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PERFORMANCE EVALUATION OF REGIONAL WET DETENTION PONDS AND A WETLAND FOR URBAN NONPOINT SOURCE CONTROL

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ABSTRACT

The pollutant removal efficiency of two regional wet detention ponds (Mall Ponds A and B) and a regional pond-wetland system (Regency) were monitored over a 12-month period to identify watershed and/or design characteristics that may influence BMP performance. Watersheds with similar land use classifications and amounts of impervious surface often had very different pollutant characteristics.

Annual pollutant removal efficiencies in Mall Pond A and B were similar to previously observed removal efficiencies in two nearby ponds (Davis and Piedmont Ponds) and to other literature reports. Total suspended solids (TSS), total phosphorus (TP), and total nitrogen (TN) removal was similar in Pond A and B and relatively constant throughout the year. However, in Pond A, dissolved nutrient removal efficiencies were more variable with higher removals observed during the growing season. In Pond B, dissolved nutrient removal was somewhat lower and more uniform than in Pond A, presumably due to the lower level of biological activity in this pond. Annual pollutant removal efficiencies for the Regency Pond and Wetland were much lower than in the other High Point ponds and average values from literature reports. However, both the Regency Pond and Wetland are much smaller than design rules specify, and consequently removal efficiencies were expected to be much lower.

Several different approaches were examined for predicting pollutant trap efficiency in wet detention ponds. The stochastic sedimentation model developed by Driscoll et al. (1986) using results from the National Urban Runoff Program provided reasonably good predictions of TSS removal for most ponds. However, in this study, TSS removal was a poor predictor of removal efficiencies for most other pollutants. In contrast, Reckow's empirical model (1988) for predicting in-lake TP concentrations in Southeastern lakes and reservoirs provided reasonably good predictions of TP removal efficiency.

(Key Words: BMP, wet detention ponds, nutrients, TSS, models, limnology)

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SUMMARY AND CONCLUSIONS

SUMMARY

The City of High Point built and operates five regional water quality control structures to control nonpoint source pollutant loads entering their two water supply reservoirs: City Lake and Oak Hollow Reservoir. In this report, we present results from a monitoring study designed to evaluate the pollutant removal efficiency of the Regency Pond-Wetland, Mall Pond A, and Mall Pond B. These results are compared to a previous study of pollutant removal in Davis Pond and Piedmont Pond to identify watershed and/or impoundment characteristics that may influence pollutant removal efficiency.

Mall Ponds A and B are large regional wet detention ponds that generally comply with the design standards of the N.C. Department of Environment and Natural Resources (NCDENR)[1] for wet detention ponds (NCDEHNR 1995). Pond A has three major tributaries that receive runoff from a mixture of medium and high-density residential, commercial, and institutional land uses originally developed in the 1960s and 1970s. Mall Pond B receives runoff from: (1) a large recently completed shopping mall; and (2) an older area containing a mixture of commercial, institutional, and residential land uses.

The Regency Pond-Wetland System treats runoff from a very large watershed containing a mixture of forest, open space, single-family residential land uses, and the Piedmont Triad International Airport. The pond-wetland system consists of two parts—an upper pond and lower wetland. The upper pond has a small permanent pool to remove coarse-grained sediment and a large temporary pool to reduce peak flows entering the lower wetland. Because of restrictions placed on alteration of natural wetlands at the site, the pond-wetland system is significantly undersized in comparison to NCDENR design standards.

Water quality conditions in Mall Pond A, Mall Pond B, and the Regency-Pond wetland were monitored from February 1997 to February 1999. However, because of difficulties with equipment, the data analysis in this report focuses on the period from March 1998 to February 1999.

Influent Water Quality

The monitoring data showed very distinct variations in pollutant concentrations from one monitoring location to another. The East Lexington monitoring station was clearly the dirtiest tributary in the Mall Pond A watershed. This tributary had the highest concentrations of solids (total dissolved solids—TDS, total suspended solids—TSS, total volatile solids—TVS), fecal coliform bacteria, nutrients (total phosphorus—TP, dissolved phosphorus—DP, total nitrogen—TN, total dissolved nitrogen—TDN, dissolved ammonia as nitrogen—D-NH_4-N, combined nitrate + nitrite as nitrogen—NO_{2+3}-N), and lead. For Mall Pond B, the off-site drainage area was much dirtier than the on-site drainage area with significantly higher concentrations of TSS, TP, DP, TN, and total metals (chromium, copper, iron, lead, and zinc). These high pollutant concentrations

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[1] The N.C. Department of Environment and Natural Resources was formerly known as the N.C. Department of Environment, Health and Natural Resources (NCDEHNR).

may be associated with the large fraction of older medium-density residential land use in each of these watersheds. The influent to Regency had high levels of TSS, volatile suspended solids (VSS), and total nutrients such as TP and TN but moderate to lower concentrations of most dissolved nutrients such as TDN, D-NH_4-N, and NO_{2+3}-N.

In general, trends for most pollutants were similar in 1997 and 1998. Monitoring points with high pollutant concentrations in 1997 typically had high pollutant concentrations for the same parameters in 1998. The only substantial change occurred in the Regency influent in winter 1999 when there was a large increase in TSS, VSS, TP, and TN and particulate metals. At this same time, a large construction project began immediately upstream of Regency.

Event Mean Concentrations (EMCs) and pollutant loading rates from the East Lexington and Pond B off-site tributaries are among the highest reported. While EMC and loading rates from the recently completed shopping mall were significantly lower than for other commercial areas, EMCs and loading rates for the other highly urbanized watersheds were comparable to those previously reported. EMCs and loading rates for the Regency watershed were also high for certain parameters, which is probably associated with the construction project immediately upstream of the pond-wetland.

In-Lake Water Quality in Pond A

Water quality conditions in Mall Pond A were controlled by the pond hydraulics, thermal stratification, and high concentrations of nitrogen and phosphorus in the influent. Mall Pond A was thermally stratified from March through August. A clearly defined epilimnion, metalimnion, and hypolimnion were evident in the early spring. However, as the summer progressed, heat was gradually transferred from the surface to deeper portions of the pond resulting in a more gradual temperature profile. Dissolved oxygen concentrations in the bottom waters began to decline shortly after the onset of thermal stratification, and the hypolimnion was anaerobic from the beginning of June until turnover in early fall.

Mall Pond A was eutrophic to hypereutrophic as evidenced by the high nutrient concentrations, high summer dissolved oxygen, and pH in the epilimnion and anaerobic conditions in the hypolimnion. Dissolved phosphorus concentrations in the epilimnion were low throughout the summer and likely limited algal productivity. While TDN concentrations were relatively high, most of the nitrogen was present as organic nitrogen, a form that is less readily available to algae. In June and August, D-NH_4-N concentrations in the epilimnion were very low and may have favored blue-green algae growth.

Pollutant Removal Efficiency

Annual pollutant removal efficiencies in Mall Ponds A and B were similar to previously observed removal efficiencies in Davis and Piedmont Ponds and to removal efficiencies reported in other literature. The TSS, TP, and TN removal was similar in Ponds A and B and was relatively constant throughout the year. However, in Pond A, dissolved nutrient removal efficiencies were more variable with higher removals observed during the growing season. In Pond B, dissolved nutrient removal was somewhat lower and more uniform than in Pond A, presumably due to the lower level of biological activity in this pond.

Annual pollutant removal efficiencies for the Regency Pond and Wetland were much lower than the removal efficiencies in the other High Point ponds and the average values from literature reports. However, both the Regency Pond and Wetland are much smaller than NCDENR design rules specify, and as a consequence, removal efficiencies were expected to be much lower. Monitoring results indicate that the Regency Pond was reasonably effective in removing solids (TSS and VSS) and nutrients (TP, DP, TN, TDN, D-NH_4-N, and NO_{2+3}-N). However, much of this removal occurred in the winter when very high pollutant loads were coming into the pond from the upstream construction site. Metals removal efficiencies varied greatly and did not follow any clear pattern. In contrast, the Regency wetland was a net generator of pollutants, including TDS, TSS, VSS, TP, DP, TN, and TDN and total copper, iron, lead, and zinc. Overall, the combined pond-wetland system had a low pollutant removal efficiency. This is likely due to the small size of both the pond and wetland in relation to the watershed area.

Current NCDENR standards required that wet detention ponds be designed to achieve 85% TSS removal. This approach is based on the assumption that high TSS removal will usually result in higher removal efficiencies for other pollutants. However, in this study, TSS removal was a poor predictor of pollutant removal efficiencies for most other pollutants, and pollutant removal efficiency was most strongly correlated with influent concentration of that pollutant.

Simulation of Pollutant Removal Efficiency

Several different approaches were evaluated to determine their accuracy and utility in simulating pollutant removal in Mall Pond A, Mall Pond B, Regency Pond, Davis Pond and Piedmont Pond. Heinemann's curve closely matched the observed TSS trap efficiency for Mall Pond B and slightly overpredicted trap efficiency for Mall Pond A and Davis Pond. The predicted TSS removal efficiency for Brune's curve is always higher than Heinemann's and consequently the prediction error is greater. All the methods significantly overpredicted TSS removal efficiency for Piedmont Pond. This is not unexpected since there is a large stormwater pond immediately upstream of Piedmont that traps much of the coarser sediment.

The method developed by Driscoll et al. (1986) was used to predict TSS removal efficiencies for the five ponds. The basin performance index, N, was set equal to 1 which is equivalent to a completely mixed basin. Driscoll's stochastic sedimentation model provided reasonably good predictions of TSS removal efficiency in Mall Ponds A and B. Driscoll's model significantly overestimated removal efficiency in Piedmont Pond. This error was presumably due to the removal of most coarse-grained sediments in the pond upstream from Piedmont. Driscoll's model significantly underestimated removal efficiency for the Regency Pond. The measured removal efficiency for Regency Pond was probably higher than is typical due to the large amount of coarse-grained sediment entering Regency from a construction site immediately upstream.

The empirical models developed by Reckhow (1988) for Southeastern lakes and reservoirs were used to predict TN and TP removal efficiency in Mall Pond A, Mall Pond B, Davis Pond, and Piedmont Pond. The empirical TP model provided reasonably good predictions of removal efficiency. When the model predicted higher TP removal efficiencies, this was reflected in the measured performance in the field with no significant positive or negative bias. The empirical TN model provided a good estimate of the average TN removal efficiencies for the four ponds. However, the TN did not match the observed variation in removal efficiency between ponds.

CONCLUSIONS

There are often significant variations in pollutant concentrations and loading rates between different watersheds with similar land use classifications. While some highly developed watersheds do generate high pollutant loads (e.g., older residential and commercial areas), other areas with high levels of impervious surfaces (e.g., new shopping mall) generate runoff with substantially lower pollutant concentrations and associated loads. Similarly, there can be large variations in pollutant concentrations and loads between different "undeveloped" areas.

In all the regional water quality ponds examined, chemical and biological processes have a major impact on pollutant removal efficiency. All of the ponds examined thermally stratify during the summer growing season with associated anaerobic conditions in the pond hypolimnion. Most of the ponds were eutrophic to hypereutrophic with significant algal production and associated removal of dissolved nutrients in the epilimnion. Common design criteria recommend that the average depth of water quality ponds be between 3 and 6 ft to prevent thermal stratification and development of anaerobic conditions in the pond bottom. Both Davis and Piedmont Ponds had average depths in this range and both ponds thermally stratified, indicating that these criteria may not be effective in preventing stratification. In any event, it is not clear that thermal stratification is necessarily bad since the highest pollutant removal efficiencies are often observed during stratified periods. However, thermal stratification does have a pronounced impact on biological and chemical processes in the ponds and should be considered when designing these facilities.

Pollutant removal efficiency was most closely correlated with the pollutant concentration in the pond influent—high influent pollutant concentrations correlated with high percentage removal efficiencies and low pollutant concentrations correlated with low removal efficiencies. This may be related to the concept of a minimum irreducible pollutant concentration. Schueler (1996) suggested that it might not be reasonably possible to reduce effluent concentrations below this irreducible pollutant concentration using conventional BMPs because of internal cycling of nutrients and turbidity by microbes, plants, and algae within a pond or wetland. This may have important implications for the planning and design of BMPs in highly urbanized areas. Some highly impervious watersheds generate high annual pollutant loads because of the large amount of runoff. However, pollutant concentrations discharging from these watersheds are close to the reported irreducible pollutant concentrations, so ponds and other BMPs would not be effective in removing pollutants.

A cost-effectiveness analysis showed that while the percent pollutant removal efficiency of the Regency Pond was relatively low, the total mass of pollutant removed per dollar of capital cost was much higher than for the other BMPs. This suggests that, in some cases, it may be desirable to construct BMPs in large watersheds, even if they cannot be sized to meet common design standards. However, this approach should be used with great caution since monitoring results from the Regency wetland showed that undersized wetlands might actually be net generators of pollutants.

Heinemann's empirical curve and Driscoll's method provided reasonably good predictions of TSS trap efficiency in Mall Pond A, Mall Pond B, and Davis Pond. Similarly, Reckhow's empirical model for Southeastern lakes and reservoirs provided reasonably good predictions of TP removal efficiency.

RECOMMENDATIONS

NC DENR and other agencies may wish to reconsider the current practice of designing ponds and other BMPs for specific TSS removal efficiency. None of the ponds examined in this project achieved the 85% TSS removal specified in NCDENR design criteria. However, all of the ponds were reasonably effective in removing nutrients and other pollutants. If the objective is to achieve a certain level of nutrient removal, then it may be desirable to include this as a specific objective in the design standards since modifications that may increase suspended solids removal may or may not enhance nutrient removal.

The outlets to most stormwater detention ponds are fit with a skirt or other device to prevent floating debris from clogging the outlet structure. While these devices are effective, they often cause the pond effluent to be withdrawn from one to two feet below the free water surface. This reduces the depth, surface area, and volume of the pond that provides effective pollutant removal. Alternative designs should be developed that withdraw water from closer to the free water surface.

INTRODUCTION

Conversion of agricultural and undeveloped areas to residential, commercial, and industrial land uses causes an increase in the total mass of pollutants released and often results in adverse impacts on surface water quality. In response to this problem, many state and local agencies require the construction and operation of Best Management Practices (BMPs) to limit the concentration and total mass of pollutants discharged.

Common pollutants associated with land development include sediment, oxygen-demanding substances, nitrogen, phosphorus, oil and grease, heavy metals, and fecal coliform (FC) bacteria. Most stormwater pollutants are initially deposited on impervious surfaces as wetfall or dryfall. During storm events, these pollutants are easily washed into receiving waters. They may originate from atmospheric deposition, pet droppings, vegetative matter, litter, and the gradual deterioration of a wide variety of man-made materials, including building materials (roofing, flashing, and preserved wood) and automobile components (brakes, tires, oil and grease, etc.). Other important pollutant sources include construction operations, accelerated stream channel erosion, and fertilizer and pesticide application. During storm events, increased impervious surfaces reduce infiltration, increasing runoff volume and the total mass of pollutants entering receiving waters. These increased pollutant loads can have a variety of adverse impacts such as loss of desirable aquatic habitat, reduced reservoir storage capacity, toxic algal blooms, undesirable tastes and odors, filter clogging, coagulation problems, and formation of disinfection byproducts.

The City of High Point, North Carolina, is attempting to find ways to allow continued economic development while simultaneously minimizing the impacts on their two water supply reservoirs: City Lake and Oak Hollow Reservoir. These reservoirs receive runoff from a variety of sources, including undeveloped, agricultural, residential, commercial, and industrial land uses. To limit adverse impacts on reservoir water quality, the City of High Point built and operates five regional water quality control structures. Two wet detention ponds and a constructed wetland have been built in the City Lake watershed, and two wet detention ponds were built in the Oak Hollow Lake watershed.

Beginning in 1993, North Carolina State University and the City of High Point have monitored pollutant loads entering and discharging from the five regional water quality control structures to develop reliable information on the pollutant removal efficiency of these facilities. In an earlier report, Borden et al. (1997) reported on the pollutant removal efficiency of two regional wet detention ponds (Davis and Piedmont) located in developing areas. In this report, we present monitoring results for a combined pond-wetland system in a large developing watershed (Regency) and two wet detention ponds located in intensively developed areas (Mall Ponds A and B). Results from the previous and current study are reviewed to identify watershed and/or impoundment characteristics that may influence treatment efficiency.

LITERATURE REVIEW

FEDERAL AND STATE CONTROLS

Runoff from urban areas carries a variety of pollutants including sediment, nutrients, heavy metals, toxic organics, and bacteria. The U.S. Environmental Protection Agency (US EPA) found that urban runoff is the second greatest cause of compromised water quality in U.S. lakes. In the 1987 Clean Water Act Amendments, Congress recognized the hazard of contaminated runoff and mandated new permit controls under the existing National Pollution Discharge Elimination System. In Phase I of this program, large industries, construction sites, and municipalities were required to develop and implement comprehensive stormwater management plans for identifying and controlling important stormwater related pollutants. Under Phase II of this program, the US EPA will require many small municipalities and construction sites to implement stormwater control programs. The N.C. Department of Environment and Natural Resources (formerly the Department of Environment, Health and Natural Resources) already requires the construction of engineered stormwater controls or BMPs to control pollutants generated by stormwater runoff from high-intensity development in certain water supply watersheds, coastal areas, and the Neuse and Tar-Pamlico River Basins.

Wet Detention Ponds and Constructed Wetlands

Wet detention ponds are the most commonly used method for controlling pollutants in stormwater runoff. These ponds are designed to retain a permanent pool of water and remove suspended solids and adsorbed pollutants by sedimentation during quiescent periods between storm events. Dissolved nutrients may be removed through algal uptake, growth, and subsequent settling. Wet ponds may also reduce flood hazards downstream by reducing the peak flow rates and provide enhanced wildlife habitat.

Constructed wetlands may also be used for pollutant removal, flood control, and enhancing wildlife habitat. Wetlands remove suspended solids and the associated pollutants by sedimentation and filtration. Wetland plants provide surfaces for bacterial growth and adsorption and assimilate nutrients such as nitrogen and phosphorus.

Borden et al. (1997) provided a detailed review of pollutant removal dynamics in wet detention ponds. This review will focus on pollutant removal processes in wetlands and the similarities and differences between wet ponds and wetlands.

Pollutant Dynamics in Wetlands

Nutrients are removed, released, and transformed in wetlands by a number of physical, chemical, and biological mechanisms (Nichols 1983; Nixon and Lee 1985; Mitsch and Gosselink 1986). These mechanisms include sedimentation, adsorption, filtration, infiltration, biochemical interactions, volatilization, aerosol formation, precipitation, and dissolution. Because of the many interactions among the physical, chemical, and biological processes, these mechanisms often work together to reduce pollutants. However, pollutants may also be released from wetlands by scouring, plant die off, or algal washout. For this reason, data during both base flow and storm events are needed to accurately assess overall pollutant removal in these complex systems.

Sedimentation rates in wetlands are controlled by the hydrologic regime, flow velocity, wetland morphometry, residence time, and particle size distribution (Boto and Patrick 1979; Kranck 1984; Schubel and Carter 1984). Hydraulic resistance from the vegetation and soil decreases the velocity of water entering a wetland and enhances the settling and deposition of suspended solids. Martin and Smoot (1986) reported that residence time and turbulence were the most important factors affecting sedimentation. Morris et al. (1981) reported that sheet flow (spreading out the flow), as opposed to channeled flow, was the most important factor affecting settling.

Sedimentation efficiency also varies as a function of particle size. Sartor and Boyd (1972) investigated stormwater runoff and found that about 6% of the total solids mass was less than 43 microns in diameter, 37% ranged from 43 to 246 microns, and 57% were greater than 246 microns. Scherger and Davis (1982) found that 100% of sediments greater than 60 microns were removed by settling. This indicates more than half of the mass of sediments in stormwater runoff could be removed in wetlands by sedimentation. However, the predominant soil in the Piedmont region of North Carolina consists of clay and fine silt materials, which results in a finer particle size distribution in runoff (Wu 1989). Wu analyzed 10 stormwater runoff samples at a site in Charlotte, North Carolina. He found that 60% of the solids mass was less than 7 microns in diameter and 100% was less than 26 microns in diameter. Therefore, the particle sizes encountered in the Piedmont region are much finer than the national average, and a longer detention time is required to settle these fine particles. Many of the nutrients, metals, and toxins in stormwater are adsorbed on the smallest sediment particles and may be difficult to remove by plain sedimentation in the Piedmont region.

Adsorption of pollutants onto the surfaces of suspended particles, sediments, vegetation, and organic matter is a principal mechanism for the removal of dissolved or floatable pollutants, metals, and synthetic organics (Strecker et al. 1992). The adsorption rates appear to be inversely proportional to particle size and directly related to the organic content of the soil particles (Harper et al. 1986). This process may be enhanced by increasing contact between stormwater and underlying soils. Strecker et al. (1992) found long residence times, shallow depths, and an even distribution of inflow enhanced the soil-water-plant interactions and increased the adsorption potential.

Nitrogen is primarily removed through biochemical reactions. In an aerobic environment, nitrifying bacteria convert ammonia into nitrate. In an anaerobic environment, nitrate is converted to nitrogen gas during denitrification. These processes occur more rapidly during warm periods when microbial activity is highest.

Heavy metals in urban runoff occur in both soluble and particulate forms. Some metals such as zinc tend to be more soluble in water and therefore more mobile. In wetlands, ion exchange, precipitation, and plant uptake are the primary removal mechanisms for soluble metals; however, groundwater infiltration can also be important if the wetland recharges the groundwater. Other metals such as lead tend to adsorb to sediments and other particles and thus are transported along with solids. These metals are removed with solids from the water column when velocities decrease, accumulating in the bottom sediments of wetlands. However, metals in wetland sediments may create toxic conditions for fish and other aquatic life through their introduction into the food web (Kadlec and Tilton 1979).

Fecal coliform bacteria, indicators of disease-bearing organisms in surface waters, also tend to be associated with sediments and other particles (Bott 1973). Thus, like solids, the concentrations of FC bacteria can be reduced in wetlands through physical settling of particles. Fecal coliform bacteria also can die off in surface waters from exposure to low water temperatures or plant excretions.

Wetland Design Considerations

Both natural and constructed wetlands may be used to treat stormwater. Constructed wetlands can be created from natural wetlands, which are modified for stormwater treatment, or can be completely designed and constructed. Stormwater wetlands temporarily store runoff in shallow pools that are conducive for emergent and riparian wetland plants. Two basic designs of stormwater wetlands are extended detention wetlands and pocket wetlands.

Permanent Pool. In extended detention wetlands, extra runoff storage is created above the marsh by a forebay, or a temporary detention pool (Figure 1). To avoid drying out, extended detention wetlands should be constructed in a watershed with a drainage area greater than 10 acres. The depth of the permanent pool of water should be limited to 3 ft, with the majority of the wetland at normal depths of zero to one ft. The NCDENR standards for water supply watersheds require that wetlands capture runoff from the first inch of rain and release it over a period of 2 to 5 days (NCDEHNR 1995). This extended detention wetland design is assumed to achieve 85% total suspended solids (TSS) removal.

Pocket wetlands have a smaller permanent pool of water, and a forebay is not required if stormwater is fed from a grassed swale or vegetated filter strip (Figure 2). Pocket wetlands are designed for smaller drainage basins, approximately 0.4 to 4.0 hectares (Schueler 1992). These shallow, constructed wetlands may provide insufficient base flow for a permanent pool and cause greater water-level fluctuations than extended detention wetlands. The NCDENR believes that pocket wetlands are less efficient in removing pollutants, and they require that other BMPs be used in combination with pocket wetlands to achieve the 85% TSS removal.

For the system to function as a wetland, 70% of the permanent pool area should be designed as a marsh with a water depth of 0 to 18 inches, equally distributing the area between 0 to 9 inches and 9 to 18 inches (NCDEHNR 1995). This large surface area should provide better treatment by allowing more light penetration for photosynthesis, more aeration for aerobes, and a shorter settling distance for particles. The length to width ratio should be at least 3:1, preferably 5:1 to maximize the flow path. Side slopes should be gradual, no steeper than 3:1, as in natural wetlands (Horner 1992).

Stormwater wetlands should be located in stream floodplains or just off stream channels to ensure proper base flow. For watershed management purposes, stormwater wetlands could be scattered throughout the upper reaches of the watershed, or one large wetland could be constructed in the lower reach. Several small stormwater wetlands typically exhibit better wetland survival of extreme events and could be placed closer to the pollutant sources. However, a single large wetland could provide more effective pollutant removal and flood flow reduction at a lower cost.

Figure 1. Extended Detention Stormwater Wetland (Schueler 1992)

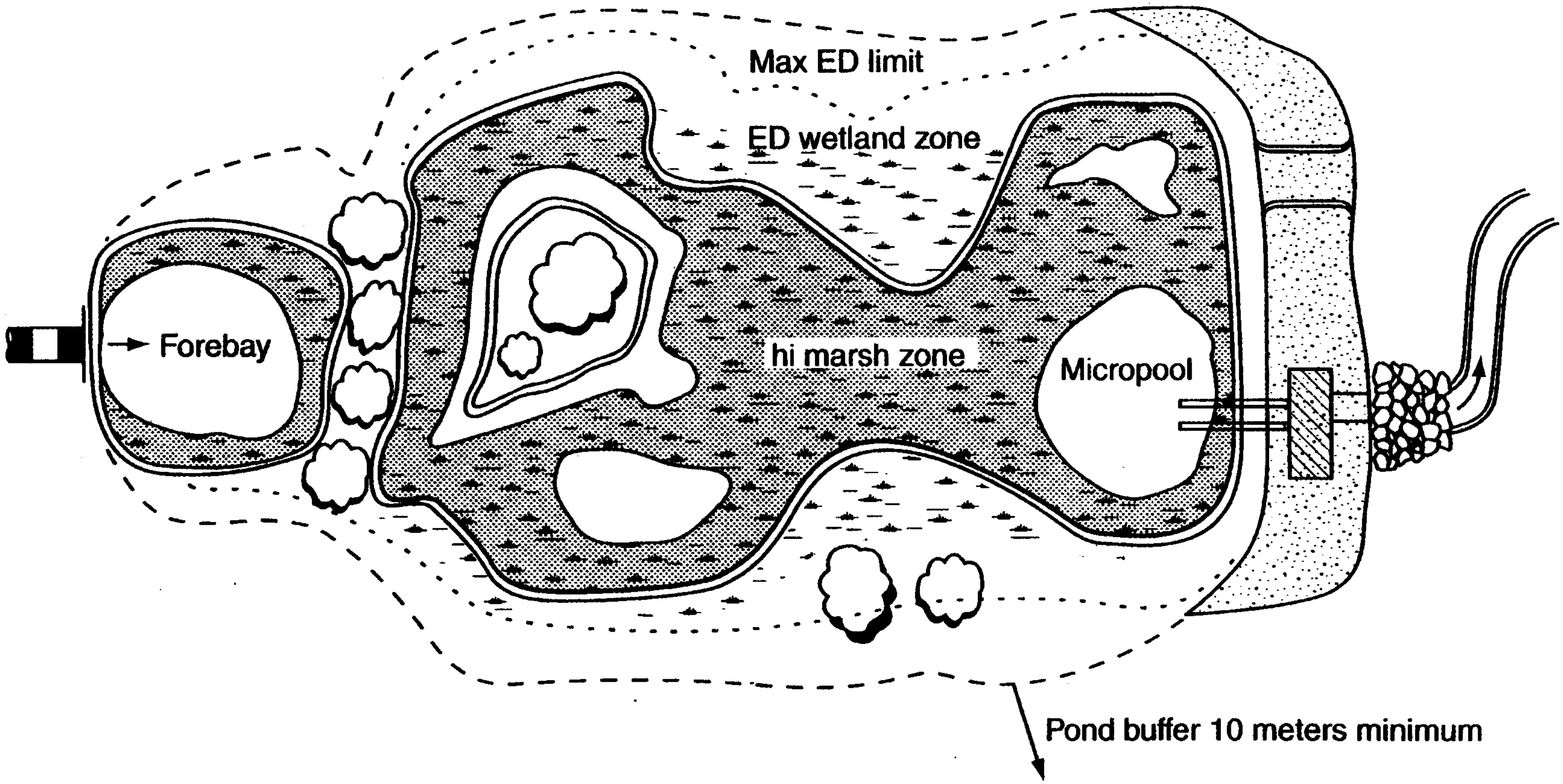
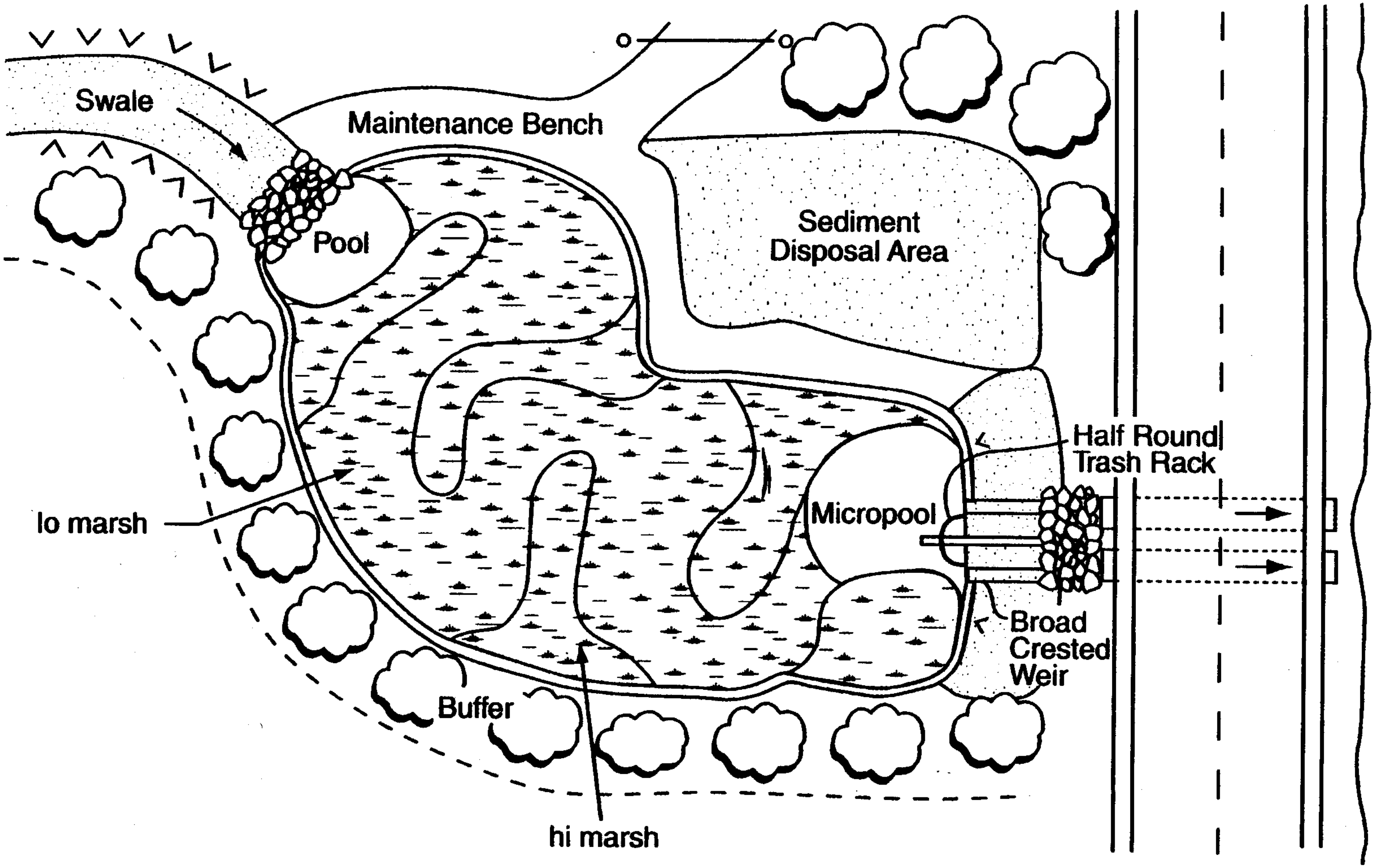


Figure 2. Stormwater Pocket Wetland (Schueler 1992)



Vegetation Selection. Garbisch (1986) compiled a list of principles for selecting general vegetation for creating wetlands. Native species should be selected whenever possible, and only a minimum number of species are needed so diversification will occur naturally. Species should be adaptable to a broad range of depth, frequency, and duration of flooding. Although vegetation selections should be based more on the prospects for successful establishment than on specific pollutant uptake capabilities, it is useful to understand specific pollutant uptake capabilities.

Kulzer (1990) prepared a summary (Table 1) of the demonstrated capabilities of plants for the various common classes of pollutants. He found the most versatile genera to be *Carex, Scirpus, Juncus, Lemna,* and *Typha.*

Pollutant Removal Efficiencies in Stormwater Wetlands

Wetlands have been used extensively for wastewater treatment. However, pollutant concentrations in stormwater are often much lower than wastewater concentrations and are highly variable. The wide range of stormwater pollutant concentrations has led to difficulty in predicting removal efficiencies in stormwater wetlands.

Table 2 summarizes monitoring results from 15 constructed wetlands and 11 natural wetlands used to treat stormwater runoff (US EPA 1993). The TSS and Fe removal efficiencies were consistently high. However, removal efficiencies for ammonia (NH_3), total phosphorus (TP), and Zn were only fair. The wide variations in reported removal efficiencies are believed to be due to differing hydraulic conditions, climate, and vegetation. Nutrient removals varied considerably due to seasonal effects, vegetation differences, wetland management methods, and differences in influent concentrations (as discussed below). Total phosphorus and nitrate removal showed the greatest consistency of the nutrients reported. In general, the removal efficiencies seemed to be more consistent and higher in constructed wetlands than in natural treatment wetlands. For the few studies that reported detention times, there was no identifiable relationship between removal efficiency and detention time. However, it is not known if the reported detention times represent base- or storm-flow conditions or an average of all conditions. An analysis of wetland to watershed area ratio also did not reveal a relationship with average removal efficiency. Strecker et al. (1992) believes a better measure of wetland capacity to treat runoff would be to evaluate runoff volumes as compared to storage volumes and contact surface area. However, the data from these studies did not give enough information to evaluate this relationship.

Some studies indicate strong seasonal effects on removal efficiencies. Meiorin (1986) reported that high summer evapotranspiration in California caused a 200 to 300% increase in total dissolved solids (TDS) concentrations. High productivity in warm months can decrease nutrient concentrations and increase biochemical oxygen demand and suspended solids in the wetland effluent. Morris et al. (1981) reported spring snowmelt in California caused an increase in effluent Total Kjeldahl Nitrogen and organic carbon.

Table 1. Wetland Plants[a]

Problem	Beneficial Plants	Specialization
Acidic waters	Cattail (*Typha latifolia, Typha angustifolia*)	
	Sphagnum moss	Acid tolerant
Bacteria	*Iris pseudacorus*	
	Juncus effusus	
	Scirpus validus, S. acutus	
	Alisma plantago-aquatica	
Metals	*Carex spp.*	Cu, Co, Ni
	Elodea canadensis	Hg, Pb; not good for Cu.
	Fontinalis (aquatic moss)	Cd, Cu, Ni
	Lemna spp.	Cu, Cr, Fe, Mn, Ni, Pb, Zn
	Myriophyllum spicatum	Pb
	Nuphar variegatum (yellow water-lily)	Cu, Zn
	Nuphar polysepalum (spatterdock)	Cu, Zn
	Phragmites	Cd, Cu, Co, Pb, Mn
	Potamogeton spp. (pondweed)	Pb, Cu, Cd, Ni
	Phalaris arundinaceae (reed canary grass)	Hg, Cu, Pb, Zn
	Ranunculus spp. (submerged)	
	Scirpus acuts, S. validus	Co, Cu, Mn, Ni, Zn
	Sparganium eurycarpum	Cu, Ni, Zn
	Sphagnum moss	Fe, Mn
	Typha spp.	Pb, Cd, Co
	Typha latifolia	Zn
	Utricularia	Hg
	Woodland mosses	Pb, Cu
Oil	*Juncus spp.*	
	Scirpus spp.	
Organics	*Juncus spp.*	Phenol, chlorophenol, cyanogen
	Lemna (duckweed)	Phenols, chlorophenols
	Scirpus spp. (bulrush)	
	Aquatic moss	PCBs
Nutrients	*Elodea canadensis*	Efficient N removal
	Juncus spp.	
	Potamogeton spp.	N, P
	Typha spp.	N, P, K

Source: Kulzer 1990.

[a] The abbreviations in the Kulzer table are defined as follows: *Cd*, cadmium; *Cu*, copper; *K*, potassium; *Ni*, nickel; *PCBs*, polychlorinated biphenyls; *Co*, cobalt; *Fe*, iron; *Mn*, manganese; *P*, phosphorus; *Cr*, chromium; *Hg*, mercury; *N*, nitrogen; *Pb*, lead; and *Zn*, zinc.

Table 2. Average Reported Removal Efficiencies (RE) in Natural and Constructed Stormwater Wetlands

Wetland Type	Detention Time (day)	Wetland to Watershed (%)	Pollutant Removal Efficiency (%)														
			TSS	Nitrogen		Phosphorus		COD	BOD	Lead		Zinc		Copper		Chromium	
				NH_4	NO_3	Total	Diss.[a]			Total	Diss.[a]	Total	Diss.[a]	Total	Diss.[a]	Total	Diss.[a]
Constructed	0.3	1.88	66	54	40	17	-30	18		73	54	56	75				
Constructed		2.36	89	61	9	43	21	17		83	70	70	65				
Natural		4.53	83	62	80	7			81	55	56	41	57	40	29	73	75
Constructed	4.8			52	64	7	17										
Const. & Nat.		3.79	50	17	33	62			35								
Constructed		0.90	96	37	70	90	78										
Natural		2.29	95	0		37	28										
Natural		10.92	88	50		27	25										
Natural		3.11	-20	25		-43	-30										
Constructed		1.15	-300	-86		-7	-10										
Constructed		1.03	87		22	36	25	79		68							
Constructed		5.98	94		63	78	53	93		90							
Natural		11.67	94	-44		78				94		82		80			
Constructed	3.0–5.0	4.94	76	55		54	40										
Constructed	4.0–40.0	3.33	63	-8	32	46			-25	30		42		-20		55	
Constructed		4.00	40	-5	2	-4			-46	27		24		-60		47	
Constructed		14.00	51	18	12	36			-18	83		-29		17		13	
Constructed		21.33	76	16	29	58			-57	88		42		-19		66	
Natural			54	20	50	5											
Natural			36	33	35	-120											
Natural	0.5–3.5	2.11	76			49				83							
Natural	1.25	3.48	87			-6			54								
Constructed		8.33	95			92											
Constructed		0.18	85		17	37	8			52							
Constructed		0.22	20		9	1	1			6							
Natural	0.14	1.06	14		4	-2											

continued

Table 2. Average Reported Removal Efficiencies (RE) in Natural and Constructed Stormwater Wetlands, continued

Wetland Type	Detention Time (day)	Wetland to Watershed (%)	Pollutant Removal Efficiency (%)														
			TSS	Nitrogen		Phosphorus		COD	BOD	Lead		Zinc		Copper		Chromium	
				NH_4	NO_3	Total	Diss.[a]			Total	Diss.[a]	Total	Diss.[a]	Total	Diss.[a]	Total	Diss.[a]
Natural	0.08	1.72	56		20	-2											
Constructed		5.56	64			55						34					
Constructed			72		70	59											
Constructed			76		42	55											
Constructed			89		70	69											
Constructed			98		95	97											
Average RE						**32**	**17**	**52**	**3**	**64**	**60**	**40**	**66**	**6**		**51**	
Median RE			**76**	**23**	**34**	**37**	**21**	**49**	**-18**	**73**	**56**	**42**	**65**	**-1**		**55**	

Sources: Strecker et al. 1992 and US EPA 1993.

[a] Diss.: dissolved.

Schueler (1996) suggests there may be minimum irreducible concentrations that represent the lowest pollutant concentration that can reasonably be achieved. Irreducible concentrations are due to the internal production of nutrients and turbidity by microbes, plants, and algae within a pond or wetland. When sedimentation is the sole removal pathway, the removal rates reach a theoretical maximum, resembling an asymptotic system in which pollutant removal does not significantly increase with increasing detention time. The idea of irreducible concentrations may explain why some reported removal efficiencies in Table 2 were negative or why the average removal efficiencies were lower than design specifications. However, since only the removal efficiencies were reported, not the influent and effluent concentrations, it cannot be determined if irreducible concentrations affected removal efficiencies in the systems shown in Table 2.

Kehoe (1993) studied 36 stormwater ponds and wetlands located in the Tampa Bay area. He collected post-storm grab samples from each site and characterized the sediment, metal, and dissolved oxygen content of the water sample. In a second study, he analyzed published event mean concentrations (EMCs) for 42 stormwater ponds, wetlands, filtering systems, and grassed channels located in many geographical regions. Based on Kehoe's studies, Schueler suggests a preliminary estimate of the irreducible concentration of pollutants in BMP's outflows (Table 3).

Table 3. Irreducible Concentrations in Stormwater Best Management Practices

Parameter	Stormwater BMP (mg/L)
Total Suspended Solids (TSS)	20–40
Total Phosphorus (TP)	0.15–0.25
Total Nitrogen (TN)	1.9
Combined Nitrate + Nitrite as Nitrogen (NO_{2+3}-N)	0.7
Total Kjeldahl Nitrogen (TKN)	1.2

Source: Schueler 1996.

The idea of irreducible concentrations can have a significant impact on watershed management. For some sensitive regions, the irreducible pollutant concentrations listed in Table 3 may still be too high to prevent algal blooms and eutrophication problems. The existence of an irreducible concentration suggests that there are some practical limits to improving treatment efficiency with additional BMPs. Schueler suggests managers and regulators should keep the idea of irreducible concentrations in mind when devising watershed protection programs.

Comparison of Pollutant Removal in Wet Detention Ponds, Wetlands, Water Quality Swales, and Filtering Systems

Brown and Schueler (1997) have developed an extensive database on pollutant removal in a wide range of BMPs used to treat stormwater runoff, including wet detention ponds, wetlands, water quality swales (grassed swales), and filtering systems. A summary of these results is presented in Table 4. Wet detention ponds, wetlands, and filtering systems all provided relatively good removal efficiencies for a range of major pollutants, including TSS, TP, and TN. Removal efficiencies were significantly lower for water quality swales, open channels (data not shown), and dry extended detention ponds (data not shown).

Table 4. Pollutant Removal Efficiencies of Four Types of Treatment Systems (%)

Parameters	Wet Detention Pond					Wetland					Water Quality Swale					Filtering System				
	N	Avg.	Med.	Max.	Min.	N	Avg.	Med.	Max.	Min.	N	Avg.	Med.	Max.	Min.	N	Avg.	Med.	Max.	Min.
Soluble Phosphorus	20	36.9	33.5	90	-12	15	33.2	40	75	-34.5	8	9.2	10.7	72	-45	2	-31	-31	-25	-37
Particulate Phosphorus	4	26	29	35	11	3	14.7	17	20	7.2	0	N/A	N/A	0	0	0	N/A	N/A	0	0
Total Phosphorus	44	47.3	45.5	91	0	35	49.0	51	99.5	-9	18	14.1	14.5	99	-100	15	42.0	45	80	-25
NH_3	4	14.5	41.5	82	-107	6	40.4	49	72	-4.4	0	N/A	N/A	0	0	0	N/A	N/A	0	0
Ammonia (as NH_4)	14	17.9	22.5	83	-107	19	25.9	43	72	-55.5	4	16	2.5	78	-19	4	68.3	68	94	43
Nitrite	0	N/A	N/A	0	0	1	57.5	57.5	57.5	57.5	0	N/A	N/A	0	0	0	N/A	N/A	0	0
Nitrate	27	28.1	23	97	-85	30	44.4	67	99	-100	13	12.7	11	99	-100	13	-24.4	-13	27	-100
Organic Nitrogen	6	22	22.5	34	2	12	0.7	1	43	-31	3	45.3	39	86	11	2	28	28	56	0
Total Khedjahl Nitrogen	17	32.6	27	68	7	10	24.2	14.5	81	-10.3	5	16.4	17	48	-20	9	57.0	57	90	32
Total Nitrogen	24	28.8	30	85	-12	22	28	20.9	83	-25	10	13.7	10.5	99	-100	9	36.3	32	71	13
Cadmium	5	25.8	47	54	-25	6	36.3	68.9	80	-79.8	6	55.2	48.5	89	20	1	26	26	26	26
Chromium	5	42.9	49	62	25	3	69.5	72.6	98	38	5	48.4	47	88	14	2	54	54	61	47
Copper	18	51.5	54.5	90	9.5	10	40.9	39.5	84	2	15	31.9	41	89	-35	9	43.7	34	84	22
Iron	4	40.9	40.5	87	-4.3	3	29.0	84	93	-90.1	0	N/A	N/A	0	0	4	75	75.5	86	63
Lead	34	57.8	66.5	95	-96.7	17	62.5	63	94	23	19	34.7	50	99	-100	11	60.3	71	89	-16
Zinc	32	46.7	50.5	96	-38	16	45.2	53.5	90	-73.5	19	27.6	49	99	-100	15	68.3	69	91	33
Total Dissolved Solids	7	3.5	5	32	-28	3	-38.7	-24	8	-100	0	N/A	N/A	0	0	6	10.5	16	46	-37
Total Suspended Solids	43	61.9	70	99	-33.3	35	66.9	78	99.5	-29	18	38.0	66	99	-100	15	74.7	81	98	8
Oil and Grease	0	N/A	N/A	0	0	0	N/A	N/A	0	0	0	N/A	N/A	0	0	2	76.5	76.5	84	69
Turbidity	0	N/A	N/A	0	0	1	68.5	68.5	68.5	68.5	3	56.4	60	65	44.1	2	-32	-32	-17	-81
Bacteria	10	66.5	74	99	-5.8	3	76.7	78	97	55	5	-30	-25	0	-100	5	54.8	37	83	36
Organic Carbon	29	36.6	35	90	-30	15	34.5	28	93	-31	11	22.0	23	99	-100	11	54.8	57	99	10
Total Petroleum Hydrocarbons	1	82.5	82.5	82.5	82.5	3	86.7	90	90	80	2	62	62	75	49	3	75.3	84	87	55

Source: Brown and Schueler 1997.

RESEARCH METHODOLOGY

The City of High Point is located in the Piedmont Region of North Carolina and operates two water supply reservoirs, City Lake and Oak Hollow Lake. Both reservoirs are experiencing increasing water quality problems because of rapid development in the watersheds. Camp, Dresser & McKee (1989) developed a management plan to mitigate the impact of land development on water quality in the two reservoirs. The plan calls for the construction of a series of regional wet detention ponds, dry detention ponds, and wetlands at strategic locations within the watershed for pollutant removal and spill containment. Currently, five regional BMPs have been completed (four wet ponds and one constructed pond-wetland system).

In a previous project, Borden et al. (1997) examined pollutant removal in two regional wet detention ponds: Davis Pond and Piedmont Pond. Davis Pond treats runoff from a rural watershed with significant dairy operations. Piedmont Pond treats runoff from an industrial area containing a large petroleum storage tank farm. In this project, pollutant removal in two additional wet detention ponds (Mall Ponds A and B) and a constructed pond-wetland system are examined (Regency).

The watersheds of Oak Hollow Reservoir and City Lake are shown in Figure 3. The drainage area of City Lake is 61 square miles. Oak Hollow Reservoir feeds into City Lake and contributes just over half of the total drainage area. Mall Ponds A and B were built in an intensely developed portion of the Oak Hollow Lake watershed in 1995. The Regency Pond-Wetland System was constructed in the headwaters of City Lake in 1995.

Water quality conditions in Mall Pond A, Mall Pond B, and the Regency Pond-Wetland were monitored from February 1997 to February 1999. However, difficulties with the flow monitoring equipment prevented us from obtaining accurate water budgets during the first year of the project, and data analysis in this report focuses on the period from March 1998 to February 1999. The total precipitation during the 12-month period from March 1998 to February 1999 was 43.85 inches or 103% of the average annual precipitation (National Oceanic and Atmospheric Administration, Annual Climatological Summary for Greensboro WSO Airport, 1998 and 1999).

MALL POND A

Mall Pond A is a relatively large wet detention pond with a normal pool surface area of 8.2 acres and average depth of 10.0 ft. A concrete gravity dam with two separate spillways forms the pond. The lower primary spillway is 20 ft wide and has a crest elevation of 814.80 ft. A hanging wall upstream of the primary spillway extends to 1.5 ft below the normal pool surface to prevent trash from entering the outflow structure. Water must flow underneath the hanging wall to discharge from the pond. This has the effect of withdrawing water from below an elevation of 813.30. The upper emergency spillway is 100 ft wide and has a crest elevation of 816.8 ft. The stage-discharge and stage-storage data for Pond A are presented in Tables 5 and 6.

Figure 3. Oak Hollow Lake and City Lake Watershed

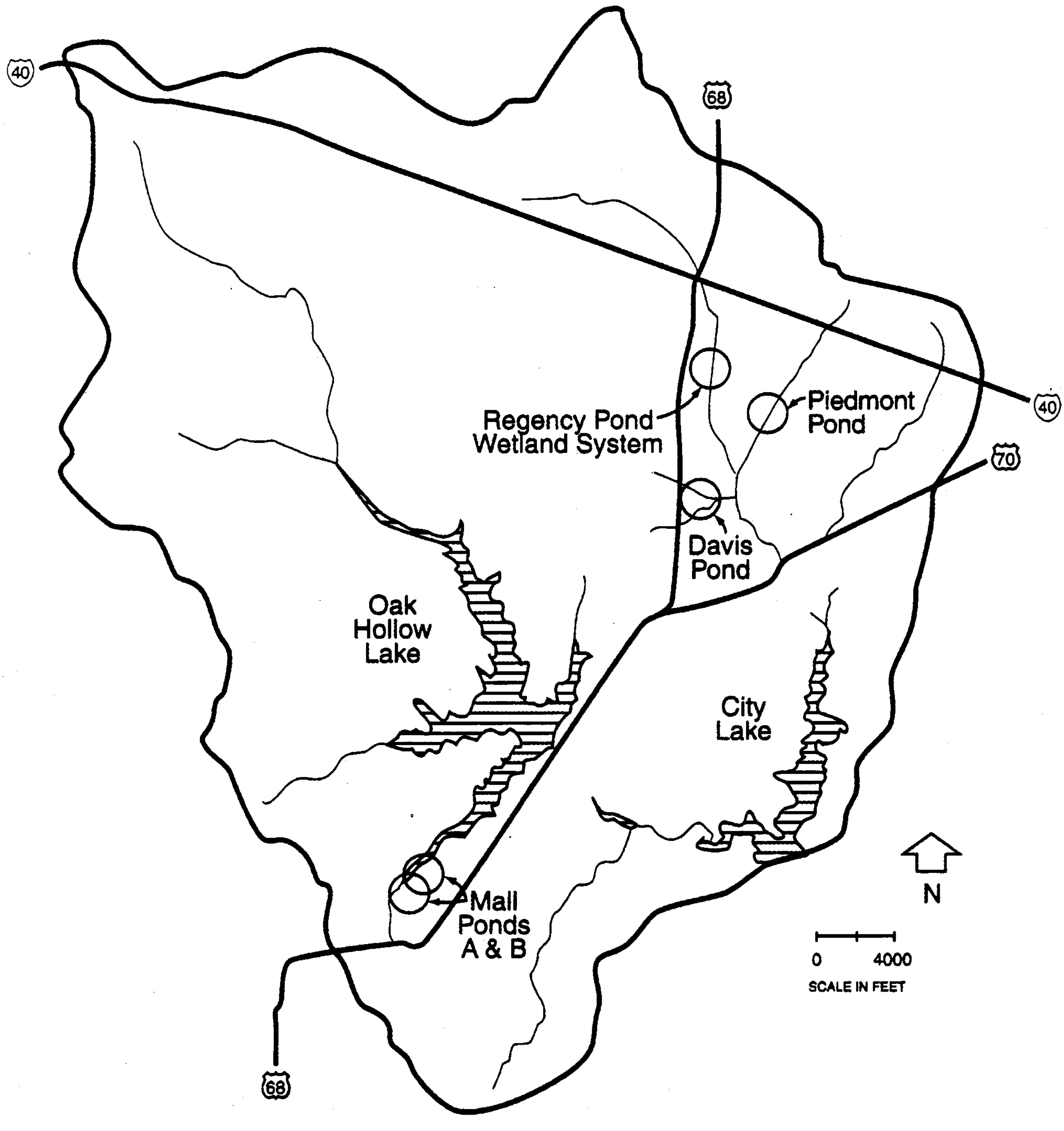


Table 5. Stage Discharge Table of Pond A

Elevation (ft)	20-Foot Weir (cfs[a])	100-Foot Weir (cfs)	Total Flow (cfs)
814.8	0.0	0.0	0.0
815.0	5.4	0.0	5.4
816.0	78.9	0.0	78.9
817.0	195.8	29.8	225.6
818.0	343.5	437.7	781.2
819.0	491.3	1086.6	1577.9
820.0	519.4	1906.2	2425.6
821.0	546.1	2866.3	3412.4

[a] The abbreviation "cfs" means cubic feet per second.

Table 6. Stage-Storage Relationship of Pond A and B

Pond A			Pond B		
Elevation (ft)	Area (acre)	Volume (acre ft)	Elevation (ft)	Area (acre)	Volume (acre ft)
800	0		826	0.31	
802	2.4	2.4	828	1.62	1.9
804	5.8	10.5	830	3.52	7.1
806	6.1	22.6	832	3.77	14.4
808	6.5	35.2	834	4.49	22.6
810	6.8	48.5	836	4.8	31.9
812	7.2	62.5	838	5.68	42.4
814	7.5	77.2	840	6.09	54.2
816	9.3	94.0			
818	9.8	113.1			
820	10.2	118.9			
822	10.9	154.2			
824	11.3	176.4			

Mall Pond A has a relatively large watershed (741.5 acres) containing a mixture of medium- and high-density residential areas and commercial/office areas (Table 7). Pond A has three major tributaries: East Lexington, K-mart, and Centennial (Figure 4). Land use in each of the tributaries is similar. Most of these areas were developed in the 1960s and 1970s and are now 20 to 30 years old. The watershed of Mall Pond A is shown in Figure 4.

Table 7. Land Use in Mall Pond A Watershed

Land Use	East Lexington, Station A3 (acres)	K-mart, Station A2 (acres)	Centennial, Station A4 (acres)	Total Drainage Area of Pond (acres)
Multifamily Residential	55.6	45.3	3.1	104.0
Commercial/Office	11.8	156.9	16.2	184.9
Institutional	5.8	10.1	47.0	62.9
Forest/Open	2.1	1.1	1.8	5.0
Low-Density Single Family	2.2	7.2	14.7	24.1
Medium-Density Single Family	186.5	67.6	33.8	287.9
Treatment Family	3.8	2.5	2.0	8.3
Roads	31.1	27.2	5.2	63.5
Total (acres)	298.7	318.9	123.9	741.5
Impervious Surfaces	50%	70%	57%	60%

MALL POND B

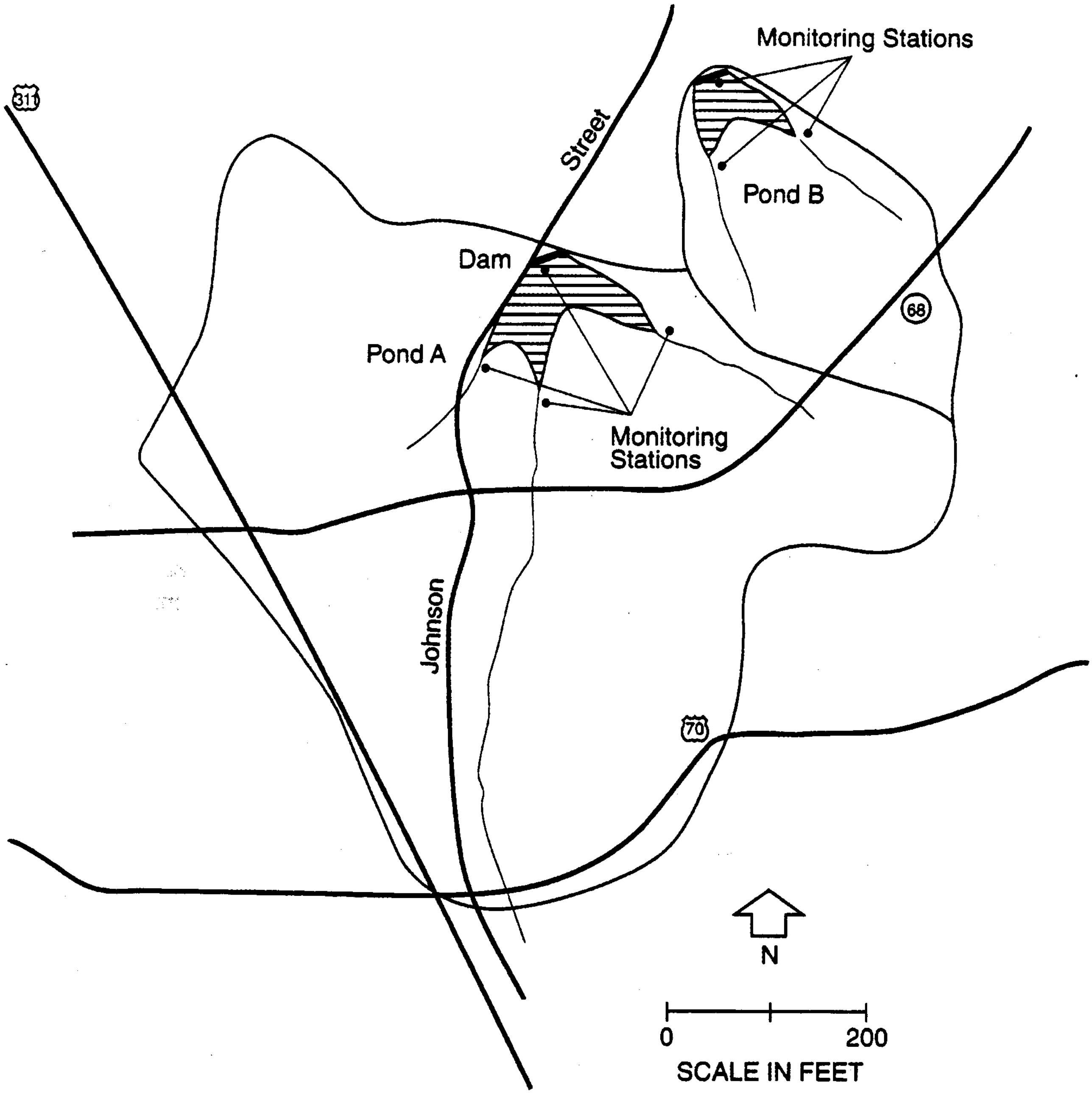
Mall Pond B is smaller than Pond A with a normal pool surface area of 4.0 acres and average depth of 4.3 ft. An earthen dam with two riser-barrel outflow structures forms the pond. The primary spillway is a 42-inch-diameter corrugated metal pipe riser with a 66-inch-diameter trash rack skirt. The emergency spillway is a 78-inch-diameter corrugated metal pipe riser with a 120-inch-diameter trash rack skirt. Water must flow underneath the trash rack skirts causing water to be withdrawn approximately 12 inches below the water surface. The primary and emergency spillways were designed to have crest elevations of 832.64 ft and 832.99 ft, respectively. Stage-storage data for Pond B is presented in Table 6.

Mall Pond B has a moderate size watershed (142.4 acres) with two tributaries, B2 and B3 (Figure 4). B2 receives runoff from a large shopping mall and adjoining commercial properties (Table 8). B3 receives runoff from a mixture of commercial, institutional, and residential land uses. Most of the B3 watershed was developed 20 to 30 years ago. The shopping mall in the B2 watershed was completed in 1995. However, satellite areas adjoining the mall continue to be developed.

Table 8. Land Use in Mall Pond B Watershed

	On-site Drainage, Mall Station B2 (acres)	Off-site Drainage, Station B3 (acres)	Total Drainage Area of Pond (acres)
Commercial	96.2	7.3	103.5
Forest/Open	4.1	0	4.1
Treatment Facility	4.4	0	4.4
Institutional	0	14.5	14.5
Low-Density Single Family	0	3.5	3.5
Medium-Density Single Family	0	12.5	12.5
Total	104.7	37.8	142.4
Impervious Surfaces	83 %	60 %	77 %

Figure 4. Watersheds of Mall Ponds A and B



REGENCY POND-WETLAND SYSTEM

The Regency Pond-Wetland System was constructed in an area that contained some natural wetlands. Consequently, the system was designed to minimize alteration of the natural wetland. The pond-wetland system consists of two parts—an upper pond and lower wetland. The upper pond has a small permanent pool to remove coarse-grained sediment and a large temporary pool to reduce peak flows entering the lower wetland. The pond is formed by a large earthen berm or control wall; the surface of the berm has been hardened with concrete matting to allow overtopping. The upper pond permanent pool depth was 8 ft when originally built, and the littoral shelf ranged in depth from 0 to 2 ft. The upper pond length to width ratio is 2.4:1, with side-slopes ranging from 4 horizontal to 1 vertical in the pond area to 10:1 in the littoral zone (HDR 1993). A 36-inch-diameter culvert that passes through a low earthen berm (or control wall) controls the outflow from the lower wetland. This berm has also been hardened with concrete matting to allow overtopping. In the wetland area, the predominant plant species consist of *Saggitaria latifolia* (arrowhead), *Juncus effusus* (soft rush), *Pontederia cordata* (pickerelweed), *Scirpus validus* (soft-stemmed bulrush), and *Nymphaea odorata* (water-lily). These plants are capable of removing bacteria, metals, oil, organics, and nutrients (Table 1).

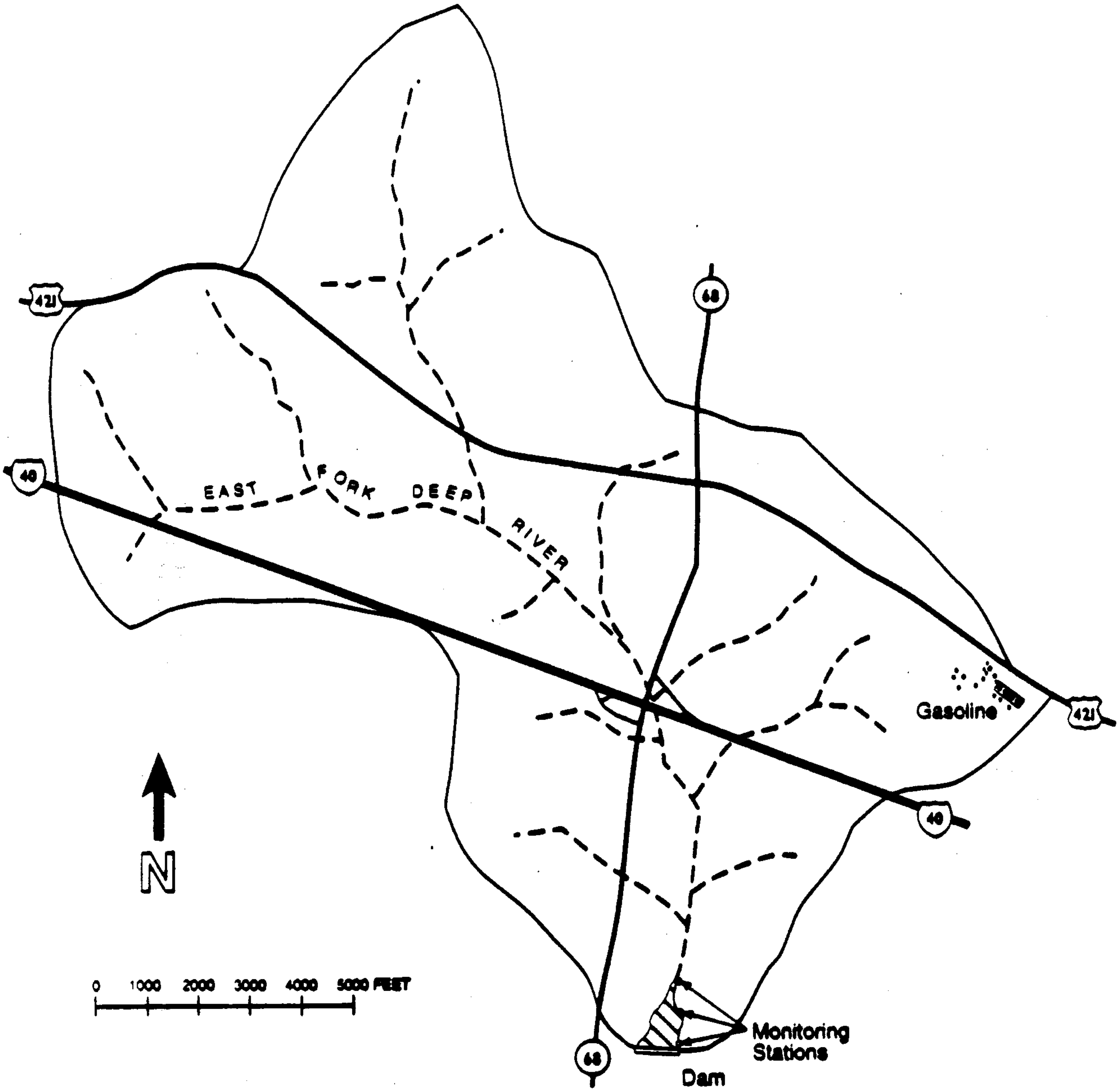
During dry weather, a small weir with a crest elevation of 792 ft controls the water depth in the pond. Water discharges from the pond through a 36-inch-diameter culvert into the natural channel and flows through the wetland to the lower berm. The culvert through the lower berm is large enough that water does not back up during dry weather and most of the wetland area remains dry. During most wet weather periods, water from the upper pond discharges through a riser-barrel structure into the natural stream channel and then travels downstream to the lower control wall. Water then backs up behind the lower berm, flooding much of the wetland. During very high flow periods, the upper control wall overtops and stormwater passes directly through the wetland before discharging over the top of the lower berm.

The Regency pond-wetland system (Figure 5) has a drainage area of approximately 6.4 square miles with three predominant land uses: 57 % is forested and open space, 28% is institutional, and 15% is single-family residential (Table 9). The Piedmont Triad International Airport makes up most of the institutional land use.

Table 9. Land Use in the Regency Wetland Watershed

Land Use	Area (acres)
Institutional	1,134
Forest/Open	2,335
Medium-Density Single Family	614
Treatment Facility	12
Total	4,095

Figure 5. Regency Watershed



COMPARISON OF PONDS AND WETLAND WITH NCDENR DESIGN STANDARDS

While Mall Ponds A and B were not specifically designed to meet the NCDENR requirements for wet detention ponds, both facilities generally comply with the design standards. Wet detention pond requirements (NC DEHNR 1995) are compared to the pond characteristics in Table 10. Mall Ponds A and B both have a somewhat greater surface area than required based on their average depth and the percent impervious cover in the watershed. However, the temporary pools for both ponds are smaller and drain more quickly than the current NCDENR specification. Both ponds also have a lower length to width ratio than NCDENR specifies.

The Regency Pond-Wetland system is significantly undersized in comparison to NCDENR design standards. The City of High Point had originally planned to construct a large, regional wet detention pond at the Regency location. However because of the presence of the natural wetlands, it was not possible to construct a facility that met the NCDENR design standards for wet detention ponds. As a compromise, the planners chose to construct a much smaller pond-wetland system to treat stormwater runoff from this large, very important tributary to the water supply reservoir. Available information suggested that the pond-wetland system would probably not achieve the same level of pollutant removal as a properly sized wet detention pond, but it would achieve some significant pollutant removal.

WATER QUALITY SAMPLING

The inflow and outflow of each structure were monitored during base and storm flow for a variety of water quality parameters. Chlorophyll, solids, TN, TP, total dissolved nitrogen (TDN), total dissolved phosphorus, and metals (including Cd, Cr, Cu, Fe, Pb, silver—Ag, and Zn) were monitored monthly during the monitoring period. Both metals and nutrients were analyzed for total and dissolved constituents to determine the treatment efficiency of both dissolved and particulate pollutants. Method detection limits for each parameter are listed in Table 11. Actual detection limits for individual samples were sometimes higher because dilution of the sample was required.

Each water quality monitoring station was equipped with a refrigerated automatic sampler (Sigma). Figures 6, 7, and 8 show the locations of the stream monitoring stations for Mall Pond A (Dam—A1, K-mart—A2, East Lexington—A3, and Centennial—A4), Mall Pond B (Dam—B1, Mall On-site—B2, and Mall Off-site—B3), and Regency (Pond Inlet—R1, Pond Outlet—R2, and Wetland Outlet—R3). Tipping bucket rain gauges were installed at each facility to record rainfall at 15-minute intervals and to initiate the flow proportional samplers.

Most stations also included a level sensor and weir to continuously monitor flow rates. However, because of physical constraints at stations A2, B3, and the Regency wetland, it was not possible to accurately measure both high- and low-stream flow rates. At A2 and B3, flow rates were estimated using data collected from the other stations and a water balance. At the Regency Pond-Wetland, flow rates through the pond-wetland system were estimated with data from the U.S. Geological Service (USGS) Stream Gage (No. 2099000) located downstream from the wetland on the East Fork Deep River. Stream flows at Regency were estimated by multiplying the flow data from the USGS gaging station by the ratio of the drainage areas of Regency and the gaging station.

Table 10. Characteristics of Mall Pond A, Mall Pond B, and Regency Pond-Wetland System

	NCDENR Requirements for Water Supply Watersheds	Mall Pond A	Mall Pond B	Regency		
				Storage Pool	Wetland	Total System
Watershed Imperious Area (%)		60	76			30
Permanent Pool Surface Area (acres)		8.2	4.0	3.6	0.2	3.8
Permanent Pool Storage Volume (inches)		1.36	1.44	0.08	0.001	0.08
Permanent Pool Detention Time (days)		16.8	17.6	0.8	0.02	0.8
Basin Length:Width Ratio	3:1 or greater	1.2:1	1.9:1	1.4:1	1.6:1	NA
Permanent Pool Mean Depth (ft)	3~6	10.0	4.3	4.4	2.5	NA
Permanent Pool Surface Area: Drainage Area Ratio	Pond A: 0.75% Pond B: 0.85% Regency: 0.64%	1.1%	2.8%	0.09%	0.005%	0.09%
Temporary Pool Surface Area (acres)		9.5	4.1	4.5	5.7	10.2
Temporary Pool Storage Volume (inches)	Runoff from 1.0-inch of rain	0.3	0.12	0.07	0.019	0.09
90% Drawdown Time for Temporary Pool (days)	2 ~ 5	~0.2	~0.1	~0.2	~0.05	NA

Table 11. Method Detection Limits for Monitoring Parameters

Parameter	Abbreviation	Units	Method Detection Limit
Total Dissolved Solids	TDS	mg/L	2
Total Suspended Solids	TSS	mg/L	2
Volatile Suspended Solids	VSS	mg/L	2
Fecal Coliform	FC	ct/100mL	1
Total Phosphorus	TP	mg/L	0.01
Dissolved Phosphorus	DP	mg/L	0.01
Total Nitrogen	TN	mg/L	0.01
Dissolved Ammonia Nitrogen	D-NH_4-N	mg/L	0.01
Combined Nitrate + Nitrite	NO_{2+3}-N	mg/L	0.01
Total Dissolved Nitrogen	TDN	mg/L	0.01
Cadmium	Cd	µg/L	1
Chromium	Cr	µg/L	5
Iron	Fe	µg/L	500
Lead	Pb	µg/L	5
Silver	Ag	µg/L	5
Zinc	Zn	µg/L	25

Figure 6. Mall Pond A Monitoring Stations

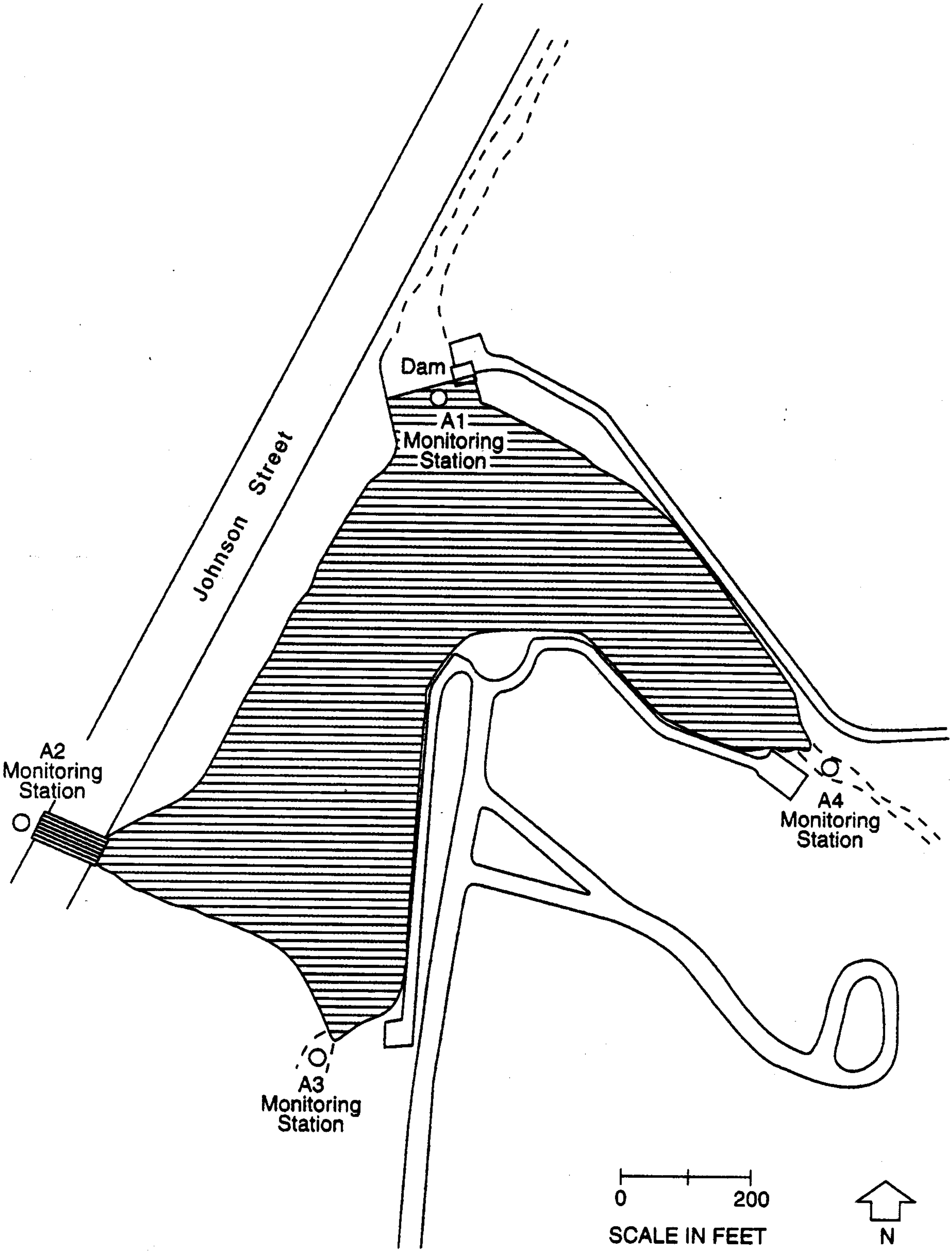


Figure 7. Mall Pond B Monitoring Stations

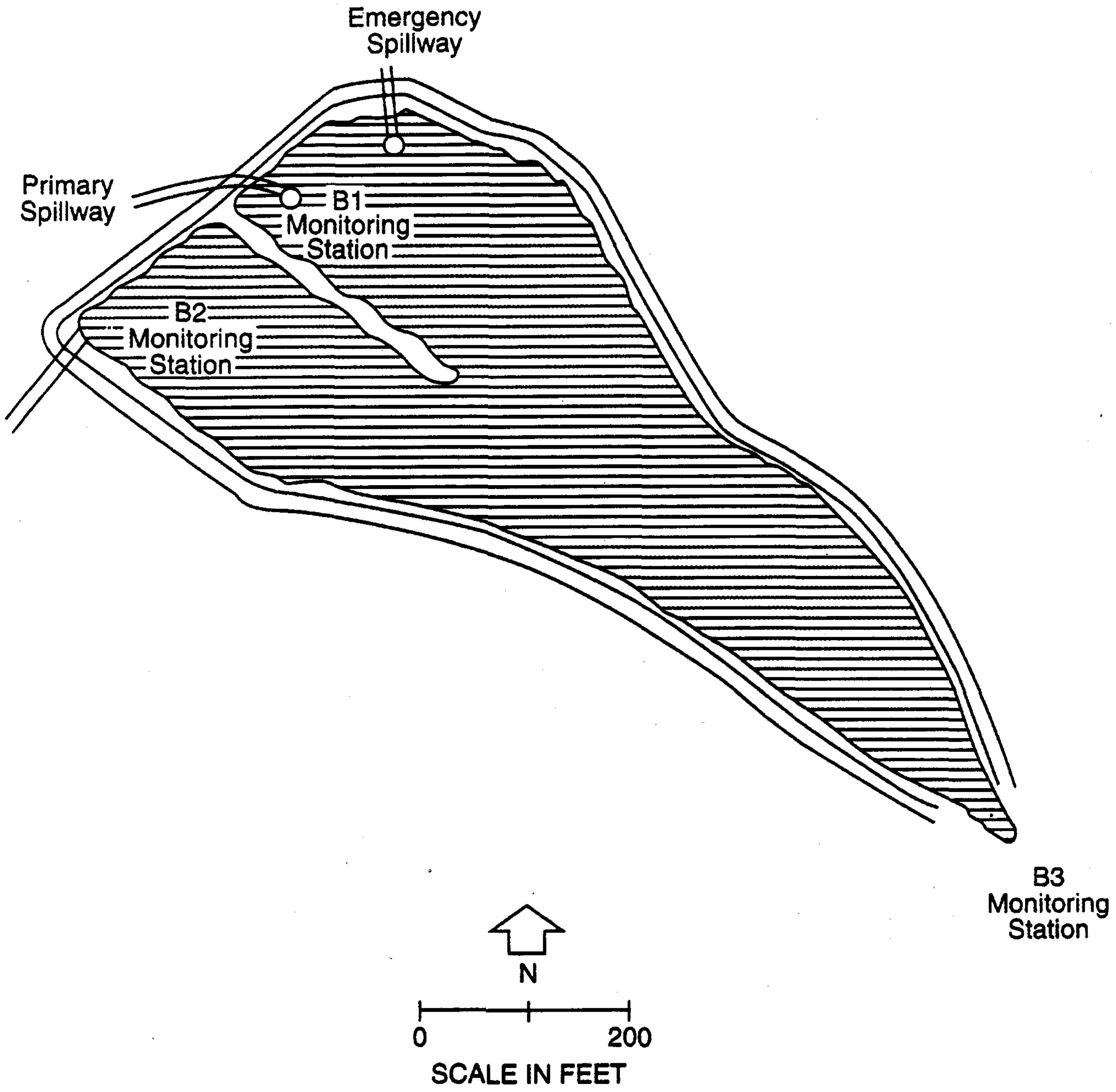
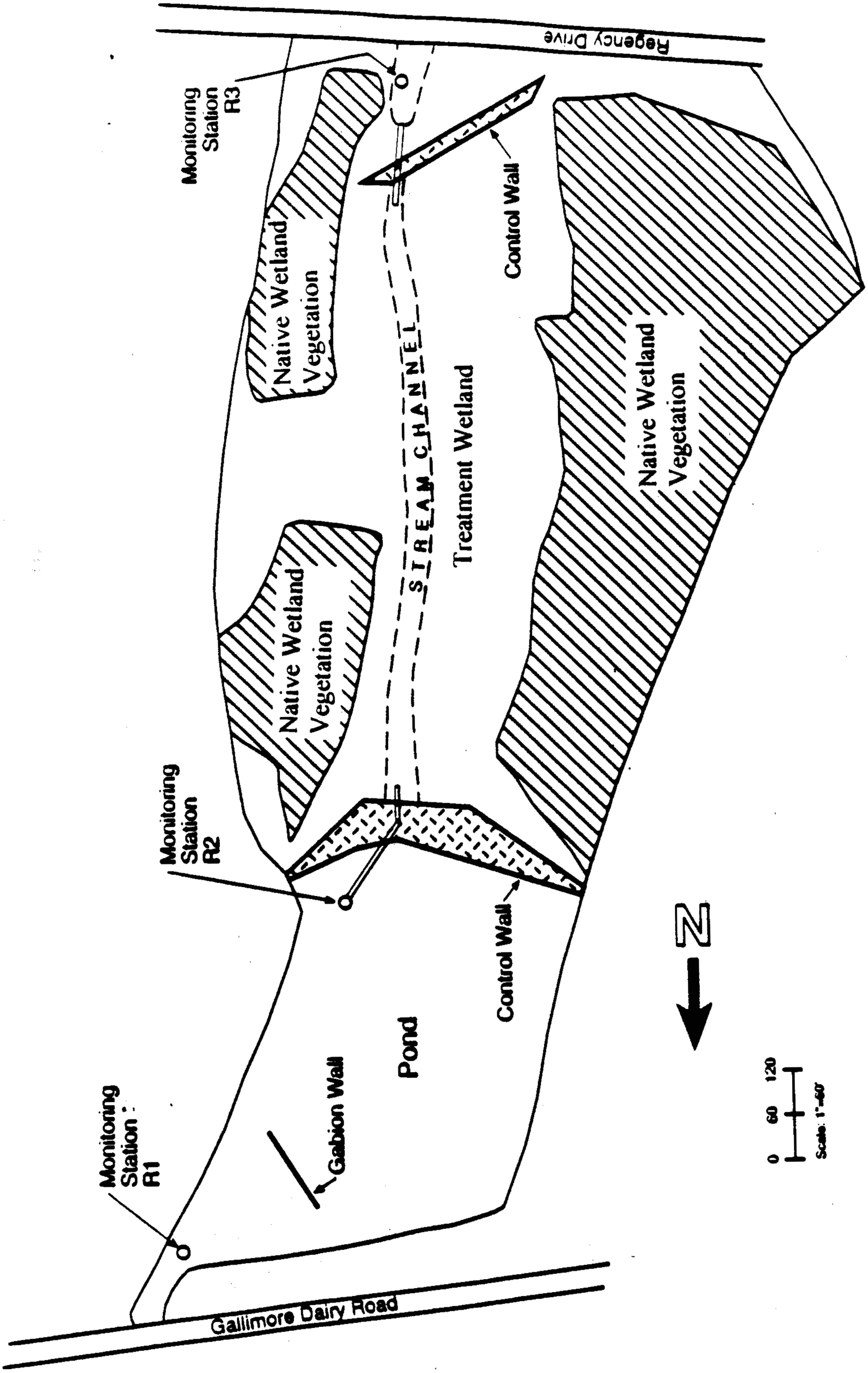


Figure 8. Regency Monitoring Stations



Local runoff can enter the treatment structures through the inflow tributaries and from overland flow. Outflow hydrographs were generated by plotting the outflow at the dam over the month-long period. Inflow hydrographs were generated by increasing the measured flow rate by a constant factor to account for the unmonitored portion of the watershed. When there were inconsistencies in data or a loss of data because of equipment failure, the hydrographs were back-calculated based on the stage-discharge and stage-storage information, or estimated according to the watershed area.

All monitoring equipment was contained in a weatherproof shelter equipped with permanent power and an access road. Monitoring data from the flow meter and rain gauge were fed continuously to City of High Point's Supervisory Control and Data Acquisition (SCADA) system. The SCADA system is monitored 24 hr a day to control the City's water and wastewater treatment systems. During storm events, stormwater sample collection was initiated by a rain gauge and continued for approximately 32 hr after the storm event. Composite samples were then automatically collected in proportion to the flow rate through the stream gage.

Pollutant loads were calculated for wet weather and dry weather periods separately. The dry weather pollutant load was calculated as the total dry weather flow volume times the measured concentration during the closest base-flow sampling event. Event Mean Concentrations (EMC) for wet weather events were obtained from the measured flow-composited sample concentration. The wet weather pollutant load was calculated as the total wet weather flow volume during a sampling period times the measured EMC during the closest sampling event.

INFLUENT WATER QUALITY

The seasonal and annual flow-weighted average concentration of each pollutant in the tributaries and outflow of Mall Pond A, Mall Pond B, and Regency Pond-Wetland System is listed in Tables 12, 13, and 14 for the 1998 monitoring period (From March 1, 1998 to February 28, 1999). Water quality monitoring data were also collected from each tributary in 1997. However, because of early flow measurement problems, it was not possible to develop an accurate water budget for 1997. Consequently, the 1997 data are reported as the arithmetic average of all the monitoring results, including both dry weather and wet weather periods. General trends in pollutant concentrations in the different tributaries were similar in 1997 and 1998. Therefore, we will focus our discussion on the 1998 monitoring period.

Over the course of the study, significant temporal variations in pollutant concentrations and loads were observed. Influent flow rates and pollutant concentrations varied in response to precipitation, temperature, and the location of each pond. In 1998, stream flows were higher in spring and early summer and then declined during the summer and fall for all three BMPs. In January 1999, there were several large storm events causing high stream flows.

The monitoring data showed very distinct variations in pollutant concentrations from one monitoring point to another. E. Lexington was clearly the dirtiest monitoring point in the Mall Pond A watershed. This monitoring point had the highest concentrations of solids (TDS, TSS, and total volatile solids—TVS), FC bacteria, nutrients (TP, dissolved phosphorus—DP, TN, TDN, dissolved ammonia as nitrogen—D-NH_4-N, and NO_{2+3}-N), and Fe. For Mall Pond B, the off-site drainage area was much dirtier than the on-site drainage area, with significantly higher concentrations of TSS, TP, DP, TN, and total metals (Cr, Cu, Fe, Pb, and Zn). These high pollutant concentrations may be associated with the large fraction of older medium-density residential land use in each of these watersheds. The influent to Regency had high levels of TSS, volatile suspended solids (VSS), and total nutrients such as TP and TN but had moderate to lower concentrations of most dissolved nutrients such as TDN, D-NH_4-N, and NO_{2+3}-N.

In general, trends for most pollutants were similar in 1997 and 1998. Monitoring points with high pollutant concentrations in 1997 usually had high pollutant concentrations for the same parameters in 1998. The only truly dramatic change occurred in the Regency influent in Winter 1999 when there was a dramatic increase in TSS, VSS, TP, TN, and particulate associated metals. At this same time, a large construction project began immediately upstream of Regency.

Average EMCs and pollutant loading rates in 1998 for each monitoring station are compared to published literature values and previous results from Davis and Piedmont Ponds in Tables 15 and 16. Pollutant concentrations and loading rates from the E. Lexington and Pond B off-site watershed are among the highest reported. While EMC and loading rates for the Pond B on-site drainage area were significantly lower than for other commercial areas, the Pond B on-site area is a new, well-manicured shopping mall. The recent construction and high level of maintenance of this area may contribute to the lower than expected pollutant concentrations. The EMC and loading rates for the other highly urbanized watersheds (A2, A4, and B2) were comparable to those previously reported. The very high EMCs and loading rates for the Regency watershed are believed to be due to the construction project immediately upstream of the sampling point at the end of the monitoring study.

Table 12. Flow-weighted Average Pollutant Concentrations in Mall Pond A

Parameter	Inflow/ Outflow	Location	Units	1997 Average	1998 Spring	1998 Summer	1998 Autumn	1998 Winter	1998 Average
Flow	Inflow	K-mart (A2)	cfs	NA	1.52	1.17	1.16	1.52	1.34
		E. Lexington (A3)	cfs	NA	0.72	0.65	0.61	0.71	0.68
		Centennial (A4)	cfs	NA	0.52	0.41	0.41	0.52	0.47
	Outflow	Dam (A1)	cfs	NA	2.76	2.23	2.18	2.76	2.48
TDS	Inflow	K-mart (A2)	mg/L	113	114	132	125	143	129
		E. Lexington (A3)	mg/L	140	146	152	161	188	162
		Centennial (A4)	mg/L	95	108	110	92	129	111
		Average Inflow	mg/L	140	122	137	135	161	139
	Outflow	Dam (A1)	mg/L	85	95	97	123	118	108
TSS	Inflow	K-mart (A2)	mg/L	34	49	27	21	84	48
		E. Lexington (A3)	mg/L	61	114	103	116	179	129
		Centennial (A4)	mg/L	34	54	66	21	41	46
		Average Inflow	mg/L	53	81	69	53	121	83
	Outflow	Dam (A1)	mg/L	30	29	33	28	38	32
VSS	Inflow	K-mart (A2)	mg/L	22	22	26	30	7	21
		E. Lexington (A3)	mg/L	18	24	20	22	15	20
		Centennial (A4)	mg/L	14	17	12	16	4	12
		Average Inflow	mg/L	22	23	21	23	10	19
	Outflow	Dam (A1)	mg/L	21	18	32	27	8	20
FC	Inflow	K-mart (A2)	ct/100mL	3467	1665	2295	12350	2268	4285
		E. Lexington (A3)	ct/100mL	16200	11719	6807	43027	4835	15840
		Centennial (A4)	ct/100mL	269	699	188	451	727	540
		Average Inflow	ct/100mL	10247	6125	4238	25925	3216	9244
	Outflow	Dam (A1)	ct/100mL	610	1422	30	1218	914	923

continued

Table 12. Flow-weighted Average Pollutant Concentrations in Mall Pond A, continued

Parameter	Inflow/ Outflow	Location	Units	1997 Average	1998 Spring	1998 Summer	1998 Autumn	1998 Winter	1998 Average
CHL	Inflow	K-mart (A2)	µg/L	11	15	13	1	0	7
		E. Lexington (A3)	µg/L	10	24	1	0	3	7
		Centennial (A4)	µg/L	7	16	1	0	0	5
		Average Inflow	µg/L	11	18	7	0	1	7
	Outflow	Dam (A1)	µg/L	22	24	9	4	2	10
TP	Inflow	K-mart (A2)	mg/L	0.104	0.130	0.137	0.147	0.237	0.166
		E. Lexington (A3)	mg/L	0.194	0.280	0.172	0.477	0.298	0.304
		Centennial (A4)	mg/L	0.071	0.060	0.100	0.071	0.156	0.098
		Average Inflow	mg/L	0.161	0.189	0.154	0.263	0.254	0.215
	Outflow	Dam (A1)	mg/L	0.102	0.119	0.072	0.166	0.121	0.119
DP	Inflow	K-mart (A2)	mg/L	0.027	0.025	0.026	0.054	0.072	0.045
		E. Lexington (A3)	mg/L	0.070	0.089	0.049	0.123	0.096	0.089
		Centennial (A4)	mg/L	0.021	0.022	0.018	0.014	0.075	0.034
		Average Inflow	mg/L	0.053	0.054	0.035	0.082	0.084	0.064
	Outflow	Dam (A1)	mg/L	0.019	0.030	0.016	0.017	0.118	0.048
TN	Inflow	K-mart (A2)	mg/L	1.186	1.254	1.683	1.163	1.285	1.336
		E. Lexington (A3)	mg/L	1.628	1.663	1.128	2.705	1.469	1.720
		Centennial (A4)	mg/L	0.855	0.946	0.775	0.714	0.832	0.826
TN		Average Inflow	mg/L	1.528	1.395	1.308	1.695	1.299	1.415
	Outflow	Dam (A1)	mg/L	1.140	0.880	1.141	1.663	0.981	1.139
D-NH_4-N	Inflow	K-mart (A2)	mg/L	0.891	0.119	0.031	0.097	0.118	0.095
		E. Lexington (A3)	mg/L	1.235	0.368	0.019	0.523	0.417	0.332
		Centennial (A4)	mg/L	0.700	0.022	0.024	0.036	0.082	0.042
		Average Inflow	mg/L	1.164	0.217	0.026	0.272	0.191	0.179
	Outflow	Dam (A1)	mg/L	0.757	0.071	0.113	0.244	0.141	0.138

continued

Table 12. Flow-weighted Average Pollutant Concentrations in Mall Pond A, continued

Parameter	Inflow/ Outflow	Location	Units	1997 Average	1998 Spring	1998 Summer	1998 Autumn	1998 Winter	1998 Average
NO_{2+3}-N	Inflow	K-mart (A2)	mg/L	0.081	0.314	0.407	0.172	0.398	0.328
		E. Lexington (A3)	mg/L	0.173	0.455	0.258	0.543	0.470	0.432
		Centennial (A4)	mg/L	0.063	0.134	0.029	0.176	0.206	0.140
		Average Inflow	mg/L	0.138	0.353	0.261	0.330	0.404	0.341
	Outflow	Dam (A1)	mg/L	0.096	0.157	0.040	0.272	0.359	0.212
TDN	Inflow	K-mart (A2)	mg/L	0.206	1.028	1.282	0.877	1.048	1.056
		E. Lexington (A3)	mg/L	0.407	0.903	0.956	1.978	1.240	1.249
		Centennial (A4)	mg/L	0.097	0.682	0.654	0.849	0.704	0.718
		Average Inflow	mg/L	0.324	0.921	1.032	1.316	1.077	1.076
	Outflow	Dam (A1)	mg/L	0.116	0.903	0.773	1.200	0.929	0.946
Total Cd	Inflow	K-mart (A2)	µg/L	1	1	1	1	1	1
		E. Lexington (A3)	µg/L	1	1	1	1	1	1
		Centennial (A4)	µg/L	1	1	1	1	1	1
		Average Inflow	µg/L	1	1	1	1	1	1
	Outflow	Dam (A1)	µg/L	1	1	1	1	1	1
Dissolved Cd	Inflow	K-mart (A2)	µg/L	1	1	1	1	1	1
		E. Lexington (A3)	µg/L	1	1	1	1	1	1
		Centennial (A4)	µg/L	1	1	1	1	1	1
		Average Inflow	µg/L	1	1	1	1	1	1
	Outflow	Dam (A1)	µg/L	1	1	1	1	1	1
Total Cr	Inflow	K-mart (A2)	µg/L	5	5	5	5	6	5
		E. Lexington (A3)	µg/L	5	6	5	6	6	6
		Centennial (A4)	µg/L	6	6	5	5	5	5
		Average Inflow	µg/L	6	6	5	5	6	6
	Outflow	Dam (A1)	µg/L	6	5	5	5	5	5

continued

Table 12. Flow-weighted Average Pollutant Concentrations in Mall Pond A, continued

Parameter	Inflow/ Outflow	Location	Units	1997 Average	1998 Spring	1998 Summer	1998 Autumn	1998 Winter	1998 Average
Dissolved Cr	Inflow	K-mart (A2)	µg/L	5	5	5	5	5	5
		E. Lexington (A3)	µg/L	5	6	5	5	5	5
		Centennial (A4)	µg/L	6	5	5	5	5	5
		Average Inflow	µg/L	5	5	5	5	5	5
	Outflow	Dam (A1)	µg/L	5	5	5	5	5	5
Total Cu	Inflow	K-mart (A2)	µg/L	5	11	6	5	11	9
		E. Lexington (A3)	µg/L	5	8	5	10	11	9
		Centennial (A4)	µg/L	5	25	10	5	14	14
		Average Inflow	µg/L	6	12	7	7	12	10
	Outflow	Dam (A1)	µg/L	9	11	4	5	14	9
Dissolved Cu	Inflow	K-mart (A2)	µg/L	4	5	5	3	6	5
		E. Lexington (A3)	µg/L	4	4	4	4	6	4
		Centennial (A4)	µg/L	4	8	8	4	14	9
		Average Inflow	µg/L	5	5	5	4	7	5
	Outflow	Dam (A1)	µg/L	5	5	4	4	5	4
Total Fe	Inflow	K-mart (A2)	µg/L	1169	1431	509	2790	2672	1876
		E. Lexington (A3)	µg/L	822	1451	748	3729	2054	1959
		Centennial (A4)	µg/L	878	1476	648	815	2095	1323
		Average Inflow	µg/L	1092	1488	656	2710	2349	1808
	Outflow	Dam (A1)	µg/L	870	979	500	1477	1511	1128
Dissolved Fe	Inflow	K-mart (A2)	µg/L	551	760	500	2522	541	1023
		E. Lexington (A3)	µg/L	500	567	500	515	500	521
		Centennial (A4)	µg/L	541	593	506	500	606	557
		Average Inflow	µg/L	596	648	502	1582	542	791
	Outflow	Dam (A1)	µg/L	509	626	500	540	500	544

continued

Table 12. Flow-weighted Average Pollutant Concentrations in Mall Pond A, continued

Parameter	Inflow/ Outflow	Location	Units	1997 Average	1998 Spring	1998 Summer	1998 Autumn	1998 Winter	1998 Average
Total Pb	Inflow	K-mart (A2)	µg/L	7	11	8	7	11	10
		E. Lexington (A3)	µg/L	7	10	7	34	12	15
		Centennial (A4)	µg/L	6	7	5	8	6	6
		Average Inflow	µg/L	8	10	7	15	11	11
	Outflow	Dam (A1)	µg/L	6	25	5	7	7	12
Dissolved Pb	Inflow	K-mart (A2)	µg/L	5	5	5	5	5	5
		E. Lexington (A3)	µg/L	5	6	5	6	5	5
		Centennial (A4)	µg/L	6	6	5	6	5	6
		Average Inflow	µg/L	6	6	5	6	5	5
	Outflow	Dam (A1)	µg/L	5	5	5	6	5	5
Total Ag	Inflow	K-mart (A2)	µg/L	3	4	4	NA	2	3
		E. Lexington (A3)	µg/L	3	6	3	NA	2	3
		Centennial (A4)	µg/L	3	5	4	NA	2	3
		Average Inflow	µg/L	3	5	4	NA	2	3
	Outflow	Dam (A1)	µg/L	3	5	4	NA	2	3
Dissolved Ag	Inflow	K-mart (A2)	µg/L	3	4	4	NA	2	3
		E. Lexington (A3)	µg/L	3	5	3	NA	2	3
		Centennial (A4)	µg/L	3	5	4	NA	2	3
		Average Inflow	µg/L	3	5	4	NA	2	3
	Outflow	Dam (A1)	µg/L	3	5	4	NA	2	3
Total Zn	Inflow	K-mart (A2)	µg/L	41	83	26	41	75	59
		E. Lexington (A3)	µg/L	37	63	24	59	57	51
		Centennial (A4)	µg/L	28	34	24	26	30	29
		Average Inflow	µg/L	43	68	25	45	61	51
	Outflow	Dam (A1)	µg/L	34	50	25	28	42	37

continued

Table 12. Flow-weighted Average Pollutant Concentrations in Mall Pond A, continued

Parameter	Inflow/ Outflow	Location	Units	1997 Average	1998 Spring	1998 Summer	1998 Autumn	1998 Winter	1998 Average
Dissolved Zn	Inflow	K-mart (A2)	µg/L	33	41	27	42	40	38
		E. Lexington (A3)	µg/L	33	39	23	36	42	35
		Centennial (A4)	µg/L	28	27	24	37	28	29
		Average Inflow	µg/L	37	38	25	40	39	36
	Outflow	Dam (A1)	µg/L	33	37	24	31	27	30

Table 13. Flow-weighted Average Pollutant Concentrations in Mall Pond B

Parameter	Inflow/ Outflow	Location	Units	1997 Average	1998 Spring	1998 Summer	1998 Autumn	1998 Winter	1998 Average
Flow	Inflow	On-site Drainage (B2)		NA	0.39	0.38	0.26	0.46	0.37
		Off-site Drainage (B3)	cfs	NA	0.12	0.12	0.08	0.15	0.12
	Outflow	Dam (B1)	cfs	NA	0.51	0.50	0.35	0.61	0.49
TDS	Inflow	On-site Drainage (B2)	mg/L	69	67	68	66	72	69
		Off-site Drainage (B3)	mg/L	71	72	73	70	75	71
		Average Inflow	mg/L	70	68	69	67	73	70
	Outflow	Dam (B1)	mg/L	61	87	86	83	86	86
TSS	Inflow	On-site Drainage (B2)	mg/L	46	40	41	38	44	42
		Off-site Drainage (B3)	mg/L	40	184	180	169	177	175
		Average Inflow	mg/L	44	79	78	73	80	78
	Outflow	Dam (B1)	mg/L	22	19	19	18	24	21
VSS	Inflow	On-site Drainage (B2)	mg/L	19	11	11	11	12	11
		Off-site Drainage (B3)	mg/L	19	31	30	29	30	30
		Average Inflow	mg/L	19	16	16	16	17	16
	Outflow	Dam (B1)	mg/L	15	9	9	9	10	9
FC	Inflow	On-site Drainage (B2)	ct/100mL	2204	3383	3338	3106	3225	3296
		Off-site Drainage (B3)	ct/100mL	2381	1715	1774	1565	1639	1645
		Average Inflow	ct/100mL	2252	2937	2919	2693	2800	2861
	Outflow	Dam (B1)	ct/100mL	291	395	394	361	381	386
TP	Inflow	On-site Drainage (B2)	mg/L	0.074	0.072	0.072	0.072	0.073	0.073
		Off-site Drainage (B3)	mg/L	0.115	0.242	0.238	0.228	0.233	0.231
		Average Inflow	mg/L	0.085	0.118	0.116	0.113	0.116	0.117
	Outflow	Dam (B1)	mg/L	0.039	0.074	0.072	0.069	0.076	0.074
DP	Inflow	On-site Drainage (B2)	mg/L	0.014	0.029	0.028	0.027	0.029	0.029
		Off-site Drainage (B3)	mg/L	0.041	0.131	0.128	0.123	0.127	0.125
		Average Inflow	mg/L	0.021	0.056	0.055	0.053	0.055	0.055
	Outflow	Dam (B1)	mg/L	0.041	0.032	0.032	0.031	0.032	0.032

continued

Table 13. Flow-weighted Average Pollutant Concentrations in Mall Pond B, continued

Parameter	Inflow/ Outflow	Location	Units	1997 Average	1998 Spring	1998 Summer	1998 Autumn	1998 Winter	1998 Average
TN	Inflow	On-site Drainage (B2)	mg/L	0.736	0.859	0.858	0.803	0.861	0.855
		Off-site Drainage (B3)	mg/L	1.331	1.378	1.365	1.355	1.364	1.338
		Average Inflow	mg/L	0.894	0.997	0.994	0.951	0.996	0.993
	Outflow	Dam (B1)	mg/L	5.192	0.750	0.786	0.711	0.734	0.751
D-NH_4-N	Inflow	On-site Drainage (B2)	mg/L	0.028	0.087	0.085	0.080	0.087	0.086
		Off-site Drainage (B3)	mg/L	0.032	0.063	0.062	0.060	0.063	0.061
		Average Inflow	mg/L	0.029	0.081	0.079	0.075	0.080	0.080
	Outflow	Dam (B1)	mg/L	0.020	0.085	0.082	0.079	0.083	0.083
NO_{2+3}-N	Inflow	On-site Drainage (B2)	mg/L	0.188	0.252	0.249	0.232	0.259	0.252
		Off-site Drainage (B3)	mg/L	0.179	0.282	0.285	0.261	0.306	0.281
		Average Inflow	mg/L	0.186	0.260	0.259	0.240	0.272	0.261
	Outflow	Dam (B1)	mg/L	0.083	0.099	0.096	0.096	0.104	0.100
TDN	Inflow	On-site Drainage (B2)	mg/L	0.796	0.700	0.706	0.674	0.707	0.704
		Off-site Drainage (B3)	mg/L	0.776	0.800	0.807	0.764	0.813	0.783
		Average Inflow	mg/L	0.792	0.727	0.733	0.698	0.736	0.730
	Outflow	Dam (B1)	mg/L	0.613	0.623	0.624	0.603	0.615	0.620
Total Cd	Inflow	On-site Drainage (B2)	µg/L	1	1	1	1	1	1
		Off-site Drainage (B3)	µg/L	1	1	1	1	1	1
		Average Inflow	µg/L	1	1	1	1	1	1
	Outflow	Dam (B1)	µg/L	1	1	1	1	1	1
Dissolved Cd	Inflow	On-site Drainage (B2)	µg/L	1	1	1	1	1	1
		Off-site Drainage (B3)	µg/L	1	1	1	1	1	1
		Average Inflow	µg/L	1	1	1	1	1	1
	Outflow	Dam (B1)	µg/L	1	1	1	1	1	1

continued

Table 13. Flow-weighted Average Pollutant Concentrations in Mall Pond B, continued

Parameter	Inflow/ Outflow	Location	Units	1997 Average	1998 Spring	1998 Summer	1998 Autumn	1998 Winter	1998 Average
Total Cr	Inflow	On-site Drainage (B2)	µg/L	7	4	4	4	4	4
		Off-site Drainage (B3)	µg/L	6	8	8	8	8	8
		Average Inflow	µg/L	7	5	5	5	5	5
	Outflow	Dam (B1)	µg/L	7	5	5	5	5	5
Dissolved Cr	Inflow	On-site Drainage (B2)	µg/L	5	4	4	4	4	4
		Off-site Drainage (B3)	µg/L	5	5	5	5	5	5
		Average Inflow	µg/L	5	4	4	4	4	4
	Outflow	Dam (B1)	µg/L	5	5	5	5	5	5
Total Cu	Inflow	On-site Drainage (B2)	µg/L	8	9	9	9	10	10
		Off-site Drainage (B3)	µg/L	7	20	20	19	20	19
		Average Inflow	µg/L	7	12	12	11	13	12
	Outflow	Dam (B1)	µg/L	4	7	7	6	7	7
Dissolved Cu	Inflow	On-site Drainage (B2)	µg/L	8	8	8	8	8	8
		Off-site Drainage (B3)	µg/L	8	6	6	6	6	6
		Average Inflow	µg/L	8	7	7	7	7	7
	Outflow	Dam (B1)	µg/L	6	5	5	5	5	5
Total Fe	Inflow	On-site Drainage (B2)	µg/L	555	407	419	405	619	478
		Off-site Drainage (B3)	µg/L	745	2202	2157	2038	2129	2095
		Average Inflow	µg/L	606	887	884	842	1023	925
	Outflow	Dam (B1)	µg/L	525	577	582	563	648	601
Dissolved Fe	Inflow	On-site Drainage (B2)	µg/L	500	401	404	400	405	405
		Off-site Drainage (B3)	µg/L	500	2044	1991	1893	1971	1940
		Average Inflow	µg/L	500	840	829	800	824	829
	Outflow	Dam (B1)	µg/L	500	671	665	646	663	666

continued

Table 13. Flow-weighted Average Pollutant Concentrations in Mall Pond B, continued

Parameter	Inflow/ Outflow	Location	Units	1997 Average	1998 Spring	1998 Summer	1998 Autumn	1998 Winter	1998 Average
Total Pb	Inflow	On-site Drainage (B2)	µg/L	8	7	7	7	7	7
		Off-site Drainage (B3)	µg/L	9	35	34	33	34	33
		Average Inflow	µg/L	8	14	14	14	14	14
	Outflow	Dam (B1)	µg/L	8	9	9	9	9	9
Dissolved Pb	Inflow	On-site Drainage (B2)	µg/L	6	4	4	4	4	4
		Off-site Drainage (B3)	µg/L	8	5	5	5	5	5
		Average Inflow	µg/L	7	4	4	4	4	4
	Outflow	Dam (B1)	µg/L	6	5	5	5	5	5
Total Ag	Inflow	On-site Drainage (B2)	µg/L	5	NA	NA	NA	NA	NA
		Off-site Drainage (B3)	µg/L	5	NA	NA	NA	NA	NA
		Average Inflow	µg/L	5	NA	NA	NA	NA	NA
	Outflow	Dam (B1)	µg/L	5	NA	NA	NA	NA	NA
Dissolved Ag	Inflow	On-site Drainage (B2)	µg/L	5	NA	NA	NA	NA	NA
		Off-site Drainage (B3)	µg/L	5	NA	NA	NA	NA	NA
		Average Inflow	µg/L	5	NA	NA	NA	NA	NA
	Outflow	Dam (B1)	µg/L	5	NA	NA	NA	NA	NA
Total Zn	Inflow	On-site Drainage (B2)	µg/L	45	48	47	46	47	47
		Off-site Drainage (B3)	µg/L	80	120	117	113	118	115
		Average Inflow	µg/L	55	67	66	64	66	66
	Outflow	Dam (B1)	µg/L	33	39	39	38	39	39
Dissolved Zn	Inflow	On-site Drainage (B2)	µg/L	79	34	34	36	34	34
		Off-site Drainage (B3)	µg/L	132	63	61	66	63	62
		Average Inflow	µg/L	93	42	41	44	41	42
	Outflow	Dam (B1)	µg/L	68	28	28	31	29	29

Table 14. Flow-weighted Average Pollutant Concentrations in Regency System

Parameter	Location	Units	1997 Average	1998 Spring	1998 Summer	1998 Autumn	1998 Winter	1998 Average
Flow		cfs		18.9	8.7	1.8	12.1	10.4
TDS	Pond inflow (R1)	mg/L	118	82	103	118	417	186
	Pond Outflow (R2)	mg/L	96	93	97	100	340	166
	Wetland Outflow (R3)	mg/L	102	98	95	108	524	222
TSS	Pond inflow (R1)	mg/L	229	480	68	42	1891	786
	Pond Outflow (R2)	mg/L	37	86	62	39	1059	363
	Wetland Outflow (R3)	mg/L	81	123	186	44	1801	622
VSS	Pond inflow (R1)	mg/L	65	43	11	15	70	43
	Pond Outflow (R2)	mg/L	16	10	14	18	21	14
	Wetland Outflow (R3)	mg/L	33	12	20	17	121	46
FC	Pond inflow (R1)	ct/100mL	1853	594	958	762	2842	1333
	Pond Outflow (R2)	ct/100mL	418	571	951	350	1852	1014
	Wetland Outflow (R3)	ct/100mL	409	129	356	248	2008	729
TP	Pond inflow (R1)	mg/L	0.179	0.423	0.077	0.046	3.258	1.160
	Pond Outflow (R2)	mg/L	0.063	0.123	0.1	0.045	2.769	0.886
	Wetland Outflow (R3)	mg/L	0.091	0.102	0.243	0.058	4.016	1.270
DP	Pond inflow (R1)	mg/L	0.022	0.015	0.027	0.023	0.023	0.020
	Pond Outflow (R2)	mg/L	0.019	0.01	0.011	0.015	0.02	0.013
	Wetland Outflow (R3)	mg/L	0.017	0.01	0.009	0.023	0.033	0.017
TN	Pond inflow (R1)	mg/L	0.762	1.848	0.992	0.371	2.418	1.770
	Pond Outflow (R2)	mg/L	0.670	1.019	1.075	0.562	1.662	1.198
	Wetland Outflow (R3)	mg/L	0.709	0.685	1.181	0.536	2.832	1.408
D-NH_4-N	Pond inflow (R1)	mg/L	0.887	0.042	0.059	0.086	0.048	0.049
	Pond Outflow (R2)	mg/L	0.671	0.029	0.057	0.03	0.059	0.044
	Wetland Outflow (R3)	mg/L	0.691	0.03	0.054	0.015	0.054	0.041

continued

Table 14. Flow-weighted Average Pollutant Concentrations in Regency System, continued

Parameter	Location	Units	1997 Average	1998 Spring	1998 Summer	1998 Autumn	1998 Winter	1998 Average
NO_{2+3}-N	Pond inflow (R1)	mg/L	0.026	0.342	0.487	0.364	0.486	0.415
	Pond Outflow (R2)	mg/L	0.022	0.279	0.331	0.275	0.39	0.322
	Wetland Outflow (R3)	mg/L	0.031	0.239	0.379	0.272	0.33	0.296
TDN	Pond inflow (R1)	mg/L	0.444	0.897	1.019	0.694	1.505	1.091
	Pond Outflow (R2)	mg/L	0.297	0.678	0.771	0.702	1.118	0.827
	Wetland Outflow (R3)	mg/L	0.293	0.692	0.788	0.562	1.236	0.865
Total Cd	Pond inflow (R1)	µg/L	1	1	1	1	1	1
	Pond Outflow (R2)	µg/L	1	1	1	1	1	1
	Wetland Outflow (R3)	µg/L	1	2	1	1	1	1
Dissolved Cd	Pond inflow (R1)	µg/L	1	1	1	1	1	1
	Pond Outflow (R2)	µg/L	1	1	1	1	1	1
	Wetland Outflow (R3)	µg/L	1	1	1	1	1	1
Total Cr	Pond inflow (R1)	µg/L	7	5	5	5	17	8
	Pond Outflow (R2)	µg/L	5	5	5	7	31	13
	Wetland Outflow (R3)	µg/L	5	5	5	5	48	18
Dissolved Cr.	Pond inflow (R1)	µg/L	6	5	5	5	5	5
	Pond Outflow (R2)	µg/L	4	5	5	5	5	5
	Wetland Outflow (R3)	µg/L	5	5	5	5	5	5
Total Cu	Pond inflow (R1)	µg/L	11	19	31	5	33	25
	Pond Outflow (R2)	µg/L	5	8	29	5	43	22
	Wetland Outflow (R3)	µg/L	7	12	10	5	58	25
Dissolved Cu	Pond inflow (R1)	µg/L	4	2	2	2	13	5
	Pond Outflow (R2)	µg/L	4	1	2	3	23	8
	Wetland Outflow (R3)	µg/L	3	3	2	3	7	4

continued

Table 14. Flow-weighted Average Pollutant Concentrations in Regency System, continued

Parameter	Location	Units	1997 Average	1998 Spring	1998 Summer	1998 Autumn	1998 Winter	1998 Average
Total Fe	Pond inflow (R1)	µg/L	4252	10973	1891	916	16857	10345
	Pond Outflow (R2)	µg/L	1507	3013	2472	1113	26846	9763
	Wetland Outflow (R3)	µg/L	2390	3207	6015	1257	41083	14747
Dissolved Fe	Pond inflow (R1)	µg/L	500	500	500	500	594	527
	Pond Outflow (R2)	µg/L	485	500	500	500	500	500
	Wetland Outflow (R3)	µg/L	500	513	500	500	700	564
Total Pb	Pond inflow (R1)	µg/L	11	20	13	8	19	18
	Pond Outflow (R2)	µg/L	9	14	15	8	31	19
	Wetland Outflow (R3)	µg/L	10	11	10	6	44	20
Dissolved Pb	Pond inflow (R1)	µg/L	5	5	5	5	5	5
	Pond Outflow (R2)	µg/L	5	5	5	5	5	5
	Wetland Outflow (R3)	µg/L	5	5	5	5	5	5
Total Ag	Pond inflow (R1)	µg/L	4	5	NA	NA	NA	NA
	Pond Outflow (R2)	µg/L	4	5	NA	NA	NA	NA
	Wetland Outflow (R3)	µg/L	4	5	NA	NA	NA	NA
Dissolved Ag	Pond inflow (R1)	µg/L	4	5	NA	NA	NA	NA
	Pond Outflow (R2)	µg/L	4	5	NA	NA	NA	NA
	Wetland Outflow (R3)	µg/L	4	5	NA	NA	NA	NA
Total Zn	Pond inflow (R1)	µg/L	68	86	26	25	90	72
	Pond Outflow (R2)	µg/L	31	40	25	25	150	68
	Wetland Outflow (R3)	µg/L	37	61	25	25	196	91
Dissolved Zn	Pond inflow (R1)	µg/L	31	25	25	25	25	25
	Pond Outflow (R2)	µg/L	28	25	25	25	25	25
	Wetland Outflow (R3)	µg/L	27	25	25	25	25	25

Table 15. Comparison of EMC at Inflow Monitoring Station to NURP Results

Pollutant	TSS (mg/L)	TP (µg/L)	DP (µg/L)	TN (µg/L)	TKN (µg/L)	NO_{2+3}-N (µg/L)
Davis North	71	499	318	2,153	1,783	370
Davis South	186	282	123	1,124	922	203
Piedmont Influent	61	162	33	1,132	867	265
K-mart (A2)	83	234	61	1,407	1,131	276
East Lexington (A3)	425	512	98	2,119	1,735	384
Centennial (A4)	70	156	72	951	785	166
On-Site Pond B (B2)	14	73	34	741	549	192
Off-Site Pond B (B3)	217	268	151	1,312	1,085	227
Regency Influent (R1)	779	1,200	22	1,751	1,265	486
NURP Residential	101	383	143	2,636	1,900	736
NURP Mixed	67	263	56	1,846	1,288	558
NURP Commercial	69	201	80	1,751	1,179	572
NURP Open	70	121	26	1,508	965	354

Source: US EPA 1983.

Table 16. Comparison of Export Rates for Different Land Uses

Study	Location/ Land use	Annual Runoff (inches)	TSS (lb/ac-yr)	TP (lb/ac-yr)	DP (lb/ac-yr)	TN (lb/ac-yr)	NO_{2+3}-N (lb/ac-yr)
Davis Pond	North	10.5	109	1.13	0.74	5.4	1.0
	South	16.1	479	1.05	0.59	4.0	0.7
	Dam	12.9	107	0.6	0.28	4.0	0.7
Piedmont Pond	Upstream	20.2	279	0.55	0.15	5.2	1.2
	Dam	20.2	223	0.33	0.13	3.4	0.4
Mall Pond A	K-mart (A2)	36.6	397	1.37	0.37	11.1	2.7
	East Lexington (A3)	19.7	574	1.35	0.40	7.7	1.9
	Centennial (A4)	32.7	338	0.73	0.25	6.1	1.0
	Dam (A1)	29.1	212	0.79	0.32	7.5	1.4
Mall Pond B	On-site (B2)	30.9	290	0.51	0.20	6.0	1.8
	Off-site (B3)	26.9	1065	1.41	0.76	8.2	1.7
	Dam (B1)	29.9	139	0.50	0.22	5.1	0.7
Regency	Pond Inlet (R1)	22.0	3921	5.89	0.10	8.8	2.1
	Pond Outlet (R2)	22.0	1809	4.42	0.07	6.0	1.6
	Wetland Outlet (R3)	22.0	3102	6.34	0.08	7.0	1.5
NURP (US EPA 1983)	Residential	12	490	1.2	0.4	7.5	2.3
	Commercial	32	1300	3.0	1.1	19.9	6.2
NVPDC (1979)	Residential		180–460	0.29		6.2–10	
	Commercial/ Industrial		440–480	0.37		10~13	
	Cropland		3600	0.4		19	
	Forest		100	0.29		3	
Smolen (1981)	Row Crop			1.2	0.08	2.9	0.49
	Forest				0.09	1.6	0.06
Crawford and Lenat (1989)	Agricultural		620				
	Urban		1180				
	Forest		260				

WATER QUALITY CONDITION IN MALL POND A

Recent work has shown that biological processes can also have an important influence on pollutant removal in wet detention ponds. In a previous study, Borden et al. (1997) examined water quality conditions in two stormwater detention ponds in High Point, North Carolina: Davis Pond and Piedmont Pond. Both ponds thermally stratified and developed an anaerobic hypolimnion during the growing season. However, the level of biological productivity was very different in the two ponds. Davis Pond was hypereutrophic as evidenced by high chlorophyll-a concentrations, high midday pH values, supersaturated midday oxygen concentration, and an anaerobic hypolimnion. During much of the growing season, algal growth in Davis Pond was carbon limited because of the high DP and dissolved nitrogen (DN) concentrations in the pond influent. Piedmont Pond was mesotrophic to slightly eutrophic as evidenced by moderate chlorophyll-a concentrations, near neutral midday pH values, and midday oxygen concentrations close to saturation. Low levels of both DP and DN limited algal growth in Piedmont Pond.

In this study, we have monitored water quality conditions in Mall Pond A from a limnological perspective, focusing on relationships between algal growth and nutrient cycling. Profiles of inorganic nutrients and other important indicators of biological activity in Pond A were measured during the growing season to better understand factors limiting algal growth and associated nutrient removal. In-lake water quality data were not collected from Mall Pond B or the Regency Pond-Wetland System. Mall Pond B is much smaller and shallower than Pond A and occasionally dries up. Consequently, a stable aquatic community has not formed. The average hydraulic retention time of the Regency is very short (0.8 days), and therefore water quality conditions vary widely in response to changing influent conditions.

WATER QUALITY CONDITION IN MALL POND A.

Water quality conditions in Mall Pond A were similar in 1997 and 1998. For brevity, our discussion focuses on the 1998 monitoring results. During the summer growing season, water quality conditions in Mall Pond A were controlled by the relatively high concentrations of nitrogen and phosphorus and low alkalinity of the influent water. Profiles of temperature, dissolved oxygen (DO), pH, conductivity, chlorophyll-a, and FC counts are shown in Figure 9 for 1998. Profiles of TP, DP, TN, TDN, D-NH_4-N, and NO_{2+3}-N are shown in Figure 10 for 1998.

Total runoff (storm and base flow) entering Mall Pond A over the twelve month monitoring period was 15.1 inches or 34% of the precipitation during the monitoring period. This resulted in total inflow to the pond of 2.48 cfs (1.6 MG/day) and an average hydraulic renewal time of approximately 16.8 days.

Mall Pond A was thermally stratified from March 31 to August 25, 1998 (Figure 9). A clearly defined epilimnion, metalimnion, and hypolimnion were evident in the early spring. However, as the summer progressed, heat was gradually transferred from the surface to deeper portions of the pond resulting in a more gradual temperature profile. By mid-summer, the afternoon stratification was so intense that no surface-mixed layer was observed. Consequently, surface mixing was not a significant source of DO on these dates. Dissolved oxygen concentrations were close to saturation in the surface layers throughout the year. Shortly after the onset of thermal

Figure 9. Water Quality Profiles in Mall Pond A During 1998: Temperature, Dissolved Oxygen, pH, Conductivity, Chlorophyll-a, and Fecal Coliform

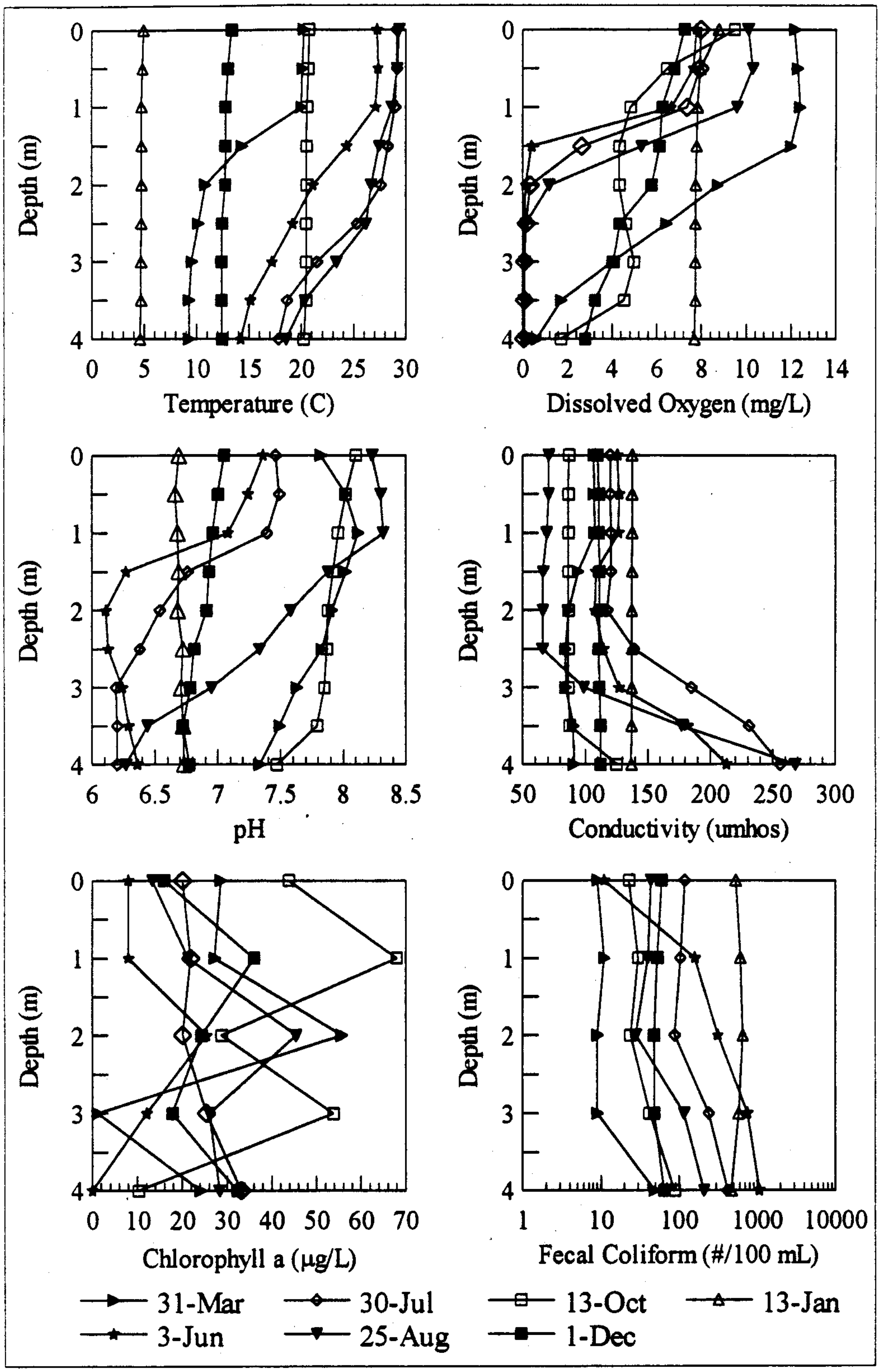
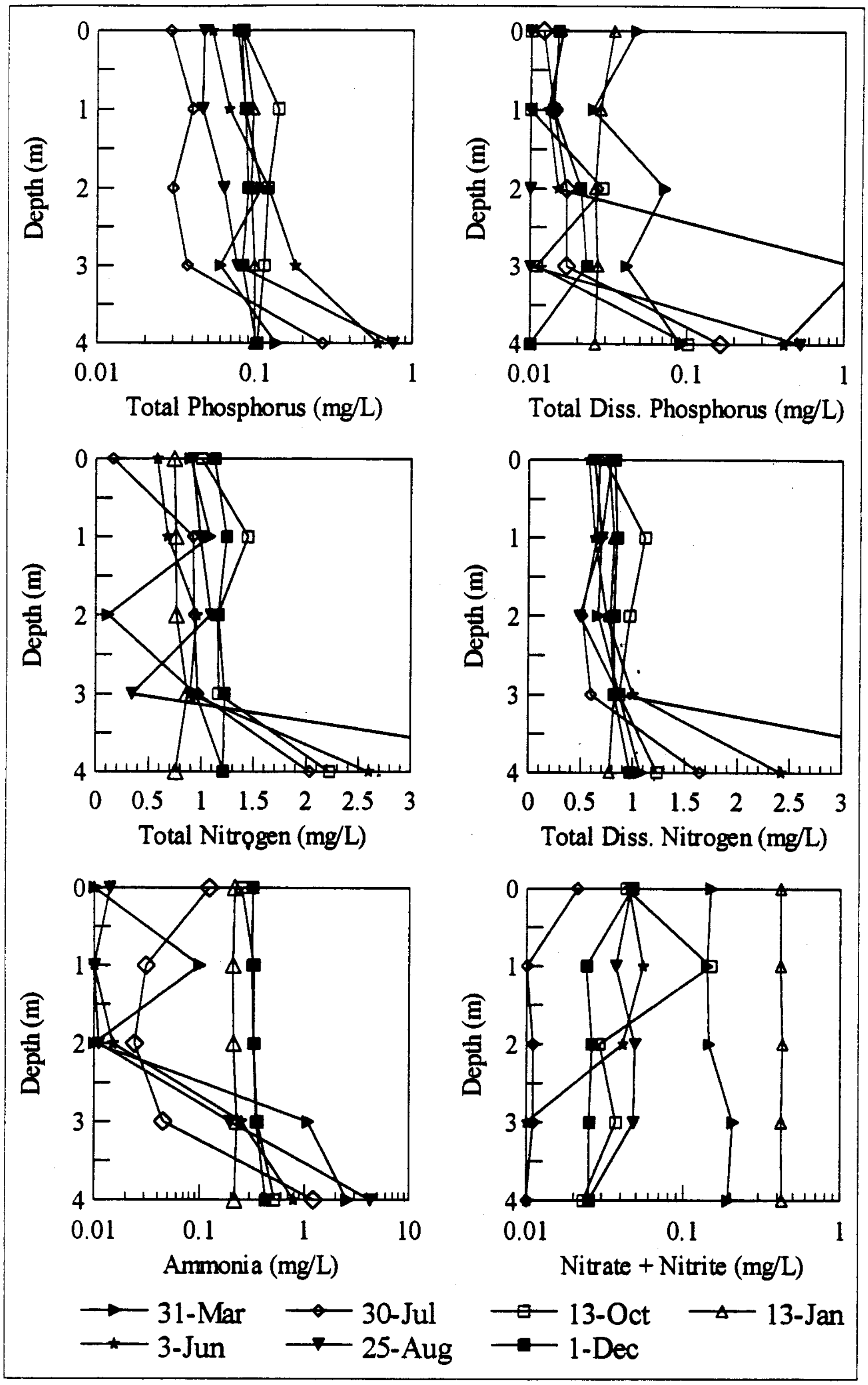


Figure 10. Water Quality Profiles in Mall Pond A During 1998: Total Phosphorus, Total Dissolved Phosphorus, Total Nitrogen, Total Dissolved Nitrogen, Dissolved Ammonia as Nitrogen, and Combined Nitrate + Nitrite as Nitrogen



stratification in the March, DO concentrations in the bottom waters began to decline. From the beginning of June to the end of August, DO was close to zero below 1.5 m. Sometime between August 24 and Oct. 13, Mall Pond A turned over and DO in the bottom waters increased. However, the DO profile did not become uniform until January when temperatures were cold enough to inhibit significant biological activity.

Algal productivity and associated chemical parameters varied over the course of the growing season. On March 31, algal productivity was very high as indicated by the high DO concentration, high pH, and high chlorophyll-a concentration in the upper one meter of the water column (Figure 9). This type of algae bloom often develops as a result of (1) elevated dissolved nutrient concentrations following the cold winter period and (2) increasing water temperatures that allow more rapid algal growth. Algal productivity was lower over the summer as indicated by the lower chlorophyll-a and DO concentrations. The decline in productivity was probably due to the very low DP concentrations present in the epilimnion throughout most of the summer (Figure 10). However a variety of other factors could also contribute to the decline in productivity such as algal species succession, zooplankton grazing, coflocculation and settling with sediments, toxins secreted by blue-green algae, light inhibition, and a free CO_2 limitation. The decline in algal productivity was probably not due to a nitrogen limitation since moderate levels of D-NH_4-N and nitrate were present in the epilimnion throughout much of the summer (Figure 10). Algal productivity was high in the fall as evidenced by the high DO, pH, and chlorophyll-a concentrations. This "fall bloom" likely occurred due to mixing of high nutrient waters present on the pond bottom.

During stratified conditions, considerable amounts of chlorophyll-a were observed in the hypolimnion and its disturbed sediments (Figure 9). The Secchi disc depth and light intensity data indicate that light would not reach these depths. Algal survival through heterotrophic growth is unlikely since the hypolimnion is anaerobic and all known species of algae that can survive by heterotrophic degradation require oxygen (Wetzel 1983). Degradation of chlorophyll-a to pheopigments occurs primarily through a photochemical reaction or as a result of zooplankton grazing. In the absence of these two mechanisms, chlorophyll degradation will be slow in the cool, dark, anaerobic hypolimnion of Mall Pond A during the summer. This suggests that the high concentrations of chlorophyll-a observed in the bottom of Mall Pond A are due to sedimentation of planktonic algae.

Total phosphorus concentrations in the epilimnion were relatively constant throughout the growing season, with some variations, presumably due to storm input. Dissolved phosphorus in the epilimnion was relatively high in the early spring, very low throughout the summer, and then increased again following fall turnover. Both total and DP were much higher in the hypolimnion, presumably due to settling of algae and suspended sediment. However, there is no evidence of an increase in TP in the hypolimnion between June and August. There was considerable TP removal over this time period, indicating that phosphorus must have been eventually trapped in the pond bottom sediments. Dissolved phosphorus made up over two-thirds of the TP in the bottom-most sampling interval throughout the summer. The high levels of DP are likely due to partial release of DP from sediment and decaying algae under reducing conditions.

The TN and TDN concentrations were high at all depths throughout the year (Figure 10). The TN concentrations were an order of magnitude greater than TP, and TDN concentrations were more than an order of magnitude greater than DP, indicating that nitrogen was not limiting algal growth. Dissolved nitrogen ranged from 50 to 90% of the TN. Ammonia concentrations increased in the anaerobic bottom waters starting in March, remained stable throughout most of the summer, and spread throughout the water column during fall turnover. Throughout most of the year, the NO_{2+3}-N concentration profiles were relatively constant with depth (Figure 10). However, in June and July, NO_{2+3}-N concentrations declined with depth, which suggests denitrification may be occurring in the warm anaerobic bottoms waters of the pond.

NORTH CAROLINA TROPHIC STATE INDEX.

The North Carolina Trophic State Index (NCTSI) was developed as part of the Clean Lakes Classification Survey to provide a quantitative index of trophic state (NC DEHNR 1992). The NCTSI is calculated as the sum of four scores based on lakewide mean concentrations of total organic nitrogen (mg/L), total phosphorus (mg/L), chlorophyll-a (µg/L), and Secchi disk depth (inches). The scores are calculated as follows:

Total Organic Nitrogen (TON) Score = $((\mathrm{Log}(TON) + 4.5)/2.4) \times 0.90$

Total Phosphorus (TP) Score = $((\mathrm{Log}(TP) + 1.55)/0.35) \times 0.92$

Secchi Disk (SD) Score = $((\mathrm{Log}(SD) - 1.73)/0.35) \times 0.82$

Chlorophyll-a (CHL) Score = $((\mathrm{Log}(CHL) - 1.00)/0.43) \times 0.83$

NCTSI = TON Score + TP Score + SD Score + CHL Score

A NCTSI score of less than -2 indicates oligotrophic conditions, -2 to 0 indicates mesotrophic condition, 0 to 5 indicates eutrophic conditions, and greater than 5 indicates hypereutrophic condition (NCDEHNR 1992). Professional judgement is used to assign a trophic state in borderline cases.

The NCTSI score for Mall Pond A was 4.76, which indicates eutrophic to hypereutrophic conditions (Table 17). The high score is primarily due the high nutrient concentrations in the pond. The high DO and pH in the epilimnion and anaerobic conditions in the hypolimnion further support this classification.

The macronutrient that may potentially limit algal growth can be identified by comparing measured ratios to those required for algal growth. Table 18 shows average concentrations of DP and TDN in Mall Pond euphotic zone for each sampling date. Based on a required nitrogen to phosphorus ratio of 16:1 (Tetra Tech, Inc. 1978), algal growth was potentially limited by DP. The actual limiting nutrient can be identified by comparing concentrations of individual nutrients to those known to limit growth. Dissolved phosphorus concentrations were low throughout the summer and likely limited algal productivity. While TDN concentrations were relatively high, most of the nitrogen was present as organic nitrogen, a form that is less readily available to algae. In June and August, D-NH_4-N concentrations in the epilimnion were very low and may have favored the blue-green algae growth.

Table 17. NCTSI Calculations for Mall Pond A—1998 Growing Season

Constituent	March 31	June 3	July 30	August 25	October 13	Average	NCTSI Score
SD (inches)	48	30	30	14	18	23.3	0.85
CHL (µg/L)	27	11	24	27	41	21.7	0.65
TP (mg/L)	0.09	0.21	0.08	0.20	0.11	0.11	1.60
TON (mg/L)	0.65	1.14	1.00	1.7	1.40	0.98	1.66
						Total	4.76

Table 18. Euphotic Zone Nutrient Concentration in Mall Pond A—1998 Growing Season

Constituent	March 31	June 3	July 30	August 25	October 13	December 1
DP (mg/L)	0.025	0.013	0.014	0.010	0.015	0.014
TDN (mg/L)	0.697	0.633	0.650	0.699	0.920	0.846
D-NH_4-N (mg/L)	0.040	0.010	0.031	0.012	0.290	0.321
pH	8.1	7.1	7.4	8.3	7.9	7
Temperature (°C)	20	27	29	29	21	13
DO (mg/L)	12.4	6.6	7.4	9.6	4.8	6.2
Potential Limiting Nutrient	P	P	P	P	P	P

POLLUTANT TRAP EFFICIENCY

Removal efficiencies were calculated as the percent difference of the pollutant mass entering and discharging from each pond for each season in 1998 and for the 12-month monitoring period. Removal efficiencies were not calculated for each storm because, in many cases, individual storms displaced only a fraction of the total pond volume.

Table 19 provides a comparison of the average annual removal efficiencies for the five regional BMPs constructed by the City of High Point with results from the BMP survey performed by Brown and Schuler (1997).

Table 19. Comparison of Average Annual Removal Efficiencies (%) for Major Pollutants.

Parameter	Davis	Piedmont	Mall Pond A	Mall Pond B	Regency Combined Pond and Wetland	BMP Database for Ponds Brown and Schuler (1997)	
						Average	Range
TSS	60	20	61	74	21	62	-33 to 99
TP	46	40	45	37	-9	47	0 to 91
DP	58	15	24	42	15	37	-12 to 90
NO_{2+3}-N	18	66	38	62	29	28	-85 to 97
D-NH_4-N	10	-64	23	-4	16	18	-107 to 83
TN	16	36	20	24	20	29	-12 to 85

POLLUTANT REMOVAL IN MALL PONDS A AND B

Annual pollutant removal efficiencies in Mall Pond A and B were similar to previously observed removal efficiencies in Davis and Piedmont and to other literature reports. Measured removal efficiencies for the Regency Pond and Wetland were significantly less than in the ponds and in most published reports. The low removal efficiency for Regency is presumably due to the very short hydraulic retention time and high hydraulic loading rate for the pond-wetland system.

Seasonal removal efficiencies of Mall Ponds A and B are listed in Tables 20 and 21 for solids, nutrients, and total metals. Removal efficiencies were not calculated for dissolved metals because, in many cases, the dissolved metal concentrations were near the analytical detection limits in the pond influents.

Total dissolved solids (TDS) removal was low and variable in both ponds. The limited TDS removal that was observed was likely due to attachment of soluble compounds onto solid particles followed by sedimentation. Attachment can occur by sorption onto inorganic particles (e.g., clays) or through nutrient uptake by algae. Conversely, TDS may be released from sediments under anaerobic conditions or when the aqueous phase is depleted in soluble compounds relative to the sediment phase.

Table 20. Mall Pond A 1998 Removal Efficiencies (%)

Parameter	Spring	Summer	Autumn	Winter	Annual Average
TDS	23	29	9	27	22
TSS	64	52	48	69	61
VSS	21	-49	-17	18	-7
FC	77	99	95	72	90
TP	37	53	37	52	45
DP	44	55	79	-41	24
TN	37	13	2	24	20
D-NH_4-N	67	-342	10	26	23
Dissolved NO_{2+3}-N	55	85	17	11	38
TDN	2	25	9	14	12
Total Cu	7	36	25	-16	6
Total Fe	34	24	45	36	38
Total Pb	-144	29	55	34	-8
Total Zn	26	0	38	32	27

Table 21. Mall Pond B 1998 Removal Efficiencies (%)

Parameter	Spring	Summer	Autumn	Winter	Annual Average
TDS	-27	-24	-23	-18	-22
TSS	77	75	76	69	74
VSS	45	44	43	41	43
FC	87	87	87	86	86
TP	37	38	39	34	37
DP	43	42	41	41	42
TN	25	21	25	26	24
D-NH_4-N	-5	-4	-5	-3	-4
Dissolved NO_{2+3}-N	62	63	60	62	62
TDN	14	15	14	16	15
Total Cu	46	46	44	46	46
Total Fe	35	34	33	37	35
Total Pb	39	38	37	37	38
Total Zn	41	41	41	41	41

The annual average TSS removal efficiency for Ponds A was 61%, with somewhat lower removal efficiencies observed when the pond was thermally stratified. Average TSS removal in Pond B was somewhat higher at 74%, with less seasonal variation than in Pond A. Pond B has a higher pond surface area to drainage area ratio than Pond A, which could have resulted in a higher TSS removal efficiency. The hydraulic retention time and average influent TSS concentrations of the two ponds were similar. However, stratification was likely less intense in Pond B, so there may have been less short circuiting of the pond during the summer months. Volatile suspended solids removal efficiencies were variable (-49 to +21%) in Pond A while they more consistent in Pond B (41 to 45%). The negative VSS removal efficiencies for Pond A were likely the result of algal growth during the summer months. Both ponds were fairly effective at removing FC bacteria, with removal efficiencies varying between 69 and 99%. However, FC concentrations in both ponds frequently exceeded the state water quality standard of 200 cells/100 mL.

Total phosphorus removal was similar in Ponds A and B and relatively constant throughout the year. However, DP removal efficiencies were more variable with higher DP removals observed in Pond A during the growing season followed by a large release of DP in the winter. The DP removal efficiencies in Pond B were somewhat lower and more uniform, presumably due to the lower level of biological activity in this pond.

Total nitrogen removal in Ponds A and B followed the same patterns as observed for phosphorus. Both ponds showed similar annual removal efficiencies for TN and TDN, but removal efficiencies in Pond A were much more variable and appeared to be more strongly influenced by biological activity. In the spring, both D-NH_4-N and NO_{2+3}-N were removed in Pond A. However, during the summer, D-NH_4-N increased in Pond A with a concurrent removal of NO_{2+3}-N. During this period, D-NH_4-N was depleted to low levels in the Pond A epilimnion (0.01 to 0.03 mg/L) but was much higher in the hypolimnion (> 0.2 mg/L). The average D-NH_4-N in the Pond A effluent was between the concentrations in the epilimnion and hypolimnion, suggesting that the pond discharge withdraws water from both zones. This is possible since water must flow underneath a hanging wall before it can discharge from the pond. The high NO_{2+3}-N removal efficiency could also be related to biological denitrification in the anaerobic hypolimnion. Following turn over in the fall, D-NH_4-N and NO_{2+3}-N returned to more typical values. In Pond B, NO_{2+3}-N removals were consistently high throughout the year, and there was a slight production of D-NH_4-N.

Total and dissolved Cd, Cr, Cu, Fe, Pb, Ag, and Zn were monitored in both Mall Pond A and B throughout this project. However total Cd, total Cr, total Ag, and all dissolved metals were close to or below the analytical detection limit in most samples. Consequently, it is not possible to calculate representative removal efficiencies for these parameters. Total Fe concentrations in the weighted average influent to both Pond A and B varied between 0.6 and 2.7 mg/L, with average annual removal efficiencies of 38% for Pond A and 35% for Pond B. The high Fe concentrations are associated with fine-grained sediment (silts and clays) where iron makes up a significant fraction of the mineral. Total Cu concentrations in the weighted average influent to both Pond A and B varied between 6 and 13 μg/L with average annual removal efficiencies of 6% for Pond A and 46% for Pond B. The effluent from Pond A frequently exceeded the surface water quality standard of 7 μg/L, while the effluent from Pond B was at or below the standard. Total Pb concentrations in the weighted average influent to both Pond A and B varied between 7 and 15 μg/L, with average annual removal efficiencies of -8% for Pond A and 38% for Pond B. The weighted average influent to both ponds was consistently below the water quality standard of 25 µg/L for lead. Total zinc concentrations in the weighted average influent to both Pond A and B varied between 55 and 67 µg/L with average annual removal efficiencies of 27% for Pond A and 41% for Pond B. Removal efficiencies were consistently higher in Pond B than in Pond A, presumably associated with the higher TSS removal efficiency in Pond B.

POLLUTANT REMOVAL IN REGENCY POND AND WETLAND

Annual pollutant removal efficiencies for the Regency Pond and Wetland were much lower than in the other High Point ponds and average values from literature reports. However, both the Regency Pond and Wetland are much smaller than NCDENR design rules specify, and consequently removal efficiencies were expected to be much lower. Seasonal removal efficiencies for the Regency Pond, Regency Wetland, and combined pond-wetland system are listed in Tables 22 to 24 for solids, nutrients, and total metals. Removal efficiencies were not calculated for dissolved metals because, in many cases, the dissolved metal concentrations were near the analytical detection in the influent.

The monitoring data indicated that the Regency Pond was reasonably effective in removing solids (TSS and VSS) and nutrients (TP, DP, TN, TDN, D-NH_4-N, and NO_{2+3}-N). Much of this removal occurred in the winter when very high pollutant loads were coming into the pond from the upstream construction site. Metals removal efficiencies varied widely and did not follow any clear pattern.

Table 22. Regency Pond 1998 Pollutant Removal Efficiencies (%)

Parameter	Spring	Summer	Autumn	Winter	Annual Average
TDS	-13	6	15	18	10
TSS	82	9	7	44	54
VSS	77	-27	-20	70	66
FC	4	1	54	35	24
TP	71	-30	2	15	24
DP	33	59	35	13	34
TN	45	-8	-51	31	32
D-NH_4-N	31	3	65	-23	11
Dissolved NO_{2+3}-N	18	32	24	20	22
TDN	24	24	-1	26	24
Total Cu	58	6	0	-30	10
Total Fe	73	-31	-22	-59	6
Total Pb	30	-15	0	-63	-7
Total Zn	53	4	0	-67	5

Table 23. Regency Wetland 1998 Pollutant Removal Efficiencies (%)

Parameter	Spring	Summer	Autumn	Winter	Annual Average
TDS	-5	2	-8	-54	-34
TSS	-43	-200	-13	-70	-72
VSS	-20	-43	6	-476	-217
FC	77	63	29	-8	28
TP	17	-143	-29	-45	-43
DP	0	18	-53	-65	-28
TN	33	-10	5	-70	-18
D-NH_4-N	-3	5	50	8	5
Dissolved NO_{2+3}-N	14	-15	1	15	8
TDN	-2	-2	20	-11	-5
Total Cu	-50	66	0	-35	-10
Total Fe	-6	-143	-13	-53	-51
Total Pb	21	33	25	-42	-7
Total Zn	-53	0	0	-31	-34

Table 24. 1998 Pollutant Removal Efficiencies (%) for Regency Pond-Wetland System

Parameter	Spring	Summer	Autumn	Winter	Annual Average
TDS	-20	8	8	-26	-20
TSS	74	-174	-5	5	21
VSS	72	-82	-13	-73	-6
FC	78	63	67	29	45
TP	76	-216	-26	-23	-9
DP	33	67	0	-43	15
TN	63	-19	-44	-17	20
D-NH_4-N	29	8	83	-13	16
Dissolved NO_{2+3}-N	30	22	25	32	29
TDN	23	23	19	18	21
Total Cu	37	68	0	-76	1
Total Fe	71	-218	-37	-144	-43
Total Pb	45	23	25	-132	-14
Total Zn	29	4	0	-118	-27

The monitoring data indicated that the Regency wetland was a net generator of pollutants such as TDS, TSS, VSS, TP, DP, TN, and TDN and total Cu, Fe, Pb, and Zn. It is possible that the negative removal efficiencies measured for the wetland were due to a systematic sampling error at one or more of the monitoring locations. However, we have reviewed the monitoring protocols and have not been able to identify any consistent bias in the sample collection and analysis methods. A number of previous investigators have found that wetlands can be net generators of pollutants (Strecker et al. 1992; US EPA 1993; Brown and Schueler 1997).

During base-flow periods, particulate pollutant concentrations (TSS, VSS, TP, TN, and total metals) downstream of the wetland were typically less than concentrations entering the wetland (i.e., discharging from the pond). However, during storm-flow periods, particulate pollutant concentrations (TSS, VSS, TP, TN, and total metals) downstream of the wetland frequently exceeded concentrations discharging from the pond, and in some cases exceeded concentrations in the pond influent suggesting that erosion of the stream channel or other areas within the wetland may have generated suspended solids and associated pollutants.

Overall, the pollutant removal efficiency of the combined pond-wetland system was low. This is likely due to the small size of both the pond and wetland in relation to the watershed area.

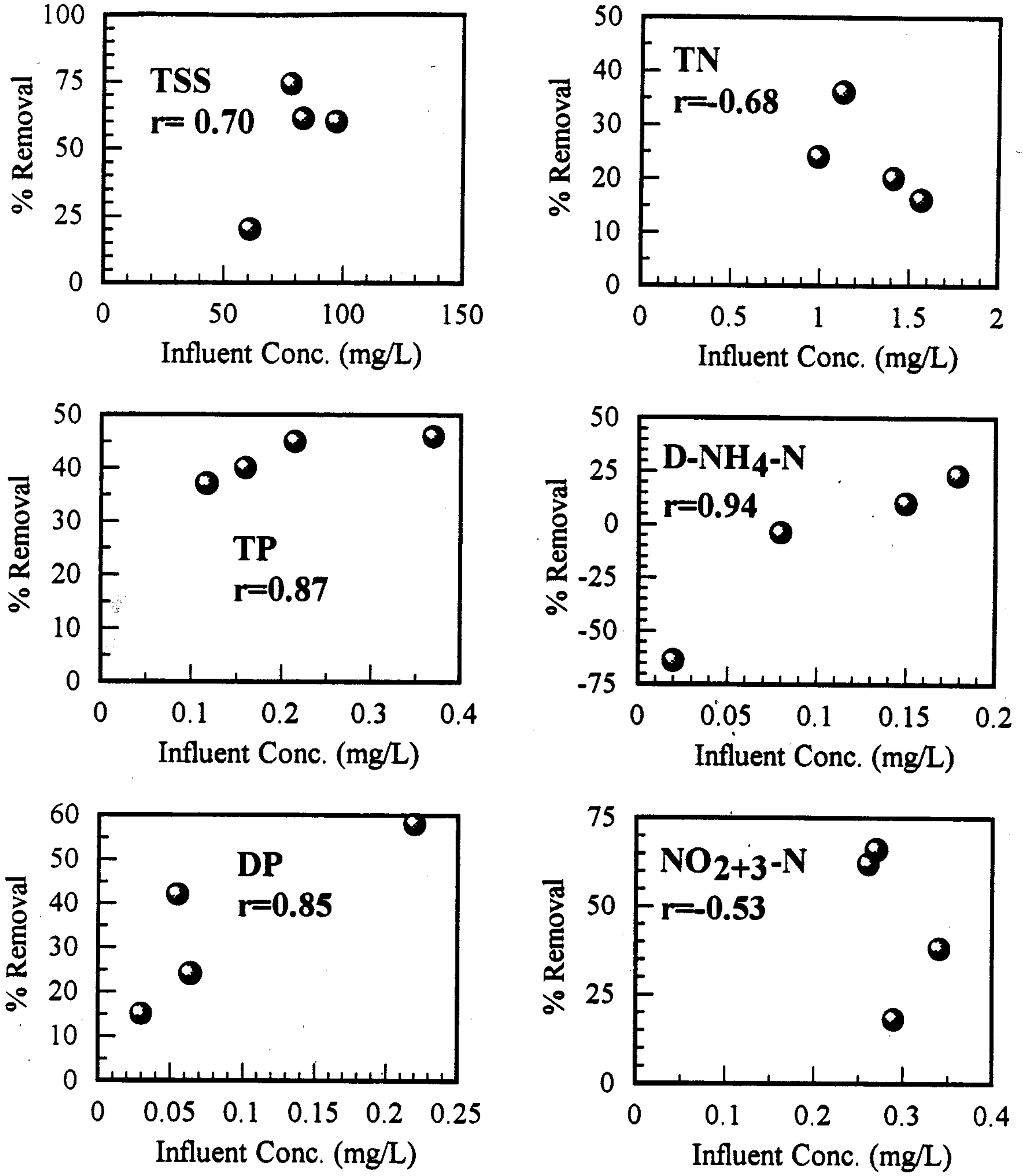
ANALYSIS OF POLLUTANT REMOVAL EFFICIENCY IN WET DETENTION PONDS

A simple statistical analysis was performed to identify variables in pond design that may influence trap efficiency for the following pollutants: TSS, TP, DP, TN, D-NH_4-N, and NO_{2+3}-N. The variables examined included permanent pool storage volume (inches over watershed area), permanent pool hydraulic retention time (days), permanent pool mean depth (ft), ratio of pond surface area to drainage basin area (%), temporary pool storage volume (inches over watershed), and average influent concentration for each pollutant. The primary data used for this analysis were the measured average annual removal efficiencies for Davis Pond, Piedmont Pond, Mall Pond A, and Mall Pond B. Results from the Regency Pond and Wetland were not used in this analysis. The Regency results were excluded because these results were so different in terms of BMP size and observed removal efficiency that inclusion of these data would significantly bias the analysis. The reader is cautioned against placing any great weight on this statistical analysis because of the very small sample size ($n = 4$). However, the results may be useful for identifying areas for further research.

None of the basin-size parameters showed any significant correlation ($r^2 > 0.5$) with pollutant removal efficiency. This is not surprising given that all the ponds were similarly sized. The parameters that most consistently correlated with trap efficiency were the influent concentrations for each pollutant. Figure 11 shows a comparison of average influent concentration vs. average annual removal efficiency for the major pollutants.

Current NCDENR standards required that wet detention ponds be designed to achieve 85% TSS removal. This approach is based on the assumption that high TSS removal will usually result in higher removal efficiencies for other pollutants. In the statistical analysis, TSS was positively correlated with pollutant removal ($r^2 > 0.5$) for one parameter (D-NH_4-N) and not correlated ($r^2 < 0.5$) or negatively correlated with pollutant removal for five parameters (VSS, TP, DP, TN, and NO_{2+3}-N). This indicates that for the four regional detention ponds operated by the City of High Point, TSS removal is a poor predictor of pollutant removal efficiencies for most other pollutants, and design modifications that enhance TSS removal may or may not enhance the removal of other pollutants.

Figure 11. Comparison of Average Annual Concentrations (conc.) in Pond Influent and Annual Removal Efficiencies for TSS, TP, DP, TN, D-NH_4-N, and NO_{2+3}-N



The pollutants that showed the strongest correlation with removal efficiency were the ones that had the greatest variation in influent concentration (TSS, TP, DP and NH_4). For all of these pollutants, higher influent concentrations correlated with higher pollutant removal efficiencies.

Both NO_{2+3}-N and TN showed a weak negative correlation with influent concentration. The reason for this is not known but may be related to the small variation in the influent concentration for these pollutants. Again, the reader is cautioned against generalizing these results given the very small data set used in this analysis—the only correlation that was statistically significant at the 90% level was for D-NH_4-N.

COST EFFECTIVENESS COMPARISON OF THE FIVE WET DETENTION PONDS

A simple analysis was performed to compare the pollutant removal benefits provided by each of the five wet detention ponds (Davis, Piedmont, Pond A, Pond B, and Regency pond [Regency Wetland not considered]) vs. the initial construction cost for each structure. Pollutant removal benefits were assumed to be equal to the pounds of TSS, TP, and TN removed by each structure. Actual construction costs were not available, so initial capital costs were estimated using the empirical cost function for large wet ponds developed by Schueler (1987) updated to Year 2000 dollars using the applicable Engineering New Record Construction Cost Indices. While the average removal efficiency of the Regency Pond was significantly lower than the other ponds, pounds of pollutant removed per dollar of capital cost were much higher because of the very large watershed treated by this small structure and the high pollutant concentration entering the pond (Table 25). If this performance could be achieved at other locations, it might be beneficial to construct BMPs even if they cannot be sized following standard design guidelines. However, the Regency wetland released more pollutants than entered the wetland portion of the BMP. This suggests that, in some cases, undersized BMPs may actually be net generators of pollutants and should be installed with great caution.

Table 25. Pounds per Year of Pollutant Removal per Dollar Initial Capital Cost

Parameter	Davis	Piedmont	Pond A	Pond B	Regency
TSS	0.17	0.05	0.27	0.18	14.79
TP	0.00045	0.00026	0.00051	0.00014	0.00958
TN	0.00031	0.00176	0.00148	0.00077	0.02000

SIMULATION OF POLLUTANT TRAP EFFICIENCY

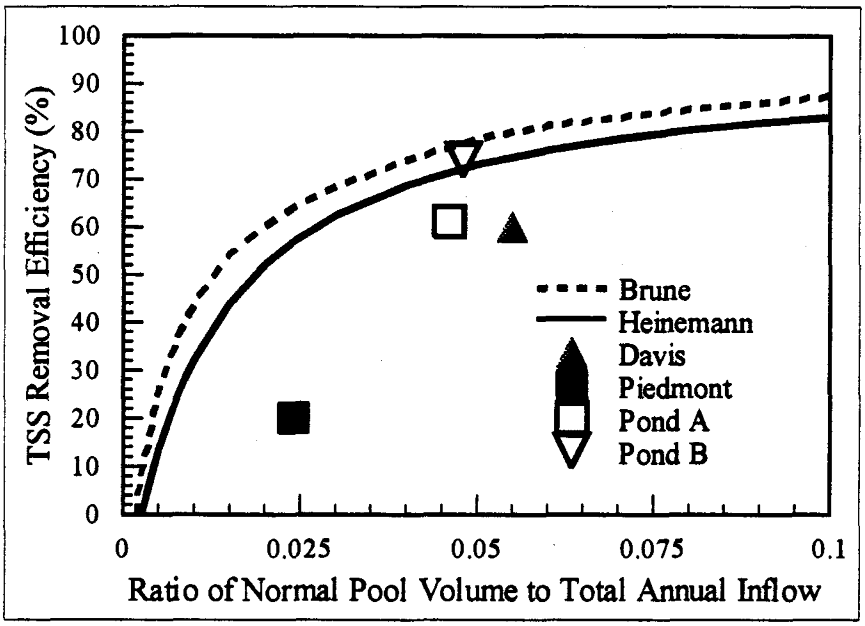
Three different approaches were evaluated to determine their accuracy and utility in simulating pollutant removal in wet detention ponds:

1. Empirical trap efficiency curves generated by Brune (1953) and Heinemann (1971).
2. A stochastic sedimentation model developed by Driscoll et al. (1986) to simulated removal of particulate pollutants in wet detention ponds assuming a stochastic distribution of storm flows.
3. An empirical model developed by Reckhow (1988) to estimate in-lake nitrogen and phosphorus concentration in southeastern lakes and reservoirs.

EMPIRICAL TRAP EFFICIENCY CURVES

Brune (1953) used data from 44 large reservoirs to develop an empirical curve relating reservoir trap efficiency versus the ratio of total reservoir volume to total annual inflow. Heinemann (1971) later developed a curve similar to Brune's using data from 20 smaller reservoirs (watershed areas < 15 square miles). Predicted and observed trap efficiencies are compared in Figure 12.

Figure 12. Comparison of Brune and Heinemann Curves with Observed TSS Removal in Regional Wet Detention Ponds



Heinemann's curve very closely matched the observed TSS trap efficiency for Mall Pond B and slightly overpredicted trap efficiency for Mall Pond A and Davis Pond. The predicted removal efficiency for Brune's curve is always higher than Heinemann's, and consequently the prediction error is greater. All the methods significantly overpredicted TSS removal efficiency for Piedmont Pond. This is not unexpected since there is a large stormwater pond immediately upstream of Piedmont that traps much of the coarser sediment.

STOCHASTIC SEDIMENTATION MODEL

Theory

As part of the National Urban Runoff Program (NURP), Driscoll et al. (1986) developed a procedure for estimating annual sediment removal in wet detention ponds. This procedure is based on a stochastic approach that accounts for trapping under storm-flow conditions and also sedimentation during the quiescent conditions that occur following the storm. Rainfall volume and associated storm runoff are represented by a gamma distribution. Settling efficiency (E) during an individual storm is determined using Hazen's equation (Fair et al. 1971) for several different ranges of particle settling velocities and summed to determine the total removal efficiency for the basin.

$$E = 1 - \left[1 + \frac{v_o A}{NQ} \right]^{-N} \tag{1}$$

where

E = settling efficiency of a particle with settling velocity of v (ft/sec)
Q = flow rate (cfs)
A = pond surface area (square ft)
N = effective number of cells in settling zone (dimensionless)

N is an index of basin performance, where N equals 1 for very poor performance and N is greater than 5 for very good performance.

One very important factor controlling the efficiency of sediment trapping is settling velocity distribution of the suspended sediment. Shown in Table 26 are settling velocity distributions measured by Driscoll et al. (1986), Wu (1989), and Borden et al. (1997). Driscoll et al. (1986) developed a national cross-sectional average settling velocity distribution for particles in urban stormwater runoff. Their estimates were based on samples taken at sites across the country for multiple storm events at each site. Wu (1989) analyzed ten different stormwater runoff samples from a single location in the Charlotte area to develop a settling velocity distribution that might be more representative of the North Carolina Piedmont. Borden et al. (1997) measured the settling velocity distribution of sediments in each of the two principal tributaries to Davis Pond during one storm event.

Wu's results indicate that NURP settling velocity distribution may be too high for application to Piedmont detention basins. The low settling velocities found by Wu may be due to the predominance of fine-grained soils in the Piedmont of North Carolina.

Result

Driscoll's method was used to calculate removal efficiencies for Mall Pond A, Mall Pond B, and the Regency Pond using runoff statistics for the monitoring period (Table 26). Also included for comparison are predicted and observed removal efficiencies for Davis and Piedmont Ponds (Table 27). Removal efficiencies were calculated using the NURP settling velocity distribution and the measured settling velocity distribution from Davis Pond. The basin performance index, N, was set equal to 1 which is equivalent to a completely mixed basin.

Table 26. Settling Velocity Distributions for Particulates in Stormwater

Size Fraction	Mass Fraction (%)	Driscoll Settling Velocity (US EPA, 1983) (ft/hr)	Wu (1989) Average Settling Velocity (ft/hr)	Davis Pond Settling Velocity (Borden et al., 1997) (ft/hr)
1	0 to 20	0.03	0.01	0.04
2	20 to 40	0.30	0.08	0.44
3	40 to 60	1.50	0.40	0.93
4	60 to 80	7.00	1.80	1.90
5	80 to 100	65.00	6.00	4.44

Table 27. Comparison of Measured and Predicted Annual TSS Removal Efficiencies (%) using the Stochastic Sedimentation Model

	Mall Pond A	Mall Pond B	Regency Pond	Davis Pond	Piedmont Pond
Observed Removal Efficiency	61	74	54	60	20
Predicted Removal Efficiency, NURP Size Distribution	73	80	18	83	83
Predicted Removal Efficiency, Wu's Size Distribution	59	69	13	71	71
Predicted Removal Efficiency, Davis Pond Size Distribution	67	77	14	82	81

Driscoll's stochastic sedimentation model provided reasonable predictions of TSS removal efficiency in Mall Pond A and Mall Pond B. Predicted removal efficiency most closely matched observed removal efficiency when the settling velocity distribution measured by Wu was used in the calculations. Driscoll's model significantly over estimated removal efficiency in Piedmont Pond. This error was presumably due to the removal of most coarse-grained sediments in the pond upstream from Piedmont. Driscoll's model significantly underestimated removal efficiency for the Regency Pond. The measured removal efficiency for Regency Pond was probably higher than is typical due to the large amount of coarse-grained sediment entering Regency from a construction site immediately upstream.

RECKHOW'S MODEL

A variety of empirical models have been developed to predict lake phosphorus and chlorophyll-a concentrations in the growing season for northern temperate natural lakes (Canfield and Bachman 1981; Larsen and Mercier 1976; Rast and Lee 1978; Vollenweider 1976; Walker 1977; Walker 1985). However, relatively few models have been developed to predict TN Concentration (Walker 1985). Typically, the empirical models assume the lake or reservoir can be modeled as a continuously stirred tank reactor (CSTR) with nutrient trapping proportional to the hydraulic residence time (Tw) or surface overflow rate. In a CSTR, the concentration of any compound in the reactor is equal to the effluent concentration, and as a result these models can be adapted easily to predict pollutant removal efficiency.

Application

In this work, we applied an empirical model developed by Reckhow (1988) for lakes and reservoirs of the southeastern United States to predict TN and TP removal efficiency in Mall Ponds A and B. Reckhow analyzed data collected as part of the US EPA's National Eutrophication Survey (NES) for 80 lakes and reservoirs in 9 southeastern states. Because of gaps and inconsistencies in the data set, 70 lakes were used in the development of the TP model and 47 in the TN model. In the NES survey, data related to trophic status were compiled for numerous lakes and reservoirs throughout the United States over a one-year period. Each lake was sampled at least once in the spring, summer, and fall at several depths for basic water quality and trophic status variables. Nitrogen and phosphorus loading and discharges were measured or estimated over the one-year period. Generally when nutrient concentrations were sampled, 12 to 14 samples were taken at evenly spaced time intervals over the year.

The nutrient models developed by Reckhow assume each lake may be modeled as a CSTR. Under steady state conditions, the average in-lake nutrient concentration (C in mg/L) during the growing season can be estimated by C = Cin / (1+ k Tw), where Cin is the average influent nutrient concentration (mg/L) and k is a nutrient trapping parameter (yr^{-1}).

Reckhow (1988) found that the TP trapping parameter (k_P) was a function of the mean annual influent TP concentration (P_{in}), hydraulic detention time (T_W), and mean depth (z), such that

$$\text{Log } P = \text{Log}\left(\frac{P_{in}}{1 + k_P T_w}\right) \tag{2}$$

where

$$k_P = 3.0 \cdot (P_{in})^{0.53} \cdot (T_w)^{-0.75} \cdot (z)^{0.58} \tag{3}$$

The expression for k_P is a function of the influent phosphorus concentration, hydraulic residence time, and mean depth (z). This differs from previous results for northern temperate natural lakes, where kp was a function of Tw alone. The positive exponential on the Pin term implies that the removal efficiency of a given lake increases as the influent phosphorus concentration increases. TP removal efficiency also increases with mean depth indicating better removal in deeper lakes. Reckhow (1988) found that the TN trapping parameter (k_N) was a function of the hydraulic retention time only (i.e., the inclusion of Nin or z in the k term did not improve the equation's predictive capability). The resulting model for TN is:

$$\text{Log } N = \text{Log}\left(\frac{N_{in}}{1 + kT_w}\right) \tag{4}$$

where

$$k_N = 0.67 \cdot (T_w)^{-0.75} \tag{5}$$

If we assume that growing season nutrient concentrations are representative of annual average concentrations in the pond effluent, then annual removal efficiencies (E) can be calculated as E = (Cin – C)/Cin.

Results

Removal efficiencies and average concentration of TP and TN in Davis Pond, Piedmont Pond, and Mall Ponds A and B effluents are compared to model predictions in Table 28.

Table 28. Comparison of Empirical Model Results with Observed Performance

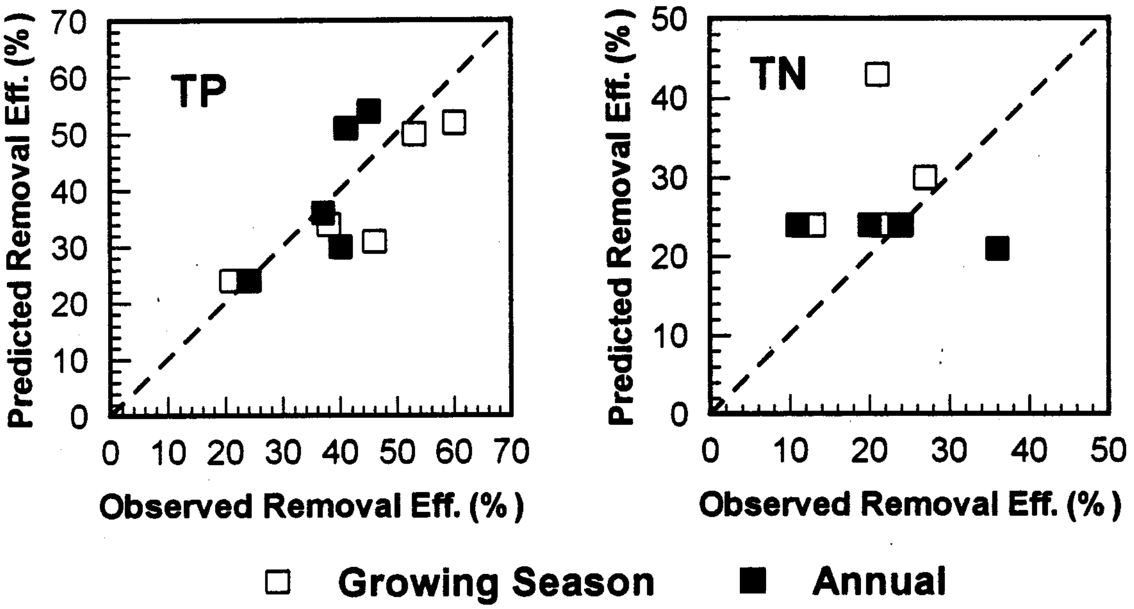
	Davis Pond		Piedmont Pond		Mall Pond A		Mall Pond B	
	TP	TN	TP	TN	TP	TN	TP	TN
Growing Season								
Measured Influent (mg/L)	0.29	1.64	0.13	1.39	0.15	1.31	0.12	0.99
Measured Effluent (mg/L)	0.12	1.15	0.07	0.79	0.07	1.14	0.07	0.79
Predicted Effluent (mg/L)	0.14	1.19	0.09	1.10	0.08	0.99	0.08	0.76
Observed Removal Efficiency (%)	60	27	46	21	53	13	38	21
Predicted Removal Efficiency (%)	52	30	31	43	50	24	34	24
Annual								
Measured Influent (mg/L)	0.36	1.63	0.12	1.14	0.22	1.42	0.12	0.99
Measured Effluent (mg/L)	0.21	1.46	0.07	0.73	0.12	1.14	0.07	0.75
Predicted Effluent (mg/L)	0.18	1.24	0.08	0.90	0.10	1.08	0.08	0.76
Observed Removal Efficiency (%)	41	11	40	36	45	20	37	24
Predicted Removal Efficiency (%)	51	24	30	21	54	24	36	24

In Mall Pond A, the TP model provided reasonably good estimates of average in-lake TP concentrations and removal efficiency during growing season. However, the TN model overestimated TN removal during the growing season. Both TP and TN models slightly overestimated annual removal efficiencies in Pond A. In Mall Pond B, the models provided very good predictions of growing season and annual removal efficiency for both TP and TN.

Figure 13 shows a comparison of predicted and observed TP removal efficiencies for Davis Pond, Piedmont Pond, Mall Pond A, and Mall Pond B for both the growing season and annual periods. The empirical TP model provided reasonably good predictions of removal efficiency for both the growing season (mean error = +8%, RMSE = 9%) and annual (mean error = -2%, RMSE = 8%). In general, when the model predicted higher removal efficiencies, this was reflected in the measured performance in the field with no significant positive or negative bias.

Figure 13 also shows a comparison of predicted and observed TN removal efficiencies for the four ponds for the growing season and annual periods. There was no significant positive or negative bias in the TN model predictions (average error for growing season = -10% and for entire year = -0.5%). However, the TN did not match the observed variation in removal efficiency between ponds.

Figure 13. Comparison of TP and TN Model Predictions with Observed Performance



In summary, Reckhow's empirical model provided reasonably good estimates of TP and TN removal efficiencies of the four regional wet detention ponds.

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Godin, J. A. 1998. Modeling and analysis of the Regency Pond-Wetland system. M.S. Thesis, Department of Civil Engineering, North Carolina State University.

GLOSSARY OF ABBREVIATIONS

Ag	Silver
BMPs	Best Management Practices
Cd	Cadmium
cfs	Cubic Feet per Second
CHL	Chlorophyll-a
Co	Cobalt
Cr	Chromium
CSTR	Continuously Stirred Tank Reactor
Cu	Copper
DN	Dissolved Nitrogen
D-NH_4-N	Dissolved Ammonia as Nitrogen
DO	Dissolved Oxygen
DP	Dissolved Phosphorus
FC	Fecal Coliform
Fe	Iron
Hg	Mercury
K	Potassium
Mn	Manganese
N	Nitrogen
NCDENR	N.C. Department of Environment and Natural Resources (formerly N.C. Department of Environment, Health and Natural Resources—NCDENHR)
NCTSI	North Carolina Trophic State Index
Ni	Nickel
NO_{2+3}-N	Combined Nitrate + Nitrite as Nitrogen

NURP	National Urban Runoff Program
P	Phosphorus
Pb	Lead
PCBs	Polychlorinated Biphenyls
SCADA	Supervisory Control and Data Acquisition
SD	Secchi Disk
TDN	Total Dissolved Nitrogen
TDS	Total Dissolved Solids
TN	Total Nitrogen
TON	Total Organic Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
TVS	Total Volatile Solids
US EPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Service
VSS	Volatile Suspended Solids
Zn	Zinc