodium hypochlorite which produces a blue color. Sodium nitroprusside and heat (60°C) help to enhance sensitivity. A spectrophotometer with a filter of 630 nm is used to measure the nitrogen concentration in the sample.

Standard Operating Procedure: Orthophosphate**Approved Method:**

EPA Method 365.1

Matrix:

Water

Scope:

Phosphorus is one of the key nutrients necessary for growth of plant and animals. Orthophosphate (a form of inorganic phosphorous) is produced by natural processes and the most common form of phosphorous found in water. In water bodies, phosphorus is often the growth-limiting nutrient. Under normal conditions, phosphate will stimulate the growth of plankton and aquatic plants which sustains healthy fish populations. This can lead to improved overall water quality. However, excess phosphate in water can cause algal blooms and overgrowth of aquatic plants causing oxygen deficiency. This condition is known as eutrophication, and can cause fish kills.

Application:

Ambient waters

Detection Limit:

0.002 to 2.0 mg P/L

Method Detection Limit = 0.002 mg P/L

Summary of Test Method:

This method detects phosphorous concentrations in form of the orthophosphate ion. Ammonium molybdate and antimony potassium tartrate mix with the orthophosphate ion in the sample and form a compound. Ascorbic acid reduces this compound and the reaction generates a blue color. The solution is heated to 37°C to enhance sensitivity. A spectrophotometer with a filter of 880 nm is used to measure the phosphorous concentration in the sample.

Standard Operating Procedure: Phosphorous (Total)**Approved Method:**

EPA Method 365.1

Matrix:

Water

Scope:

Phosphorus is one of the key nutrients necessary for growth of plant and animals. In water bodies, phosphorus is often the growth-limiting nutrient. Under normal conditions, phosphate will stimulate the growth of plankton and aquatic plants which sustains healthy fish populations. This can lead to improved overall water quality. However, excess phosphate in water can cause algal blooms and overgrowth of aquatic plants causing oxygen deficiency. This condition is known as eutrophication, and can cause fish kills.

Application:

Ambient waters

Detection Limit:

0.001 to 1.0 mg P/L

Method Detection Limit = 0.001 mg P/L

Summary of Test Method:

This method detects phosphorous concentrations in form of the orthophosphate ion. It converts polyphosphates via a sulfuric acid digest and organic phosphorous via a persulfate digestion into orthophosphate. Ammonium molybdate and antimony potassium tartrate mix with the orthophosphate ion in the sample and form a compound. Ascorbic acid reduces this compound and the reaction generates a blue color. The solution is heated to 37°C to enhance sensitivity. A spectrophotometer with a filter of 880 nm is used to measure the phosphorous concentration in the sample.

Appendix II.
Water Sampling Protocols

Water Sampling Protocols

Water quality samples consisted of two samples collected at each of the groundwater wells. For each monitoring well, one sampling bottle consisted of filtered, churned, and chilled groundwater (FCC), while the other churned and acidified (WCA). Sample water quality data sheets are provided in Attachment D.

Groundwater quality samples were collected as follows:

- 1) Retrieve the portable peristaltic pump, tubing, turbidimeter, pH/DO/SC/temp meters, sample bottles, and measuring tape
- 2) Record the depth to water and well depth in the groundwater quality data sheets
- 3) Purge the groundwater well with the peristaltic pump and tubing
- 4) Wait until the well is recharged
- 5) Purge the well and record measurements of turbidity, pH, DO, SC, and temperature
- 6) Recharge and purge the groundwater well, and record the field measurements, until a turbidity measurement of less than or equal to 10 NTU is achieved
- 7) When a reading of 10 NTU is achieved, the groundwater quality samples may be processed
- 8) If a reading of 10 NTU cannot be achieved, samples may be processed when the readings of turbidity between recharges are holding constant.
- 9) After an acceptable turbidity measurement is achieved, obtain a FCC sample bottle.
- 10) Attach a Whatman filter to the end of the tubing and remove the cap from the filter
- 11) Purge the groundwater through the filter and replace the cap onto the filter
- 12) Discard the de-ionized water from the FCC bottle and rinse the bottle with the filtered groundwater
- 13) Fill the FCC bottle to the shoulder with the filtered groundwater.
- 14) Cap the FCC bottle and label as follows:

FCC
Station ID #: xxxxxxxx
M/DD/YY
HH:MM

- 15) Discard the used filter
- 16) Place the FCC bottle in a container with ice
- 17) Obtain the WCA sample bottle
- 18) Discard the de-ionized water in the WCA bottle and rinse the bottle with the groundwater
- 18) Fill the WCA bottle to the shoulder with the groundwater
- 20) Cap the WCA bottle and label as follows:

WCA
Station ID #: xxxxxxxx
M/DD/YY
HH:MM

- 21) In a clean environment acidify the WCA sample as follows:

Acidification of groundwater quality samples (WCA):

- a) Only acidify the clear WCA sample bottles
 - b) Retrieve a sterilized plastic bag, pH paper, H₂SO₄ and place the WCA bottle inside the sterilized bag.
 - c) Retrieve a vial of H₂SO₄ and remove the cap from the WCA bottle inside of the sterilized bag
 - d) Pour the acid into the WCA bottle and test the water sample for pH
 - e) Samples with pH < 2 are acceptable. Samples with pH > 2 must be recorded and the sampling procedures for the WCA sample must be restarted/
 - f) If the pH < 2, cap the bottle and place the sample in the container with ice.
 - g) Place the pH paper and empty acid vial in the solution of baking soda.
- 22) Complete the groundwater quality data sheets.

Stormwater quality samples were collected as follows:

- 1) During the morning of the sampling event, each of the surface water quality sample bottles was rinsed three times with de-ionized water
- 2) Grab samples of surface water were collected with a sterile container (1 liter)
- 3) Grab samples were taken at 5 sampling intervals throughout the entire width of the stream or from the center of the discharge pipe
- 4) Using sterile gloves, grasp the container near the base at a downward 45-degree angle
- 5) Plunge the container though the depth of stream, to the bottom without stirring any sediments, and back to the surface of the water filling approximately one-half of the container
- 6) Fill the sterilized churn (encased in a sterilized plastic bag), with 5 samples of surface water
- 7) Rinse the churn by shaking and churning the surface water inside and discarding the water though the tap at the bottom of the churn
- 8) Steps 4-6 are repeated for the collection of the surface water samples
- 9) Begin the processing of the surface water samples
- 10) In a clean environment, while wearing sterilized gloves, churn the surface water 10 times at a constant 0.9 ft/sec before collecting samples
- 11) While churning the surface water, a turbidity measurement was recorded by filling a corvette with surface water from the tap of the churn
- 12) Fill the corvette to the white line and clean off lint and dirt with a non-abrasive cloth
- 13) Place the corvette in the turbidimeter and read the output
- 14) Record the turbidity measurement in the surface water quality data sheet
- 15) Rinse the corvette with de-ionized water
- 16) Restart the churning of the surface water at 0.9 ft/sec at a minimum of 10 churns
- 17) While churning, fill the clear WCA sample bottle with the surface water and rinse thoroughly. Discard the water.
- 18) Restart churning at 0.9ft./sec a minimum of 10 times if churning has been halted. Continue churning
- 19) Fill the clear WCA bottle to the shoulder with the surface water using the tap at the bottom of the churn
- 20) Cap the WCA bottle and label as follows:

WCA
Station ID #: xxxxxxxx
M/DD/YY
HH:MM

- 21) Obtain the FCC bottle
- 22) Attach sterile L/S 15 C-flex tubing from the surface water churn to a Whatman Suspended Solids Filter via the portable peristaltic pump
- 23) Uncap the filter and restart the churning process
- 24) Turn the pump on and run the surface water through the filter
- 25) Re-cap the filter after the surface water begins to run through the filter
- 26) Fill the FCC bottle half way and rinse thoroughly
- 27) Restart the churning process if churning has been halted. Continue churning
- 28) While running the surface water through the filter, fill the FCC sample bottle to the shoulder with the surface water
- 29) Turn off the pump and discard the filter
- 30) Cap the FCC bottle and label as follows:

FCC
Station ID #: xxxxxxxx
M/DD/YY
HH:MM

- 31) Place the FCC bottle in a container with ice.
- 32) Clean the tubing with de-ionized water for at least 10 seconds by placing the middle of the tubing in the pump head and attaching one end to the de-ionized water tap.
- 33) Place tubing in a sterilized bag

Acidification of surface water quality samples (WCA):

- a) Only acidify the clear WCA sample bottles
 - b) Retrieve a sterilized plastic bag, pH paper, H₂SO₄ and place the WCA bottle inside the sterilized bag
 - c) Retrieve a vial of H₂SO₄ and remove the cap from the WCA bottle inside of the sterilized bag
 - d) Pour the acid into the WCA bottle and test the water sample for pH
 - e) Samples with pH < 2 are acceptable. Samples with pH > 2 must be recorded and the sampling procedures for the WCA sample must be restarted/
 - f) If the pH < 2, cap the bottle and place the sample in the container with ice
 - g) Place the pH paper and empty acid vial in the solution of baking soda
- 34) Complete the surface water quality data sheets

APPENDIX III.
Paper presented at the Meadowlands Symposium 2007

DEVELOPMENT OF A WATER BUDGET FOR KEARNY MARSH

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Kearny Marsh is a freshwater ecosystem located in the heavily urbanized Hackensack Meadowlands District. The marsh drains to the Lower Passaic River. The New Jersey Meadowlands Commission (NJMC) has determined that remediation of this ecosystem is a high priority and has partnered with Rutgers to achieve this goal. The current hydrologic conditions of the marsh are the result of human alterations including municipal stormwater inputs from the Town of Kearny, construction of railroads and highways around the marsh, creation of mosquito drainage ditches throughout the marsh, channeling of marsh drainage to a partially clogged pipe in the northeast corner of the marsh, and diverting stream flow from the Hackensack River into the Passaic River. Due to the surrounding urban land use, significant impacts are suspected from groundwater and surface water interactions and discharges from storm drains into the marsh. In addition, a bulkhead separating Kearny Marsh from Frank's Creek, which is conveying stormwater from the Town of Kearny, has been breached, allowing for the interchange of water to the marsh.

To determine the routes and magnitudes of water flows entering and exiting the marsh, a water budget was developed. The water budget is an accounting of each component of the hydrologic cycle in order to quantify its contribution to a particular system (Figure 1). A water budget is commonly calculated using a mass balance approach where the inputs and outputs equal some change in water storage, either an increase or decrease in water level or volume (inputs – outputs = change in water storage). The water budget equation used for Kearny Marsh is expressed as:

$$\Delta V/\Delta t = P + S_i - ET - S_o$$

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/runoff

ET = evapotranspiration

S_o = surface water outflow

Inputs include precipitation and runoff (S_i) while outputs include evapotranspiration and surface water outflows (Table 1). Runoff was used as the surface water input to this system because there are no natural streams flowing into Kearny Marsh. The highly urban areas surrounding the Marsh create increased amounts of runoff when compared to non-urban areas, making runoff the dominant surface water input. Groundwater flows were assumed to be negligible compared to the surface flows for this system. Tidal exchange was also suspected at the bulkhead breach along Frank's Creek but its influence on the system as a whole is considered small.

Monthly values of water flows in each compartment (expressed in million gallons per day, MGD) were calculated from January 2000 through December 2006 (Figure 2; Figure 3). The water budget was considered to be balanced for this timeframe, i.e. $\Delta V/\Delta t$ equaled zero.

According to the water budget, the surface water system is dominating the hydrology as runoff was the largest input and surface water outflows were the largest outputs (Figure 2; Figure 3).

The water budget was developed to answer the question, “What contaminant loads are currently going into Kearny Marsh?” The volume computed for each component can be used to calculate the loads of any pollutants in each compartment of the water budget. Water quality analyses of both stormwater and groundwater are currently being performed and incorporated into the water budget. Further research into groundwater dynamics in the marsh is being conducted to verify our assumption that groundwater flows are negligible. Additional monitoring of evaporation through the use of lysimeters will be used to improve our PET calculations. Individual components of the water budget can also be used to identify sources of these pollutants and their contribution to overall degradation of Kearny Marsh. Water level data in the marsh obtained from NJMC is being reviewed to determine if it verifies the change in water volume calculated through this water budget model. This data will also be used to determine the error in the calculations used for the various components of the water budget. Future hydrologic monitoring is focused on refining this water budget.

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Figure 1: Schematic of generalized water budget showing hydrologic additions and losses to a wetland system.

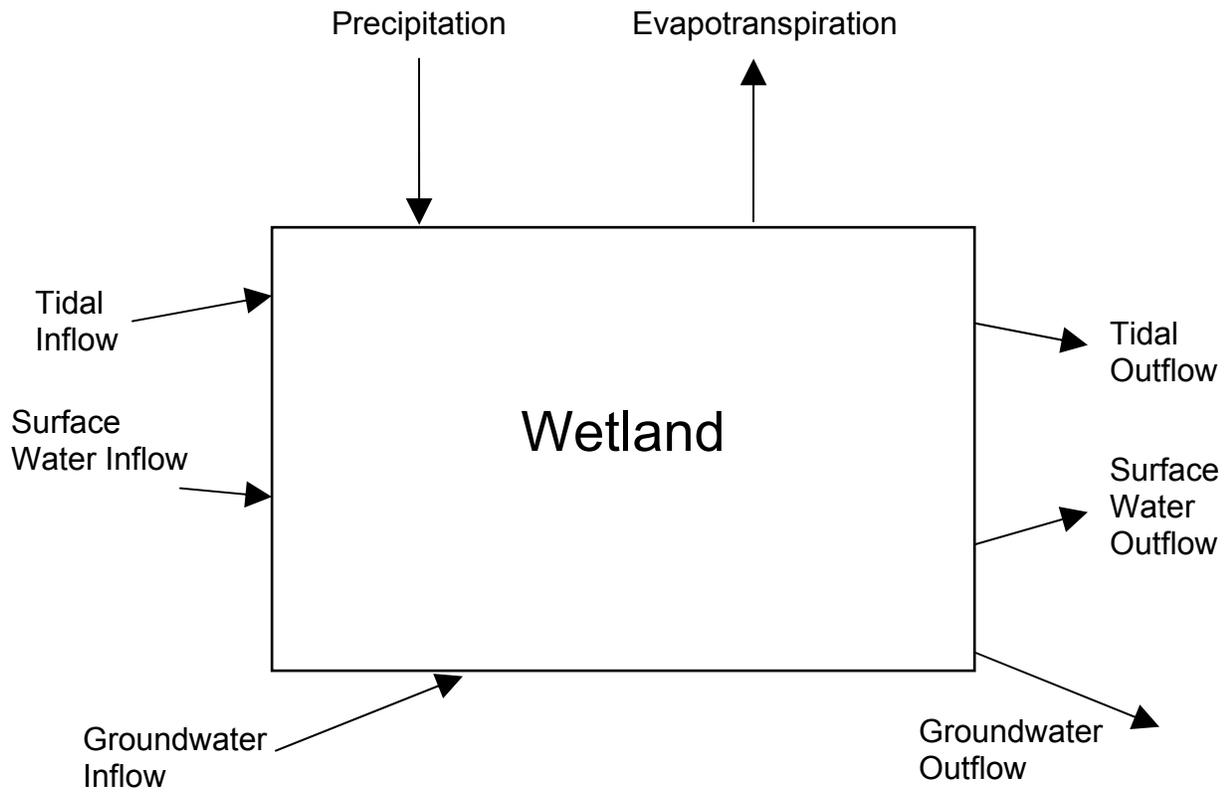


Table 1: Components of the Kearny Marsh water budget and how each was calculated.

INPUTS	OUTPUTS
<p><i>Precipitation</i> – Total monthly precipitation values were taken from Newark Liberty International Airport data obtained by the New Jersey State Climatologist’s Office at Rutgers University.</p>	<p><i>Evapotranspiration</i> – Potential evapotranspiration (PET) was calculated using the Thornthwaite equation: $PET_i = 16(10T_i/I)^a$ Where, PET_i = PET for month i (mm/mo) T_i = mean monthly temperature (in °C) I = local heat index, $\Sigma (T_i/5)^{1.514}$ $a = (0.675 \times I^3 - 77.1 \times I^2 + 17,920 \times I + 492,390) \times 10^{-6}$</p> <p>The Thornthwaite equation used monthly air temperature, which was obtained via web download of Meadowlands Environmental Research Institute (MERI) continuous weather monitoring data at their headquarters in Lyndhurst, NJ. PET results were multiplied by a correction factor to account for the duration of sunshine in each month and latitude.</p>
<p><i>Surface Water Inflow/Runoff</i> – Runoff was calculated using the Natural Resources Conservation Service’s Runoff Curve Number method, which is appropriate for use on small urban watersheds such as Kearny Marsh.</p>	<p><i>Surface Water Outflow</i> – In order to balance the hydrologic budget, surface water outflows were calculated as the remainder after PET was subtracted from all inflows (Precipitation + Runoff).</p>

APPENDIX IV.
ANALYTICAL DATA – ATTACHED CD
MODEL DATA – ATTACHED CD