FINAL REPORT

CONSTRUCTED WETLANDS FOR STORMWATER MANAGEMENT

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INTRODUCTION

Wetland mitigation and stormwater management provisions in the 1987 Clean Water Act (CWA) significantly impact transportation agencies. CWA Section 404 stipulates that when highway construction results in the displacement of natural wetlands, the highway agency is required to create artificial wetlands to compensate for that loss. Section 402 directs the U.S. Environmental Protection Agency (EPA) to regulate stormwater runoff from certain areas under the National Pollutant Discharge Elimination System (NPDES). Highway stormwater runoff, runoff from road construction sites with five or more disturbed acres, and runoff from maintenance and storage facilities are subject to NPDES permit requirements.

In addition to the EPA regulations, the Virginia Department of Transportation (VDOT) must also comply with the Chesapeake Bay Preservation Act, Virginia's Stormwater Management Regulations, and State Erosion and Sediment Control Regulations. A common requirement of all of these stormwater regulations is the use of best management practices (BMP), such as detention ponds and infiltration for the control of runoff quantity and quality.

To date, VDOT has constructed over 220 wetlands and more than 350 stormwater detention basins. Wetland mitigation is a significant item in the VDOT road-building budget. Compliance with applicable stormwater regulations can add between ten and fifteen percent to the cost of an average construction project. A potentially cost-effective approach to satisfying wetland mitigation requirements and stormwater regulations is the use of mitigated wetlands as stormwater BMPs. It is believed that if a mitigated wetland site is properly engineered and maintained, it will perform adequately as a stormwater BMP without jeopardizing its desired wetland functions. It may also be possible to design a detention basin to include emergent wetland vegetation to enhance pollutant removal.

PURPOSE AND SCOPE

This study examined the potential for using mitigated wetlands as stormwater BMPs in Virginia. The objectives of this research effort were:

1. To document water quality benefits of mitigated wetlands and vegetative detention basins through monitoring of selected mitigated wetland sites and detention basins with emergent wetland vegetation. Monitoring focused on pollutant removal efficiency and stormwater impacts.

2. To develop a modeling framework for simulating the transport and fate of pollutants in wetland systems and to develop a link between a GIS and a watershed model for simulating pollutant transport. The former provides a tool for predicting the effectiveness of constructed wetlands for water quality improvement; the latter allows planners to compare siting alternatives for constructed wetlands and detention basins by looking at geographical constraints and anticipated runoff characteristics.

3. To develop a geographic information system (GIS) that would 1) serve as an inventory of VDOT's constructed wetlands throughout the state; 2) become a selection tool for future constructed wetland site locations; and 3) serve as a data source for the hydrologic models used by VDOT.

The following report presents findings for each of these objectives in separate sections. Section I presents results of wetland monitoring, Section II describes wetland modeling, and Section III details GIS development.

SECTION I: WETLAND MONITORING

BACKGROUND

Constructed wetlands have been used for decades for the treatment of municipal and industrial wastewater (Hammer, 1989 and Moshiri, 1993) and are considered to be more cost effective than advanced wastewater treatment systems. However, the use of wetlands to control nonpoint source (NPS) pollution has only recently been investigated. A number of studies conducted since the mid-1980s on the use of constructed wetlands for urban stormwater treatment have suggested that constructed wetlands may improve stormwater runoff quality. In their study of the pollutant removal efficiency of a detention pond-wetland system receiving runoff from a four-lane concrete roadway, Martin and Smoot (1986) found removal rates between 41 and 73 percent for total solids, lead, and zinc. Athanas (1988), Munger, et al. (1995), Strecker, et al. (1990) have also reported significant removal of solids and metals in wetlands. Other studies have reported removal of nitrogen (10 to 50 percent) and phosphorus (16 to 70 percent) (Bautista and Geiger, 1993; Crumpton, 1995; Kappel, *et al.* 1985; Martin and Smoot, 1986;

Niswander and Mitsch,1995; Strecker et al., 1990). The complexity of nutrient cycling in wetland systems leads to a wide range of removal efficiencies for nitrogen and phosphorus. Depending on seasonal effects, vegetation type, and management practices, wetlands may serve as a source, sink, or transformer of nutrients (Raisin and Mitchell, 1995, Strecker, et al. 1990). However, well designed wetlands may attain long-term nutrient removals on the order of 25 percent for total nitrogen and 45 percent for total phosphorus (Schueler, 1992).

The U.S. EPA encourages the use of constructed wetlands for nonpoint source pollution control, especially in agricultural areas (USEPA, 1992) and recognizes the need to combine wetland protection and nonpoint source pollution control strategies (Baker, 1993). A report prepared for the Federal Highway Administration describes the applicability of constructed wetland technology for nonpoint source pollution from highways (Dorman, et al., 1988):

> *Artificial wetlands offer many more options for the management of highway runoff . . . the constructed wetland can be sized to accommodate a projected hydraulic load and to provide a specific residence time; constructed within the highway right-of-way, in median strips, in cloverleafs, or alongside the highway, and designed to facilitate operations and maintenance.*

Though data collected to document the performance of wetlands constructed for stormwater quality improvement are increasing (Yu, et al., 1996, 1997), most studies have examined wetlands designed specifically for water quality improvement rather than for the purpose of mitigation.

METHODS

Site Selection, Preparation, and Description

There are over 220 mitigated wetland sites listed by VDOT as of 1997, most located in the coastal region of Virginia. The VDOT Environmental Division and the research team reviewed candidate sites to determine which would be best for sampling and monitoring. Candidate sites were selected based on the following criteria:

1. Site located on state or public property
2. Stormwater runoff as main water source
3. Vegetation well developed and aged at least 3 years
4. Clearly defined inlet(s) and outlet(s)
5. Accessibility by the research team

The research team visited candidate sites and compared them before making final selections. The most common reason for elimination of a candidate site was the lack of well-defined inlets and outlets. Also, many sites were found unsuitable for sampling and monitoring because they had multiple inlets and outlets. In general, sites with more than three inlets and outlets were not selected due to the limited number of automatic samplers available.

A total of eight sites, presented in Table 1, were ultimately chosen for monitoring over a three year study period. Locations of these sites are illustrated in Figure 1.

Table 1. Study Sites

Location	Years Monitored	Size ha (acre)	Runoff Types	Type of Wetland
Rio Hill Pond/ Rio Hill Shopping Center/ Albemarle, VA	1995	0.28 (0.7)	Parking Lot, Highway	Stormwater Detention Basin with Emergent Vegetation
Buster Pond/ Richmond VDOT District Office/ Colonial Heights, VA	1996	0.04 (0.1)	Office Complex, Auto Shop, Gas Pump Island	Natural Wetland
Route 637/ Kingsland Creek Mitigation Area/ Chesterfield, VA	1996	1.21 (3.0)	Highway, Residential, Forest	Mitigated Wetland
Route 295/ Fort Lee Mitigation Area/ Fort Lee, VA	1996-97	7.32 (18.1)	Highway	Mitigated Wetland
Route 288/ Mitigation Site 14/ Chesterfield, VA	1996-97	2.02 (5.0)	Highway	Mitigated Wetland
Brooke Commuter Rail Parking Lot/ Brooke, VA	1996	0.08 (0.2) for detention basin 2.83 (7.0) for wetland	Parking Lot, Railway	Stormwater Detention Basin with Emergent Vegetation and Mitigated Wetland
I - 64/ Bower's Hill/ Chesapeake, VA	1996	0.70 (1.7)	Highway	Mitigated Wetland
Rt. 211/ Covington River Mitigation Area/ Rapahannock, VA	1997	0.40 (1.0)	Agricultural, Highway	Mitigated Wetland

Figure 1. Stormwater sampling locations.

All sites were prepared for monitoring in accordance with the project's 1997 Quality Assurance/ Quality Control (QA/QC) Plan (provided in Appendix A). Figure 2 depicts an inflow monitoring station at the Rt. 288 site in Richmond. This station is a typical example of a site prepared for monitoring. Rainfall is measured by a tipping bucket rain gage, while flow is measured using a rectangular weir. An automatic sampler records rainfall and flow measurements and collects samples during runoff events. Similar monitoring stations were established at all sites. Wetland delineations determined for the Rio Hill, Rt. 295, Rt. 288, Brooke, and Covington River sites are shown in Figure 3, along with their inlets and outlets.

Figure 2. Typical monitoring station (Rt. 288 infow)

Site Descriptions

Rio Hill

The Rio Hill detention basin (Figure 4) is a 0.28 ha (0.7 acre) impoundment serving a 30 ha (75 acre) drainage area in Albemarle County. The box and raingage at the far end of the basin monitor the basin's outflow. Runoff to the basin is supplied from a shopping center with an extensive parking area and from a nearby intersection (average daily traffic (ADT) 33,000 vehicles). Unvegetated open water area accounts for less than 5 percent of the wetland area. The lower section of the basin usually has shallow standing water and is dominated by moderately dense emergent vegetation including *Juncus effusus* (Soft Rush), *Typha latifolia* (Cattail), *Euthamia graminifolia* (Goldenrod), and *Scirpus cyperinus* (Wool Grass). Woody vegetation and

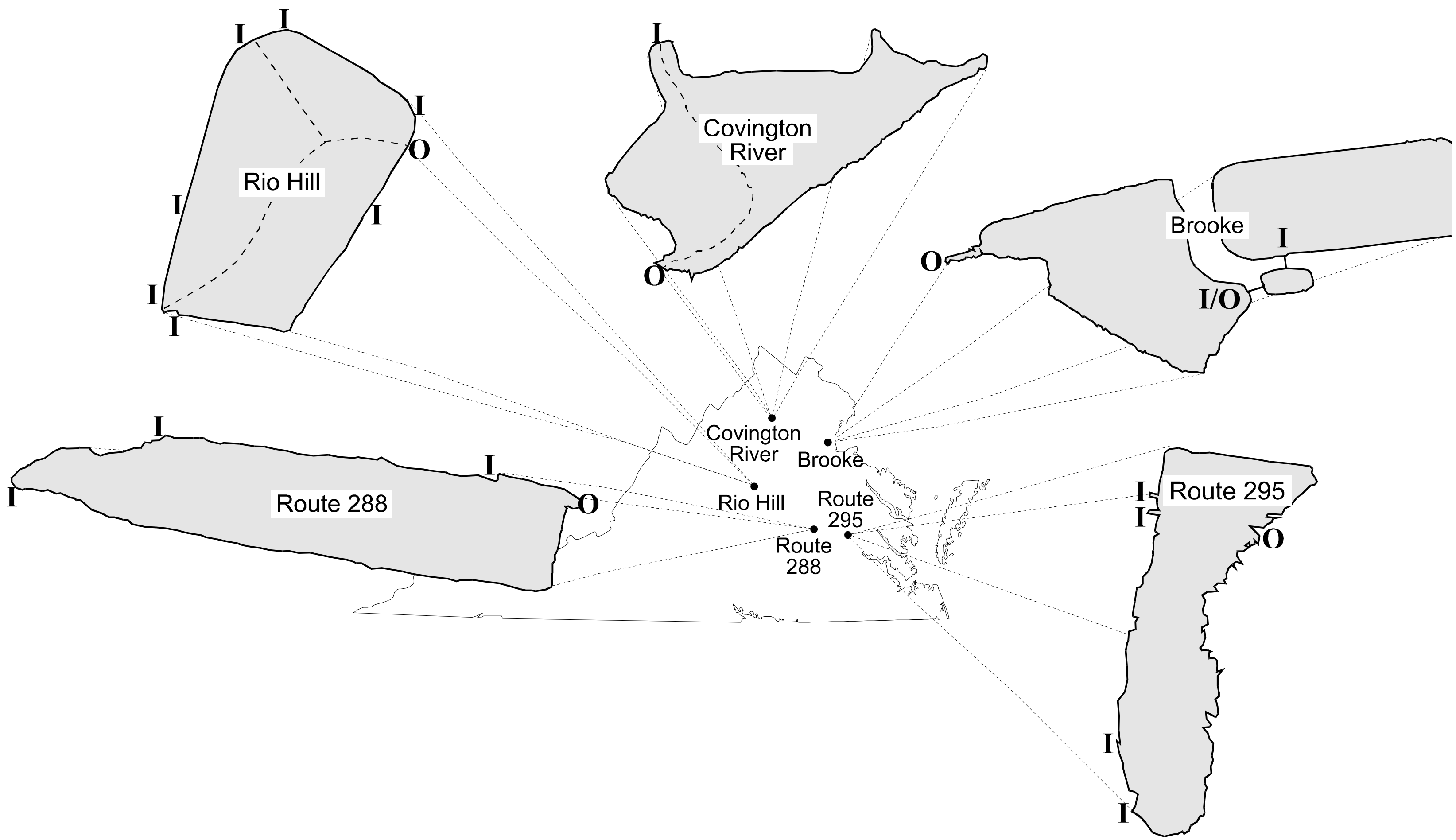


Figure 3. Wetland Site Delineations

Figure 4. Rio Hill detention basin

Figure 5. Rt. 288 outlet zone

shrubs, primarily *Gleditsia aquatica* (Swamp Locust), *Juniperus virginiana* (Eastern Red Cedar), *Albizzia julibrissin* (Mimosa), and *Pinus taeda* (Loblolly Pine), are moderately dense in the high marsh areas along the banks. *Salix nigra* (Black Willow) is dense along the main channel.

Buster Pond

The Buster Pond wetland is a small 0.04 ha (0.1 acre) wetland that receives runoff from the office complex, auto shop, and gas island at the VDOT Colonial Heights District Office. *Salix spp.* (Black Willow and Weeping Willow) are dominant in a small upland area in the proximity of the inlet; however, the vast majority of the wetland is permanently flooded and supports a dense stand of *Typha latifolia* (Cattail). During the process of monitoring this site during 1995, it became apparent that this site was unsuitable for monitoring due to difficulty in measuring outflow. Since the outflow from the wetland merges into a pond, the outlet from the wetland is not well defined. Although monitoring is possible at the outlet of the pond, sampling at this point could not isolate the effect of the wetland alone on water quality.

Rt. 637 Kingsland Creek Mitigation Area

The Kingsland Creek Mitigation Area is a 1.21 ha (3.0 acre) constructed wetland in Chesterfield designed as mitigation for impacts to palustrine emergent, scrub-shrub, and forested wetlands resulting from road and bridge improvements. Woody species present at the site include *Acer rubrum* (Red Maple), *Betula nigra* (River Birch), *Liquidamber styraciflua* (Sweet Gum), *Juniperus virginiana* (Eastern Red Cedar), *Pinus taeda* (Loblolly Pine), and *Quercus alba* (White Oak). Shrubs present include *Vaccinium corymbosum* (Highbush Blueberry) and *Viburnum dentatum* (Arrowwood), while emergent species include *Juncus spp.* (Rush), *Carex spp.* (Sedge), and *Polygonum spp.* (Tear Thumb). Monitoring at this site was discontinued due to a leaking concrete culvert at the inlet. Flow measurement and sampling equipment was set up at the end of the culvert at the point of discharge into the wetland; however, gaps between the sections of the culvert allowed water to leak from the culvert into the ground prior to the monitoring point. While this water eventually reached the wetland by flowing beneath the culvert, there was no effective way to monitor it.

Rt. 295 Fort Lee Mitigation Area

This 7.32 ha (18.1 acre) site in Fort Lee was the largest site monitored in the study. Although monitoring of all inflows and outflows at this site proved to be beyond the resources of the project, the researchers studied the runoff entering the mitigation area from one inflow for two years in order to characterize it. Land use (primarily interstate highway Rt. 295 and associated right-of-way) was similar for all inflows into the wetland. In addition to this inflow station, in 1997 some outflow measurements were collected in the main outflow channel. The majority of the wetland is semi-permanently flooded and supports a variety of emergent vegetation that is dominated by *Scirpus cyperinus* (Wool Grass), *Juncus spp.* (Rush), and *Typha latifolia* (Cattail).

Rt. 288 Mitigation Area 14

The Rt. 288 mitigation site is a 2.02 ha (5 acre) mitigated wetland located in the median of a four-lane highway with a 50,000 vehicle ADT in Chesterfield. The site is characterized by a combination of wet meadow, fresh marsh, and tree swamp area, with a large open water zone near the outlet (approximately 25 percent of the site). Although some dry areas exist, soil conditions are mainly saturated, evidenced by shallow standing water (2.5-10 cm) covering most of the site. *Salix nigra* (Black Willow), *Scirpus cyperinus* (Wool Grass), *Juncus effusus* (Soft Rush), and *Typha latifolia* (Cattail) were prevalent in areas with shallow standing water. *Lemna* spp. (Duckweed) was prevalent in open water areas, while *Pinus taeda* (Loblolly Pine) was prevalent in the higher marsh area. Figure 5 shows the outlet zone of the Rt. 288 wetland.

Brooke Detention Basin and Wetland

The Brooke site consists of a 0.08 ha (0.2 acre) emergent detention pond and a 2.83 ha (7 acre) mitigated wetland in series. The site receives stormwater runoff from a commuter parking lot, a grassed area, and a railway. Conditions range from permanently flooded regions where deep (up to 1 m) pools exist to intermittently flooded regions where surface water is present during storm events and near-saturated to saturated soil conditions prevail during dry weather. The site has approximately 0.4 ha (14 percent of total area) of open water. The detention basin is intermittently flooded with water levels rising as high as 2 m during large storm events. Like the rest of the site, the basin's soil is usually at or near saturation during dry periods. Vegetation density is moderate to dense in all but the open water area. *Scirpus cyperinus* (Wool Grass), *Typha latifolia* (Cattail), and *Juncus effusus* (Soft Rush) are the dominant emergent species and Salix nigra (Black Willow) is dense along the main channel of the wetland. Primary species in the detention basin are *Scirpus cyperinus* (Wool Grass), *Typha latifolia* (Cattail), *Solidago spp.* (Goldenrod), and *Juncus effusus* (Soft Rush).

I-64 Bower's Hill Mitigation Site

The Bower's Hill site is a 0.70 ha (1.7 acre) mitigated wetland in Chesapeake surrounded on all sides by highways. The primary sources of runoff for the wetland are the eastbound lanes of I-64 and an exit ramp from the westbound lane. While some dry areas exist, soil conditions are mainly saturated, evidenced by shallow standing water covering much of the site. Dense vegetation at this site includes *Typha latifolia* (Cattail), *Arundinaria gigantea* (Giant Cane Grass), and woody species including *Acer rubrum* (Red Maple), *Quercus michauxii* (Swamp Chestnut Oak) and *Quercus bicolor* (Water Oak).

Rt. 211 Covington River Mitigation Area

The Covington River wetland is an approximately 0.4 ha (1 acre) mitigation area, located in an agricultural area of Rappahannock County. Soil conditions range from extremely dry on the western side of the wetland in a high marsh area to saturated conditions with shallow pools of standing water in the low marsh covering the remainder of the site. Unvegetated open water area accounts for less than 5 percent of the wetland area. The upper marsh is dominated by *Andromeda glaucophylla* (Bog Rosemary), while common low marsh species observed include *Juncus effusus* (Soft Rush), *Impatiens capensis* (Jewel Weed), *Aster puniceus* (Purple Aster), and *Typha latifolia* (Cattail). *Salix nigra* (Black Willow) is dense along the banks of the channel while *Acer rubrum* (Red Maple), and *Alnus serrulata* (Common Alder) are common throughout the wetland. Figure 6 depicts the main channel of the Covington River mitigation area. Though this photograph was taken prior to the start of the growing season, the abundance of dead plant material in the picture is indicative of the productivity of this site.

Figure 6. Covington River Mitigation Area

Sample Analysis

Analytical parameters for analysis were selected based on the objectives and resources of the project. Since a primary objective of the project was to monitor highway runoff entering constructed wetlands, it was important that constituents chosen for analysis adequately characterize stormwater runoff. Table 2 lists analytical parameters recommended by the Nation-Wide Urban Runoff Program (NURP) to adequately characterize urban runoff. Parameters chosen were total suspended solids (TSS), chemical oxygen demand (COD), total phosphorus (TP), orthophosphate (OP), and zinc (Zn). In addition, the researcher performed limited analysis of total nitrogen (TN), nitrate (NO_3-N), and fecal coliform (FC) for the Covington River site.

Samples were collected using automatic samplers at monitoring stations during storm events. The research team retrieved, chilled, and preserved the samples as soon as possible after collection. Samples were analyzed at the University of Virginia Stormwater Laboratory in accordance with the QA/QC plan in Appendix A. The University of Virginia Stormwater

Laboratory utilized the spectrophotometric, U.S.EPA-approved Zincon method (Hach Co., 1991) to perform most zinc analyses. Analysis of samples with very low levels of zinc was only possible by atomic absorption spectrometry, however. The Aqua Air Laboratory in Charlottesville, Virginia performed this analysis.

Three methods were used to examine pollutant removal in the constructed wetlands. A mass balance was used to determine mass removal efficiency during storm events based on volumes of inflow and outflow and event mean concentrations (EMC) from the composite samples. Mass removal efficiency (MRE) was calculated as:

$$MRE(\%) = \frac{(Volume\ in \times Concentration\ in) - (Volume\ out \times concentration\ out)}{(Volume\ in \times Concentration\ in)} \times 100$$

The researchers also used the determination of event mean concentration (EMC) removal efficiency to assess pollution removal. Event mean concentrations were determined from analysis of flow-weighted composite samples or from flow-weighting of analytical results from analysis of discrete samples. EMC removal was calculated as:

$$EMC\ Efficiency\ (\%) = \left(1 - \frac{outlet\ EMC}{inlet\ EMC}\right) \times 100$$

The third method used was the calculation of the sum of the loads (SOL) efficiency. SOL efficiency is calculated based on mass entering and leaving the wetland over all storms completely monitored (a storm was considered to have been completely monitored when stormwater samples and flow measurements were collected at every monitoring station at the site). SOL removal efficiency was calculated as:

$$SOL\ Efficiency\ (\%) = \left(\frac{\sum_{i=1}^{\#storms} Volume\ in\ (i) \times Concentration\ in\ (i) - \sum_{i=1}^{\#\ storms} Volume\ out\ (i) \times Concentration\ out\ (i)}{\sum_{i=1}^{\#\ storms} Volume\ in\ (i) \times Concentration\ in\ (i)} \right) \times 100$$

Of the three methods, the EMC reduction method is the most conservative estimate of removal for a single event, since it does not account for the storage of water. The SOL method, on the other hand, provides a calculation of removal over a longer time period than an individual event. It should be noted that in some instances, the calculated MRE or SOL removal will be lower than the EMC reduction. EMC removal efficiencies are greater than MRE when rain (assumed to have minimal pollutant concentrations) falling directly onto a wetland with little storage available results in additional outflow. The contribution of direct rainfall can be quite significant, especially for the larger sites. For most sites EMC, MRE, and SOL removal efficiencies were similar; however, large variation between these three measures was observed at

Table 2. Analytical Parameters Recommended by NURP to Adequately Characterize Urban Runoff (USEPA 1991)

Conventional Parameters pH Total Suspended Solids Biological Oxygen Demand Chemical Oxygen Demand Settleable Solids Temperature	**Metals** Copper Lead Zinc
Nutrients Total Phosphorus Soluble Phosphorus Total Kjeldahl Nitrogen Nitrate/Nitrite Nitrogen	**Biological Parameters** Fecal Coliform

the Brooke site. This variation is attributable to the small number of storms monitored at this site and the large amount of storage for the storms that were monitored.

Vegetation and Wildlife Monitoring

Beginning in 1996, surveys of vegetation were conducted at the Rt. 288, Brooke, Rio Hill, and Covington River sites. The research team conducted an initial survey of each site to identify the species present. After this inventory was performed, square meter plot counts of vegetation were conducted throughout the wetland. Density of vegetation was noted on a qualitative scale ranging from sparse to abundant. A qualitative assessment of vegetative health was also made. Observations of wildlife present, whether from visual identification or from indirect evidence such as animal tracks, were made every time the sites were visited.

RESULTS

Between 1995 and 1997 fifty-nine storm events were monitored at the eight sites. Thirty-nine of these events were considered 'completely monitored.' For sites where inflows and outflows were monitored (Rio Hill, Rt. 288, Rt. 460, Brooke, and Covington River) these 'completely monitored' events yielded data necessary for EMC, MRE, and SOL analysis. It should be noted that inflow 3 at Rt. 288 was not monitored until 1997, since the contribution of this source is minor compared to inlets 1 and 2. Table 3 lists storms monitored by site.

Table 3. Storm Events Monitored

Site	Number of Stations	Number of Events	Number of Completely Monitored Events
Rio Hill	3	5	5
Buster Pond	2	2	2
Rt. 637	1	2	2
I-295	1	12	11
Rt. 288	4	13	7
Brooke	3	13	3 for basin, 2 for wetland, 1 overall
Rt. 460	3	7	2
Covington River	2	5	3

Precipitation and Flow

Mean precipitation data for storms monitored at the study sites are shown in Figure 7. Only storms that produced runoff are indicated in the range of precipitation. For sites with highly impervious drainage areas such as the Rio Hill and Brooke sites, as little as 5 mm of rainfall produced sufficient rainfall to trigger samplers. Figure 8, constructed from data collected during a storm event at the Rt. 288 site on November 3, 1995, illustrates typical flow and precipitation data.

Flood control is an important hydrologic function of wetlands. This function is especially critical for mitigated wetland sites located in developed or paved areas where there is more runoff due to increased imperviousness. Results from six storm events monitored at Route 288, five events monitored at Brooke, and four events monitored at the Covington River site indicate that these wetlands significantly reduced peak flows during storm events. An average peak reduction of 40 percent was observed at the Rt. 288 site for rainfall events ranging from 18.3 mm (0.72 in) to 51.6 mm (2.03 in). The most intense storm monitored at Route 288, with 40.4 mm (1.59 in) of rain in 4 hours, resulted in a peak reduction of 58 percent. At the Brooke site, inflows and outflows were monitored for rainfall events ranging from 3.8 mm (0.15 in) to 47.2 mm (1.86 in). At the Brooke site, the detention basin is a major factor in peak reduction, reducing peak inflows an average of 83 percent. Data from the Brooke wetland indicate average peak reductions of 46 percent, resulting in an average peak reduction of nearly 90 percent for the system. The most intense event monitored, with 47.24 mm (1.86 in) of rain in 50 minutes, resulted in a peak reduction of 93 percent for the entire system. An average peak reduction of 48 percent was observed at the Covington River site for rainfall events ranging from 2.0 mm (0.08 in) to 28.5 mm (1.12 in).

Water Quality

Total Suspended Solids (TSS)

TSS inflow concentrations varied widely between study sites. They ranged from less than 8 mg/L at the Rt. 295 site, where flow passes over a grassed embankment prior to collection, to well over 300 mg/L at the Rio Hill site, where ongoing construction and a highly impervious

Figure 7. Mean precipitation and range for storms monitored

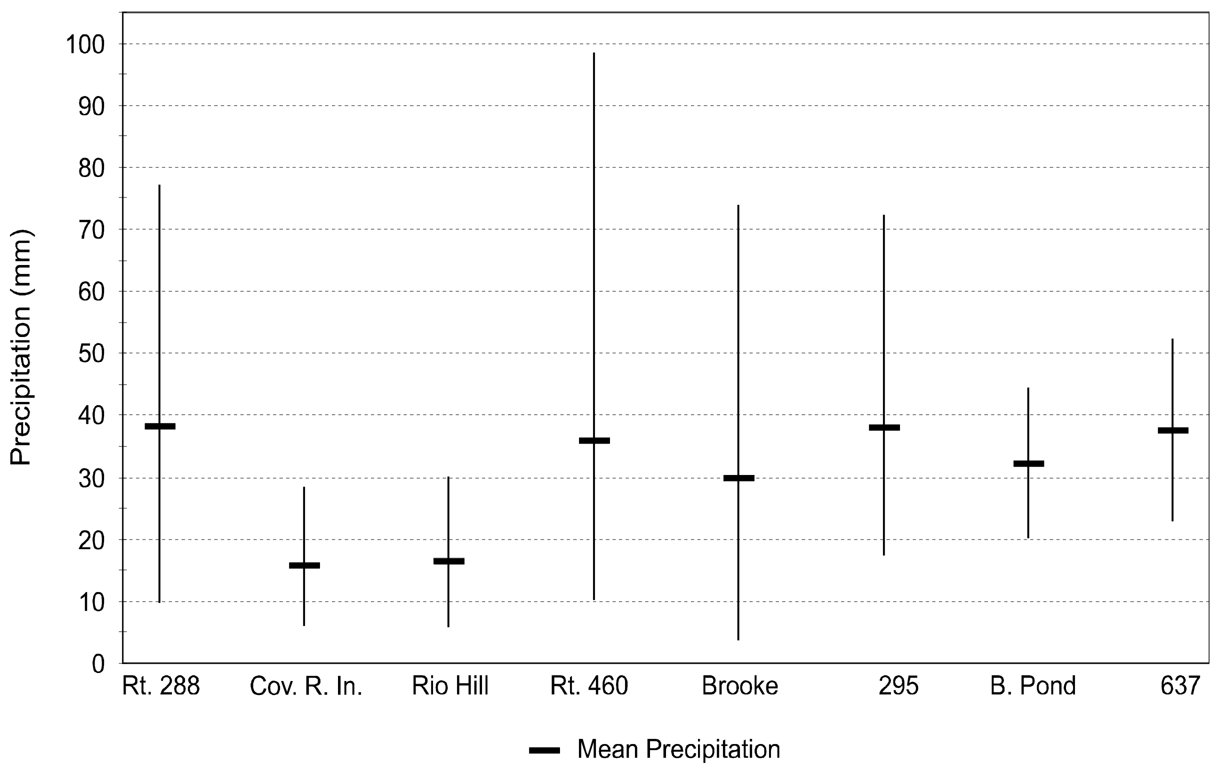


Figure 8. Typical flow and precipitation data collected at monitoring station

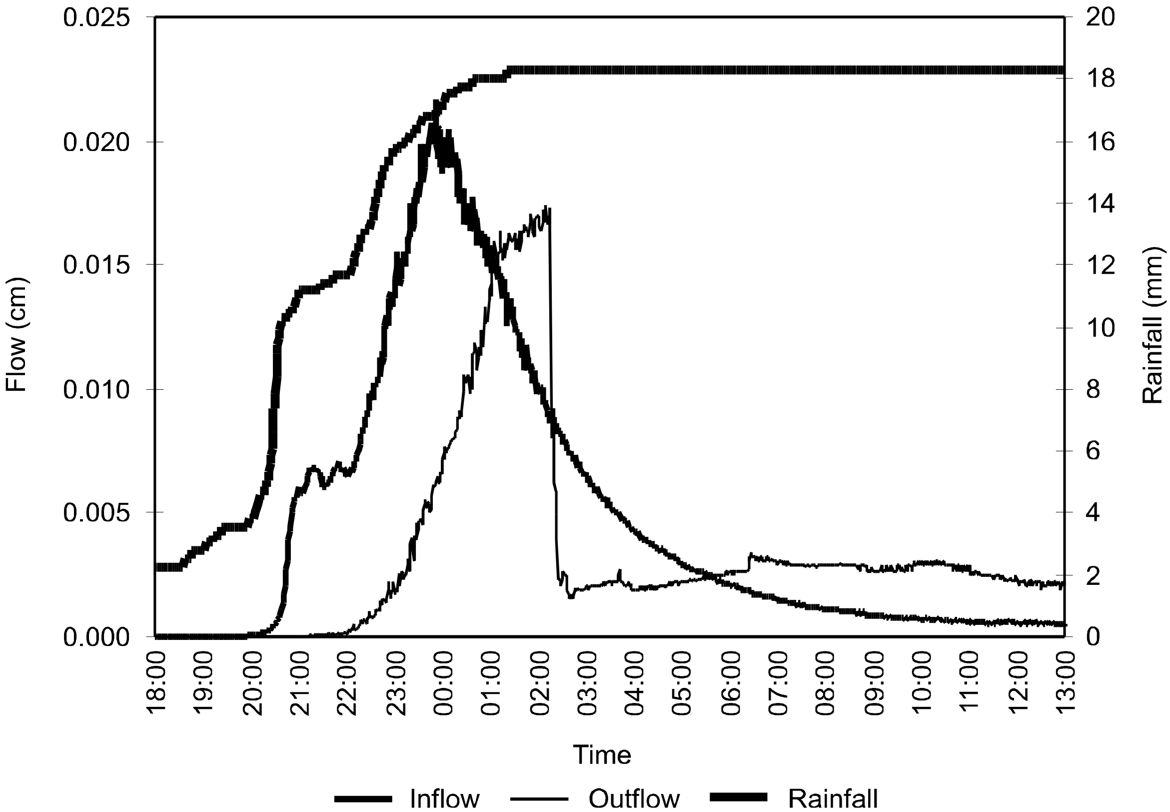
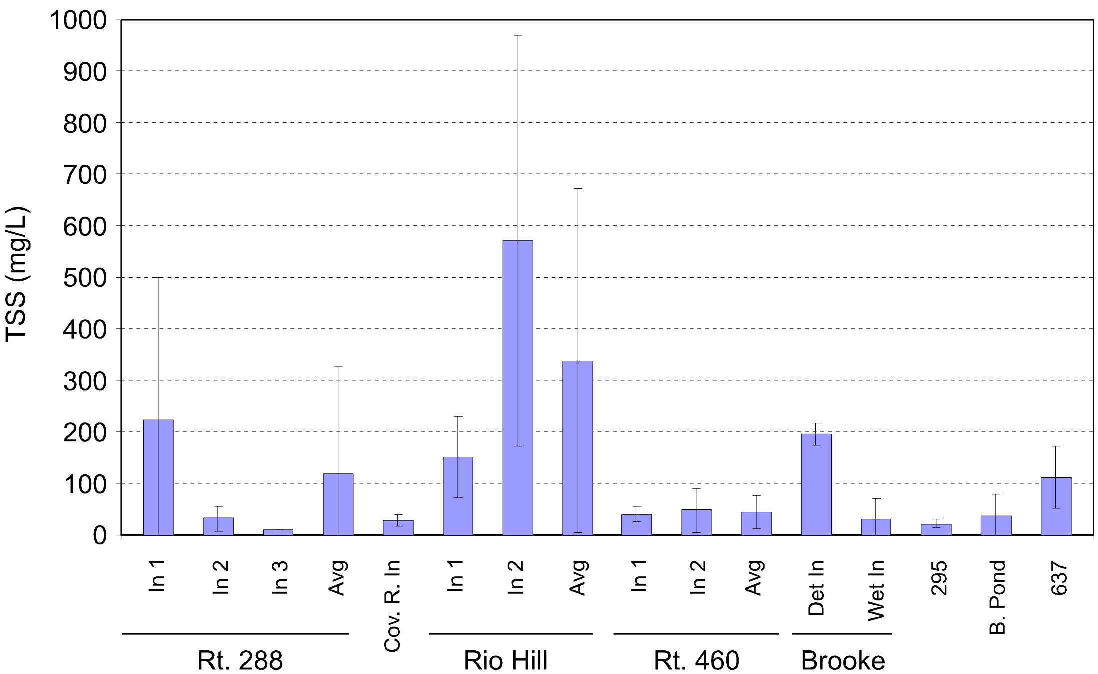


Figure 9. Mean TSS inflow concentration at study sites



surface contributed to high levels. Figure 9 illustrates mean TSS inflow concentrations at study sites, with error bars showing one standard deviation. In general, greater variability was observed for higher mean concentrations.

EMC reduction of TSS is shown in Figure 10 and is presented in Table 4 along with MRE and SOL removal (standard deviations are noted parenthetically).

Figure 10. Mean EMC reduction of TSS

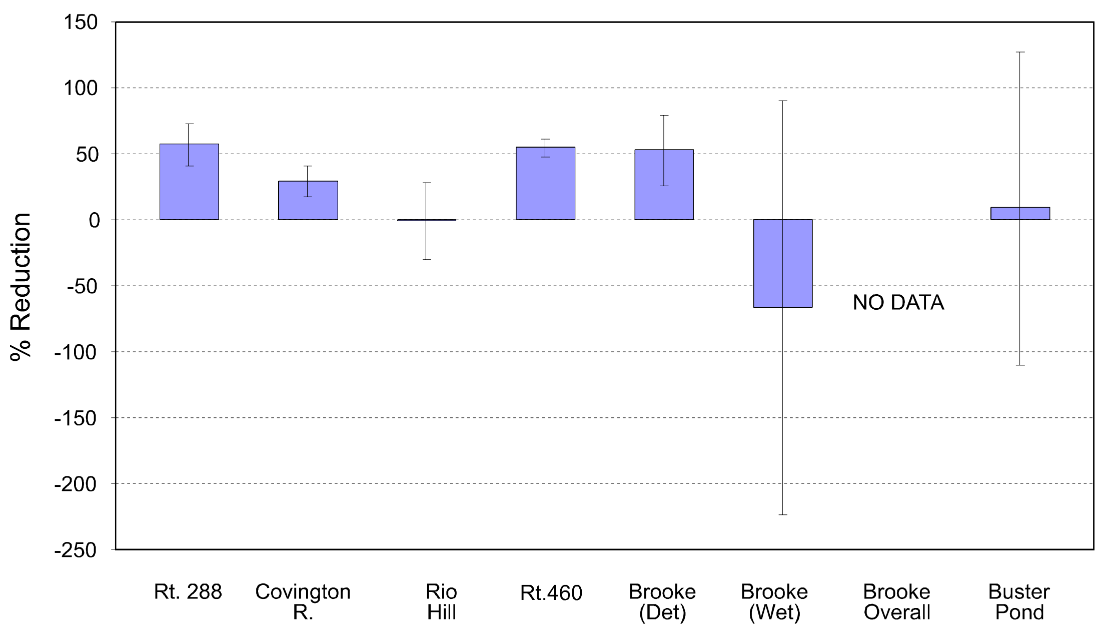


Table 4. Removal Efficiency for Total Suspended Solids (TSS)

Site	EMC Reduction % and (standard deviation %)	MRE % and (standard deviation %)	SOL Removal %
Rt. 288	56.96 (16.08)	61.17 (15.75)	52.02
Covington River	29.02 (12.19)	68.29 (30.77)	62.45
Rio Hill	-1.32 (29.02)	4.98 (24.13)	30.10
Rt. 460	54.35 (6.76)	40.36 (12.26)	48.67
Brooke Detention Basin	52.38 (26.94)	67.48 (4.43)	65.68
Brooke Wetland	-66.75 (157.02)	60.66 (-----)	60.66
Brooke Overall	-----[1]	-----	-----
Buster Pond	8.71 (118.40)	-----	-----

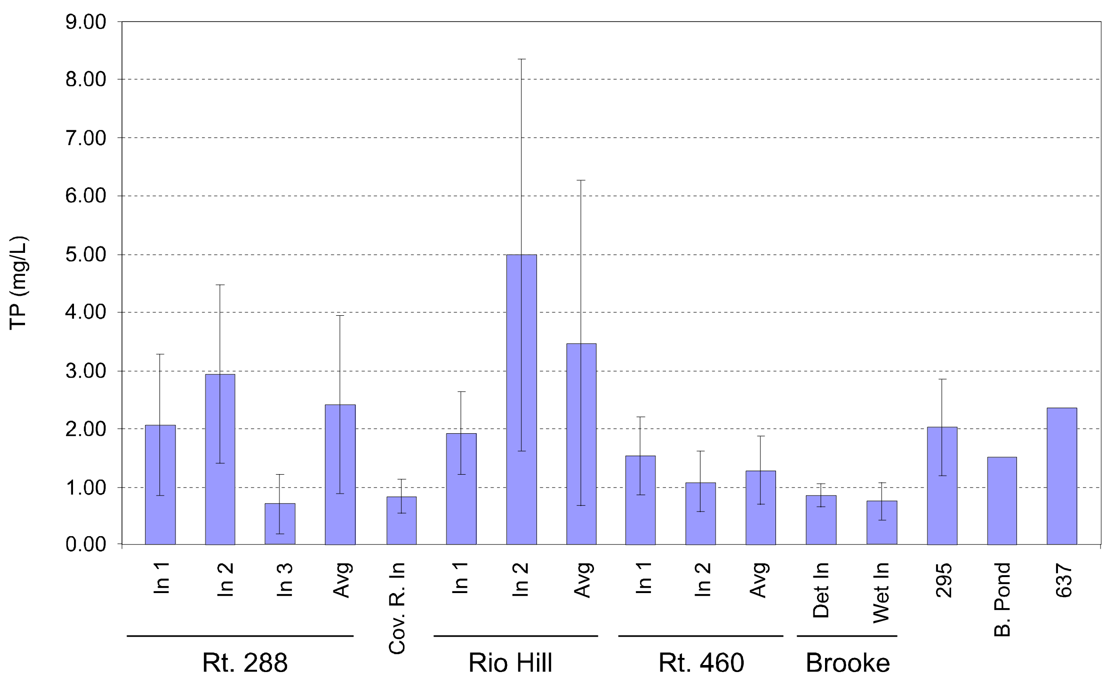
[1] Indicates insufficient data

Average EMC reduction as high as 57 percent (with even higher MRE and SOL reductions) was observed at the Route 288 site. Analysis of variance for the Rt. 288 site indicated a significant ($\alpha = 0.05$) difference between mean TSS concentration in the outflow and at least one inflow. The increase in concentration observed at the Brook wetland should be viewed with two factors in mind: 1) the extremely high standard deviation and small sample size (two events with 44 percent and –178 percent changes, respectively); and 2) positive MRE and SOL removal, indicating the effect of retention of stormwater in the wetland. Greater variability in inflow concentrations tended to produce greater variability in removal (as evidenced by Rio Hill). Nonetheless, SOL calculations indicated removal of TSS for all sites.

Total Phosphorus (TP)

Figure 11 illustrates mean TP inflow concentrations at study sites with error bars showing one standard deviation. As with TSS, greater variability was observed for higher mean concentrations. Mean inflow concentrations range from less than 1 mg/L at the Brooke site to nearly 3 mg/L at Rio Hill. Mean TP concentrations are strongly correlated (0.88) with mean TSS concentrations, indicating that a significant portion of influent TP may be bound to solids.

Figure 11. Mean TP inflow concentration at study sites



EMC reduction of TP is shown in Figure 12 and is presented in Table 5 along with MRE and SOL removal (standard deviations are noted parenthetically). EMC reduction ranged from –19 percent for Rt. 460, to nearly 70 percent for the Rt. 288 site. The sites with the best removal of TP, Rt. 288 and Covington River, showed far less variation (standard deviation < 10 percent for EMC reduction) than the sites that did not perform as well. Analysis of variance for the Rt. 288 site indicated a significant ($\alpha = 0.05$) difference between mean TP concentration in the outflow and at least one inflow. Poor TP removal reported for the Rt. 460 site was based on only one storm, and data for removal at Brooke were also limited. The sites with the most extensive documentation (Rio Hill, Rt. 288, Covington River, and the Brooke Basin) indicated SOL TP removal greater than 20 percent.

Figure 12. Mean EMC reduction of TP

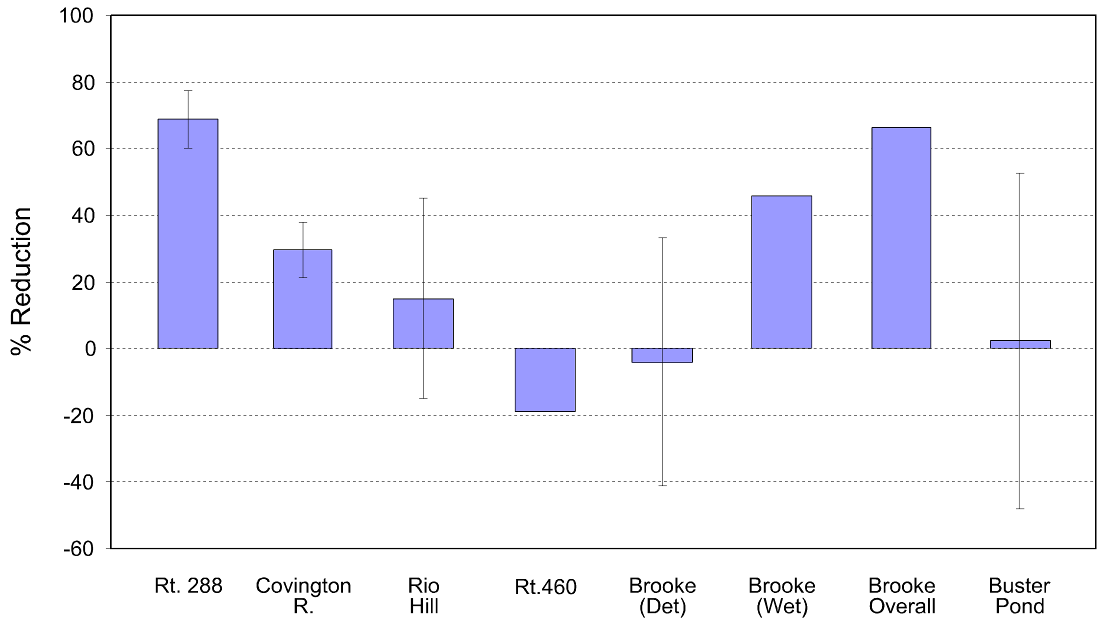


Table 5. Removal Efficiency for Total Phosphorus (TP)

Site	EMC Reduction % and (standard deviation %)	MRE % and (standard deviation %)	SOL Removal %
Rt. 288	68.61 (8.67)	68.92 (17.67)	68.09
Covington River	29.46 (8.37)	71.22 (23.79)	67.36
Rio Hill	14.86 (29.95)	18.89 (25.42)	27.46
Rt. 460	-19.11 (-----[1])	-61.35 (-----)	-61.35
Brooke Detention Basin	-4.22 (37.25)	4.27 (34.32)	22.85
Brooke Wetland	45.83 (-----)	-----	-----
Brooke Overall	66.23	-----	-----
Buster Pond	2.19	-----	-----

[1] Indicates insufficient data

Orthophosphate (OP)

Figure 13 shows mean inflow concentrations for OP with error bars indicating one standard deviation. As with other parameters, larger standard deviations were generally associated with higher mean concentrations. Average inflow concentrations were less than 1 mg/L for the most pervious sites (Rio Hill and Brooke). They were about 2 mg/L for sites where inflow passed over grassed embankments prior to entering the inlet channel of the wetland (Rt. 288 and Rt. 295).

Figure 14 illustrates EMC reduction of OP. Table 6 presents MRE and SOL removal (standard deviations are noted parenthetically).

Figure 13. Mean OP inflow concentration at study sites

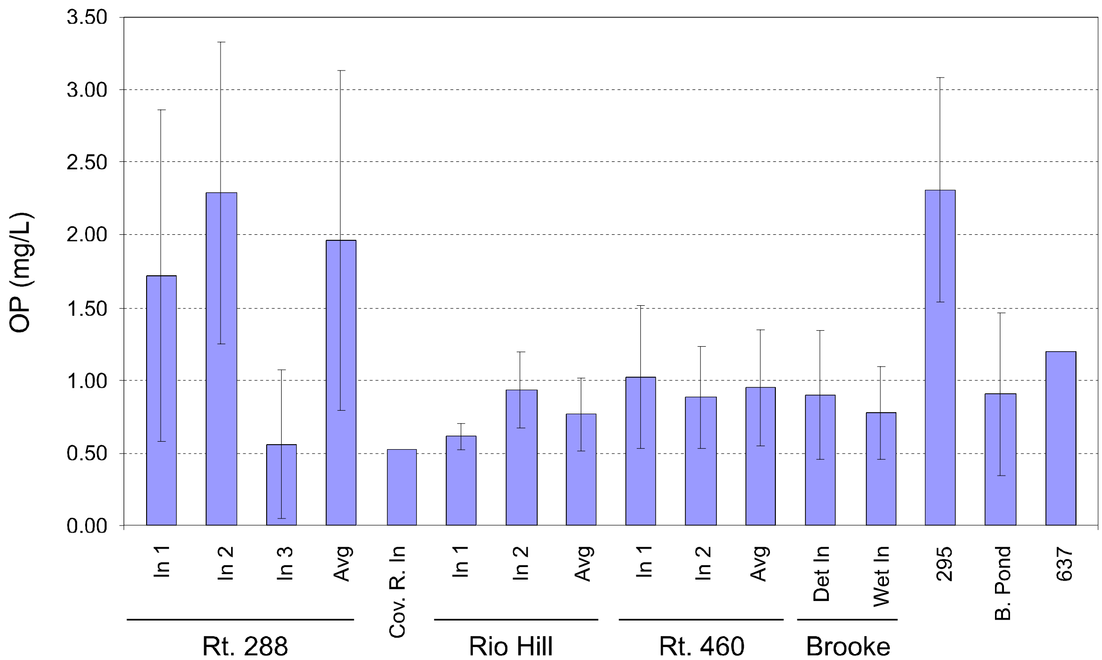


Figure 14. Mean EMC reduction of OP

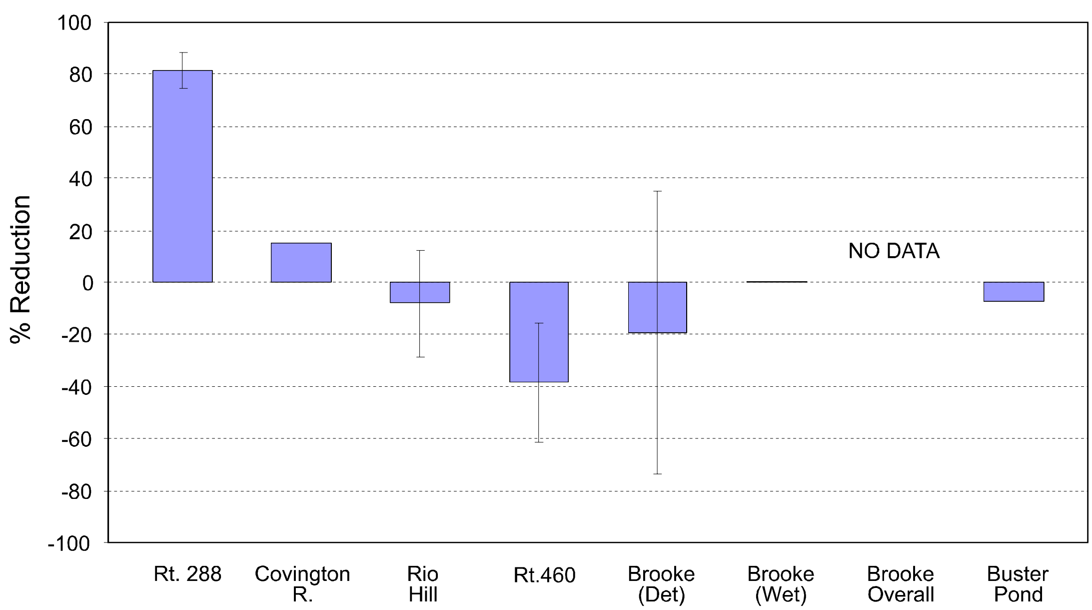


Table 6. Removal Efficiency for Orthophosphates (OP)

Site	EMC Reduction % and (standard deviation %)	MRE % and (standard deviation %)	SOL Removal %
Rt. 288	81.50 (6.78)	81.6 (14.26)	82.46
Covington River	15.38 (-----[1])	32.21 (-----)	32.21
Rio Hill	-8.00 (20.49)	-4.59 (21.87)	0.67
Rt. 460	-38.41 (22.65)	-80.92 (39.98)	-56.24
Brooke Detention Basin	-19.34 (54.23)	11.04 (81.04)	45.74
Brooke Wetland	0.45 (-----)	1.12 (-----)	1.46
Brooke Overall	-----	-----	-----
Buster Pond	-7.33 (-----)	-----	-----

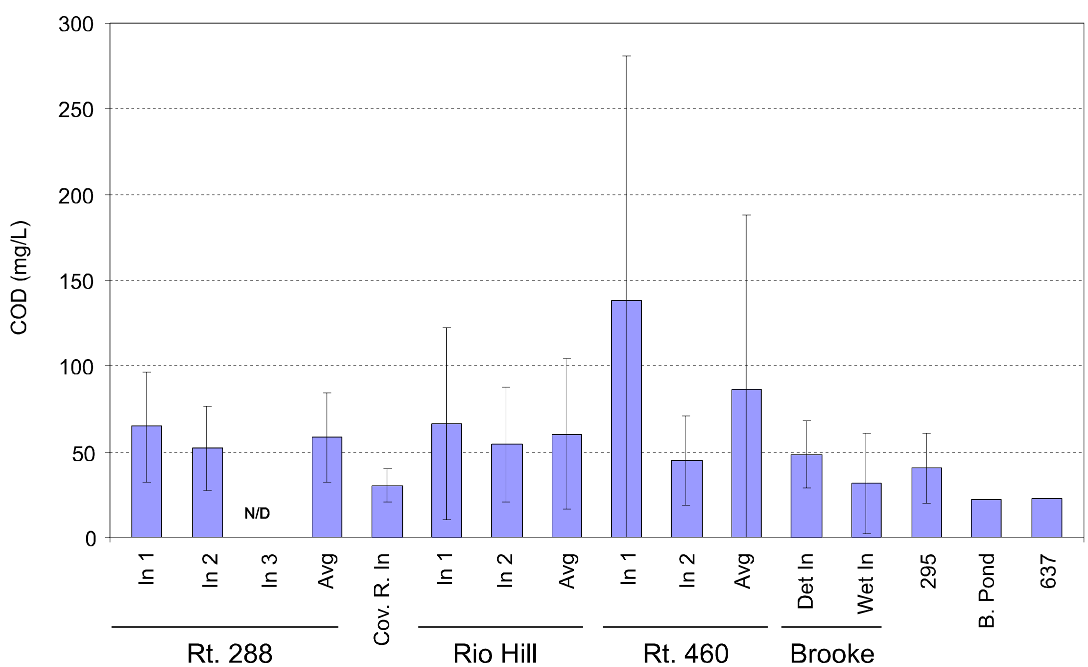
[1] Indicates insufficient data

Excellent removal was achieved at the Rt. 288 site, with significant mass removal also at the Covington River site. Analysis of variance for the Rt. 288 site indicated a significant ($\alpha = 0.05$) difference between mean OP concentration in the outflow and at least one inflow. OP removal followed a trend similar to TP removal, with the Brooke detention basin and the Rt. 460 site showing poorest performances. As with TP data, OP data for these sites were limited, resulting in large standard deviations for removal. On a SOL basis, there was positive removal of OP for all but the Rt. 460 site. Observed increases in concentration are likely attributable to release of bound phosphorus from sediments due to decomposition and hydrolysis of organic phosphorus.

Chemical Oxygen Demand (COD)

Figure 15 illustrates mean COD inflow concentrations at study sites with error bars showing one standard deviation.

Figure 15. Mean COD inflow concentration at study sites



Average concentrations ranged from slightly over 20 mg/L at Buster Pond to over 80 mg/L for the average inflow at Rt. 460. Variability in event mean inflow concentration tended to increase as the average concentration increased. With the exception of the Rt. 460 inlet 1, average COD inflow concentrations did not vary as drastically between sites as other parameters monitored.

EMC reduction of COD is shown in Figure 16 and is presented in Table 7 along with MRE and SOL removal (standard deviations are noted parenthetically). As with other parameters monitored, positive removal was achieved by the Rt. 288 site (greater than 20 percent) and the Covington River site (greater than 50 percent). Although the Brooke wetland had a high percent increase in EMC concentration and caused increased COD on a mass basis, the Brooke site overall had a significant removal of COD. This removal was attributable to greater than 60 percent removal of COD by the detention basin. As with TP and OP, the Rt. 460 wetland performed poorly based on some events sampled. SOL removal was positive for this site, however, indicating that extremely poor performances for individual events may have skewed EMC reduction and MRE averages.

Figure 16. Mean EMC reduction of COD

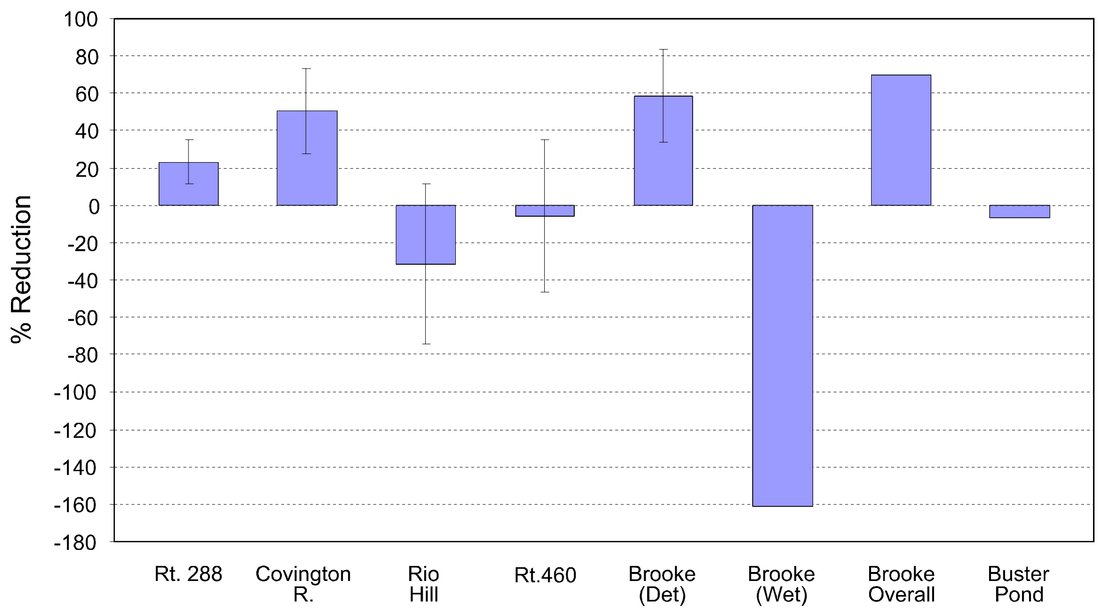


Table 7. Removal Efficiency for Chemical Oxygen Demand (COD)

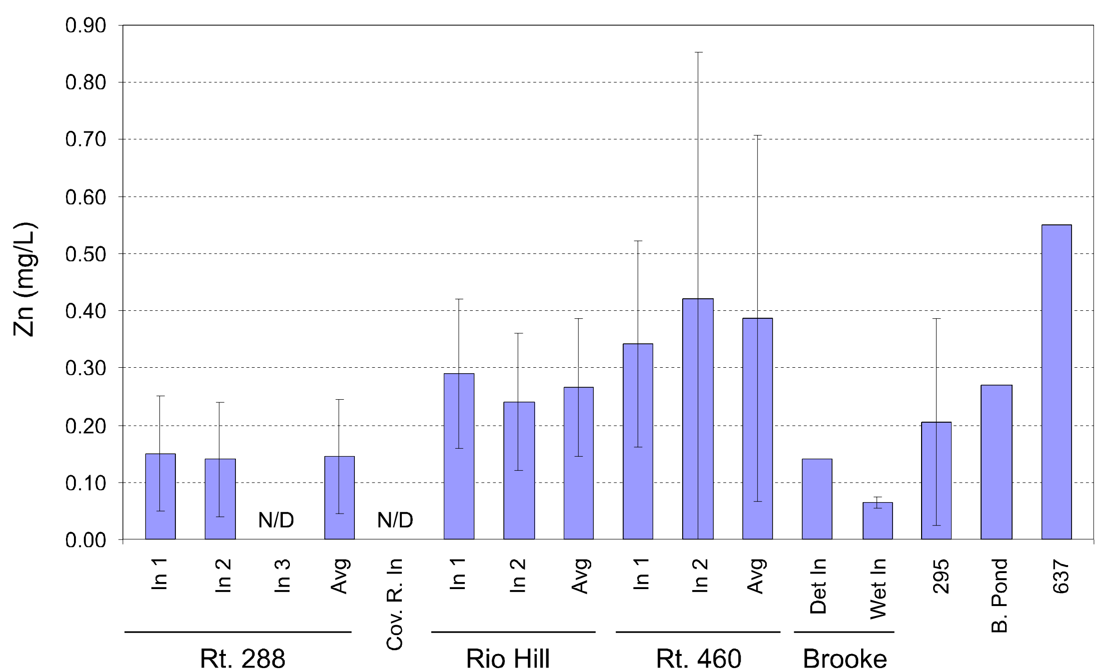
Site	EMC Reduction % and (standard deviation %)	MRE % and (standard deviation %)	SOL Removal %
Rt. 288	23.24 (11.87)	22.18 (28.86)	24.23
Covington River	50.33 (22.98)	74.63 (74.63)	62.19
Rio Hill	-31.59 (42.67)	-24.88 (29.13)	-22.76
Rt. 460	-5.88 (40.85)	-32.29 (61.19)	2.21
Brooke Detention Basin	58.51 (24.85)	67.19 (16.05)	71.73
Brooke Wetland	-161.38 (-----[1])	-145.86 (-----)	-132.64
Brooke Overall	69.66 (-----)	-----	-----
Buster Pond	-6.82 (-----)	-----	-----

[1] Indicates insufficient data

Zinc (Zn)

Figure 17 illustrates mean Zn inflow concentrations at study sites with error bars showing one standard deviation. Correlation between TSS average inflow concentration and Zn average inflow concentration was poor (-0.40), suggesting that a large fraction of Zn entering the studied wetlands was in a dissolved form. As with other parameters monitored, variability of Zn inflow concentration tended to increase as the average inflow concentration of Zn increased. An initial test for Zn at the Covington River site was below the detection limit of the atomic absorption method (.05 mg/L), so further testing for Zn at this site was discontinued.

Figure 17. Mean Zn inflow concentration at study sites



EMC reduction of Zn is shown in Figure 18 and is presented in Table 8 along with MRE and SOL removal (standard deviations are noted parenthetically). Consistent removal in the range of 40 percent was found at the Rt. 288 site, while average removals at other sites ranged from around 20 percent at Rio Hill to more than 80 percent for the Brooke detention basin. Though concentration of Zn increased in the Brooke wetland, mass was removed as indicated by MRE and SOL removal. No change in Zn concentration was observed at the Buster Pond site.

Figure 18. Mean EMC reduction of Zn

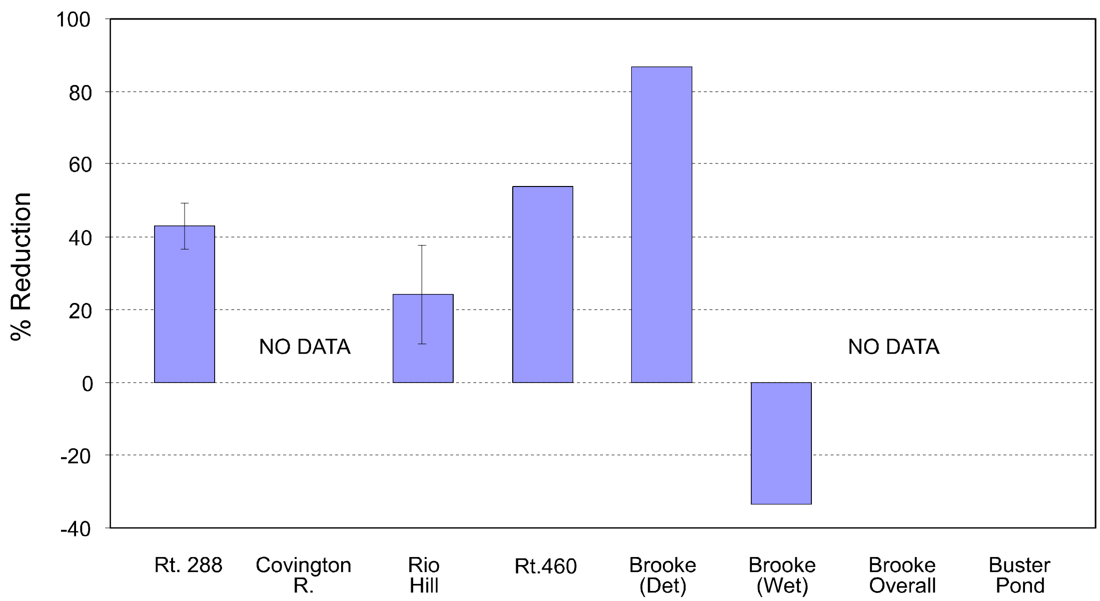


Table 8. Removal Efficiency for Zinc (Zn)

Site	EMC Reduction % and (standard deviation %)	MRE % and (standard deviation %)	SOL Removal %
Rt. 288	43.01 (6.31)	48.12 (22.59)	31.63
Covington River	-----[1]	-----	-----
Rio Hill	24.23 (13.51)	26.22 (16.85)	29.47
Rt. 460	53.93 (-----)	42.55 (-----)	42.55
Brooke Detention Basin	86.79 (-----)	-----	-----
Brooke Wetland	-33.33 (-----)	36.28 (-----)	62.35
Brooke Overall	-----	-----	-----
Buster Pond	0.00 (-----)	-----	-----

Other Parameters

In addition to monitoring of TSS, TP, OP, COD, and Zn, samples from the Covington River site were analyzed for total nitrogen (TN), nitrate (NO_3-N), and fecal coliform (FC). Influent concentrations of 3.8 mg/L, 1.6 mg/L, and 8000 cfu/100mL were reduced to outflow concentrations of 3.1 mg/L, 0.73 mg/L, and 2000 cfu/100mL for TN, NO_3-N, and FC, respectively, resulting in EMC reductions of 18.42 percent for TN, 54.38 percent for NO_3-N, and 75.00 percent for FC.

Vegetation and Wildlife

The research team collected vegetation data at Rio Hill, Rt. 288, Brooke, and Covington River to examine the diversity and abundance of vegetation present and to document any apparent impacts due to stormwater runoff. Initially, the team conducted a survey of species present. Subsequently, square meter plots were studied to assess the relative abundance of wetland plants. The researchers noted vegetation density on a qualitative scale ranging from sparse to abundant. During each site visit (approximately once a week), the team also recorded any observations of wildlife present. Observations included visual identification and/or indirect evidence such as animal tracks.

Figures 19a-d illustrate the distribution of dominant plant species at each site where vegetation was monitored. No record for initial planting was available for the Rio Hill site; however, the abundance of species observed (greater than 20) is far greater than that of a typical planting plan. Density of vegetation at the Rio Hill site was moderate with scattered stands that were very dense. Only a small, dry section along the southeastern bank was sparsely vegetated. Mitigation plans at the other three sites specified the planting of a variety of emergent plants, shrubs, and woody species. The plans specified in-kind replacement of any species not surviving after the first year. Plantings took place in 1991, 1992, and 1993 for the Brooke, Rt. 288, and Covington River sites, respectively. No planting was performed for the Brooke detention basin. Comparisons of species planted and species observed are presented in Tables 9 – 11. Density of vegetation was moderate to very dense at all three of these sites, with the greatest density at Rt. 288.

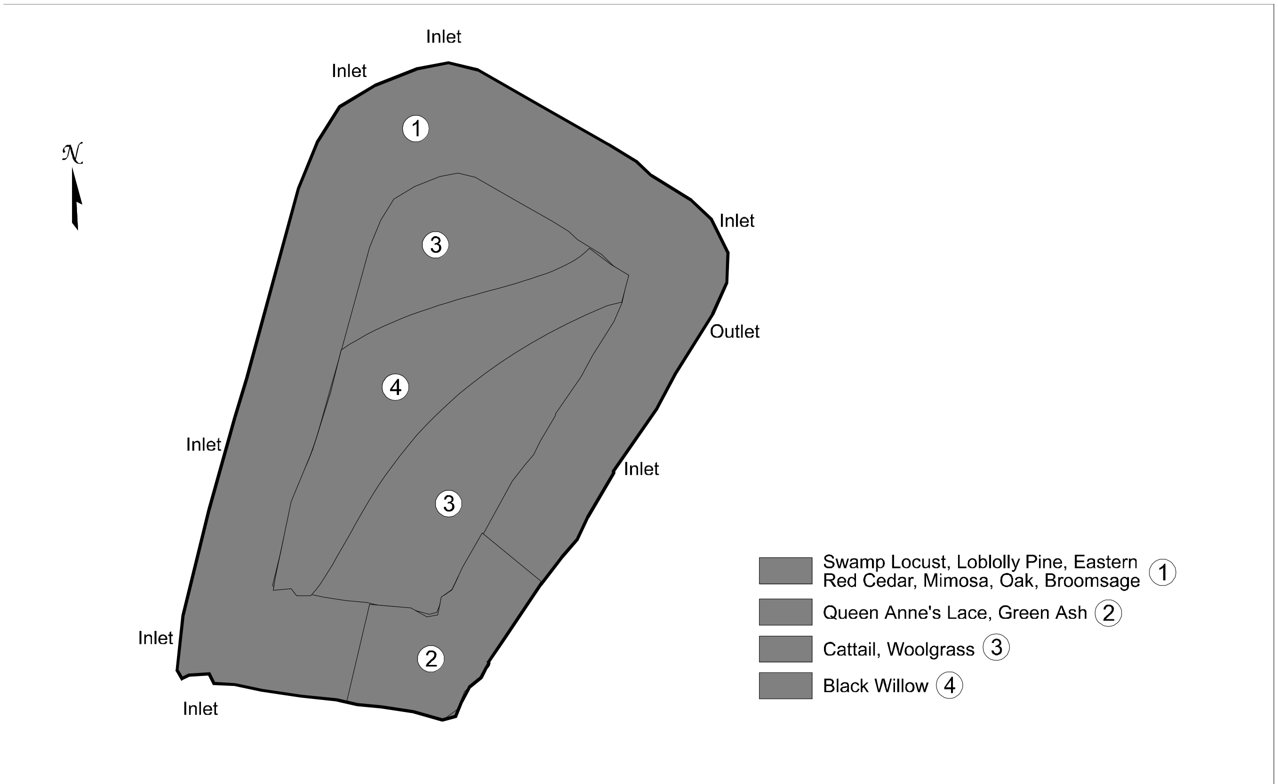


Figure 19a. Rio Hill

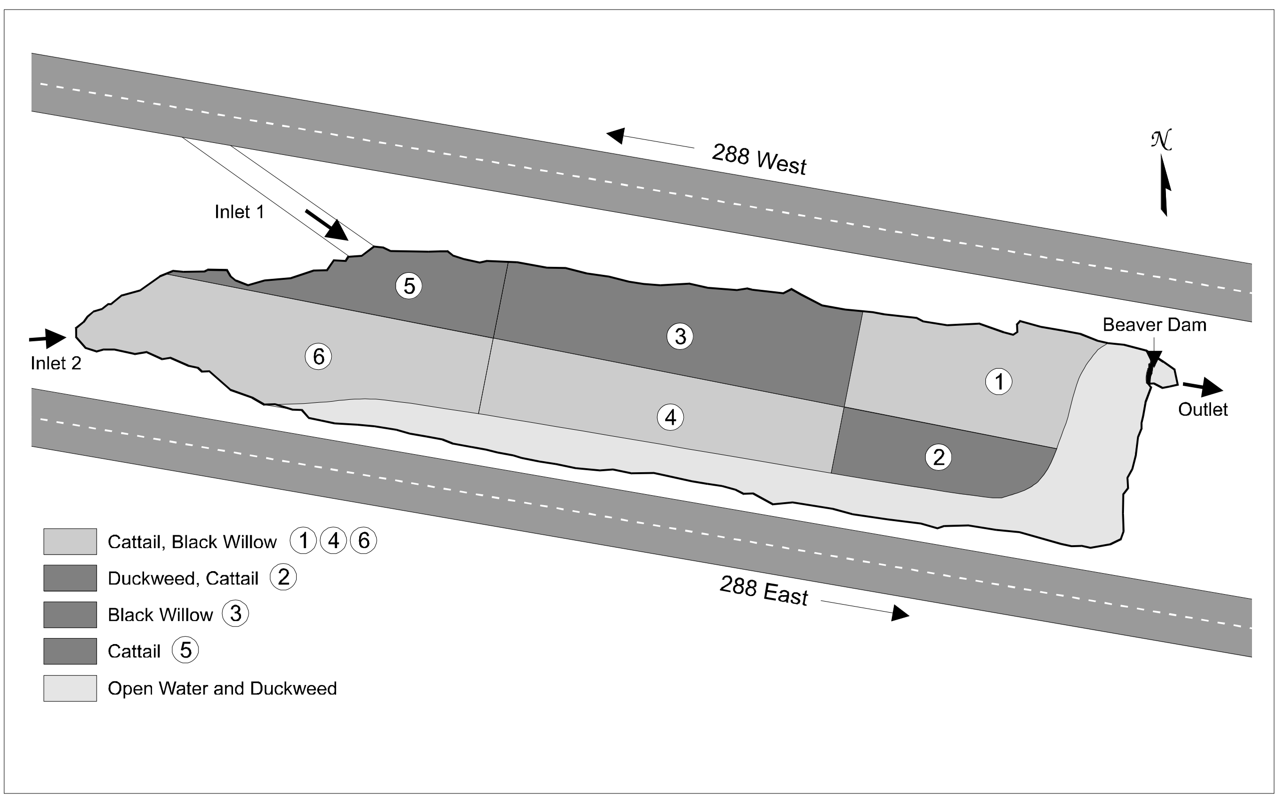


Figure 19b. Brooke

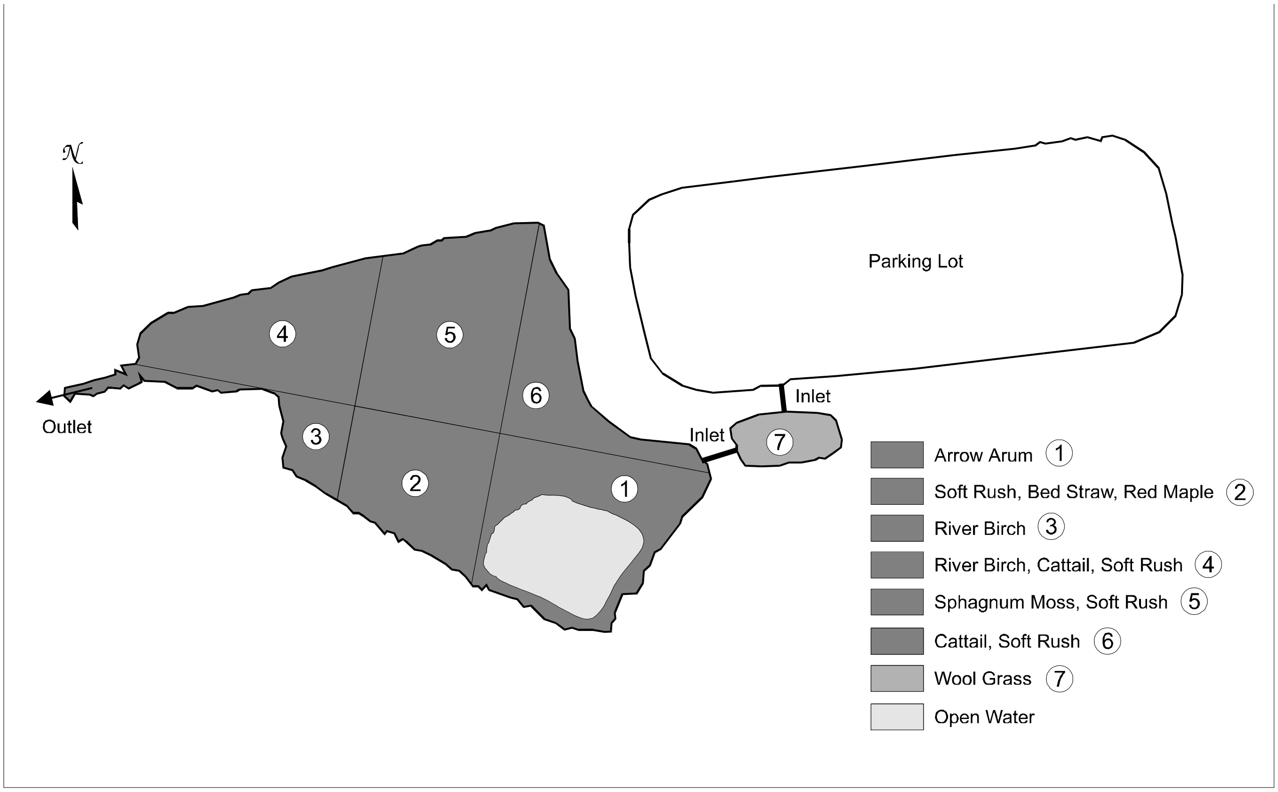


Figure 19c. Brooke

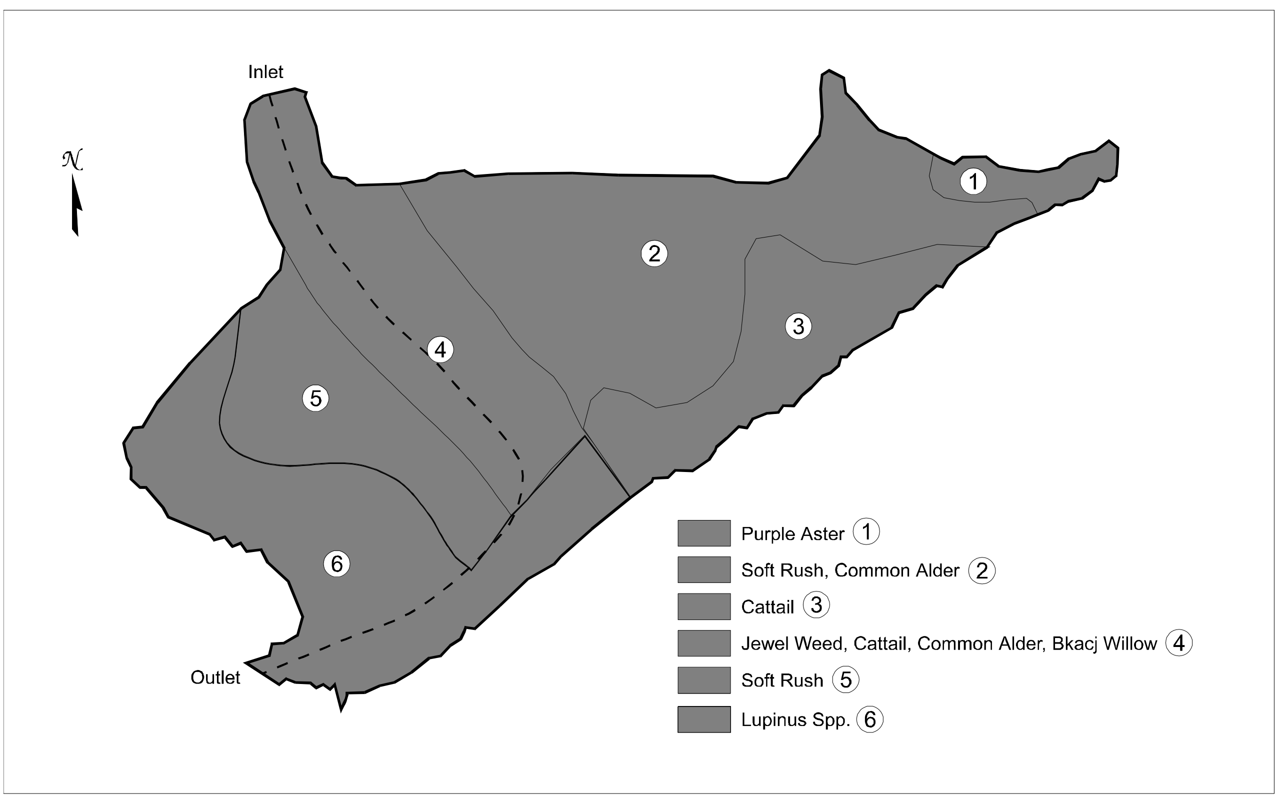


Figure 19d. Covington River

Table 9. Planted and Observed Vegetation at Route 288 Site

	Species at Route 288 Site	
	Planted 1992	Observed 1996
Emergent, Floating Aquatic Vegetation, and Wildflowers	*Polygonum pennsylvanicum* (Giant smartweed) *Echinochloa crusgalli* (Japenese Millet)	*Scirpus cyperinus* (Wool grass) *Typha latifolia* (Broad leaf cattail) *Juncus effusus* (Soft rush) *Rhynchospora capitellata* (Small-headed beak rush) *Eleocharis rostellata* (Beaked spike rush) *Scirpus atrovirens* (Green bulrush) *Carex scoparia* (Broom sedge) *Carex lurida* (Lurid sedge) *Cicuta maculata* (Water hemlock) *Ludwigia alternifolia* (Seedbox) *Sphagnum magellanicum* (Sphagnum moss) *Polygonum pennsylvanicum* (Giant smartweed) *Lemna spp.* (Duckweed)
Shrubs	*Ilex verticillata* (Common Winterberry) *Cephalanthus occidentalis* (Buttonbush) *Sambucas canadensis* (American Elder) *Viburnum dentatum* (Southern Arrowwood)	*Alnus serrulata* (Common Alder) *Cephalanthus occidentalis* (Buttonbush)
Woody Species	*Betula nigra* (River Birch) *Salix nigra* (Black willow) *Fraxinus pennsylvanica* (Green Ash) *Nyssa sylvatica* (Black gum)	*Betula nigra* (River Birch) *Salix nigra* (Black willow) *Juniperous virginiana* (Eastern Red Cedar) *Pinus taeda* (Loblolly Pine) *Acer rubrum* (Red Maple) *Fraxinus pennsylvanica* (Green Ash)

Table 10. Planted and Observed Vegetation at Brooke Site

	Species at Brooke Site	
	Planted 1991	Observed 1996
Emergent, Floating Aquatic Vegetation, and Wildflowers	*Peltra virginica* (Arrow Arum) *Saururus cernuus* (Lizard's Tail) *Leersia oryzoides* (Rice cutgrass)	*Peltra virginica* (Arrow Arum) *Saururus cernuus* (Lizard's Tail) *Leersia oryzoides* (Rice cutgrass) *Cicuta maculata* (Water hemlock) *Juncus effusus* (Soft rush) *Typha latifolia* (Broad leaf cattail) *Carex scoparia* (Broom sedge) *Carex lurida* (Lurid sedge) *Lemna spp.* (Duckweed) *Eupatorium maculatum* (Joe-Pye-Weed) *Pluchea camphorata* (Stinking Marsh-Fleabane) *Sphagnum magellanicum* (Sphagnum moss) *Erigeron annus* (Daisy Fleabane) *Solidago spp.* (Goldenrod) *Hypericum spp.* (St. John's Wort)
Shrubs	*Alnus serrulata* (Common Alder) *Cephalanthus occidentalis* (Buttonbush) *Sambucus canadensis* (Common Elder)	*Alnus serrulata* (Common Alder) *Cephalanthus occidentalis* (Buttonbush) *Sambucus canadensis* (Common Elder)
Woody Species	*Betula nigra* (River Birch) *Liquidambar styraciflua* (Sweetgum) *Acer rubrum* (Red Maple)	*Betula nigra* (River Birch) *Liquidambar styraciflua* (Sweetgum) *Acer rubrum* (Red Maple) *Fraxinus pennsylvanica* (Green Ash) *Pinus taeda* (Loblolly Pine)

Table 11. Planted and Observed Vegetation at Covington River Site

	Species at Covington River Site	
	Planted 1993	Observed 1997
Emergent, Floating Aquatic Vegetation, and Wildflowers	*Juncus effusus* (Soft rush) *Typha latifolia* (Broad leaf cattail) *Scirpus validus* (Softstem bulrush) *Scirpus pungens* (Common three-square)	*Juncus effusus* (Soft rush) *Scirpus validus* (Softstem bulrush) *Scirpus pungens* (Common three-square) *Scirpus cyperinus* (Wool grass) *Impatiens capensis* (Jewel weed) *Polygonum sagittatum* (Arrow leafed tearthumb) *Polygonum punctatum* (Water smartweed) *Carex lurida* (Lurid sedge) *Euthamia graminifolia* (Goldenrod) *Mentha spicata* (Spearmint) *Typha latifolia* (Broad leaf cattail) *Vernonia noveboracensis* (New York ironweed) *Eupatorium maculatum* (Joe-Pye-Weed) *Liliceae spp.* (Lily family vegetation) *Aster puniceus* (Swamp aster) *Cuscuta grovovii* (Common dodder) *Verbesina alternifolia* (Wingstem) *Pluchea camphorata* (Stinking Marsh-Fleabane) *Galium tinctorium* (Dye bedstraw) *Elatine americana* (American waterwort)
Shrubs	*Alnus serrulata* (Common Alder) *Viburnum spp.* (Arrowwood) *Ilex verticillata* (Winterberry)	*Alnus serrulata* (Common Alder) *Viburnum spp.* (Arrowwood) *Ilex verticillata* (Winterberry)
Woody Species	*Betula nigra* (River Birch) *Liquidambar styraciflua* (Sweetgum) *Acer rubrum* (Red Maple) *Quercus spp* (Oak) *Fraxinus pennsylvanica* (Green Ash) *Salix nigra* (Black Willow)	*Betula nigra* (River Birch) *Liquidambar styraciflua* (Sweetgum) *Acer rubrum* (Red Maple) *Quercus spp* (Oak) *Fraxinus pennsylvanica* (Green Ash) *Salix nigra* (Black Willow)

The number of plant species observed at each site is one measure of diversity. The relative abundance of these various species is also important as well. While the scale of the one-meter plots is too small to accurately evaluate the composition of woody species in an area, such plots reveal considerable information on emergent species diversity. Figures 20-22 show the relative abundance of species in the 288, Brooke, and Covington River wetlands, respectively. These figures are based on composites of all meter plots conducted at the site as to provide an overall composition of the wetland. They do not include woody species or floating aquatic plants that cannot be easily counted individually such as *Lemna* (Duckweed). Both Rt. 288 and Brooke have strong presence of *Typha latifolia* (Cattail) and *Juncus effusus* (Soft Rush); however, neither species' presence is overwhelming. Since the Covington River site was not monitored until 1997, the amount of vegetation data collected at this site were limited. Species composition fails to reflect some significant populations present, including a dense *Typha latifolia* stand.

Figure 20. Composite composition (%) of vegetation at Rt. 288

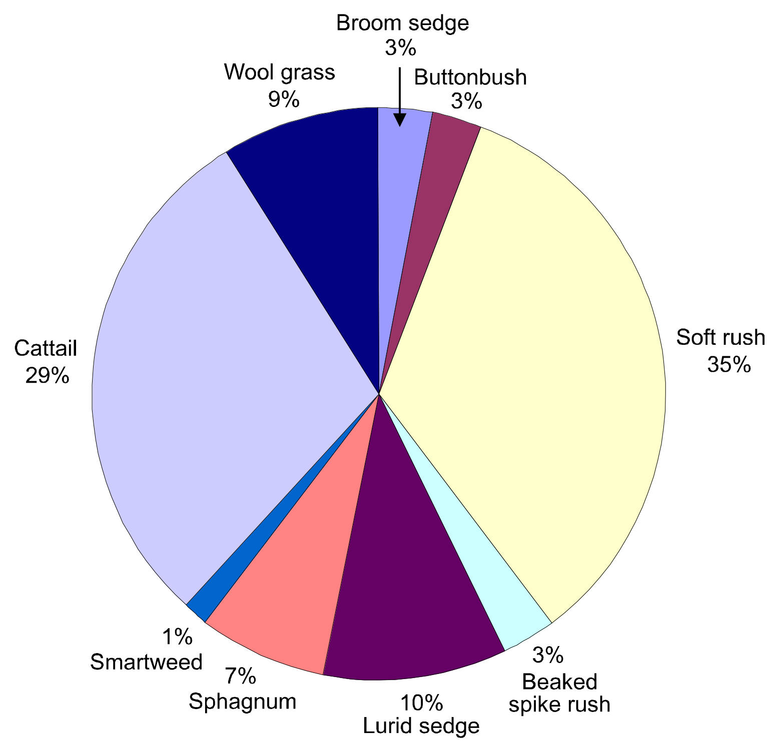


Figure 21. Composite composition (%) of vegetation at Brooke

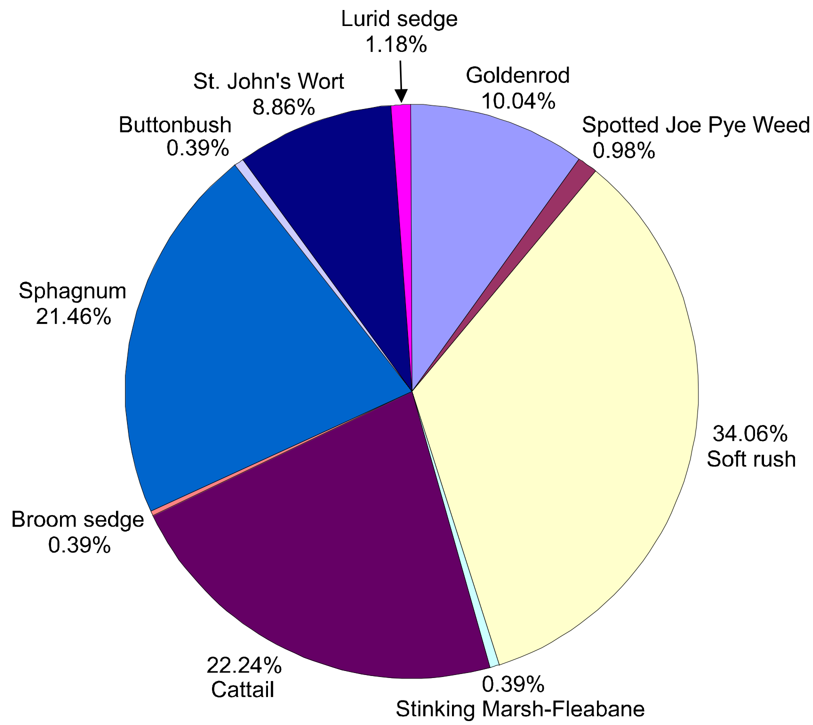
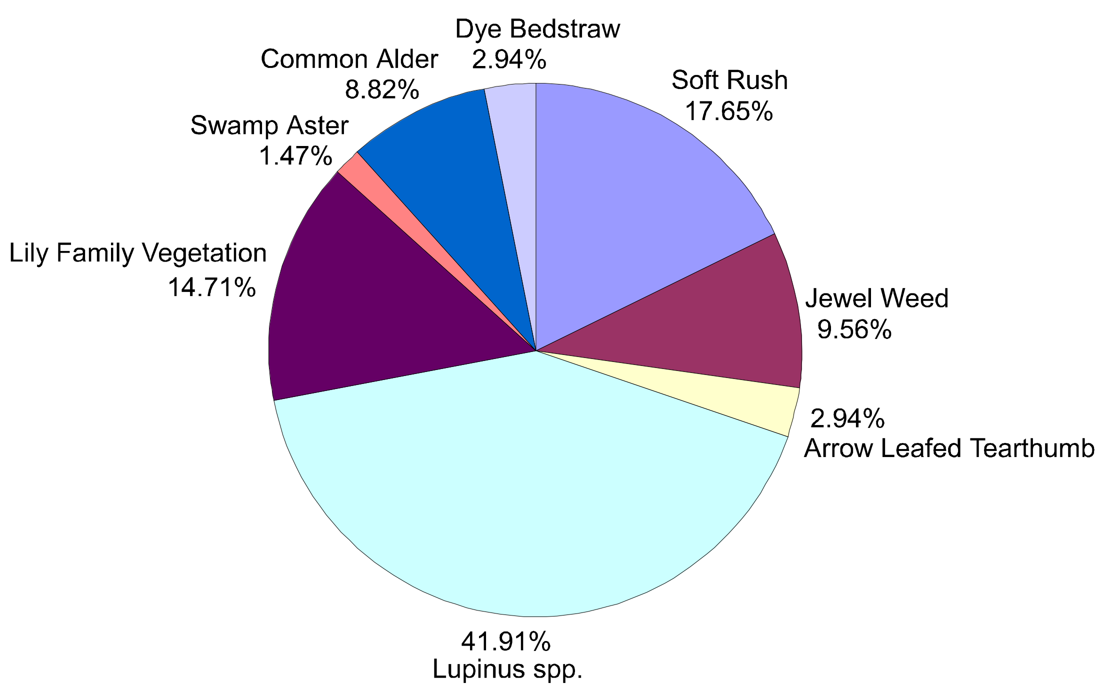


Figure 22. Composite composition (%) of vegetation at Covington River



The research team observed a variety of wildlife at sites during field visits. Since visits to the sites were almost exclusively during daylight hours (most often in mid-afternoon) nocturnal species and species that prefer cooler periods of the day were not likely to be observed. The most extensive observation of wildlife was at the Rt. 288, Brooke, and Covington River sites. Wildlife observed at these sites include beaver, muskrat, field mice, frogs, turtles, ducks, snails, and a variety of snakes. Numerous birds, including red winged black birds and a blue heron were also observed. Deer, field mice, a variety of snakes, frogs, and turtles have been observed at the Covington River and Rt. 295 sites as well.

While the presence of wildlife at the wetland sites is a promising indicator of successful habitat creation, the activity of beaver at the Route 288 site presented problems for monitoring the site (Figure 23). From late 1996 to June 1997, the beavers in the wetland constructed a large dam at the outflow from the wetland. While the additional storage created by the dam greatly increased stormwater retention, the dam impeded flow measurement and was detrimental to some of the less water-tolerant vegetative species. *Pinus taeda* (Loblolly Pine) especially experienced an increased hydroperiod from the damming. The research team constructed and installed a pond leveler to subvert the beaver dam. Monitoring since August 1997 indicates excellent performance of the pond leveler.

Figure 23. Beaver Dam at Rt. 288 Outflow

DISCUSSION

To utilize mitigated wetlands as stormwater BMPs, two sets of priorities must be addressed. First and foremost, the mitigated wetland must replace functions lost in the displacement of the natural wetland. Second, the wetland must effectively control the quantity and quality of stormwater runoff. The diverse vegetation and habitat observed at the Route 288, Brooke, and Covington River mitigation sites, coupled with pollutant removal efficiencies and peak attenuation comparable to conventional BMPs such as detention ponds (Yu et al. 1997), illustrate the ability of well-designed mitigation sites to serve both priorities.

All sites monitored supported apparently healthy wetland vegetation. Species identification at Rt. 288, Brooke, Rio Hill, and Covington River indicated more than 20 species at each site. Observations at these and other study sites indicated moderately dense to very dense vegetation despite the input of highway runoff as a primary water source. A comparison of the Rt. 288 and Brooke sites reveals that mean inflow concentrations into the Rt. 288 wetland were two to eight times higher than mean inflows into the Brooke wetland. Despite these significant differences in pollutant inputs, similarities exist in vegetative diversity and wildlife habitat. Both wetlands support over 20 vegetative species, with significant populations of *Juncus effusus* (Soft Rush) and *Typha latifolia* (Cattail). The balance of emergent vegetation, shrubs, and woody vegetation is similar at the Rt. 288 and Brooke wetlands, as well. Both wetlands provide habitat for a variety of wildlife including birds, reptiles, and small mammals. The Brooke detention basin and Rio Hill basin, which receive runoff with pollutant concentrations comparable to the Rt. 288 wetland inflow, also support dense emergent vegetation with no apparent impacts from the pollutant loading.

Wildlife observations at these sites demonstrate that a mitigated wetland that is acting as a BMP can also provide habitat for many species. Despite the physical barrier and noise associated with its location in the median of a four-lane highway, the Rt. 288 site appears to provide a habitat for a range of animals similar to that of the Brooke and Covington River sites, both of which are located adjacent to streams in rural areas. Frequency of observation was similar at these three sites, with observations of wildlife common during even the shortest visits to the sites. The large size of the Rt. 288 wetland and the presence of a significant portion of open water likely contribute to its success as a habitat despite its adverse location.

The Rt. 288 and Covington River mitigation sites illustrate the ability of a well- designed mitigated wetland to also serve as a stormwater BMP. Both sites achieved removal of all pollutants monitored with mean EMC reductions as high as 57 percent for TSS, 68 percent for TP, 81 percent for OP, 50 percent for COD, and 43 percent for Zn. While the performance of these sites is comparable to conventional BMPs, other sites monitored tended to produce mixed results, with a great deal of variability in removal from storm to storm. This variability is due in part to the small number of events sampled for some sites and also to wide variation in storm characteristics (i.e. a rainfall range of 10.2 to 98.6 mm for the Rt. 460 site). It should be noted that with the exception of the Rt. 460 site, positive EMC reductions were within one standard deviation of the mean EMC reduction for all sites monitored.

Differences in removal efficiencies for the sites monitored are likely attributable to differences in key design parameters, including the configuration of inlets and outlets, the length to width ratio, and (consequently) residence time. Both the Rt. 288 and Covington River sites are fairly linear with inlets adequately separated from the outlet as reflected by their length to width ratios (4:1 (4.0) and 5:3 (1.67), respectively). Outflow at both sites is controlled by contracted rectangular weirs. A primary difference between these two sites, however, is the nature of flow through the wetland. Much of the flow at Rt. 288 is shallow flow through vegetation, while the flow at Covington River is very channelized with minimal obstruction from vegetation. Some short-circuiting is suspected at Rt. 288 due to the proximity of inlet 3 to the outlet; however, the magnitude of flow at inflow 3 is small relative to the contributions of the other inlets. Resulting average residence times of 27.9 hours and 8.5 hours for Rt. 288 and Covington River, respectively, reflect these differences in flow characteristics.

The Rio Hill detention basin, on the other hand, has several inlets spread out around the detention basin. The position of the inlets with respect to the outlet causes a great deal of short circuiting in the wetland and channelization further decreases residence time. A length to width ratio based on an average of distances between inlets and the outlet is 5:8 (0.625) and residence time for this site averages 4.4 hours. Additionally, the area of the Rio Hill wetland is less than 0.95 percent of the drainage area, which is less than the minimum recommendation of 1 percent (Schueler 1992). Short circuiting is also believed to occur at the Rt. 460 site, with an inlet draining an exit ramp of I-64 within 10 meters of the outlet structure. Flow path (even for water traveling from the farthest spaced inlet and outlet) at the Rt. 460 site is minimized as the length to width ratio is only 1:1. It should be noted as well that means from the Rt. 460 site include data from Hurricane Bertha, an extremely large event which had the effect of 'flushing out' a lot of debris from the wetland.

While minimal or negative removals (export of pollutant) are indicated for the Brooke wetland for TSS, OP, COD, and Zn, these figures must be viewed within the context of the system as a whole. A comparison of the detention basin inflow and the relatively lower wetland inflow (detention outflow) concentrations for the Brooke wetland indicate that a significant portion of removal at the Brooke site occurs in the detention basin rather than in the wetland. While effluent from the Brooke wetland may contain higher pollutant concentrations for some parameters than the wetland inflow, the concentration is still far lower that that in the inflow to the system, resulting in overall pollutant reductions.

SECTION II: WETLAND MODELING

BACKGROUND

Mathematical models are valuable tools for understanding the function of constructed wetlands, quantifying pollutant removal, and developing successful management strategies. Mathematical modeling of ecological systems is currently an emerging science, and little attention has yet been paid to the mathematical modeling of wetlands receiving stormwater runoff.

Since the 1980s, a number of wetland models have been developed. These efforts range from attempts to describe very specific wetland processes, to detailed models of wetland hydrology and nutrient cycles. Many of these have been designed to simulate wetland systems designed to treat wastewater; few have dealt with wetlands receiving stormwater as a primary source. Those models that have addressed wetlands receiving stormwater runoff tend to very site-specific and are not widely applicable.

Two primary approaches have been taken in modeling flow in wetlands: a hydrodynamic approach (Guardo and Tomasello, 1995) and a hydrologic budget approach. While the hydrodynamic approach yields detailed flow information for a wetland system, these models generally are applied on a relatively short time scale and they neglect major components of wetland hydrology such as evapotranspiration and infiltration. Hydrologic models, on the other hand, are applied over longer time scales but are often formulated as "black box" models and yield little information concerning the internal dynamics of wetlands that affect pollutant transport. These hydrologic models are also often applied on large spatial scales (i.e. watershed or region) and therefore provide little detailed information about specific wetland sites.

The development of water quality models for wetlands has both limitations and challenges. A vast majority of research in wetland water quality modeling has focused on the cycling of nitrogen and phosphorus in wetlands. Detailed research has been conducted since the 1970s to understand nutrient uptake by plants (Boyd, 1970, 1978; Caassen and Barber, 1976; Hearn, et al. 1991; Neilsen, 1976; Taylor, 1983). A number of conceptual models for nutrient cycling have been developed as well (Heliotis and DeWitt, 1983, Jørgensen, 1986). Several mathematical models have been applied to simulate nutrient cycles; however, they have largely been very site-specific. Kadlec and Hammer (1988) and Jørgensen (1988) employed similar approaches, modeling nutrients in surface water, vegetation, and three subsurface zones in great detail. Simpler approaches to simulating wetland mescosms include a "black box" phosphorus model (Niswander and Mitsch, 1995) and a batch reactor model (Laio, 1996).

The importance of nutrient cycles in wetlands cannot be understated, and further research into modeling nutrient cycles in wetlands is critical. Nitrogen and phosphorus are only two of many pollutants responsible for water quality impairment, however. Runoff from urban areas and highways may contain significant levels of metals and hydrocarbons that constructed wetlands may have the ability to remove or transform. A copper model by Light (1992) utilizing the USEPA Water Quality Analysis Simulation Program (WASP) (Ambrose, 1993) model and a metal speciation model represents one of few efforts to model metal transport in wetlands aside from acid mine drainage sites.

METHODS

Modeling Criteria

The researchers evaluated three models for possible field scale application: USEPA's WASP (Ambrose, 1993), U.S. Department of Agriculture's Chemical, Runoff, and Erosion from Agricultural Management Systems model (CREAMS) (Knisel, 1980), and the Virginia Stormwater Wetland Simulation Program (VASWETS) (Liao, 1996).

The following criteria were considered in model evaluation and selection:

1. Ability to describe physical and chemical processes in a wetland system

2. Amount of data required for input, and the ability to obtain this data by measurement or estimation

3. Extent of modifications required to model a wetland system, and ability to implement these modifications within the framework of the existing code

The research team determined that all of the models would require extensive modifications in order to work. For that reason, they developed a new model, the Virginia Field Scale Wetland Model (VAFSWM), part of which is based on the VASWETS conceptual model.

Modeling Approach

VASWETS models mechanisms of settling, diffusion, adsorption to plant and substrate, and vegetative uptake for a pollutant in dissolved and particulate forms in a two segment (water column and substrate), two state (completely mixed and quiescent) batch reactor system. Conceptually, VAFSWM takes the kinetics portion of this batch system and applies it on a field scale. It adds a hydrologic subroutine to model pollutant inputs and outputs from stormwater runoff and to route flows through the treatment system, and a routine to model suspended solids in the water column. Figure 24 illustrates the hydrologic balance modeled, while Figure 25 illustrates the pollutant mass balance.

Figure 24. Wetland model - hydrologic balance

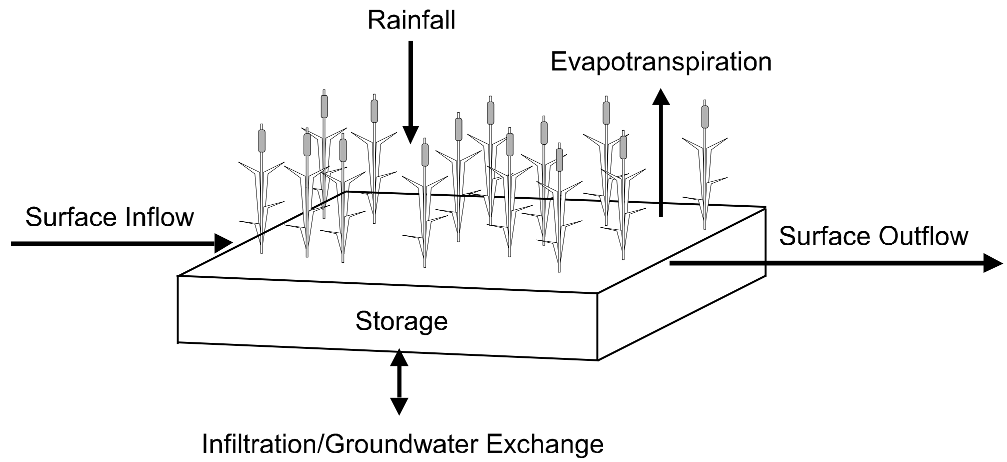
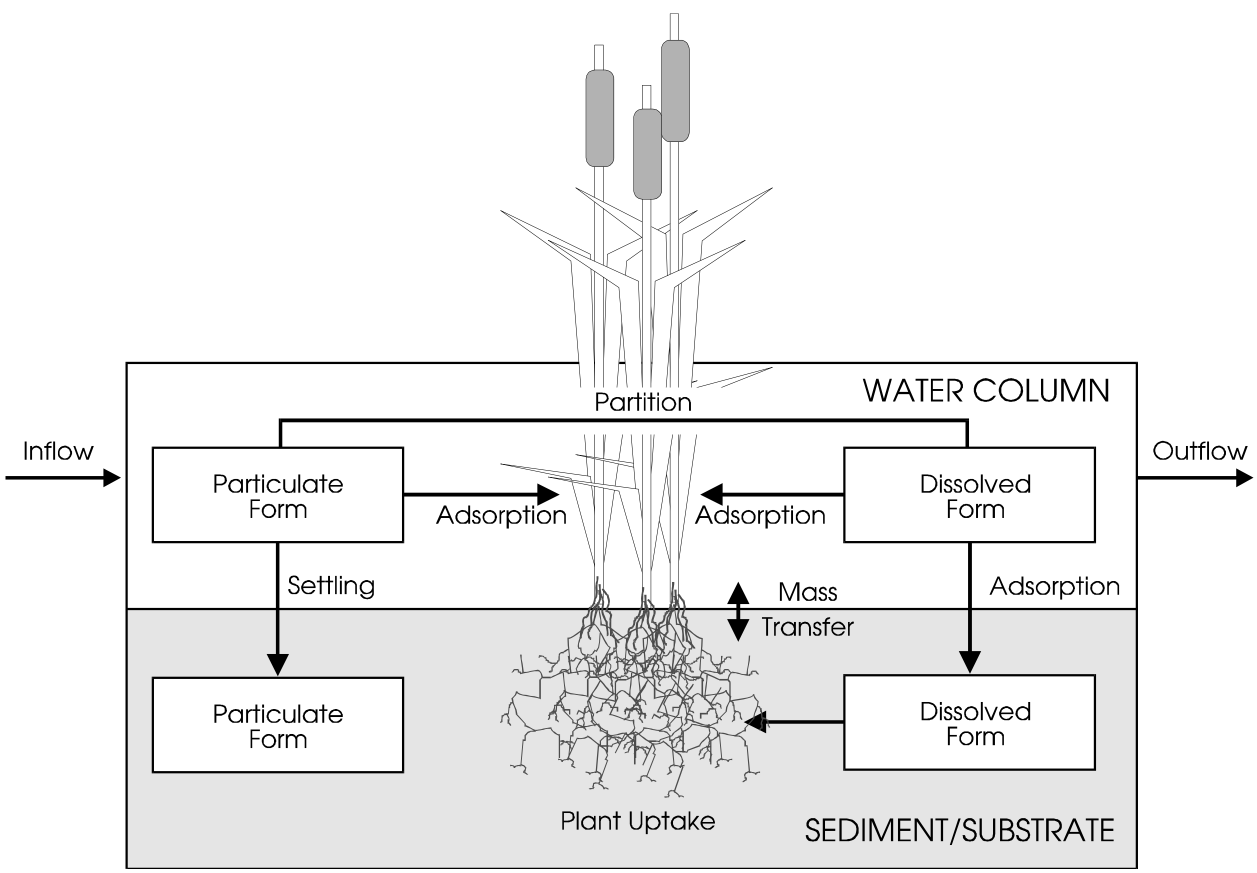


Figure 25. Pollutant mass balance approach



Hydrologic Balance

The movement of water in the constructed wetland is described in terms of a hydrologic balance on the surface water segment with the volume of this segment (the water storage) as the state variable. Subsurface inflows and outflows are assumed negligible. The governing equation for the hydrologic balance is:

$$\frac{dS}{dt} = Q_{IN} - Q_{OUT} + P - EX$$

where

S = Storage [L^3]
Q_{IN} = Inflow [L^3/T]
Q_{OUT} = Outflow [L^3/T] = *f(S)*
P = Precipitation [L^3/T]
ET = Evapotranspiration [L^3/T]
EX= Exchange with subsurface Groundwater Input (EX negative) or Infiltration (EX positive) [L^3/T]

With Q_{OUT} specified as a function of storage, the resulting equation is an ordinary differential equation which is then solved using a fourth order Runge Kutta integration with a fifth order accuracy check to yield storage and wetland outflow.

Pollutant Mass Balance

The governing equations for pollutant mass balances for suspended solids (C1), the pollutant in the water column (C2) and the pollutant in the substrate (C3) are:

$$V_W \frac{dC1}{dt} = Q_{IN} C1_{IN} - Q_{OUT} C1 - \nu_{SW} A C1$$

$$V_W \frac{dC2}{dt} = Q_{IN} C2_{IN} - Q_{OUT} C2 - \nu_{SW} A f_{PW} C2 - (k_2 + k_3) Vw f_{DW} C2 + k_1 A \left(f_{DS} \frac{C3}{\phi} - f_{DW} C2 \right)$$

$$Vs \frac{dC3}{dt} = \nu_{SS} A f_{PS} C3 + \nu_{SW} A f_{PW} C2 - (k_2 + k_4) Vs f_{DS} C3 - k_1 A \left(f_{DS} \frac{C3}{\phi} - f_{DW} C2 \right)$$

where

$C1$ = Concentration of suspended solids [M/L^3]
$C2$ = Concentration of pollutant in water column [M/L^3]
$C3$ = Concentration of pollutant in substrate [M/L^3]
V = Volume of water column [L^3]
V^W = Volume of substrate [L^3]
Q^S = Inflow to water column [L^3/T]
Q^{IN} = Outflow from water column [L^3/T]
v^{OUT} = Settling velocity in water column [L/T]
v^{SW} = Settling velocity in substrate [L/T]
k^{SS} = First order exchange coefficient [1/T]
k^1 = Adsorption coefficient to substrate [1/T]
k^2 = Adsorption coefficient to plant [1/T]
k^3 = Plant uptake coefficient [1/T]
f^4 = Fraction of particulate pollutant in compartment i
f^{Pi} = Fraction of dissolved pollutant in compartment i
ϕ^{Di} = Porosity of substrate

and

$$f_{Pi} = \frac{k_P C1_i}{1 + k_p C1_i} \qquad f_{Di} = \frac{1}{1 = k_p C1_i}$$

with

k_p = Partition coefficient [L^3/M]

The above equations assume that pollutant fluxes due to precipitation and exchange with subsurface are minimal compared to other mechanisms. The resulting three ordinary differential equations are solved simultaneously using a fourth order Runge-Kutta integration with a fifth order accuracy check. Governing equations for the quiescent state are identical to the equations presented above; however, inflows and outflows do not occur in the quiescent state and settling velocities are assumed to be far lower in this state. Liao (1996) utilized a two-way regression on laboratory data to determine the duration of the completely mixed state. For the VAFSWM, this duration must be estimated.

Model Verification

The researchers verified the VAFSWM kinetics by comparing it with an alternative computational framework, VASWETS. VASWETS was chosen for comparison because input data files were available and because VASWETS had been verified previously with the WASP model incorporating two-phase, two-segment kinetics (Liao, 1996). Agreement between VASWETS and the WASP model was excellent. Computation schemes for integration for the newly developed model and VASWETS are quite similar; however, the WASP model utilizes an Eulerian step size predictor, followed by a second order Runge Kutta step size corrector for integration of the coupled first order ordinary differential equations. For comparison with VASWETS, the VAFSWM's kinetic routine was isolated by assuming that system inflows and outflows were equal to zero. Precipitation, evapotranspiration, and infiltration were also assumed to be zero. Table 12 provides a list of input parameters used in the comparison. These input parameters were taken from VASWETS simulations for TP in a batch system (Liao, 1996). A comparison of model results with VASWETS results (Figure 26) shows excellent agreement. Similar agreement was observed for a range of simulations that were performed by varying parameters (listed in Table 12).

Figure 26. Model verification by comparison with VASWETS

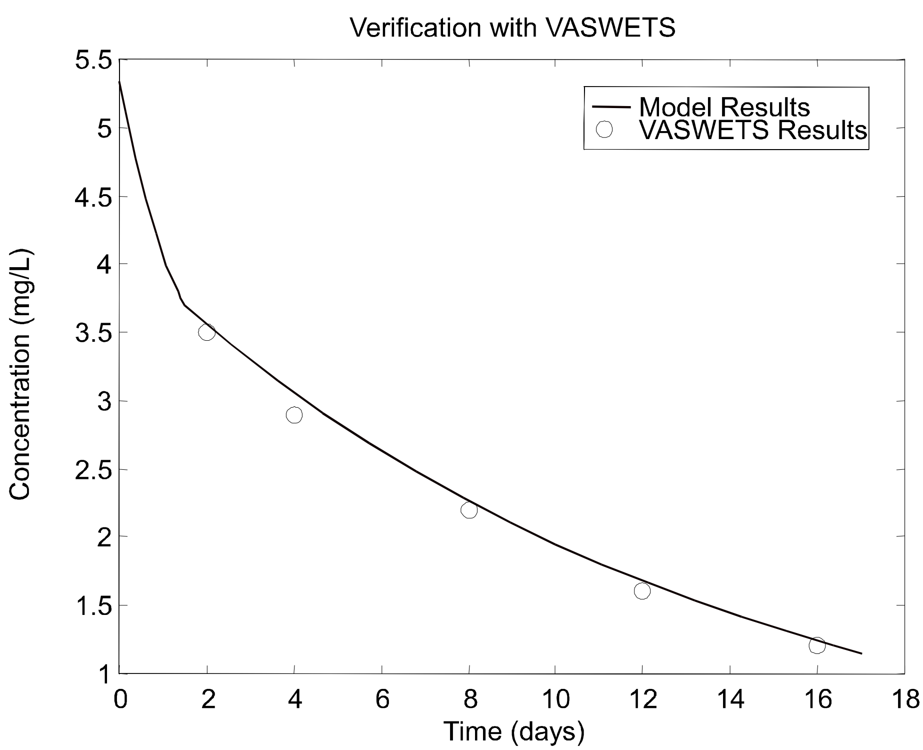


Table 12. Model Verification Input Parameters

Parameter	Description	Value
$C1_0$	Initial concentration of suspended solids	25.0 mg/L
$C2_0$	Initial concentration of pollutant in water column	5.34 mg/L
$C3_0$	Initial concentration of pollutant in substrate	5.34 mg/L
k_1	Transfer coefficient between substrate and water column	0.0002 /day
k_2	Adsorption coefficient to substrate	0.018 /day
k_3	Adsorption coefficient to vegetation	0.058 /day
k_4	vegetation uptake coefficient	0.096 /day
V_W	Volume of water column	$7.28\ 10^{-3}\ m^3$
V_S	Volume of substrate	$7.28\ 10^{-3}\ m^3$
ϕ	Porosity	0.21
v_{SS}	Setting velocity in substrate	0.44 m/day
v_{SW}	Settling velocity in water column	0.093 m/day
$v_{SS\ q}$	Settling velocity in substrate (quiescent)	0.01 m/day
v_{SWq}	Settling velocity in water column (quiescent)	0.01 m/day
k_p	Partition coefficient	0.021 [m^3/kg]
TMAX	Simulation time	17 days

RESULTS

To illustrate application of the Virginia field scale model, a test case was developed to simulate TSS and TP. This test case, which was based on a storm at Rt. 288 in July 1997, was selected due to the input requirements of the model. While the amount of input required for this model is far less than that of some other applicable models (Ambrose et. al., 1993; Hammer and Kadlec, 1988; and Knisel, 1980), an extremely dry summer in Virginia in 1997 limited data collection for storm events. Further, the presence (until mid-summer 1997) of the beaver dam at Rt. 288 hindered collection of the outflow data necessary for a rigorous calibration. Parameters for the test case are based on data collected at Rt. 288 and on typical values from the literature. Simulation parameters are presented in Table 13. Details of parameter selection for kinetic coefficients are discussed by Liao (1996). Figure 27 shows rainfall and runoff while Figure 28 shows TSS and TP concentrations for the inflow for the wetland simulation. Exchange with the subsurface (infiltration and groundwater inputs) was assumed negligible for this simulation. Figure 29 shows the results of this simulation. The results are illustrative of the capabilities of the model and were as expected.

Table 13. Simulation parameters for Rt. 288 test case

Parameter	Description	Value
$C1_0$	Initial concentration of suspended solids	5.0 mg/L
$C2_0$	Initial concentration of pollutant in water column	0.9 mg/L
$C3_0$	Initial concentration of pollutant in substrate	0.9 mg/L
k_1	Transfer coefficient between substrate and water column	0.0002 /day
k_2	Adsorption coefficient to substrate	0.018/day
k_3	Adsorption coefficient to vegetation	0.035/day
k_4	vegetation uptake coefficient	0.055/day
S_W	Initial volume of water column	2286 m^3
S_S	Volume of substrate	4572 m^3
S_{DEAD}	Volume of dead storage	2286 m^3
ET	Evapotranspiration rate	2.20 mm/day
A	Area of wetland (plan view)	15000 m^2
ϕ	Porosity	0.30
v_{SS}	Setting velocity in substrate	0.45 m/day
v_{SW}	Settling velocity in water column	0.15 m/day
$v_{SS\,q}$	Settling velocity in substrate (quiescent)	0.01 m/day
v_{SWq}	Settling velocity in water column (quiescent)	0.01 m/day
k_p	Partition coefficient	0.00202 m^3/kg
C_D	Discharge coefficient	0.9
L	Weir length	0.9144 m
TMAX	Simulation time	2.5 days

Figure 27. Rainfall and runoff for wetland simulation

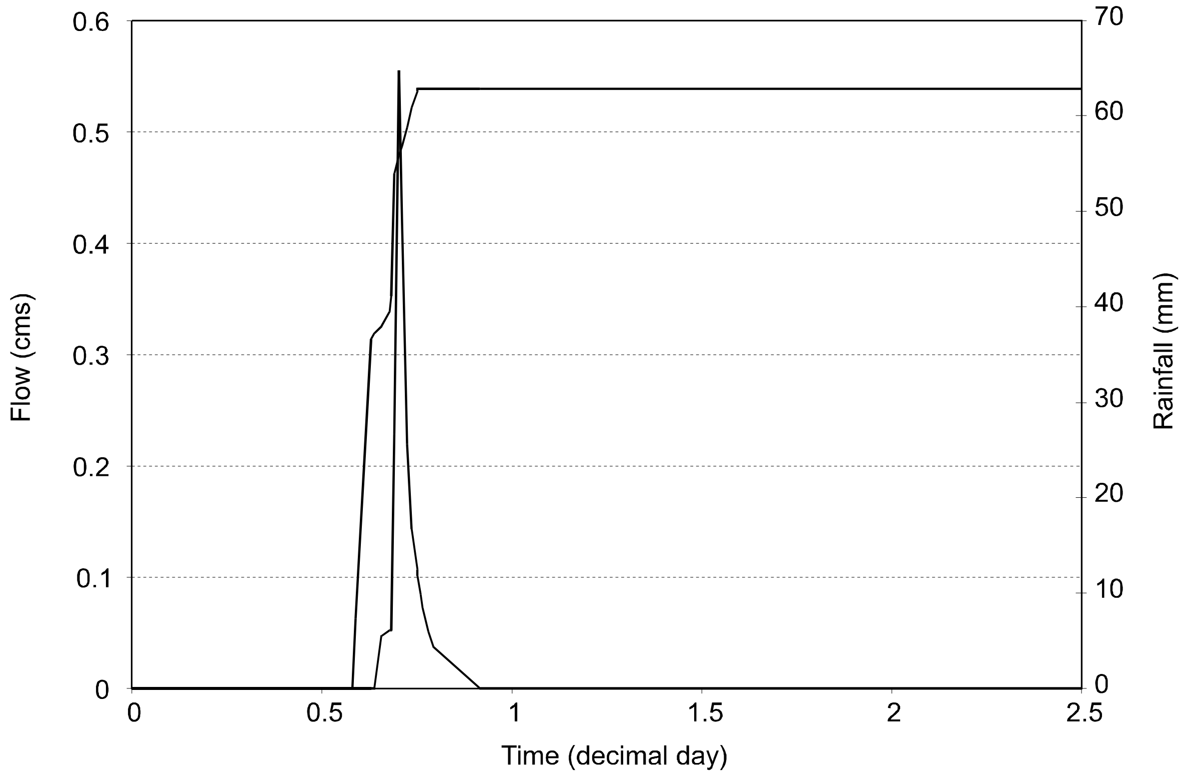


Figure 28. Influent pollutant concentrations for wetland simulation

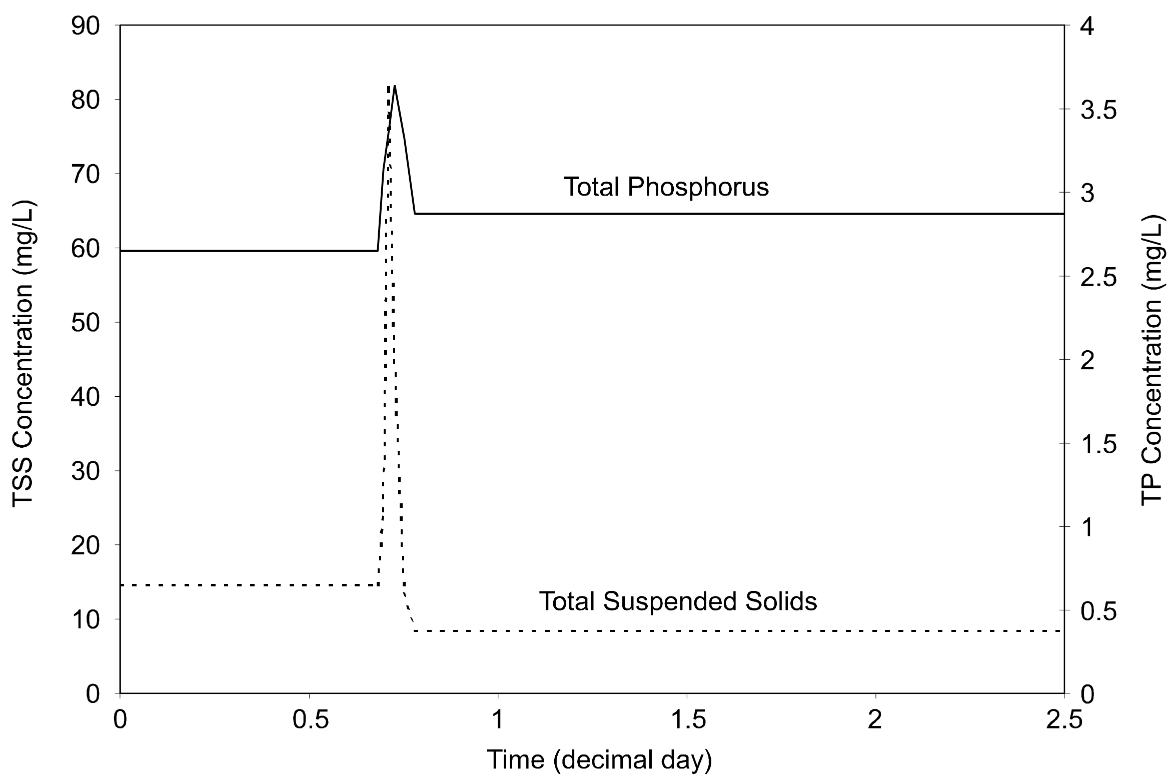
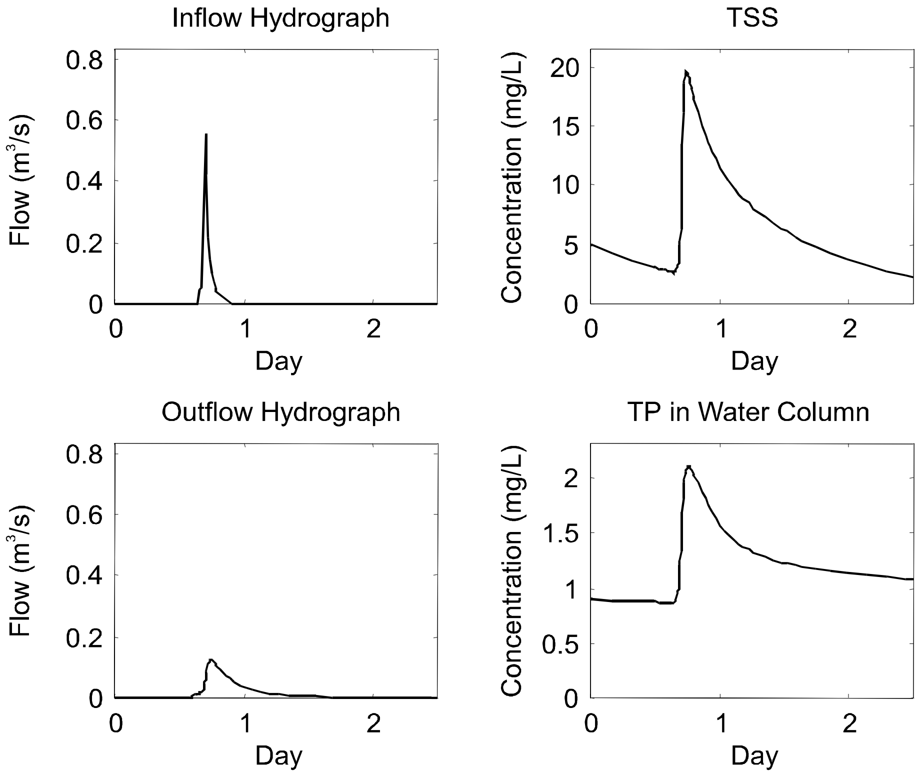
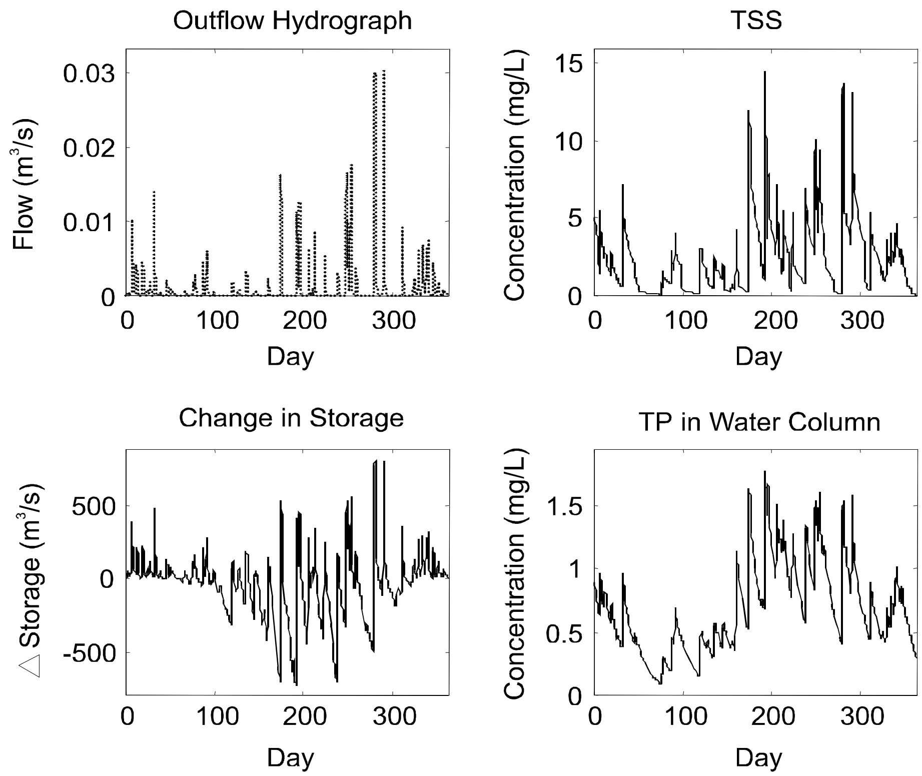


Figure 29. Event simulation results



To illustrate the ability of the model to simulate wetland water quality over an extended period of time, a simulation was also conducted for the Rt. 288 site for 1996. Kinetic parameters were the same as those used for the event simulation. A continuous precipitation record from the Richmond International Airport was used for input, and inflows that were not monitored at the site were determined based on a regression of rainfall and average daily flow from monitored events. Evapotranspiration rates used for the simulation were taken from thirty-year average monthly evapotranspiration rates as calculated by the Thornthwaite method. EMCs from monitoring data from 1996 were utilized for input for monitored storms, while a mean of EMCs from all events monitored at the site were used as inflow concentrations for storms that were not monitored. Again, the necessity of estimating much of the input data and the lack of sufficient site data prevent formal calibration. Results of the simulation are shown in Figure 30.

Figure 30. 1996 Simulation results



DISCUSSION

While the inability to formally calibrate the model at this time prohibits inference of actual wetland performance from modeling results, the mass removal efficiencies calculated by the model for this simulation of 48 percent for TSS and 24.5 percent for TP are in the range of removal efficiencies reported in the literature and observed in the field at the Rt. 288 site. Removal efficiencies of 79 percent for TSS and 47 percent for TP for the extended simulation also agree well with values from the literature.

Though a “design storm” approach is commonly used for the design of stormwater facilities for the control of runoff quantity, such an approach is not as applicable for the design of a wetland to improve water quality. Long-term wetland performance is affected by storage and transformation of pollutants within the wetland and by seasonal changes in nutrient uptake, vegetation growth, senescence, and nutrient release. Vegetative uptake (and release) of pollutants and other significant processes such as diffusion occur at rates that are orders of magnitude slower than more rapid processes such as sedimentation. A design approach based on a single event fails to account for the potentially significant impact of these less rapid processes on long term removal efficiency. Continuing modifications to the model include the incorporation of more sophisticated uptake and release kinetics to more accurately model the seasonal variations of these processes for simulations of long term performance.

SECTION III: GEOGRAPHIC INFORMATION SYSTEM DEVELOPMENT

BACKGROUND

VDOT and other state departments of transportation face a significant challenge in deciding how best to maintain their state inventories of mitigated wetlands. Specific information pertaining to many of Virginia's mitigated wetlands has become increasingly difficult to locate and maintain due to employee turnover, the disperse locations of the sites, and the elapsed time since initial site creation. Monitoring requirements placed on VDOT by the US Army Corps of Engineers continue to increase as well.

A geographic information system (GIS)-based inventory system is a useful method of storing information on existing sites, as well as providing needed data for future wetland planning. Proper site selection is one of the most important factors determining the success of constructed wetlands: A well-designed GIS allows planners to factor in numerous spatial data sets prior to committing any resources to site construction.

Since modeling tools typically lack sufficiently flexible spatial analytic components, GIS can also be used to provide spatially varied data for selected stormwater management models. A link between the data residing in a wetland GIS and the selected stormwater management model enables users to input spatially varied data, enhancing the accuracy of model simulations.

The GIS developed as a part of this study has three applications or modes:

1. *Constructed wetland inventory*. The inventory stores information on existing VDOT-created mitigation sites the agency monitors.

2. *Wetland site selection guide*. The guide serves as a tool to help locate new mitigation sites.

3. *Arc/INFO GIS-stormwater management model interface*. This interface provides a link between data stored in the GIS and a stormwater management model.

Each of these modes could be useful to personnel responsible for wetland mitigation in and of themselves; however, VDOT's Environmental Division is in the early stages of the creation of a division-wide GIS. The above three modes may or may not become part of the division's GIS, depending on the type of system that is ultimately developed. At the very least, the GIS created as a part of this study should serve as a learning tool for further GIS development in the Environmental Division.

METHODS

Constructed Wetland Inventory

A mitigation site database was developed using PC Arc/INFO and ArcView 3.0. To create a point coverage representing VDOT created wetland sites, latitude/longitude coordinate pairs for all existing mitigation sites were taken from project files, USGS quad sheets, and/ or global positioning system (GPS) reading using a Trimble GeoExplorer receiver. All GPS readings were differentially corrected using a public base station located in Charlottesville. For some of the larger sites, GPS was used to delineate the entire wetland boundary. GPS files were exported as Arc/INFO coverages using Pathfinder Office GPS software.

In addition to the point coverage created for the sites, all existing attributes for the wetland sites, previously stored in a rudimentary database by VDOT's Environmental Division, were transferred to the attribute table of the coverage. Attributes added include: project name, project number, permit number, watershed, impact type, impact function, impact size, mitigation type, mitigation function, mitigation size, monitoring due dates, and monitoring comments. Once coverage development was complete in Arc/INFO, a shape file was created in ArcView, thereby allowing additional edits to be made within the ArcView environment. County and state boundary themes were added to give the user a spatial frame of reference when using the wetland site point theme. Additional information, such as digital photographs, aerial infrared photographs, GPS derived delineations, and detailed maps indicating major areas of vegetation, inlets, outlets, etc., were also hot-linked to specific sites when available.

The research team used Avenue programming language to slightly amend the standard ArcView graphical user interface (GUI) for the constructed wetland inventory. In order to simplify the standard ArcView interface, some of the default options and tools normally available to the user were eliminated. The simplified interface reduces the chances that an inexperienced user will inadvertently alter the database, while allowing more experienced personnel sufficient access to complete more complex queries and analyses, and to update the database as changes to the wetlands occur.

Site Selection

To aid VDOT personnel in the selection of potential sites for newly created wetlands, the second phase of the GIS construction included the development of a site selection mode. Numerous factors are considered in a siting selection; the research team conducted a literature search and conducted interviews with VDOT wetland personnel in order to identify the specific data sets necessary for this process.

A total of 13 data sets or layers of information were identified as being useful. From these, a weighting system was used to select out the most important data sets. Following the identification process, data were acquired from a variety of sources at the largest scale (highest resolution) possible.

The Staunton District was chosen as the study area for this portion of the GIS due primarily to the availability of data for this area of the state. The coverages were created within Arc/ INFO and transferred to ArcView for viewing, query, and analysis. A specific sequence of queries was developed to aid the user in the selection process of potential sites. Additional functions were added to the default ArcView GUI to assist the user in carrying out necessary steps for site selection.

Modeling Linkage

Modeling tools typically lack sufficiently flexible spatial analytic components. To address this deficit, the researchers searched for an available link between existing stormwater models and GIS, thereby allowing the user to take advantage of the spatial analysis capabilities of the GIS. They conducted a literature search to determine the availability of existing stormwater model-GIS interfaces. Those interfaces deemed potentially suitable were acquired and tested for applicability for VDOT using sample data sets. Factors that were considered when characterizing the interfaces included: model usage, cost, platform requirements, operational difficulty, and data requirements. A single interface was selected and further tested using data for a small watershed in Rappahannock County. Finally, the researchers identified modifications that would improve the interface.

RESULTS

Constructed Wetland Inventory

Figures 31 and 32 are screen captures of the GIS-constructed wetland inventory mode. All available information for the over 220 created wetland sites is available to the user by clicking on the point representing the site, by viewing the entire attribute table for the theme, or by submitting a user-defined query.

Figure 31. Constructed wetland mode showing attribute table and infrared aerial photograph

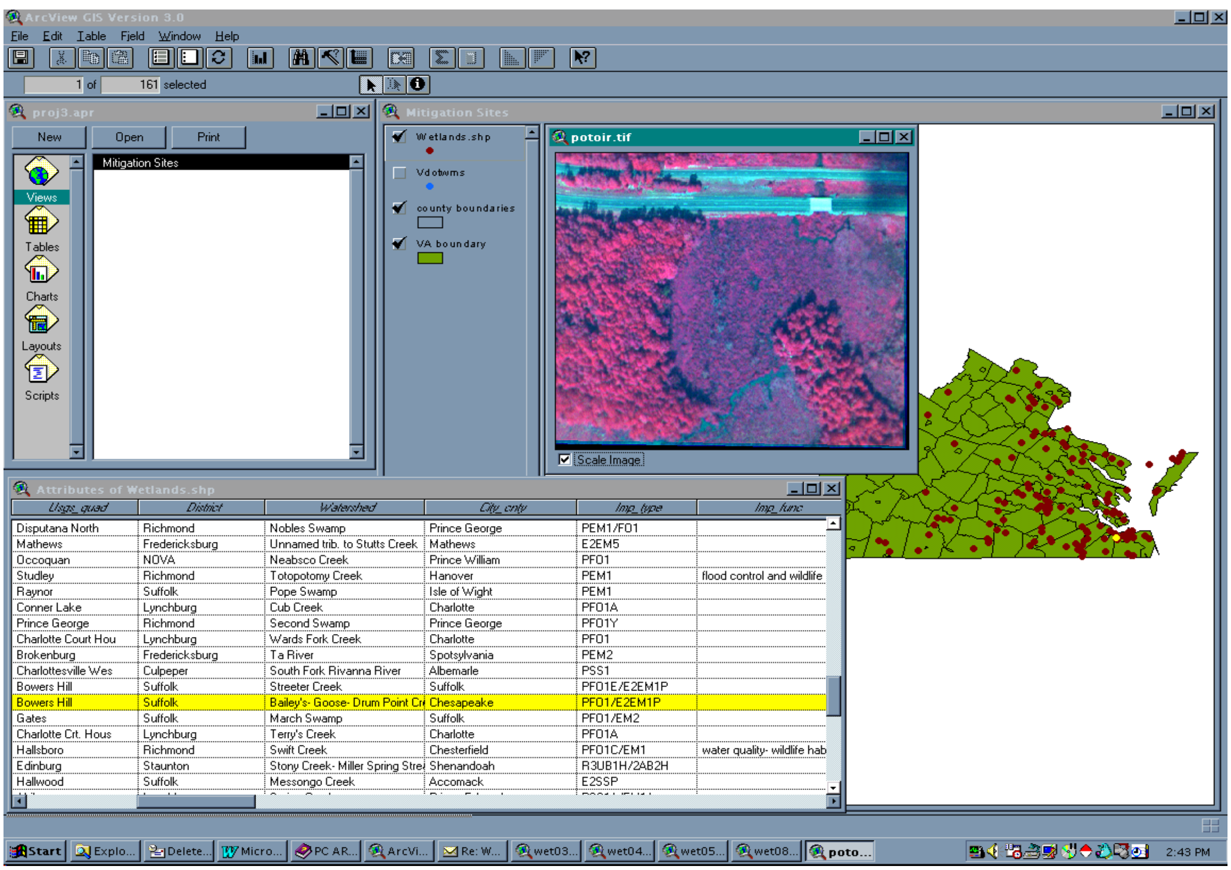
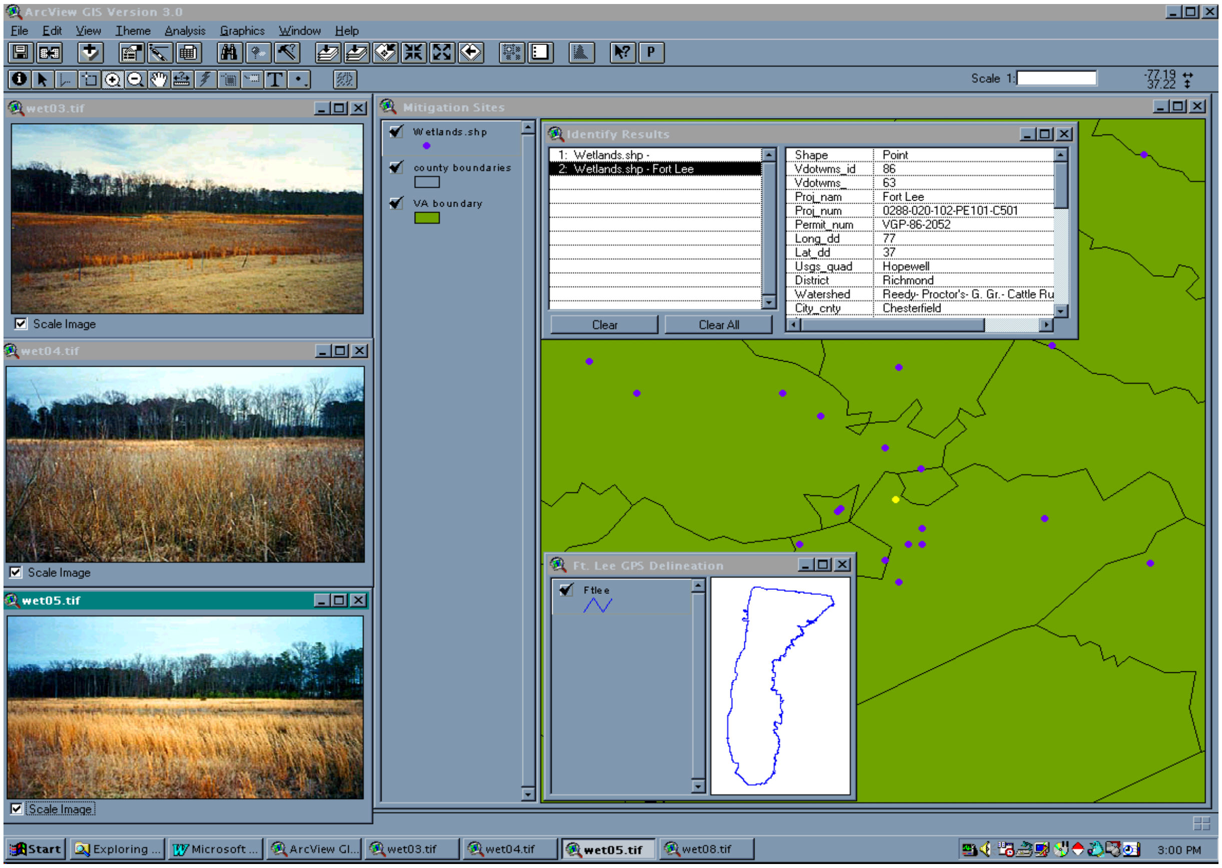


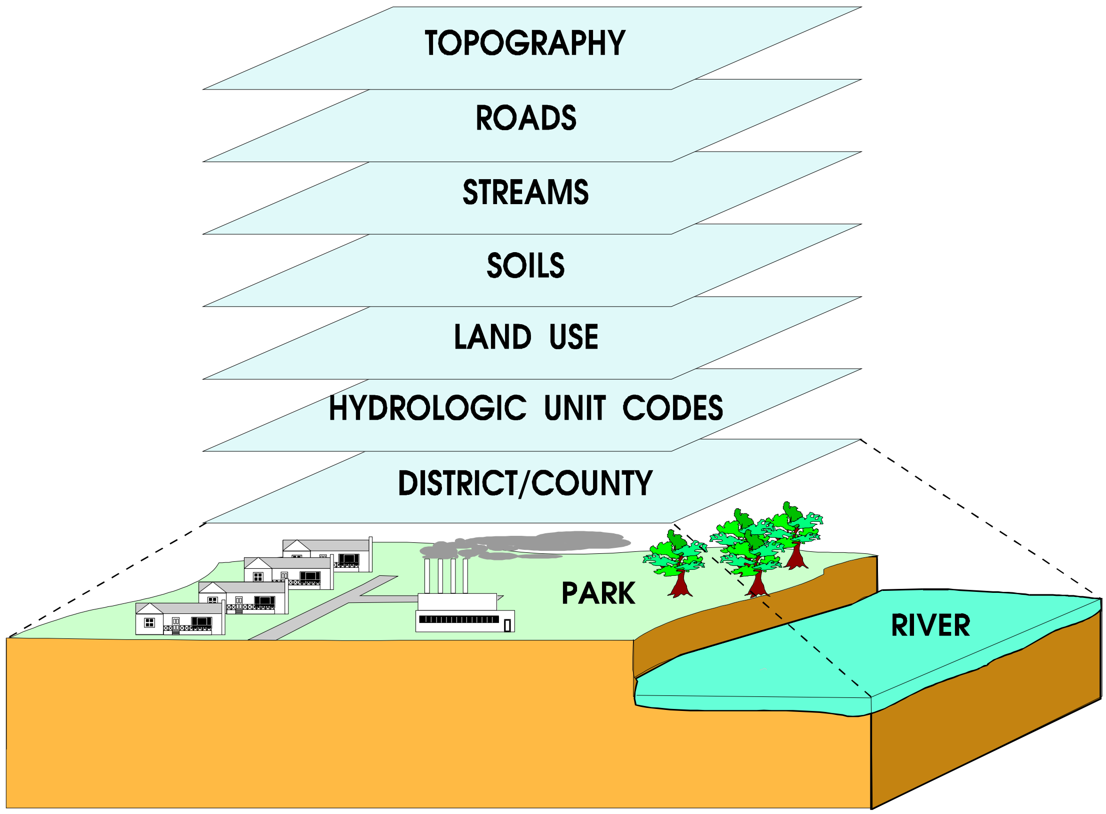
Figure 32. Constructed wetland mode showing site attributes. GPS delineation and ground photographs



The researchers identified 13 data sets that are useful for site selection: hydrologic unit codes, streams and rivers, groundwater hydrology, flooding potential, land use, soil type, vegetation cover, elevation (topology), transportation, land cost, National Wetlands Inventory, water intake/discharge permit points, and endangered species locations. The most critical of these 13 data sets were prioritized using a weighting scheme devised by Daigle (1996). After applying this weighting scheme, the data sets determined to be necessary for future mitigation site selection included: soils, water bodies, streams, roads, land use, hydrologic unit codes, and elevation data. All of these coverages were obtained for the Staunton District, most at a scale of 1:100,000. Most were taken from the Southern Appalachian Assessment GIS Data Base (1996). Higher resolution data were requested from various sources, but could not be obtained for all the counties making up the district. Additional information (such as vegetation cover, endangered species habitat, land cost, and groundwater hydrology) would be extremely useful for this mode of the GIS, but were only available for relatively small, discontinuous areas throughout the state. Figure 33 depicts the site selection overlay procedure.

From the Site Selection mode GUI, the user can issue the commands necessary to identify sites meeting predetermined criteria. The recommended order of data display and query is as follows:

Figure 33. Site selection coverage overlay procedure



1. Determine hydrologic unit code (HUC) for which wetlands will be mitigated
2. Select this HUC with the selection tool and zoom in to the extent of this using zoom to selection tool (Figure 34)
3. Select areas containing the desired land use(s) using the query builder (Figure 35)
4. Select areas meeting soil type requirements from previously selected set
5. Draw streams and roads coverages (Figure 36)
6. Create buffers of a specified distance for both streams and roads using buffer tool
7. Visually determine intersections between buffered sections and previously selected polygons
8. Determine sites that meet topography requirements from this set by intersecting with elevation coverage or by making elevation theme active and requesting elevation information for each of the potential polygons individually.

Figure 34. Site selection mode with hydrologic unit codes highlighted

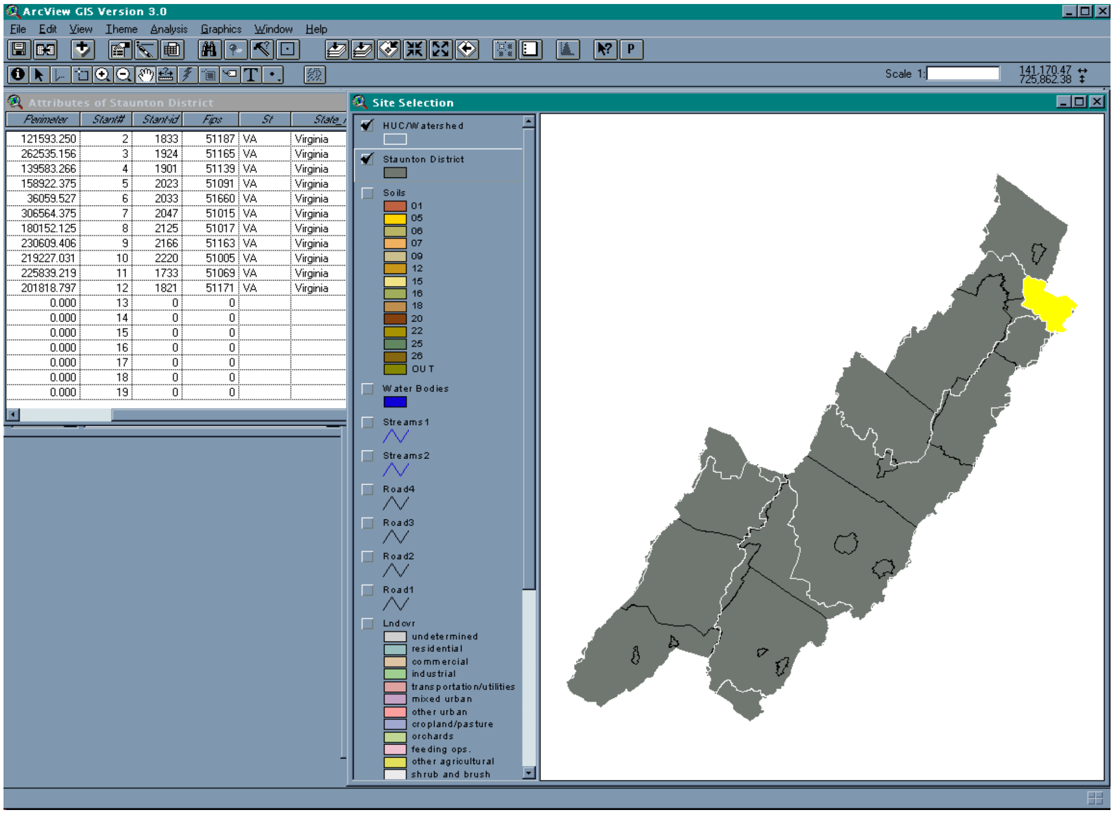


Figure 35. Site selection mode with land use and query builder displayed

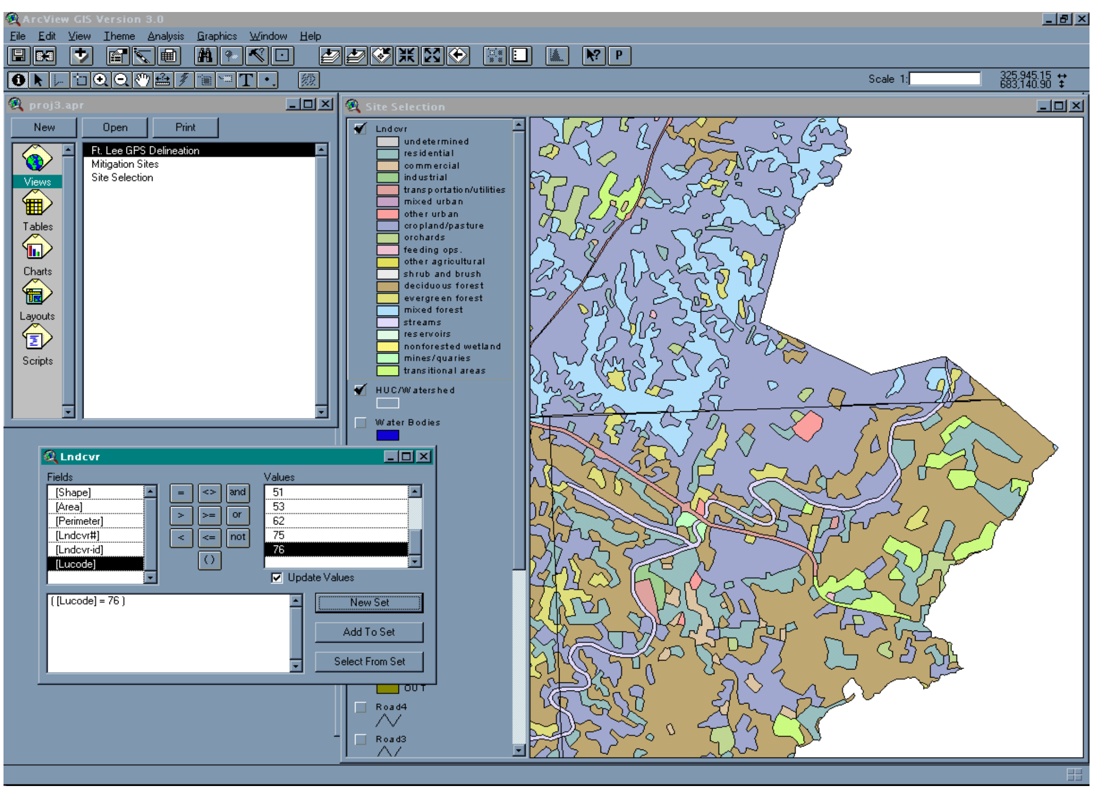
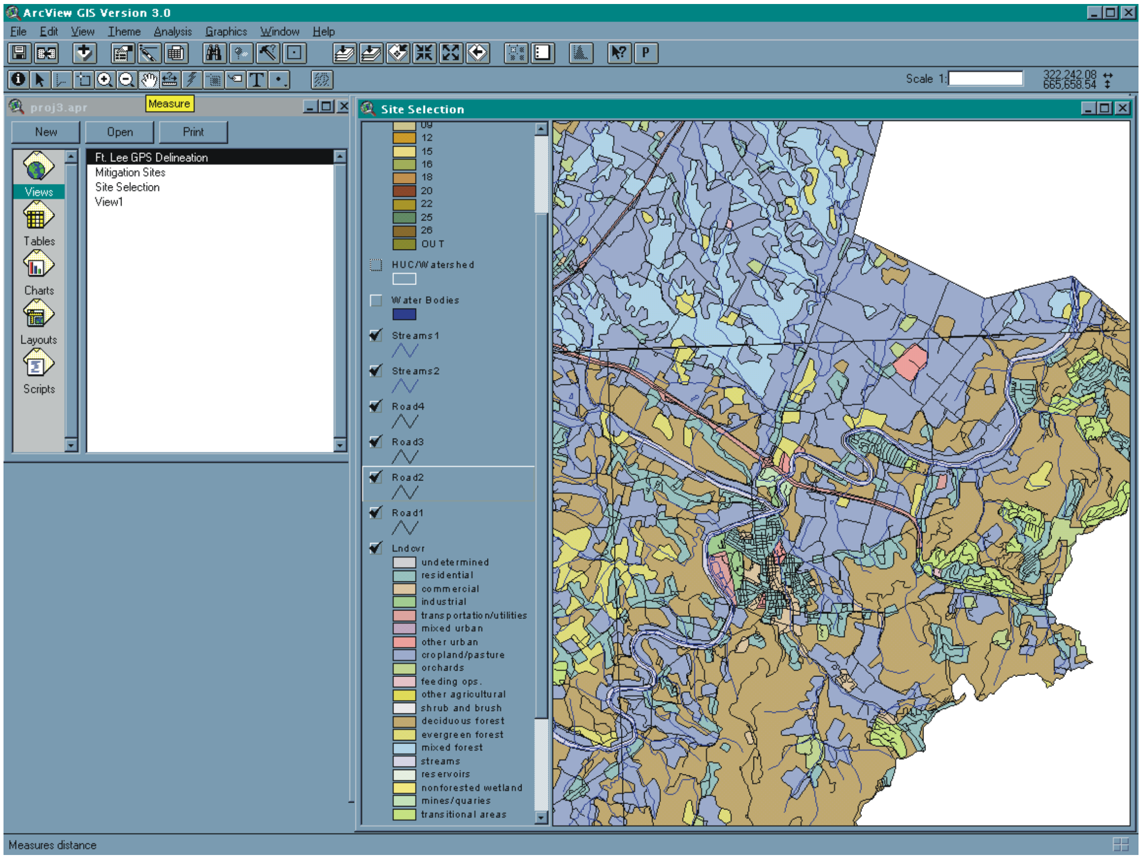


Figure 36. Site selection mode showing roads, streams, and land use intersection



Maximum slope characteristics can be derived from the elevation coverage by way of analysis tools provided in the Spatial Analyst extension in ArcView. This extension, while providing various other hydrologic functions, allows for the derivation of a watershed, again from the elevation coverage. If the user would prefer to have the replacement site located within the same local watershed (as opposed to the same hydrologic unit code), the watershed can be delineated, the area calculated, and the polygon selected as the initial steps in place of the previously described step 1.

Modeling Linkage

Numerous hydrologic model GIS interfaces have been developed over the past five to seven years. The majority of the earlier interfaces were what is referred to as loosely coupled interfaces, meaning that the GIS simply output data in a format that was readable by the model. Closely coupled models, those that pass data between the model and the GIS via memory-resident data models as opposed to external files, are becoming more common (Haddock and Jankowski, 1993; Liao and Tim, 1997). While significantly more difficult to develop, closely coupled interfaces are much faster and more efficient for the user.

Four stormwater model-GIS interfaces were identified in the literature search. The interfaces include Watershed Modeling System (WMS), Agricultural Nonpoint Source Model (AGNPS), Better Assessment Science Integrating Point and Nonpoint Sources (BASINS), and ArcView Sand (AVsand). The results of the model characterization can be found in Table 14. Interfaces that connect other GIS packages such as Geographical Resource Analysis Support System (GRASS) and AGNPS do exist, but were not investigated in this study (Osmond et al., 1997).

Table 14. GIS-Stormwater Model Interface Characterization

Name	Analysis Emphasis	Approximate Cost	Operating System	GIS - Model Linkage	Difficulty	Notes
WMS	water quantity	$750	Windows 95 Windows NT UNIX	ArcView w/ HEC-1 NFF TR-20 Rational Method	low	Excellent for delineation and extraction of watershed characteristics
BASINS	water quality	$0	Windows 95	ArcView w/ HSPF QUAL2E TOXIROUTE	moderate	Analysis done at county level or smaller scale
AGNPS	water quality	$0	UNIX	Arc/INFO w/ AGNPS	high	UNIX skills necessary
AVsand	water quality	$4,400	Windows 95 Windows NT UNIX	ArcView w/ SWMM SAND	moderate	More user friendly

The AGNPS interface, a closely-coupled interface developed by Hsiu-Hua Liao and U.S. Tim at Iowa State University, was tested for potential VDOT application. AGNPS had several advantages over the other interfaces, including cost and the fact that it linked Arc/INFO to AGNPS 5.0. Arc/INFO is a fully functional GIS, providing the user with a much greater set of spatial analysis functions than most "desktop" GIS packages, such as ArcView, to which the other interfaces are linked. AGNPS is a powerful, single event, distributed parameter model that simulates nonpoint pollution from watersheds. The model can be used to predict runoff volume, eroded and delivered sediment, chemical oxygen demand, nitrogen concentrations, and phosphorus concentrations in the runoff. The AGNPS model was developed by the Agricultural Research Service in 1987 (Young et al., 1987). The AGNPS interface will compute nonpoint source loads (and some point source loads) for a number of pollutants and a wide range of watershed sizes. The interface therefore may be used for a general or detailed water quality analysis. Figures 37-40 show the AGNPS interface for each of the program's four modules.

Figure 37. AGNPS-Arc/INFO data generation module

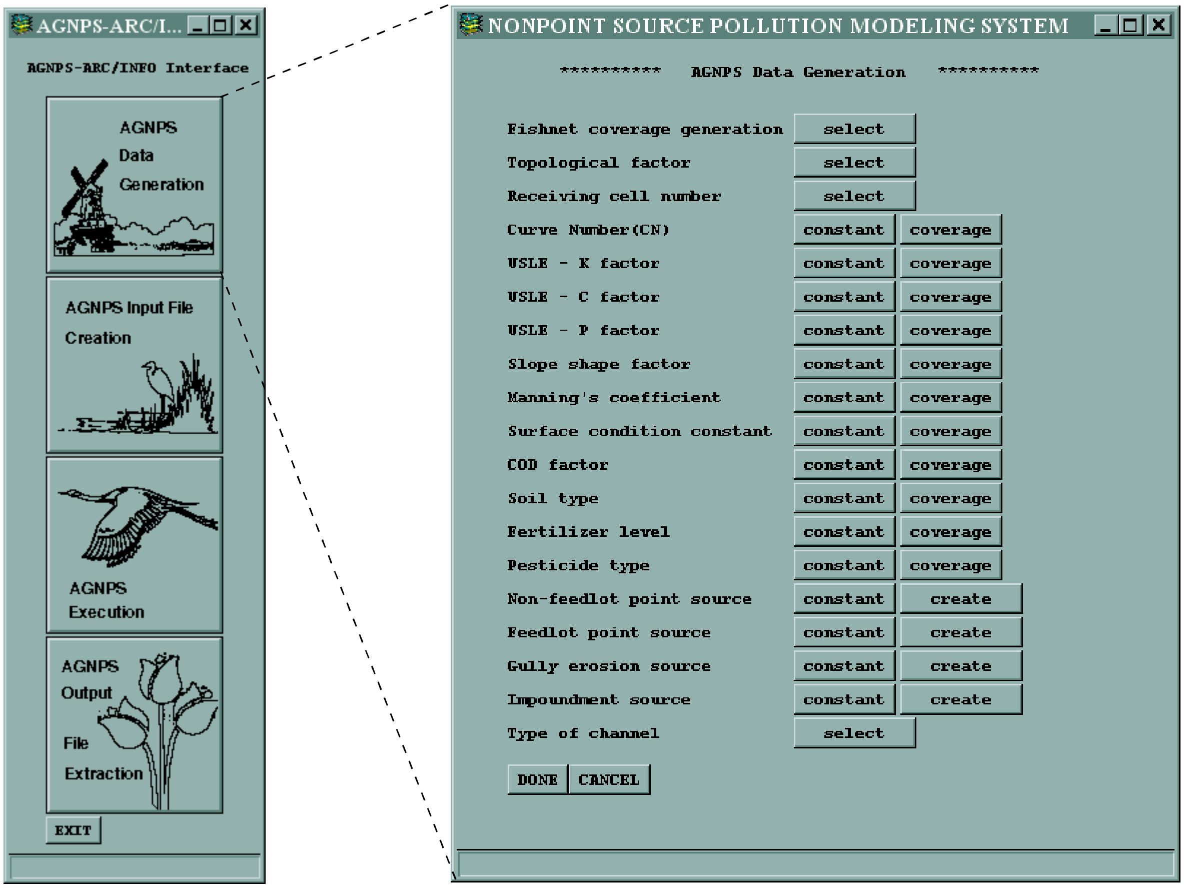


Figure 38. Input file creation module

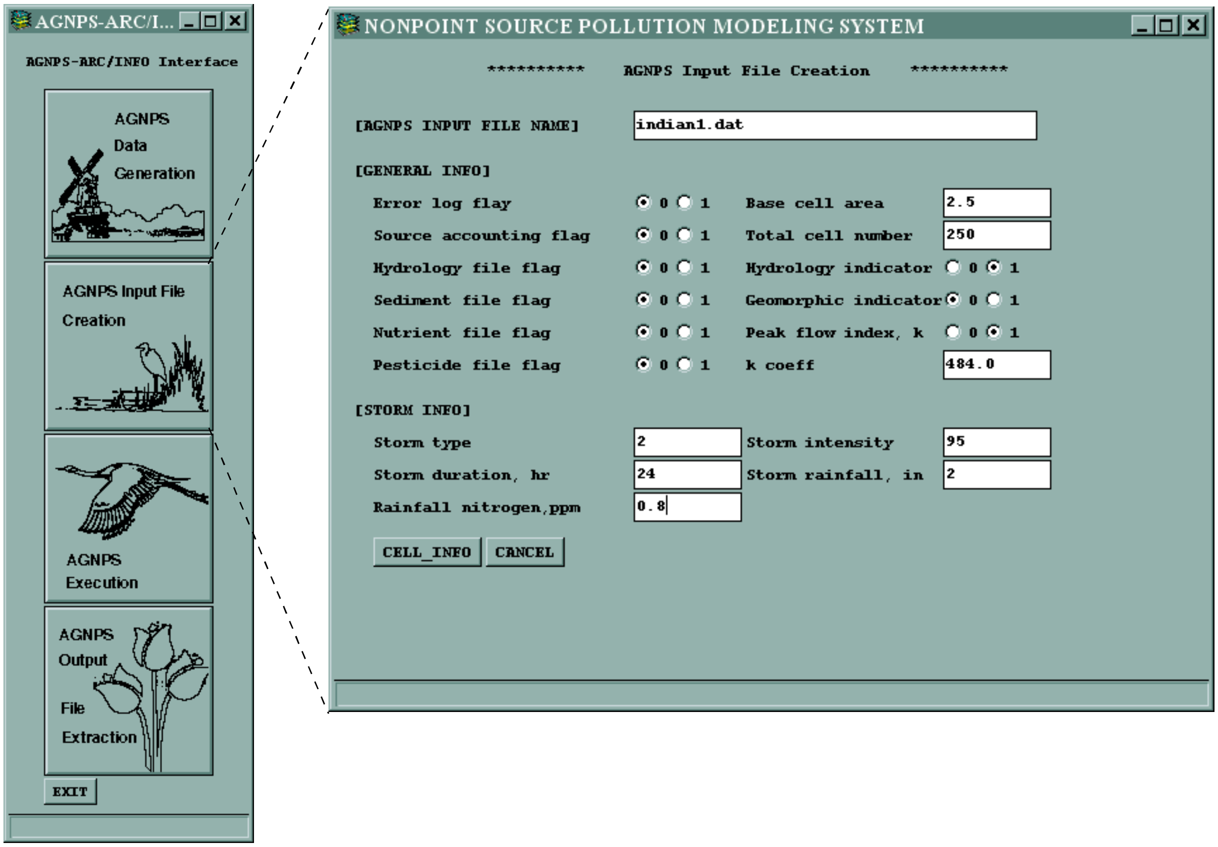


Figure 39. AGNPS Execution module

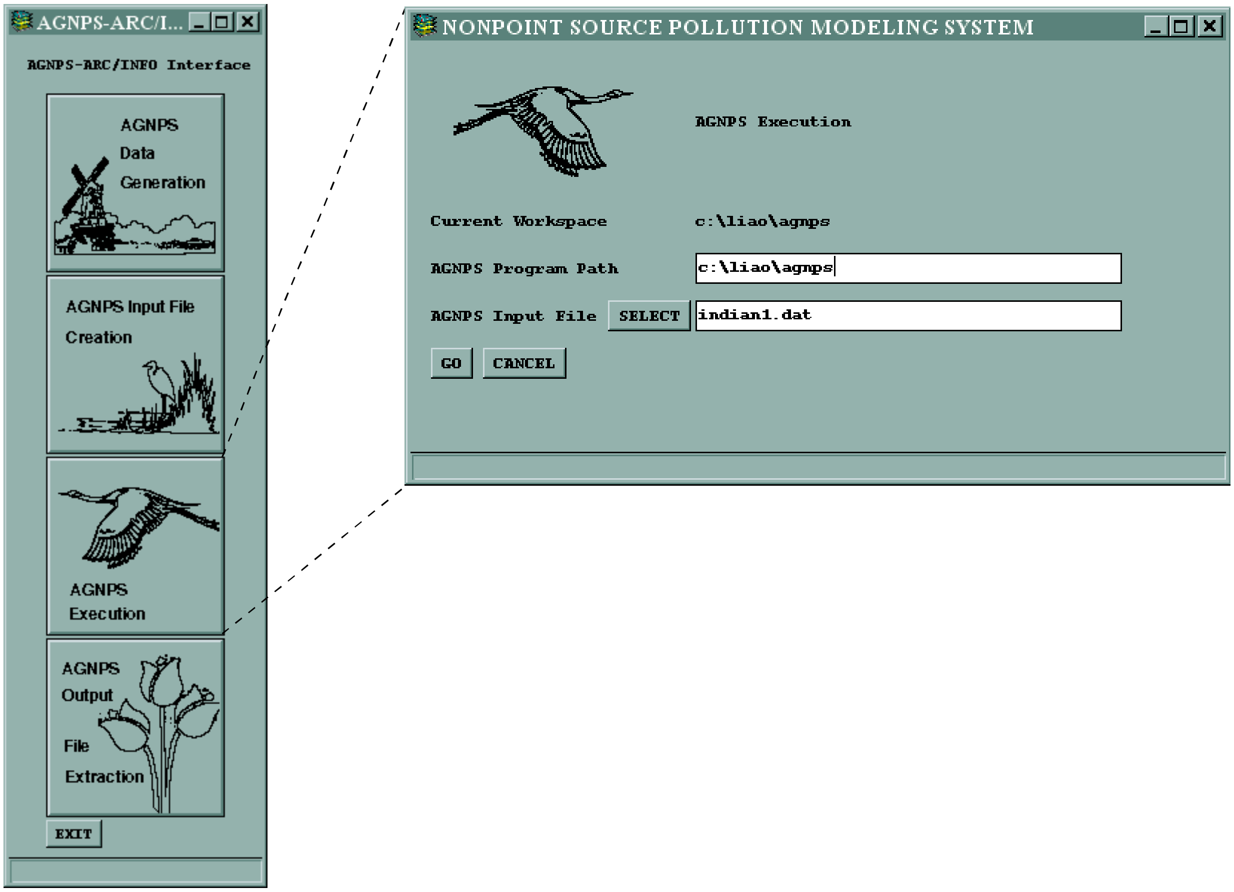
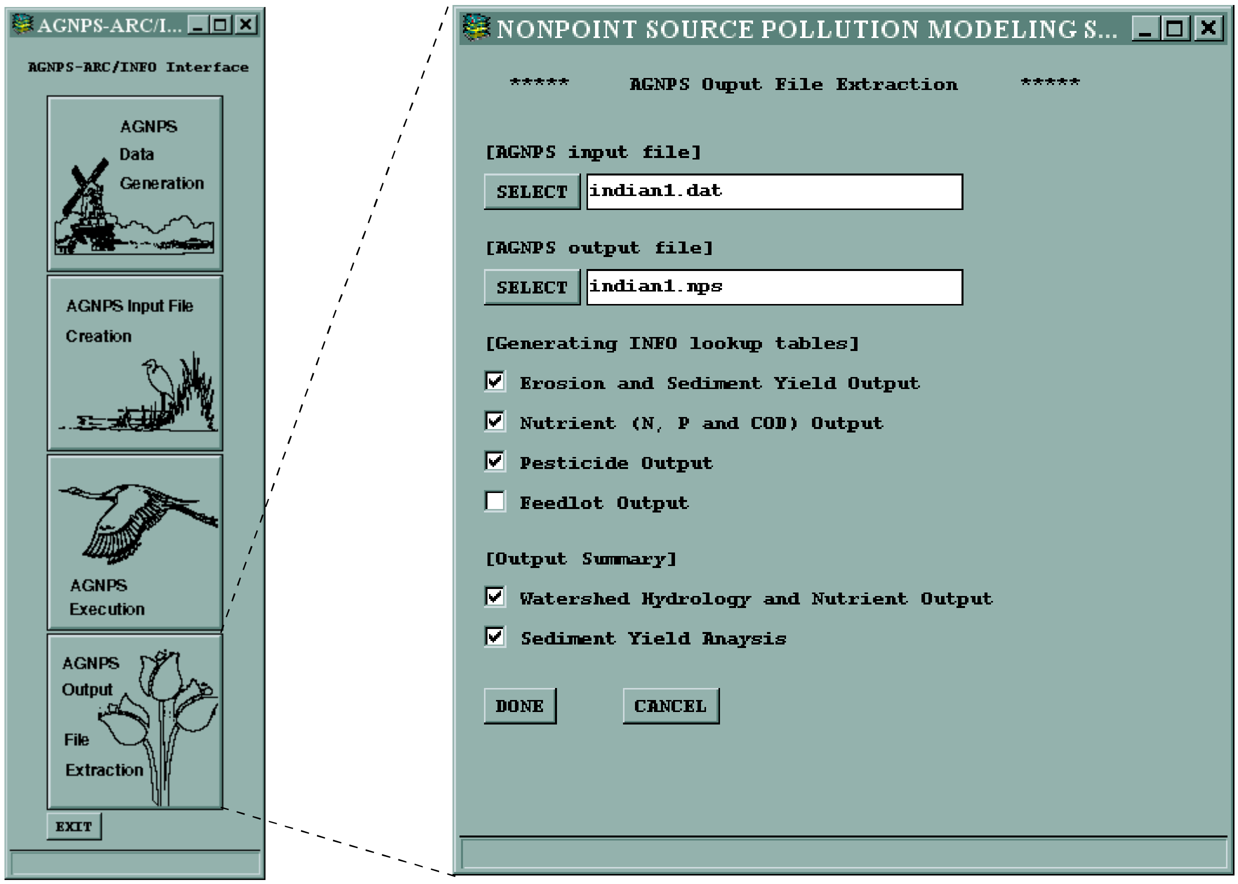


Figure 40. AGNPS-Arc/INFO ouput file extraction module



DISCUSSION

Constructed Wetland Inventory

The research team selected ArcView, Environmental Systems Research Institute's desktop GIS package, as the software for this application primarily because of its compatibility with Arc/INFO and because it is one of the more user friendly GIS packages available. It was assumed that the end user of the Constructed Wetland Inventory would not necessarily have extensive formal training in GIS, and therefore would not need a more sophisticated/complicated package. Additionally, since it was assumed that any changes or updates to the system would be done in ArcView, all Arc/INFO coverages used were converted to ArcView shape files (shp). This eliminates any need for users to make changes in Arc/INFO. All available information for the sites is included in the GIS. Additional information on new or existing sites will be added to the system as it becomes available. If not updated consistently, the system will not serve its intended purpose and will become increasingly difficult to manage.

Potentially, VDOT could utilize the GIS developed for the mitigation for three types of tasks: monitoring, maintenance/remedial action, and long term management. Monitoring of mitigation sites ensures that the hydrology and planting criteria established in the permit conditions are being met. The US Army Corps of Engineers requires that most emergent sites be monitored for five years; forested sites may require monitoring for 10 or even 20 years. Storing all data digitally will lessen the burden of data management. The photographs stored in the system will allow for direct comparison of vegetative success at specific locations from year to year. Digitally mapping the wetland delineations, specific habitats, and areas of major vegetation dominance will allow for quantitative spatial analysis between sites and within the same site over time.

The GIS database will enhance maintenance and remedial actions required by providing a tracking mechanism for work conducted at the sites (e.g., a specific area may require replanting several times). As data are collected for the sites and added to the system over the years, it will be possible to carry out trend analyses. The GIS will aid long term management of the sites too. Ideally, this system will be linked with the Environmental Division's GIS and ultimately to VDOT's department-wide GIS, making the wetland information available to environmental personnel outside of Aquatic Ecology as well as to other VDOT divisions. By having the spatial information available, divisions which would not normally know the location of the wetland sites, will be able to avoid them when conducting unrelated work tasks (e.g., maintenance would know where to avoid spraying herbicides).

Site Selection

Proper placement of newly constructed wetlands is a critical component of their ultimate success. Placement of the mitigation site in the same hydrologic unit code (HUC) is, in most cases, required (Daigle, 1996). Other hydrologic criteria can be derived from the streams and water body coverage as well as the elevation or topography coverages. The GIS land use coverage provides land use and land cover information based on the Anderson classification system taken to the level 2 characterization (Hermann, 1996). Desired proximity to roads and streams can be specified using these coverages along with the buffer tool.

The site selection mode of the GIS, like most any information system, is only as good as the data that comprises it. A great deal of time was spent trying to gather the data required for this mode. The data sets that were obtained are sufficient to allow the user to identify potential areas to investigate further; possibly more importantly, the user can quickly eliminate areas for consideration. Additional information (such as land cost and groundwater hydrology), if it were readily available, would greatly benefit this mode of the GIS. Also, larger scale (higher resolution) data (such as soils) would also be very helpful. There is a tradeoff when gathering this kind of data, however: Some forms of data acquisition (i.e., digitizing higher resolution soils data) could easily offset any time saving benefits of the system. As the Environmental Division's GIS begins to develop, these additional, high-resolution data sets should become more readily available.

Modeling Linkage

It was originally envisioned that a GIS-stormwater model interface would be developed as a part of this project. During the literature search, however, it became evident that several interfaces already existed for a variety of GIS packages and stormwater models. It also became clear that developing a closely-coupled interface would be well beyond the scope of the original project. The AGNPS interface provides all the functionality needed and is public domain. From VDOT's perspective, the most significant drawback to this interface is the fact that it currently only runs on a UNIX platform, which requires the user to run UNIX Arc/INFO and AGNPS for UNIX. The majority of VDOT environmental personnel do not have easy access to these programs and are not proficient with the UNIX operating system. Some of the other PC-based interfaces that have been developed link PC Arc/INFO to stormwater models, but these are limited by the reduced capabilities of a PC-based GIS. This constraint alone can severely limit the size of the watershed being modeled and/or the resolution of the data sets used for model input. The developer of the AGNPS interface indicated that both the interface and AGNPS could be compiled to run on Windows NT (Liao, 1997). The interface was written in C code, while the actual AGNPS program was written in FORTRAN code. Therefore, the AGNPS interface and program should be compilable within Windows NT. The Windows NT version of Arc/INFO closely resembles that of UNIX Arc/INFO in overall functionality.

The AGNPS interface will significantly reduce the time requirement for constructing AGNPS input and output files. Before construction of the interface, users had to manually enter more than 20 inputs for each cell of grids covering each study area. Hence, data entry was extremely time consuming when modeling watersheds with many cells. With the interface, inputs for each cell are automatically derived for grids containing up to 32,000 cells (Liao, 1997).

Even with this reduced data entry time, however, considerable time should be allocated for preparing the GIS coverages. AGNPS is very data-intensive when a high level of accuracy is desired. For example, when modeling relatively small watersheds (1.5 –15 km), the use of high-resolution data is imperative for accurate results. Consequently, data at or greater than 1:24,000 scale is desirable for these watersheds. Another time- consuming aspect of the AGNPS interface is the checking of overland flow paths derived from a triangular irregular network (TIN), one of the GIS coverages required by the interface. Determining the overland flow path for every cell in a grid is cumbersome when working with coverages composed of a relatively large number of cells.

CONCLUSIONS

1) Mitigated wetlands receiving highway runoff may be as effective as conventional BMPs at improving the quality and controlling the quantity of highway runoff. Peak reductions in excess of 40 percent were observed, with attenuation of greater than 90 percent for a system combining a detention basin and a mitigated wetland in series. Average removal rates as high as 90 percent for TSS, 65 percent for COD, 70 percent for TP and OP, and 50 percent for Zn were monitored at study sites.

2) Differences in removal efficiencies for the sites monitored are likely attributable to differences in key design parameters, including the configuration of inlets and outlets, the length to width ratio, and (consequently) residence time. Greatest removal is achieved for

sites that maximize the length to width ratio and flow path through the system. Poor placement of inlets and outlets results in short-circuiting that decreases residence time of water in the wetland.

3) Despite having stormwater runoff as a primary water source, sites monitored supported apparently healthy and diverse vegetation and a variety of wildlife. More than twenty vegetative species were catalogued at each site monitored, and frequent observations of wildlife were made at all sites

4) Existing mitigation sites can be more easily managed and new sites more successfully located with the GIS developed as part of this project. Stormwater modeling can also be enhanced with data input directly from the GIS; however, the excessive hardware, software, and data requirements presently preclude the operational use of this closely-coupled modeling approach.

RECOMMENDATIONS

1) When required to construct wetland mitigation sites, VDOT should consider stormwater quality improvement as a mitigation objective. Critical functional aspects of a wetland mitigation site, including habitat for wildlife and vegetation, should not be compromised for the sake of stormwater treatment. However, when compatible with other mitigation objectives, water quality benefits should be maximized.

2) Constructed wetlands and vegetated detention basins are viable alternatives for NPS pollution control and attenuation of peak flows. These alternatives should become accepted stormwater BMPs. They are especially desirable in areas in close proximity to mitigated (or natural) wetlands where a constructed wetland or vegetated basin may serve as pretreatment for stormwater entering a mitigation site and at the same time provide additional habitat.

3) Data from the Site Selection mode of the GIS should be incorporated in the Environmental Division's division-wide GIS. This database should be utilized and maintained by Aquatic Ecology personnel to meet mitigation site monitoring requirements.

4) The Arc/INFO AGNPS interface should be recompiled to run on the Windows NT environment. This will allow more VDOT personnel to use the program without converting existing data sets or maintaining a different operating environment.

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REFERENCES

Ambrose, R.B., Wool, T.A., & Martin, J.L. (1993). *The water quality analysis simulation program, WASP5, Part A: Model Documentation*. Athens, GA: Environmental Research Laboratory, U.S. Environmental Protection Agency.

American Sigma. (1996). *Operating and maintenance manual Sigma 900MAX portable sampler.* Medina, NY: Author.

Athanas, C. Wetlands creation for stormwater treatment (1988). In *Proceedings of the National Wildlife Federation Corporate Conservation Council Meeting* (pp. 61-66). Washington, D.C.: National Wildlife Conservation Council.

Baker, L.A. (1993). Introduction to nonpoint source pollution and wetland mitigation. In R.K. Olson (Ed.), *Created and natural wetlands for controlling nonpoint source pollution* (pp. 7-41). Boca Raton, FL: C.K. Smooley, the Office of Research and Development and Office of Wetlands,U.S Environmental Protection Agency.

Bautista, M.F. & Geiger, N.S. (1993, July). Wetlands for stormwater treatment. *Water Envionment and Technology,* 5(7), 50-55.

Boyd, C.E. (1970). Chemical analyses of some vascular aquatic plants. *Arch. Hydrobiol,* 67, 78-85.

Boyd, C.E. (1978). Chemical composition of wetland plants. In R.E.Good, D.F. Whigham and R.C. Simpon, Eds., *Freshwater wetlands, ecological processes and management potential*. New York: Academic Press.

Caassen, N. & Barber, S.A. (1976). Simulation model of nutrient uptake from soil by a growing plant root system. *Agronomy Journal*, 68, 961-964.

Clesceri, L.S., Greenburg, A.E., Trussell, R.R.(Eds). (1989). *Standard methods for the examination of water and wastewater, seventeenth edition*. Washington, DC.: American Public Health Association

Crumpton, W.G. (1995, Summer). Technical Note 54: Pollution dynamics within stormwater wetlands: II. Mesocosms illuminate the role of organic matter in nutrient removal. *Watershed Protection Techniques* 1(4), 214-216.

Daigle, S. D. (1996, May). *Geographic information systems database development of VDOT mitigated wetlands for stormwater management*. Masters thesis, University of Virginia. Charlottesville.

Dorman, M.E., Hartigan, J., Johnson, F. & Maestri, B. (1988). *Retention, detention, and overflow for pollutant removal from highway stormwater runoff.* (FHWA/RD-87-056). Washington, DC: Federal Highway Administration.

Guardo, M. & Tomasello, R.S. (1995). Hydrodynamic simulations for a constructed wetland in South Florida. *Water Resources Bulletin*, 31 (4), 687-701.

Hach Company. (1991). *Hach DR/2000 spectrophotometer handbook, procedures manual.* Loveland, CO: Hach Company, USA.

Haddock, G. & Jankowski, P. (1993). Integrating nonpoint source pollution modeling with a geographic information system. *Computers, Environment, and Urban Systems*. 17,

Hammer, D.A. (Ed.). (1989). Constructed wetlands for wastewater treatment: Municipal, industrial, and agricultural. In *Proceedings from the first international conference on constructed wetlands for wastewater treatment*, *Chattanooga, TN*, June 13-17, 1988. Chelsea, MI: Lewis Publishers.

Hearn, C. J., Chambers, J.M. & McComb, A.J. (1991). A model of flow and nutrient absorption in artificial wetland systems. *Applied Mathematical Modeling,* 15, 267-273.

Heliotis, F. D. & DeWitt, C.B. (1983). A conceptual model of nutrient cycling in wetlands used for wastewater treatment: A literature analysis. *Wetlands*, 3, 134-152.

Hermann, K. A. (ed.). *The southern Appalachian assessment GIS data base*. [CD ROM Set]. (1996). Norris, TN: The Southern Appalachian Man and the Biosphere Program.

Jørgensen, S. E. (1996). *Fundamentals of ecological modelling*. Amsterdam: Elsevier.

Jørgensen, S. E. (1988). Modelling of wetlands. In A. Marani, Ed. *Advances in environmental modelling* (pp. 534-544). Amsterdam: Elsevier.

Kadlec, R.H. & Hammer, D. E., (1988). Modeling nutrient behavior in wetlands. *Ecological Modeling*, 40, 37-66.

Kappel, W.M., Yanger, R.M., & Zarriello, P.J. (1985). *Quantity and quality of urban stormwater runoff in the Ironequoit Creek basin near Rochester, N.Y.* (U.S.G.S. Water Resources Investigation Report No. 85-4113). Reston, VA: U.S. Geological Survey.

Knisel, W.G. (Ed.). (1980). *CREAMS: A field scale model for chemicals, runoff, and erosion from agricultural management systems* (Conservation Report No. 26). Washington, D.C.: Science and Education Administration, U.S. Department of Agriculture.

Liao, H. H. (1997). *AGNPS Arc/INFO User Interface*. Author.

Liao, H. H. & Tim, U.S. (1997, June). An interactive modeling environment for non-point source pollution control. *Journal of the American Water Resources Association*. 33(3).

Liao, S. L. (1996). *An experimental evaluation of using constructed wetlands for controlling stormwater pollution*. Ph.D. dissertation, University of Virginia, Charlottesville.

Light, R. N. (1992). *Modeling of heavy metal removal in wetlands*. Master's thesis, University of Virginia, Charlottesville.

Martin, E. H. & Smoot, J.L. (1986). *Constituent load changes in urban stormwater runoff through a detention-wetland system in central Florida* (Water Resources Investigation Report No. 85-4310). Reston, VA: U.S. Geological Survey.

Moshiri, G. A. (Ed.). (1993). *Constructed wetlands for water quality improvements*. Chelsea, MI: Lewis Publishers.

Mungur, A. S., Shutes, R.E., Revitt, D.M. & House, M.A. (1995). An assessment of heavy metal removal from highway runoff by a natural wetland. *Water Science Technology*, 33(3), 169-175.

Nielsen, N. E., (1976). A transport kinetic concept for ion uptake by plants, II: The concept and some theoretic considerations. *Plant and Soil*, 37, 561-576.

Nielsen, N. E. (1976). A transport kinetic concept for ion uptake by plants, II: Test of the concept and results from water culture and pot experiments. *Plant and Soil*, 45, 659-677.

Niswander, S. F. & Mitsch W. J. (1995, September). Functional analysis of a two-year-old created instream wetland: hydrology, phosphorus retention, and vegetation survival and growth. *Wetlands* 15(3), 212-225.

Office of Water Enforcement and Permits, U.S. Environmental Protection Agency. (1991). *Guidance manual for the preparation of part I of the NPDES permit applications for discharges from municiple separate storm sewer systems*. Washington, D.C.: U.S. Environmental Protection Agency.

Office of Wetlands, Oceans, and Watersheds, U.S. Environmental Protection Agency. (1992). *Workshop Report: Evaluating the role of created and natural wetlands in the control of rural NPS pollution.* Washington, DC: Author.

Osmond, D. L., Gannon, R. W., Gale, J. A., Line, D. E., Knott, C. B., Phillips, K. A., Turner, M. H., Foster, M. A., Lehning, D. E., Coffey, S. W., & Spooner, J. (1997, April). WATERSHEDSS: A decision support system for watershed-scale nonpoint source water quality problems. *Journal of the American Water Resources Association*, 33(2), 327.

Raisin, G. W., & Mitchell, D. S. (1995). The use of wetlands for the control of nonpoint source pollution. *Water Science and Technology*, 32(3), 177-186.

Schueler, T. R. (1992). *Design of stormwater wetland systems: Guidelines for creating diverse and effective stormwater wetlands in the Mid-Atlantic region*. Washington, DC: Metropolitan Washington Council of Governments.

Smith, D. L., & Lord, B. N. (1990). Highway water quality control – summary of fifteen years of research (Transportation Research Circular, No. 1279). Washington, DC: Transportation Research Board.

Strecker, E. W., Palhegyi, G. E., & Driscoll, E.D. (1990). The use of wetlands for control of urban runoff pollution in the USA. In *Proceedings of the Fifth International Conference on Urban Storm Drainage* (pp. 1495-1500). Osaka, Japan: Osaka University.

Taylor, G. J. & Crowder, A. A. (1983). Uptake and accumulation of heavy metals by Typha latifolia in wetlands of the Sudbury, Ontario region. *Canadian Journal of Botany*, 61, 63-73.

Young, R. A., Onstad, C.A., Bosch, D. D., & Anderson, W. P. (1987). *AGNPS agricultural nonpoint source pollution model: A watershed analysis tool* (Conservation Research Report 35). Morris, MD: U.S. Department of Agriculture Research Service.

Yu, S. L., Liao, S. L., Fitch, G. M., & Long, S.L.. (1996). Constructed wetlands for stormwater management. In *Proceedings WEFTEC '96*. Dallas, TX: Water Environment Federation Conference.

Yu, S. L., Kaighn, R. J. Jr., & Earles, T. A. (1997). A summary report on field test of stormwater best management practices. *Proceedings 10th Annual Virginia Water Conference '97.* Fredericksburg, VA.

Yu, S. L. Kaighn, R. J. Jr., & Earles, T.A. (1997). Field test of constructed wetlands in Virginia. In *Proceedings American Society of Civil Engineers Water Resources Planning Division Meeting.* Houston, TX: American Society of Civil Engineers.

APPENDIX A:

1997 QUALITY ASSURANCE/QUALITY CONTROL PLAN