Stormwater treatment trains in subtropical Australia — wetland and pond systems: How effective are they in improving water quality and enhancing ecosystem biodiversity?

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Abstract

Sediment basins, wetlands and ponds are commonly used in subtropical Australia for stormwater storage and water-quality improvement. A crucial question is: “How effective are these stormwater treatment devices?”. Wetlands and ponds, being “natural systems”, also have the potential to enhance aquatic biodiversity. Our research efforts have focused on monitoring water quality and macroinvertebrates in a wetland system consisting of a sediment basin and two wetlands, and a pond system consisting of a sediment basin (Pond 1) and five ponds. Reductions in TSS occurred in the wetland system during short, intense events but increased in longer, more intense events due to resuspension. Reductions in TSS in the pond system largely occurred in Pond 1. TSS increased in both systems in dry weather due to resuspension by ducks. NO_3 decreased in both systems in wet and dry weather. NH_4 increased, probably due to ammonification of organic matter. PO_4 decreased in both systems, but removal was highest in the pond system. Neither system achieved TN and TP Water Quality Objectives on a regular basis, due to NH_4, organic N and P. Macroinvertebrate species richness increased in both systems.

Keywords

Macroinvertebrates; nutrients; ponds; stormwater; suspended solids; wetlands

Introduction

Constructed wetlands and retention ponds are two common stormwater treatment devices for both storage and water-quality improvement. Vegetation (usually emergent macrophytes) is the dominant feature of wetlands, whereas open water is the dominant feature of ponds. Ponds, also referred to as sediment basins, retention basins, detention basins, lagoons or lakes in an urban area, are open-water bodies, often deeper than 1.5 m. Macrophytes are usually absent, except for the shallow littoral margins. Submerged species may occur if there is sufficient light. Phytoplankton and bacterioplankton communities are important in open water. Periphyton communities are an important component covering the submerged portion of macrophyte stems and leaves. Phytoplankton, bacterioplankton and periphyton play major roles in nutrient removal and recycling (Wetzel, 2001).

Wetzel (2001) stresses the importance of maximum biodiversity of aquatic plants and periphyton for effective retentive wetland systems. He also notes that maximum biodiversity occurs where wetland and littoral zones interface with open water. In addition to providing stormwater treatment, wetlands and ponds can also improve aquatic biodiversity and provide a range of ancillary community benefits (Knight *et al.*, 2001). Wetland plant diversity is important for determining macroinvertebrate diversity because of the creation of habitats and food resources. Thus wetlands would be expected to support higher macroinvertebrate biodiversity than ponds. Mosquito larvae are an integral component of aquatic food webs. However, because mosquitoes can pose a risk to public health, there is often concern that wetlands will encourage mosquito breeding. If wetlands and ponds are designed to function as ecosystems with a diversity of aquatic organisms, then natural predators will control mosquito breeding (Greenway *et al.*, 2003).

The decision to use ponds or wetlands, or a combination of both, depends on several factors (Greenway, 2004): catchment land use and area, pollutant characteristics of the stormwater, pollutant loading, hydrology and hydraulics, treatment performance expectations, the ability of the system to remove pollutants by physical, biological or chemical processes, available area for construction, and community opinion and benefits including aesthetic value, recreational value, wildlife habitat, water storage and reuse. Physical processes for the removal of suspended particles depend primarily on passive, density-dependent settlement in ponds and more active filtration by the vegetation in wetlands. Sticky biofilm surfaces assist in the trapping of finer particles. Biological processes for the uptake of soluble nutrients depend mostly on phytoplankton and bacterioplankton in ponds, and the macrophytes and associated periphyton in wetlands. Microbial processes for nitrogen transformation occur in both systems. Retention time in both systems is crucial for the removal of both TSS and nutrients (Shutes *et al.*, 1997; Carleton *et al.*, 2001). However, being natural systems, measurable concentrations of TSS and nutrients will always occur in outflows. Thus, if inflow concentrations are low, performance will appear ineffective.

Frequently asked questions are: “How effective are these stormwater treatment devices in improving water quality?” and “What are the ecological impacts of stormwater runoff on ecosystems health?”. There is limited information and case studies pertaining to the effectiveness of stormwater-quality improvement devices in urban areas of south-east Queensland, Australia. Brisbane City Council has set the following Water Quality Objectives (WQO): 15 mg L^{-1} TSS, 5 mg L^{-1} TVS, 0.65 mg L^{-1} TN, 0.035 mg L^{-1} NH_4-N, 0.13 mg L^{-1} NO_3-N, 0.07 mg L^{-1} TP, 0.035 mg L^{-1} PO_4-P, to meet legislative requirements to improve the quality of urban stormwater runoff which ultimately flows into Moreton Bay, a RAMSAR-listed marine park with significant ecological and fisheries value. The purpose of the Griffith University Urban Stormwater Quality Program (Cooperative Research Centre for Catchment Hydrology) was to gain a greater understanding of the processes and effectiveness of treatment devices. Our research efforts have focused on two field sites in Brisbane: a wetland-system “treatment train” consisting of a sediment basin and two wetlands, and a “pond system” consisting of a sediment basin and five ponds. The wetlands are unusual in that they are dominated by water lilies, aquatic creepers and submerged pond weeds, rather than emergent sedges or reeds. In addition to monitoring water quality, our study investigated macroinvertebrate biodiversity in the treatment trains.

Methods

Site description

Brisbane, south-east Queensland, Australia has a subtropical climate with dry winters and wet summers. The average annual rainfall is 1030 mm, with an average of 10 days/y > 50 mm rainfall. Intense rainfall events (10 y ARI 1-hour duration intensity of 71 mm/h) are common in the rainy season. The wetland system and pond system are both retrofit structures (Table 1).

Golden Pond “Wetland System”. Located at Calamvale, urbanisation occurred in the early 1990s. The wetland system was constructed in 1999. It is a linear system. The sediment basin is a trapezoidal concrete structure (21 m × 13.5 m). It receives water from a 160 ha catchment. Wetland 1 is 80 m × 15-20 m, and Wetland 2 is 55 m × 20 m. Wetland 2 also receives stormwater from a piped drainage system (14 ha catchment) (Stormwater Outlet 1). At the bottom of Wetland 2, there is a narrow (1 m) outlet channel through which the water flows into the natural downstream creek. Both wetlands are dominated by floating-leaved emergent macrophytes (water lilies), aquatic creepers (Ludwigia, Paspalum, Persicaria), and submerged pond weeds (Elodea, Ceratophyllum) (Greenway and Polson, 2004).

Table 1. Comparison of physical attributes of Golden Pond “Wetland System” and Bridgewater Creek “Pond System” stormwater treatment trains

	Golden Pond (2% catchment)		**Bridgewater Creek (4% catchment)**	
	Sediment basin	**Wetlands 1 and 2**	**Pond 1**	**Ponds 2-6**
Vegetation	Absent	Water lilies, aquatic creepers, submerged pond weeds	Littoral emergent sedges	
% cover	0	75-90%	4.5%	12%
Area	284 m^2	2600 m^2	1000 m^2	7000 m^2
Depth	1.5 m	0.2 - 1.2 m	2 m	0.2 - 1.5 m
Volume SWL	100 m^3	1300 m^3	2000 m^3	3550 m^3
Storm event	150 m^3	2000 m^3	2500 m^3	9640 m^3
Discharge rate	Baseflow 0.0015 - 0.0003 $m^3\ s^{-1}$			
Storm events	4.22 - 0.15 $m^3\ s^{-1}$		2.33 - 0.33 $m^3\ s^{-1}$	

Bridgewater Creek “Pond System”. Located at Coorparoo, urbanisation occurred prior to 1950. The pond system was constructed in 2001. There are six interconnected ponds and stormwater is received from two tributaries. The main Bridgewater Creek (creek inlet) has a catchment of 157 ha, whereas the piped drainage system (piped inlet) has a 40 ha catchment. Pond 1, the sediment basin, is triangular in shape. Ponds 2 to 5 are oval-shaped, with dimensions of 40-50 m length and 15-20 m width. Pond 6 is triangular in shape. Macrophyte establishment is poor (Greenway and Polson, 2004). During extended rainfall and storm events, water levels rise rapidly so that Ponds 2 to 6 form a single lake-like water body. The stormwater from Pond 1 can overflow into a “bypass channel” which re-enters Bridgewater Creek flow path downstream.

Water quality monitoring

Grab samples were collected during and after storm events, and in dry weather (baseflow). Data are also presented from samples collected after a rain squall (5 mm in five minutes). Samples collected within 12 hours of a storm were categorised as 12 h wet, and those collected 24 hours after an event as 24 h wet. Samples were analysed for TSS, TVS, TN, TP, NH_4-N, NO_3-N and PO_4-P. At Golden Pond, monitoring occurred from November 2000 to August 2002, and at Bridgewater Creek from March 2002 until December 2004.

Macroinvertebrate monitoring

As some macroinvertebrate species are more tolerant of polluted waters than others, they are useful indicators of the water quality and ecological health of freshwater habitats. Therefore the monitoring of macroinvertebrate taxa upstream and downstream may give an indication of the success of a stormwater treatment device in improving water quality. Macroinvertebrates were sampled using a dip net. Mosquito larvae were sampled using a 200 mL scoop.

Results and discussion

Golden Pond “Wetland System” Treatment Train

Data for total suspended solids (TSS) and total volatile solids (TVS) are given in Table 2. TSS concentrations are relatively low in this catchment. The 12 h wet samples showed considerable variation in TSS between events and the time of sampling, reflecting the problems of sampling logistics following a storm event in the absence of automated samplers, as well as differences in rainfall intensity and duration. TSS and TVS were consistently higher at the outflow of Wetland 1, indicating resuspension. Short-circuiting occurs at flow rates greater than 0.5 $m^3\ s^{-1}$. The 24 h samples demonstrate how quickly inflow and outflow TSS assumes background concentrations. During dry weather, TSS increased at the outflow due to resuspension caused by ducks.

Table 2. TSS and TVS (mg L^{-1} $\bar{x}$ ± SD) for Golden Pond “Wetland System” treatment train for samples collected within 12 hours of a storm event, after 24 hours, and during dry weather

Location	Within 12 h of storm			24 h after storm			Dry weather		
	n	TSS	TVS	n	TSS	TVS	n	TSS	TVS
In Sediment Basin	6	17 ± 12	4 ± 3	8	7 ± 6	3 ± 1	14	6 ± 4	3 ± 2
Out Sediment Basin	6	20 ± 8	5 ± 2	8	7 ± 5	3 ± 1	14	6 ± 3	3 ± 3
Out Wetland 1	6	26 ± 10	6 ± 3	8	10 ± 6	5 ± 3	13	14 ± 6	6 ± 3
Stormwater Outlet 1	5	12 ± 2	4 ± 2	7	8 ± 4	4 ± 2	14	6 ± 3	4 ± 2
Out Wetland 2	6	24 ± 12	5 ± 3	8	13 ± 9	6 ± 5	13	13 ± 9	7 ± 5

Figure 1 provides data for the short, intense rain squall. Prior to the squall, flow at the sediment outlet was 0.005 m^3 s^{-1}. Within 15 minutes this increased to 0.17 m^3 s^{-1} and peaked at 0.35 m^3 s^{-1} after 25 minutes before decreasing. TSS peaked at 105 mg L^{-1}, but within 60 minutes fell to 14 mg L^{-1}. In the wetland outflow, TSS initially decreased due to rainfall dilution, but then increased as the stormwater from the sediment basin flowed through, peaking at 17 mg L^{-1} 40 minutes after the rain. The reduction in TSS shows the effectiveness of the wetland in filtration during small storm events.

Data for nutrients are given in Table 3. The 12 h wet samples showed negligible removal of nutrients in the sediment basin. However, an overall reduction in concentrations occurred in Wetland 1 and Wetland 2. Wetland 2 was particularly effective in reducing the high nutrient concentrations for the stormwater outlet. Figure 1 shows negligible increase or removal of soluble inorganic nutrients entering and leaving Wetland 1 pre- and post-rain squall. The slightly higher NO_3 concentrations in Wetland 1 40 minutes after the squall appear to represent the “plug” of outflow from the sediment basin. TN and TP increased substantially in the sediment basin outflow and would have largely been associated with the increase in TSS and TVS. Background concentrations were achieved within less than 60 minutes. There was only a slight increase in TN and TP at the wetland outlet, again confirming the settlement of particulates as the stormwater flowed through the wetland.

The 24 h samples showed nutrient removal in the sediment basin and the wetlands, except for NH_4 which increased in the wetlands, possibly due to amination and ammonification. In dry weather, the sediment basin was not effective in nutrient removal, but decreases in soluble nutrient concentrations occurred in Wetland 1. Wetland 2 was effective in removing nutrients (except NH_4) from the stormwater outlet, but outflow concentrations were higher than WQO. Aquatic plants, in particular the submerged *Ceratophyllum*, and periphyton would remove soluble nutrients. An increase in NH_4-N suggests ammonification.

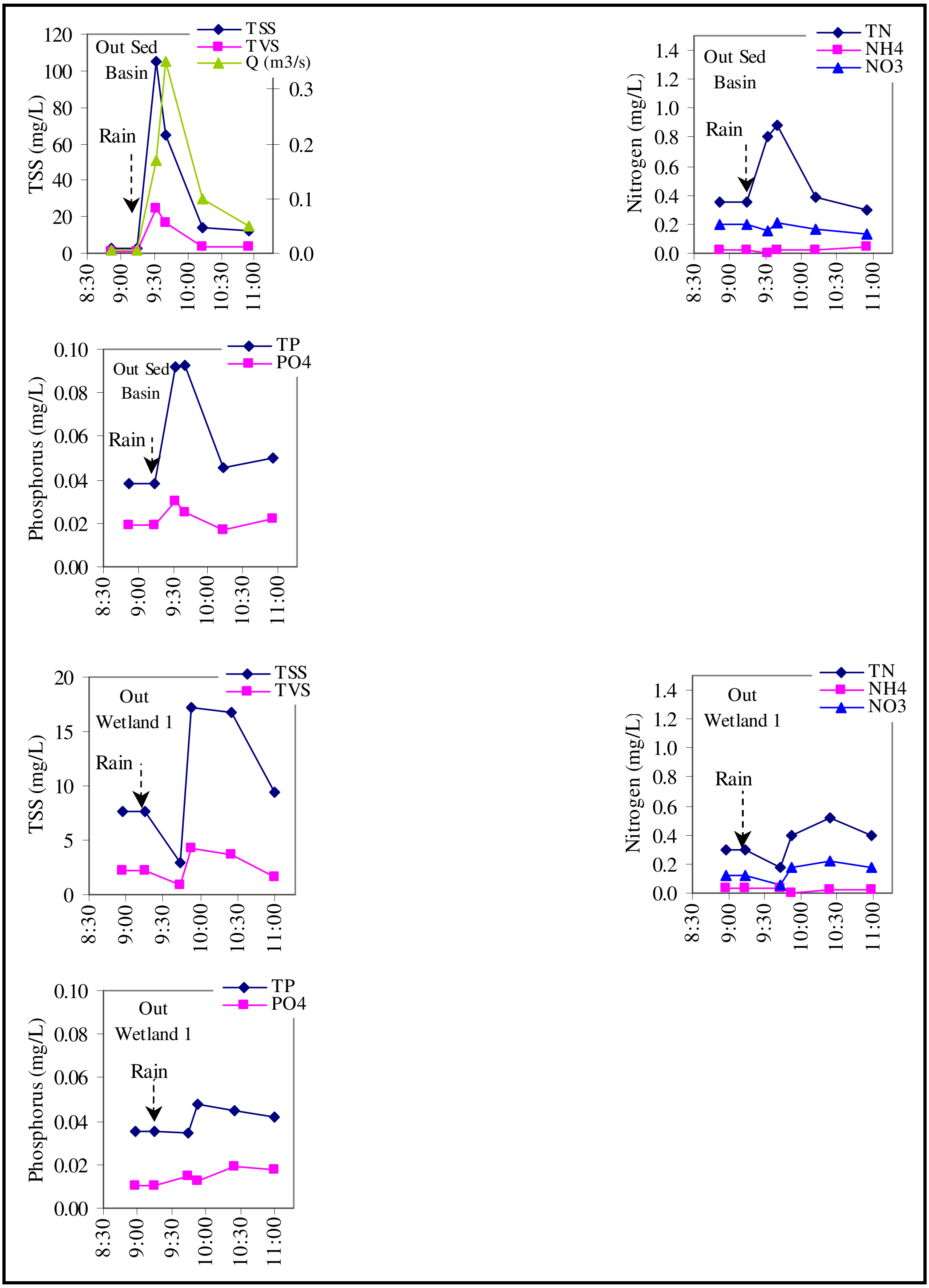

Figure 1. Time series for suspended solids and nutrients leaving the sediment basin and the bottom of Wetland 1 before and after a five-minute rain squall

Table 3. Nitrogen and phosphorus speciation (mg L^{-1}) for Golden Pond Wetland System for grab samples collected within 12 hours of a storm, after 24 hours, and during dry weather

	Event	In Sed Basin	Out Sed Basin	Out Wetland 1	S/W Outlet	Out Wetland 2
TN	12 h	1.27 ± 0.63	1.22 ± 0.58	1.12 ± 0.58	2.50 ± 1.22	0.94 ± 0.51
NO_3-N	12 h	0.44 ± 0.33	0.38 ± 0.28	0.28 ± 0.18	1.92 ± 1.47	0.22 ± 0.16
NH_4-N	12 h	0.10 ± 0.10	0.09 ± 0.09	0.08 ± 0.07	0.11 ± 0.05	0.07 ± 0.04
TP	12 h	0.11 ± 0.05	0.12 ± 0.05	0.13 ± 0.07	0.34 ± 0.22	0.11 ± 0.06
PO_4-P	12 h	0.06 ± 0.05	0.06 ± 0.06	0.06 ± 0.06	0.25 ± 0.15	0.05 ± 0.05
TN	24 h	1.43 ± 0.22	1.09 ± 0.28	0.79 ± 0.23	2.39 ± 2.02	0.78 ± 0.06
NO_3-N	24 h	1.23 ± 0.48	0.98 ± 0.38	0.43 ± 0.46	2.67 ± 1.89	0.37 ± 0.28
NH_4-N	24 h	0.07 ± 0.04	0.06 ± 0.05	0.08 ± 0.06	0.12 ± 0.05	0.12 ± 0.05
TP	24 h	0.15 ± 0.08	0.11 ± 0.03	0.08 ± 0.03	0.26 ± 0.14	0.07 ± 0.03
PO_4-P	24 h	0.11 ± 0.09	0.08 ± 0.04	0.05 ± 0.06	0.24 ± 0.15	0.05 ± 0.05
TN	Dry	0.57 ± 0.31	0.70 ± 0.33	0.63 ± 0.33	2.35 ± 0.37	0.97 ± 0.50
NO_3-N	Dry	0.53 ± 0.67	0.56 ± 0.71	0.25 ± 0.49	1.76 ± 0.78	0.25+ 0.23
NH_4-N	Dry	0.03 ± 0.03	0.05 ± 0.05	0.03 ± 0.03	0.07 ± 0.06	0.08 ± 0.09
TP	Dry	0.08 ± 0.02	0.08 ± 0.01	0.07 ±0.02	0.19 ± 0.05	0.14 ± 0.07
PO_4-P	Dry	0.04 ± 0.04	0.03 ± 0.03	0.02 ± 0.02	0.11 ± 0.06	0.05 ± 0.08

Bridgewater Creek "Pond System" treatment train

Data for TSS and TVS are given in Table 4. TSS in Bridgewater Creek catchment is high compared to Golden Pond. Pond 1 was effective in reducing TSS, but mean values show no further reduction between Pond 1 and Pond 6. The 24 h samples show a reduction in TSS. In dry weather, TSS is highly variable in the stormwater, but almost 50% reduction occurred in Pond 1 to produce good water clarity (10 mg L^{-1}). However, between Pond 1 and Pond 6, TSS increased (16 mg L^{-1}) due to resuspension of sediment (Kasper and Jenkins, 2005).

Table 4. TSS and TVS (mg L^{-1}, $\bar{x}$ ± SD) for Bridgewater Creek "Pond System"

Location	Within 12 h of storm			24 h after storm			Dry weather		
	n	TSS	TVS	n	TSS	TVS	n	TSS	TVS
Creek Inlet	26	66 ± 40	21 ± 14	7	13 ± 10	3 ± 1	9	18 ± 17	5 ± 3
Piped Inlet	10	33 ± 16	10 ± 4	6	6 ± 4	3 ± 2	9	17 ± 16	5 ± 3
Out Pond 1	23	24 ± 16	8 ± 4	19	16 ± 7	7 ± 4	30	10 ± 6	7 ± 5
Out Pond 6	26	22 ± 12	8 ± 5	28	16 ± 12	6 ± 5	54	16 ± 8	7 ± 4

Data for nutrients are given in Table 5. Nutrient concentrations in stormwater were similar to the piped stormwater outlet at Golden Pond. The 12 h wet samples show a large reduction in NO_3 and some NH_4 in Pond 1. Reductions in TN and TP suggest settlement of particulates. Between Pond 1 and Pond 6, there was a large reduction in NO_3 (82%) and PO_4 (75%) concentrations, suggesting biological removal. However, there was no reduction in NH_4 concentrations. These trends were similar to the wetland system at Golden Pond. In the 24 h wet samples, high NO_3 entered Pond 1 in stormwater runoff. Large reductions in concentrations occurred in Pond 1 (75%). About 30% reduction in NO_3 and PO_4 occurred between Pond 1 and Pond 6, whilst NH_4 increased. In dry-weather, NO_3 and PO_4 were both substantially reduced in Pond 1, with further reductions in PO_4 to 0.02 mg L^{-1} in Pond 6. Reductions in soluble N in Pond 1 appear to be due to bacterioplankton (Bayley *et al.*, 2005).

Table 5. Nitrogen and phosphorus speciation (mg L^{-1}) for Bridgewater Creek Pond System for grab samples collected within 12 hours of a storm event, after 24 hours, and during dry weather

	Event	n	Creek inlet	n	Pipe inlet	n	Out Pond 1	n	Out Pond 6
TN	12 h	13	2.71 ± 1.50	14	2.42 ± 1.50	17	1.45 ± 1.05	20	1.08 ± 0.36
NO_3-N	12 h	8	0.68 ± 0.46	9	0.97 ± 0.75	16	0.38 ± 0.40	16	0.07 ± 0.09
NH_4-N	12 h	8	0.26 ± 0.26	9	0.15 ± 0.13	18	0.10 ± 0.09	18	0.13 ± 0.15
TP	12 h	9	0.40 ± 0.24	10	0.31 ± 0.16	18	0.22 ± 0.09	20	0.19 ± 0.11
PO_4-P	12 h	8	0.15 ± 0.07	9	0.15 ± 0.07	17	0.12 ± 0.08	17	0.03 ± 0.02
TN	24 h	3	2.55 ± 0.73	3	2.66 ± 0.63	16	1.19 ± 0.44	12	1.20 ± 0.34
NO_3-N	24 h	4	1.93 ± 0.53	4	1.82 ± 0.65	12	0.47 ± 0.92	12	0.30 ± 0.47
NH_4-N	24 h	4	0.04 ± 0.04	5	0.07 ± 0.06	12	0.08 ± 0.06	14	0.10 ± 0.11
TP	24 h	5	0.15 ± 0.06	3	0.23 ± 0.12	16	0.23 ± 0.10	12	0.22 ± 0.09
PO_4-P	24 h	5	0.11 ± 0.07	5	0.15 ± 0.12	12	0.10 ± 0.04	14	0.07 ± 0.05
TN	Dry	9	1.84 ± 1.01	9	1.97 ± 0.28	22	1.28 ± 0.45	26	1.04 ± 0.36
NO_3-N	Dry	9	0.57 ± 0.60	9	1.10 ± 0.40	22	0.12 ± 0.24	26	0.10 ± 0.14
NH_4-N	Dry	9	0.08 ± 0.09	9	0.06 ± 0.05	20	0.10 ± 0.09	22	0.11 ± 0.11
TP	Dry	9	0.26 ± 0.11	9	0.24 ± 0.09	22	0.22 ± 0.10	26	0.17 ± 0.07
PO_4-P	Dry	9	0.19 ± 0.18	9	0.16 ± 0.10	20	0.08 ± 0.06	26	0.02 ± 0.01

Water quality and retention time

At Golden Pond, discharge rates calculated for stormwater leaving the sediment basin and entering Wetland 1 ranged from 3 to 5.7 $m^3 s^{-1}$ for extreme (> 20 y ARI) storm events, and from 0.15 - 0.8 $m^3 s^{-1}$ for high-intensity rain squalls. At discharge rates greater than 0.45 $m^3 s^{-1}$, short-circuiting occurs through the middle due to the positioning of a single V-notch weir, the lack of dense emergent macrophytes, and the linear nature of the flow path through the wetland. Between Wetland 1 and Wetland 2, the water flows over a wide concrete sill, and the narrow outlet (1 m width) ensures that the water backs up, thereby increasing the retention time. It has been estimated that the average retention time for both wetlands during non-extreme storm events would be between 3 and 5 hours, and between 5 and 32 hours for less intense rainfall events. By contrast, the retention times for the pond system at Bridgewater Creek during wet weather range from 36 hours for a major storm event to 6 days for less intense rainfall. These longer retention times would account for the higher removal efficiency of NO_3 and PO_4 in the pond system compared to the wetland system at Golden Pond. Halcrow suggested that runoff should be retained for a minimum of 3 to 5 hours, and preferably 10 to 15 hours for good treatment efficiency (Shutes *et al.*, 1997).

In a comparative study of vegetated and non-vegetated stormwater basins, Bartone and Uchrin (1999) found negative removal efficiencies for TKN, NO_3, TP and PO_4 in the vegetated basin over four storm events with export loads exceeding input loads. This they attributed to the stormwater flushing out stored water and associated organic matter and nutrients.

Ecosystem biodiversity

Macroinvertebrate taxa are given in Table 6. Both the stormwater wetlands and ponds increased species richness. However, at Bridgewater Creek, the vegetated modified downstream creek channel had the highest species richness. Our study suggests that improved habitat diversity rather than improved water quality has increased biodiversity. This is supported by research on wastewater treatment wetlands (Knight et al., 2001; Greenway et al., 2003).

Table 6. Major macroinvertebrate taxa at Golden Pond and Bridgewater Creek

Macroinvertebrate Taxa	Golden Pond "Wetland System"					Bridgewater Creek "Pond System"			
	Upstream Channel	Sediment Basin	Wetland 1	Wetland 2	Downstream Natural Creek	Upstream Channel	Pond 1	Pond 6	Downstream Modified Channel
"Worms"	3	4	5	6	6	3	9	3	5
Gastropoda	5	5	8	8	8	4	4	2	4
Microcrustaceans	4	4	5	3	4	1	4	1	1
Acarina	3			1			2	1	3
Epiproctophora	5	2	11	6	3	6	4	3	11
Zygoptera	1	1	3	3	5	1	2	5	4
Ephemeroptera	1	1	1	1	0	1	0	1	2
Hemiptera	1	1	4	4	1	2	3	8	6
Diptera	3	2	3	4	2	6	6	5	8
Coleoptera	1	0	0	0	4	3	0	8	6
Trichoptera	0	0	1	1	1	0	0	2	3
TOTAL TAXA	23	20	43	37	34	27	34	39	53
FAMILIES	12	11	20	16	18	18	19	25	26

In the wetlands at Golden Pond and Pond 6 at Bridgewater Creek, less than 5% of sampling dips over a 24-month period contained mosquito larvae, and when present, they were in very low numbers (< 10/200 mL scoop). No pupae were found, indicating that the larvae did not complete their life cycle. Predation by abundant microcrustaceans and notonectids appears to be controlling mosquito larvae. These results confirm the previous findings of (Greenway *et al.*, 2003) for effluent treatment wetlands.

Conclusions

Improved TSS in stormwater in the 24 h samples shows the effects of flushing. In comparing the performance of the wetland system and the pond system, TSS concentrations actually increased slightly in the wetlands due to resuspension from high flow velocities, but decreased in the ponds. The absence of dense stands of emergent macrophytes in the wetlands would have been a major factor in resuspension. During dry weather, TSS also increased in the wetlands due to resuspension caused by the activity of water birds. In the pond system, considerable reduction in TSS occurred in Pond 1 (the sediment basin), but increased again largely due to resuspension.

During wet weather, there was a small reduction in soluble inorganic nutrients in the wetlands despite relatively short retention times, which would limit biological uptake. In the ponds, the greater reduction of soluble inorganic nutrients occurred in Pond 1. In the 12 h samples, considerable reduction of NO_3 and PO_4 occurred between Pond 2 and Pond 6. This can be explained by the fact that once Pond 1 is full, further incoming stormwater overflows into the bypass channel, whereas the stormwater already in Pond 2 has a minimum 36-hour retention time before reaching Pond 6 outlet, sufficient for biological nutrient removal. During dry weather, considerable reduction in NO_3 and PO_4 occurred in both wetland and pond systems. Despite the ability of both systems to remove nutrients, neither the wetlands nor the ponds were able to consistently achieve water quality guidelines. A longer detention time would have improved the removal of soluble inorganic N and P during wet weather in both systems. There was some removal of particulate organic nutrients, but ammonification increased NH_4. As natural systems, there needs to be greater recognition that there will always be irreducible concentrations of nutrients due to the continuous process of biological uptake and decomposition. WQO need to consider that different treatment systems will not necessarily achieve the same water quality, no matter how well they are designed. Both systems are important for increasing the biodiversity of aquatic organisms.

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