Pollutant Removal Efficacy of Three Wet Detention Ponds

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ABSTRACT

Monthly inflow and outflow data were collected from three wet detention ponds in Wilmington, North Carolina, for a 29-mo period. Two ponds drained urban areas consisting primarily of residential, mixed services, and retail usage, while the third mainly drained residential and golf course areas. One of the urban ponds achieved significant reductions in total nitrogen, nitrate, ammonium, total phosphorus, orthophosphate, and fecal coliform bacterial counts. This pond was characterized by a high length to width ratio, with most inputs directed into the upper area, and extensive coverage by a diverse community of aquatic macrophyte vegetation. The second urban pond achieved significant reductions in turbidity and fecal coliform bacterial counts, but there were no significant differences between inflowing and outflowing water nutrient concentrations. There were substantial suburban runoff inputs entering the mid- and lower-pond areas that short-circuited pollutant removal contact time. The golf course pond showed significant increases in nitrate, ammonium, total phosphorus, and orthophosphate in the outflow relative to the inflow, probably as a result of course fertilization. However, nutrient concentrations in the outflow water were low compared with discharges from a selection of other area golf courses, possibly a result of the outflow passing through a wooded wetland following pond discharge. To achieve good reduction in a variety of pollutants, wet pond design should include maximizing the contact time of inflowing water with rooted vegetation and organic sediments. This can be achieved through a physical pond design that provides a high length to width ratio, and planting of native macrophyte species.

Wet detention ponds are commonly used as a means to reduce pollutant levels in urban and suburban stormwater. In general, these ponds are designed primarily to reduce suspended sediments. For example, in North Carolina the only pollutant removal criterion required is an 85% reduction in suspended solids (North Carolina Department of Environment, Health, and Natural Resources, 1995). However, these ponds can effectively reduce concentrations of other pollutants such as nutrients, fecal bacteria, and heavy metals, depending on the situation. Schueler (1994) reviewed a broad selection of detention pond performance studies and found generally good removal of suspended solids, variable removal of phosphorus, and rather poor removal efficiencies for nitrogen. Within New Hanover County, North Carolina, where the present research was conducted, Cahoon (1994) conducted a survey of 16 wet detention ponds. He found that approximately half of the ponds surveyed had higher total phosphorus in the pond effluents than at sites within the ponds, and several of the ponds exported higher concentrations of chlorophyll *a* as well. In the North Carolina piedmont, Borden et al. (1997) found that two large wet detention ponds in close proximity to each other had very different pollutant removal performances. Factors influencing this included detention time, incoming nutrient load and algal bloom formation in-pond, and incoming sediment size. Schueler (1994) concluded that two important factors influencing wet pond performance were the nature of the techniques used for treatment and internal design geometry of the system.

As part of a large-scale water quality analysis of freshwater and estuarine streams in New Hanover County (Mallin et al., 1999), three wet detention ponds, all within the boundary of the City of Wilmington, were analyzed for pollutant removal performance. Sampling was conducted on a pre-set schedule, with no attempt made to favor either rain events or dry periods. The streams entering and exiting the ponds maintained sufficient water depth for sample collection year-round.

SITE DESCRIPTION

Ann McCrary Pond, located in the Burnt Mill Creek watershed, is a large (8.82 ha) regional wet detention pond approximately 700 m in length with a length to width ratio of 4.5 (Table 1; Fig. 1). It was built in 1990 and primarily drains mixed retail and residential land use, including both single-family and multiple-family residences. The pond contains two islands within the basin (Fig. 1). It was sampled at three locations: at the inflow to the pond (AP1), along shore at mid-pond (AP2), and about 40 m downstream of the pond outfall (AP3) (Fig. 1). The pond itself usually maintains a thick growth of submersed aquatic vegetation, particularly Florida elodea [*Hydrilla verticillata* (L. f.) Royle], Brazilian elodea (*Egeria densa* Planch.), alligatorweed [*Alternanthera philoxeroides* (Mart.) Griseb.], coontail (*Ceratophyllum demersum* L.), and tapegrass (*Vallisneria americana* Michx.), with lesser coverage of parrotfeather [*Myriophyllum aquaticum* (Vell.) Verdc.], soft rush (*Juncus effusus* L.), and false water-pepper (*Polygonum hydropiperoides* Michx.). A survey in late summer 1998 indicated that approximately 70% of the pond area was vegetated. There have been efforts to control this growth, including addition of triploid grass carp (*Ctenopharyngodon idella* Val.) as grazers. Varying amounts of waterfowl also use this pond, particularly the middle and lower reaches. During the early portion of the study active apartment construction was under-

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Abbreviations: TSS, total suspended solids.

Table 1. Comparison of attributes for three wet detention ponds in New Hanover County, North Carolina, USA.

Attribute	Ann McCrary	Silver Stream	Echo Farms
Surface area (SA), ha	8.82	1.04	0.51
Drainage area† (DA), ha	378.4	28.7	56.7
DA/SA	42.9	27.6	111.2
Total drainage area (TDA), ha	874.4	93.5	68.3
TDA/SA	99.1	89.9	133.9
Length, m	700	upper 209 lower 216 total 425	upper 142 lower 85 total 227
Average width, m	155	upper 21 lower 28 total 24	upper 23 lower 18 total 21
Length to width ratio	4.5	upper 10.0 lower 7.7 total 17.7	upper 6.2 lower 4.7 total 10.8
Maximum width, m	246	53	30
Mean depth, m	1.8	0.6	2.0
Volume, m^3	158 760	6 240	10 200
Major land uses, %	residential, 31 undeveloped, 25 mixed services, 17 retail, 13	mixed services, 36 residential, 23 undeveloped, 21	undeveloped, 55 residential, 18 gold course, 12

† Area draining into uppermost pond sampling station only.

way near AP1; during the last year of the study construction efforts were largely completed and the apartments were largely occupied.

Greenfield Lake is an urban lake that is considered to have severely degraded water quality (Mallin et al., 1999; North Carolina Department of Environment, Health, and Natural Resources, 1996). One of the major pollution mitigation features in the Greenfield Lake watershed is an extensive wet detention pond along the Silver Stream branch (Fig. 2) built in 1991. The total length of the pond is 425 m, and it has a length to width ratio of 17.7 (Table 1). The pond is divided into an upper and lower basin by a causeway pierced by three pipes connecting the flow. In early summer 1998 approximately 70% of the upper pond was covered by a mixture of floating and emergent aquatic macrophyte vegetation, with about 40% of the lower pond covered by vegetation. Principle species in the upper basin were alligatorweed, pennywort (*Hydrocotyle umbellata* L.), water primrose [*Ludwigia leptocarpa* (Nutt.) Hara]), and cattail (*Typha latifolia* L.), with lesser coverage of duckweed (*Lemna perpusilla* Torr.), reed [*Phragmites australis* (Cav.) Trin. ex Steud.] and rushes (*Juncus effusus* L., *J. polycepalus* Michx., and *J. coriaceus* MacKenzie). Vegetation coverage in the lower basin was dominated by alligatorweed, water primrose, and cattail, with lesser amounts of pennywort and pickerelweed (*Pontederia cordata* L.).

The third pond is located on the Echo Farms Country Club, in the Barnard's Creek watershed (Fig. 3). It was constructed about 1970, and it is also divided into an upper and lower pond by a narrow causeway (Fig. 3). Pond length is about 227 m, with a length to width ratio of 10.8. A portion of the golf course drainage enters the pond, which discharges through about 210 m of wooded wetland (Fig. 3). The headwaters of the pond also accept suburban drainage from a residential area of approximately 57 ha (Table 1). Aquatic macrophyte coverage in June 2000 consisted primarily of alligatorweed, parrotfeather, and cattail, with total surface coverage of approximately 45%. We sampled a pond input station draining the suburban area (EF1) and the pond outflow exiting the riparian wetland (EF2).

Areal coverage of aquatic vegetation was estimated as follows. Five biologists made visual estimates of percent coverage of each pond. The independent estimates were compared and percent coverage was derived by consensus. Samples were collected of the vegetation, returned to the laboratory, and identified using the following primary references: Beal (1977), Radford et al. (1983), and Weldon et al. (1973).

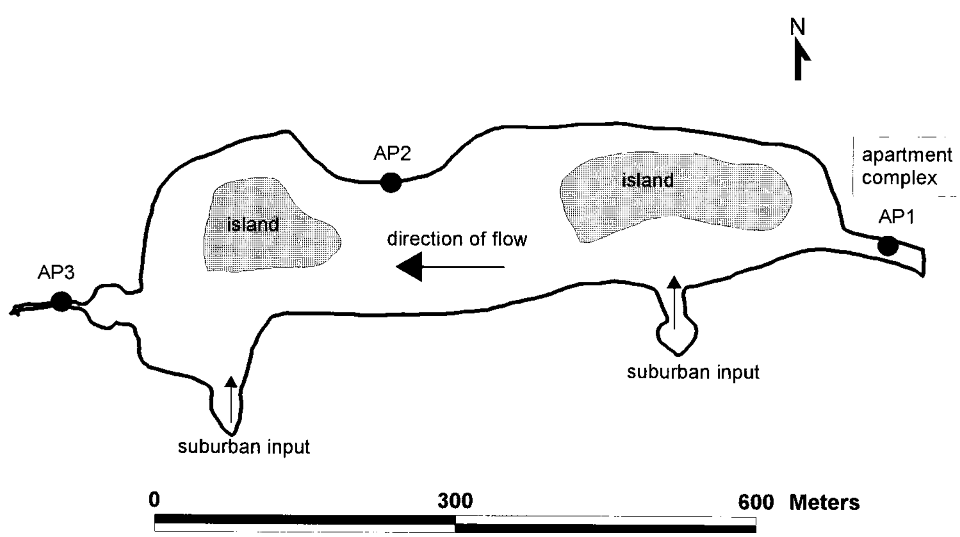

Fig. 1. Ann McCrary Regional Wet Detention Pond. AP1, inflow station; AP2, midpond station; AP3, outflow station.

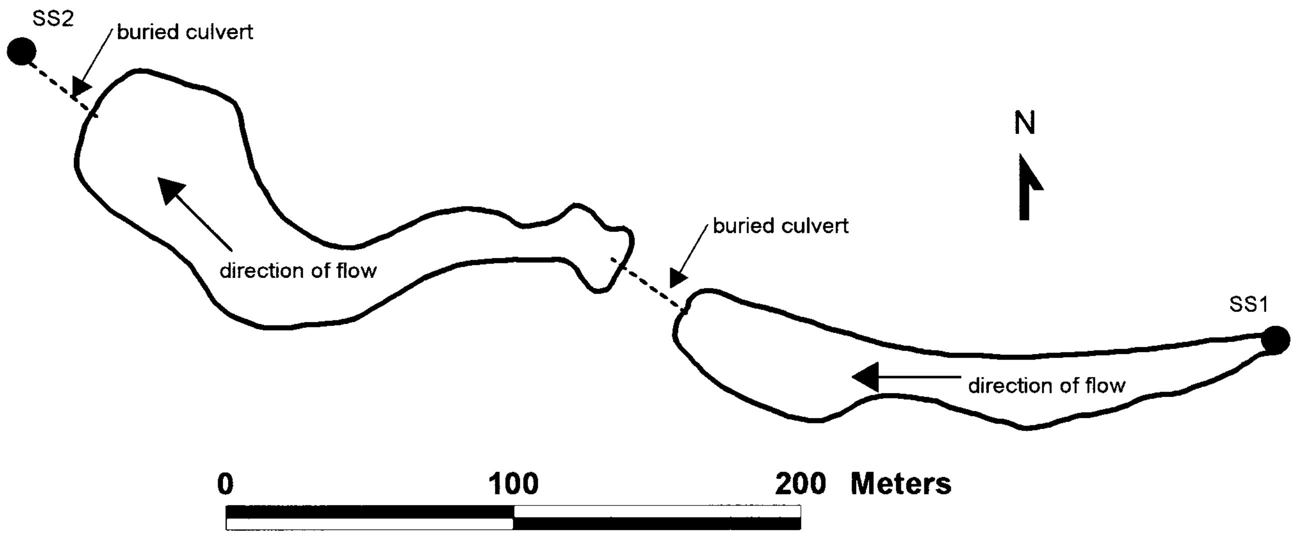

Fig. 2. Silver Stream Wet Detention Pond. SS1, inflow station; SS2, outflow station.

Pond dimensions were measured using aerial photographs. The islands in Ann McCrary Pond were excluded from surface area computations. Average pond width was computed by determining pond width at 50-ft (15.2-m) intervals for Silver Stream and Echo Farms Ponds and 100-ft (30.4-m) intervals for Ann McCrary Pond, and computing averages from these data. Impervious surfaces were measured in Arcview (Environmental Systems Research Institute, 1999) using data layers provided by the City of Wilmington and New Hanover County. Impervious surfaces measured consisted of all concrete, asphalt, and gravel areas (excluding state-owned right-of-ways and residential parcels) and commercial–industrial building footprints. A factor of 26% was applied to all residential parcels to estimate impervious surface coverage. A factor of 50% was used to estimate impervious coverage on state-owned right-of-ways. Catchments were delineated using ESRI's Watershed Delineator (Environmental Systems Research Institute, 1998) and a 50-ft Digital Elevation Model developed by the City of Wilmington Stormwater Services.

MATERIALS AND METHODS

Sampling was conducted on a monthly basis from October 1997 through February 2000. Field parameters were measured at each site using either a YSI (Yellow Springs, OH) 6920 multiparameter water quality probe (sonde) linked to a YSI 610 display unit, or a Solomat 803PS multiparameter sonde coupled with a Solomat 803 datalogger (Solomat Neotronics, Norwalk, CT). Individual probes within the instruments measured water temperature, pH, dissolved oxygen, turbidity, and conductivity. The instruments were calibrated prior to each sampling trip to ensure accurate measurements.

For chlorophyll *a* samples, three replicate acid-washed 125-mL bottles were placed approximately 10 cm below the surface, filled, capped, and stored on ice until processing. In the laboratory the triplicate samples were filtered simultaneously through 1.0-μm pore size glass fiber filters using a manifold with three funnels. The filters were wrapped individually in aluminum foil, placed in an airtight container containing dessicant, and stored in a freezer until analysis. During the analytical process, the glass filters were extracted in 10 mL of a 90% acetone solution for 24 h. Each solution was then analyzed for chlorophyll *a* concentrations using a Turner Model 10-AU fluorometer (Turner Designs, Sunnyvale, CA) as described in Welschmeyer (1994) and USEPA (1997). Fecal coliform samples were collected by filling pre-autoclaved containers approximately 10 cm below the surface, facing into the stream. Samples were stored on ice until processing (<6 h). Fecal

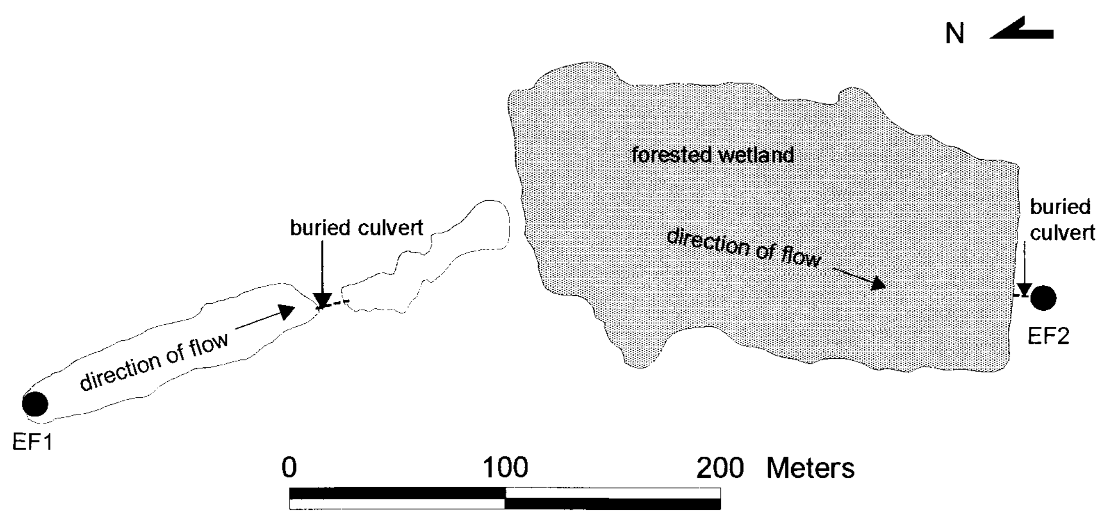

Fig. 3. Echo Farms Pond. EF1, inflow station; EF2, outflow station.

coliform concentrations were determined using a membrane filtration (mFC) method that uses a 24-h incubation time at 44.5°C and an enriched lactose medium (Method 9222-D; American Public Health Association, 1995), and reported as colony-forming units (CFU) 100 mL^{-1}.

Nutrient and total suspended solids (TSS) samples were collected in 500-mL plastic containers, stored on ice, and returned to the laboratory. Nutrients including nitrate (Method 4500-NO3 F), ammonium (Method 4500-NH3 H), total Kjeldahl nitrogen (Method 4500-Norg B), orthophosphate (Method 4500-P E), and total phosphorus (Method 4500-P E with persulfate digestion) and total suspended solids (Method 2540-D) were analyzed according to standard methods of the American Public Health Association (1995). Total nitrogen was computed as total Kjeldahl nitrogen plus nitrate. We also computed inorganic nitrogen to phosphorus molar ratios for relevant sites (N to P ratio). Sediment samples for USEPA priority pollutant metals were collected in triplicate from inflow and outflow sites for all three ponds. A clear plexiglass tube was used to collect the top 5 cm of sediment, which was stored frozen until analysis. USEPA methods were used for digestion (Method 3050B) and inductively coupled plasma (ICP) analysis (Method 200.7).

We used generated data to test for statistically significant differences in pollutant concentrations between pond input and output stations. The data were first tested for normality using the Shapiro–Wilk test. Normally distributed data parameters were tested using the paired-difference *t* test, and nonnormally distributed data parameters were tested using the Wilcoxon Signed Rank test. Sediment metal concentrations for input and outflow pond stations were compared using *t* tests. Rainfall data were obtained from the Wilmington Airport, and the effects of rainfall on the day of sampling and within the 1- and 2-d periods prior to day of sampling were compared with inflow and outflow constituent concentrations using correlation analysis. All statistical analyses were conducted using SAS (Schlotzhauer and Littell, 1987).

RESULTS

Long-Term Pond Performance

The performance of Ann McCrary Pond was mixed (Table 2). Specific conductance, turbidity, and fecal coliform bacterial counts all showed statistically significant decreases between the inflow and outflow stations, with fecal coliforms decreasing by approximately 56% overall. Dissolved oxygen, pH, and chlorophyll *a* all showed significant increases. There were no statistically significant changes in nutrient concentrations or total suspended solids. The inorganic molar nitrogen to phosphorus ratio decreased by half, indicating that there was somewhat greater removal of nitrogen compared with phosphorus (Table 2).

Sediment metals were analyzed from the input (AP1) and outflow (AP3) stations of Ann McCrary Pond (Table 3). Concentrations were generally low entering the pond, but tended to increase at the outflow station. Increases in arsenic, iron, and nickel were all statistically significant. However, sediment metals at AP3 were still well below levels considered harmful to aquatic life (Long et al., 1995).

The Silver Stream wet detention pond achieved a high degree of success in pollutant removal (Table 4). Statistically significant decreases were realized for specific conductance, fecal coliform bacteria, and all nutrient parameters except for total Kjeldahl nitrogen. Dissolved oxygen and pH significantly increased. Particularly high reduction occurred for fecal coliform bacteria (86%), ammonium (83%), orthophosphate (77%), and nitrate (63%). The inorganic N to P ratio increased only slightly during pond passage. Turbidity and suspended solids were generally low entering the pond and did not significantly change.

Sediment metals were analyzed at the input (SS1) and output (SS2) stations of Silver Stream wet detention pond. All sediment metals except mercury were lower

Table 2. Mean and (standard deviation) of water quality parameters in Ann McCrary wet detention pond. AP1, input; AP2, mid-pond; AP3, outflow. Fecal coliforms are given as geometric mean, inorganic N to P molar ratio as median. n = 29 mo.

Parameter	AP1	AP2	AP3
Dissolved oxygen, mg L^{-1}	7.2 (1.2)	8.0 (2.2)	9.3 (1.5)**
Conductivity, μS cm^{-1}	272 (27)	235 (44)	233 (56)**
pH	6.6 (0.5)	7.2 (0.4)	7.2 (0.6)**
Turbidity, NTU	22.0 (40.0)	12.0 (20.0)	9.0 (13.0)*
Total suspended solids, mg L^{-1}	10.5 (37.2)	4.4 (3.4)	3.7 (2.9)
Nitrate, mg L^{-1}	0.236 (0.417)	0.158 (0.171)	0.224 (0.507)
Ammonium, mg L^{-1}	0.077 (0.041)	0.058 (0.078)	0.055 (0.070)
Total N, mg L^{-1}	0.622 (0.540)	0.631 (0.357)	0.645 (0.527)
Phosphate, mg L^{-1}	0.028 (0.022)	0.023 (0.026)	0.026 (0.025)
Total P, mg L^{-1}	0.061 (0.073)	0.039 (0.026)	0.047 (0.037)
N to P molar ratio	16.9	13.7	8.1
Fecal coliforms, 100 mL^{-1}	488	124	70**
Chlorophyll *a*, μg L^{-1}	2.4 (2.6)	5.6 (6.2)	5.0 (5.7)*

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.

Table 3. Mean and standard deviation of sediment metal concentrations in input and output waters of Ann McCrary wet detention pond. AP1, input; AP3, outflow.

Parameter	AP1	AP3
	mg kg^{-1}	
Al	395.0 (120.8)	790.3 (176.2)
As	0.022 (0.009)	0.130 (0.036)*
Cd	0.051 (0.006)	0.093 (0.016)
Cr	0.97 (0.06)	1.01 (0.41)
Cu	0.45 (0.08)	0.78 (0.14)
Fe	180.3 (41.0)	773.0 (86.5)*
Pb	1.46 (0.22)	1.45 (0.51)
Hg	0.003 (0.000)	0.004 (0.002)
Ni	0.21 (0.05)	0.53 (0.12)*
Zn	3.71 (0.44)	3.81 (1.86)

* Significant at the 0.05 probability level.

Table 4. Comparison of pollutant concentrations in input (SS1) and output (SS2) waters of Silver Stream regional wet detention pond. Fecal coliforms are given as geometric mean, inorganic N to P molar ratio as median. n = 29 mo.

Parameter	SS1	SS2
Dissolved oxygen, mg L^{-1}	5.8 (1.9)	7.9 (1.8)**
Conductivity, μS cm^{-1}	203 (44)	163 (40)**
pH	6.6 (0.5)	6.8 (0.6)**
Turbidity, NTU	7.3 (14.3)	9.5 (20.9)
Total suspended solids, mg L^{-1}	4.3 (7.9)	5.9 (14.2)
Nitrate, mg L^{-1}	0.314 (0.196)	0.117 (0.109)**
Ammonium, mg L^{-1}	0.210 (0.731)	0.035 (0.034)**
Total N, mg L^{-1}	0.850 (0.399)	0.513 (0.245)**
Phosphate, mg L^{-1}	0.100 (0.083)	0.023 (0.016)**
Total P, mg L^{-1}	0.141 (0.105)	0.060 (0.034)**
N to P molar ratio	10.2	12.2
Chlorophyll *a*, μg L^{-1}	9.6 (32.9)	5.8 (7.1)
Fecal coliforms, 100 mL^{-1}	97	43*

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.

Table 5. Mean and standard deviation of sediment metals concentrations in the input (SS1) and output (SS2) stations of Silver Stream wet detention pond.

Parameter	SS1	SS2
	mg kg^{-1}	
Al	704.3 (137.4)	182.7 (38.4)*
As	0.060 (0.048)	0.028 (0.003)
Cd	0.378 (0.257)	0.077 (0.045)
Cr	3.68 (0.78)	1.21 (0.23)*
Cu	12.58 (7.99)	0.54 (0.41)
Fe	211.6 (8.92)	49.2 (1.57)*
Pb	8.92 (3.53)	1.57 (0.42)
Hg	0.010 (0.007)	0.010 (0.006)
Ni	1.85 (0.85)	0.30 (0.11)
Zn	93.4 (117.6)	1.69 (0.32)

* Significant at the 0.05 probability level.

at the pond outfall site than at the input station (Table 5). The decreases in aluminum, chromium, and iron were statistically significant. While other metal levels were reduced substantially, high variability among the replicate samples for some of the metals (i.e., copper, lead, nickel, zinc) precluded a statistically significant difference. Regardless, this pond functioned well as a metal removal system.

Echo Farms Pond differed from the others in that it received direct golf course runoff. No parameters significantly decreased, while specific conductance, pH, ammonium, nitrate, orthophosphate, and total phosphorus all significantly increased (Table 6). The inorganic N to P ratio was low entering the pond and increased slightly during passage.

Sediment metals concentrations were assessed at the input and outflow stations of the wet detention pond at Echo Farms. The wet detention pond analysis showed that every metal parameter was greater in the pond outflow than the input stream, but due to high variability among the replicate samples none of the differences was statistically significant (Table 7). All of the outflow area metal levels were below concentrations considered harmful to aquatic life (Long et al., 1995).

Effect of Rainfall on Pollutant Constituents

Rainfall during the 24 h preceding pond sampling did have some effect on constituent levels. Fecal coliform concentrations both entering and exiting all three ponds were strongly correlated with rainfall occurring the day of sample collection (Table 8). Turbidity and TSS entering and exiting the ponds were correlated primarily with cumulative rainfall for the day of sample plus one day previous (Table 8). Nutrient (except for ammonium) movement into and out of the ponds was primarily related to the cumulative rainfall for the day of sample plus the two preceding days (Table 8).

Table 6. Mean and standard deviation of water quality parameters in input (EF1) and output (EF2) waters of the wet detention pond on Echo Farms Country Club. Fecal coliforms are given as geometric mean, inorganic N to P ratio as median. n = 29 mo.

Parameter	EF1	EF2
Dissolved oxygen, mg L^{-1}	6.3 (1.3)	6.4 (1.5)
Conductivity, μS cm^{-1}	150 (25)	247 (65)**
pH	6.9 (0.5)	7.1 (0.4)**
Turbidity, NTU	9.1 (15.0)	7.5 (12.1)
Total suspended solids, mg L^{-1}	3.6 (4.9)	4.4 (4.3)
Nitrate, mg L^{-1}	0.040 (0.072)	0.073 (0.111)*
Ammonium, mg L^{-1}	0.020 (0.018)	0.080 (0.274)*
Total N, mg L^{-1}	0.437 (0.264)	0.618 (0.575)
Phosphate, mg L^{-1}	0.025 (0.019)	0.044 (0.047)**
Total P, mg L^{-1}	0.051 (0.070)	0.069 (0.053)**
N to P molar ratio	2.8	4.4
Chlorophyll a, μg L^{-1}	2.8 (5.2)	2.1 (2.0)
Fecal coliforms, 100 mL^{-1}	74	85

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.

Table 7. Mean and standard deviation of sediment metal concentrations in input and output waters of the wet detention pond on Echo Farms Golf Course.

Parameter	EF1	EF2
	mg kg^{-1}	
Al	633.0 (181.6)	5966.7 (4018.5)
As	0.017 (0.003)	0.585 (0.587)
Cd	0.076 (0.021)	0.597 (0.380)
Cr	0.80 (0.20)	6.59 (4.05)
Cu	0.94 (0.75)	14.27 (13.72)
Fe	484.0 (98.8)	4556.7 (3477.4)
Pb	2.09 (0.50)	7.33 (6.65)
Hg	0.004 (0.002)	0.005 (0.002)
Ni	0.37 (0.10)	1.81 (1.30)
Zn	16.7 (10.3)	21.3 (18.1)

The correlation analysis also provided some evidence that suspended sediments (and turbidity) serve as carriers of phosphorus into (and out of) detention ponds. In Ann McCrary Pond, orthophosphate and turbidity entering the pond were correlated ($r = 0.401$; $p = 0.035$) as were orthophosphate and TSS exiting the pond ($r = 0.472$; $p = 0.011$). In Silver Stream Pond, incoming TSS was correlated with both orthophosphate ($r = 0.834$; $p = 0.001$) and total phosphorus ($r = 0.814$; $p = 0.001$). Incoming turbidity was correlated with both orthophosphate ($r = 0.788$; $p = 0.001$) and total phosphorus ($r = 0.725$; $p = 0.001$), and total phosphorus and TSS exiting the pond were positively correlated ($r = 0.391$; $p = 0.036$). In Echo Farms Pond turbidity entering the pond was correlated with orthophosphate entering the pond ($r = 0.788$; $p = 0.001$), and turbidity and orthophosphate exiting the pond were weakly correlated ($r = 0.383$; $r = 0.040$).

DISCUSSION

Significant increases in dissolved oxygen occurred in passage through both Ann McCrary Pond and Silver Stream Pond. This was probably a result of two factors: an increase in dissolved oxygen from photosynthesis by the large amount of plant material in the ponds, and physical aeration from the outfall (there are drops in elevation at both outfalls). The pH increases seen in each pond were statistically significant, but relatively small, as in all cases pH values were within 0.5 units of neutral (Tables 2, 4, and 6).

Silver Stream Pond functioned very effectively in pollutant removal. Inorganic nutrients (those species generally involved in eutrophication problems) showed particularly high removal rates. Along with water quality improvement, sediment metals showed declines between inflow and outflow areas. We suspect that this high degree of pollutant removal was a result of two

Table 8. Statistically significant ($p < 0.05$) correlations among rainfall and pollutant concentrations. Pearson correlation coefficient (r)/probability (p).†

Parameter	RAIN24	RAIN48	RAIN72
	Ann McCrary Pond		
FCIN	0.841 0.001		
FCOUT	0.873 0.001	0.464 0.013	
NITIN			0.731 0.001
NITOUT			0.739 0.001
AMMIN	0.516 0.005		
AMMOUT	0.485 0.009		
TNIN			0.709 0.001
TNOUT			0.710 0.001
OPOUT			0.387 0.042
TURBOUT		0.506 0.006	0.472 0.011
TSSOUT		0.480 0.010	
	Silver Stream Pond		
FCIN	0.831 0.001	0.539 0.003	
FCOUT	0.807 0.001	0.419 0.024	
NITOUT		0.479 0.009	
TURBOUT	0.815 0.001	0.577 0.001	
	Echo Farms Pond		
FCIN	0.777 0.001	0.446 0.015	
FCOUT	0.430 0.020		
NITOUT			0.484 0.008
OPIN			0.561 0.002
TURBIN		0.370 0.048	
TSSOUT			0.709 0.001

† RAIN24, rainfall occurring day of sample collection; RAIN48, rainfall day of sample plus the previous 24 h; RAIN72, rainfall day of sample plus the previous 48 h; FC, fecal coliform counts; NIT, nitrate concentration; AMM, ammonium; TN, total nitrogen; OP, orthophosphate; TURB, turbidity; TSS, total suspended solids.

major factors: large areal coverage by a diverse aquatic plant community, and a design in which most inputs occurred at the upper end of the system (Fig. 2). This allowed for more contact time for plant and sediment uptake of pollutants as the water passed throughout the length of the pond.

Ann McCrary Pond also had extensive vegetation coverage (although not as diverse a community) yet was much less effective in removing nutrients. Pond input locations probably were a major factor causing this difference. Besides the upper inflow, Ann McCrary Pond has major inflows near the middle of the pond and near the outfall itself (Fig. 1). Thus, some inputs from suburban drainages are short-circuited and do not get the benefit of full pond passage, reducing pollutant removal efficacy. The increase in sediment metals downstream of the pond is perplexing. It is possible that some metals enter the pond downstream of the main inflow. Also, these metals may have been deposited earlier, while the sampled sediments near the main inflow were freshly derived from land-clearing in the immediate pond vicinity for apartment construction.

Pollutant removal performance varied over time in Ann McCrary Pond. During the period October 1997–July 1998 there were no significant differences in nutrient concentration between incoming and outflowing water; however, during October 1998–July 1999 there were significant reductions in nitrate and ammonium. Regardless, for the entire 29-mo period there were no significant nutrient reductions. The effect of apartment construction may have been a factor. During the first year there was active construction, which was largely completed by the second year. In that first year turbidity at AP1 averaged 33 NTU, probably reflecting earth-moving activities, while in the second year average turbidity dropped to 21 NTU. In the first year geometric mean fecal coliform counts at AP1 were 303 colony-forming units (CFU) 100 mL^{-1}, while in the second year geometric mean counts more than doubled to 624 CFU 100 mL^{-1}. We suspect that this increase was caused by greater impervious surface coverage following construction, coupled with increased pet waste disposal near such surfaces following apartment population (Young and Thackston, 1999; Mallin et al., 2000).

The outflow from Echo Farms Pond showed significant increases in nutrient concentrations compared with the inputs. This is not surprising, given that the pond collects golf course drainage and golf courses are sites of considerable fertilizer usage (Walker and Branham, 1992; Mallin and Wheeler, 2000). However, actual nutrient concentrations in the Echo Farms outflow water were low in comparison with outflow from other area golf courses (Mallin and Wheeler, 2000). The nutrient concentrations in the Echo Farms outflow were comparable with and even lower in some cases than those of the urban stormwater pond discharges. We suspect that, in addition to contact with pond vegetation, passage of the outflow water through the wooded wetland following discharge from the pond was an important factor in mitigating the effect of course fertilization, through uptake, adsorption, and denitrification. We also note that a significant portion of the drainage area was undeveloped, as well, which probably contributed to less pollutant loading to the pond (Table 1).

The effect of rainfall on pollutant constituents was variable. Fecal coliform bacteria appeared to be most amenable to immediate movement into and out of the ponds, as this parameter was strongly related to rainfall on the day of sample collection. Fecal coliform pollution is primarily a surface runoff issue in urbanized environments, with animal waste deposited on or near impervious surfaces leading to bacterial runoff problems (Young and Thackston, 1999; Mallin et al., 2000). The concentrations of turbidity and suspended sediments were influenced by rainfall, but in a more cumulative manner than with fecal coliform bacteria. Nutrient movement was most affected by cumulative rainfall over a 3-d period; perhaps some of this effect was due to movement of nutrients entrained in shallow ground water as well as surface runoff. The positive correlations between phosphorus and both turbidity and TSS lead us to argue that stricter sedimentation controls or enforcement are needed near land-disturbing activities to help prevent offsite movement of phosphorus, particularly when nutrient removal within a given detention pond is inefficient.

To summarize, vegetation type and coverage, pond geometry, and post-treatment are important factors in increasing efficacy of wet detention ponds. We recommend that whenever possible wet detention ponds be constructed with a design that maximizes length to width ratio and directs major inputs into the upper areas to maximize detention time of incoming water. We also recommend planting to achieve extensive coverage of a diverse array of native aquatic macrophyte species, particularly rooted emergents. This will aid in pollutant uptake, increase aeration of incoming waters, and, upon death and decay, increase the organic content of pond sediments. Extensive macrophyte coverage may also help limit the potential for phytoplankton blooms (Richard and Small, 1984) that may subsequently export organic nutrients downstream of the detention pond during high-flow periods. We note that in recent years (1995) North Carolina regulations have been revised to include addition of a forebay to increase retention and achieve primary settling in wet ponds, and construction of a shallow shelf around the pond to encourage rooted macrophyte growth. Finally, where space permits, we suggest that final treatment by passage of effluents through wetland areas can help reduce pollutant loads even further.

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