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 in improving water quality?". Wetlands and ponds, being "natural systems", also have the potential to enhance aquatic biodiversity. Our research efforts have focussed on two retrofit field sites in Brisbane, south-east Queensland: the Golden Pond "wetland system" treatment train, consisting of a sediment basin and two vegetated constructed wetlands; and the Bridgewater Creek "pond system" treatment train, consisting of a sediment basin and five ponds, a natural riparian wetland, and a natural stream channel. We have been monitoring water quality during wet and dry weather, and ecosystem health in terms of macroinvertebrate species richness, mosquito larvae and phytoplankton. TSS (and TVS) increased in the wetland system at Golden Pond during both wet and dry weather. TSS (and TVS) was reduced in the pond system at Bridgewater Creek during wet weather, but increased during dry weather due to resuspension by ducks and the presence of phytoplankton. NO_3-N decreased in both the wetland system and the pond system in wet and dry weather. In the dry, NO_3-N removed was highest in Pond 1 (sediment basin), probably due to phytoplankton uptake. NH_4-N increased in both systems, probably due to ammonification of organic matter. PO_4-P decreased in both systems. In the wet, removal was highest in Ponds 2-6, and in the dry was highest in Pond 1. At Golden Pond, Wetland 2 was highly effective in removing the nutrients entering the wetland from the piped drainage and below-ground GPT stormwater outlet. The removal of soluble NO_3 and PO_4 is indicative of biological uptake by phytoplankton in the pond system and by submerged pond weeds, aquatic roots of creepers, and periphyton attached to the stems and leaves of aquatic macrophytes in the wetland system. Unfortunately, despite nutrient removal, neither system achieved the Brisbane City Council Water Quality Objectives (p2) on a regular basis.

Keywords

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

Introduction

Urban stormwater runoff is now recognised as a potential pollution source to downstream waterways and aquatic ecosystems. Major pollutants include suspended solids (sediment and organic particles) and nutrients (ammonium, nitrite, nitrate, organic nitrogen, orthophosphate, organic phosphorus and organic carbon). These can impact aquatic ecosystem health. Suspended solids increase water turbidity which reduces light penetration and photosynthesis. If there is a high proportion of organic particles, then biochemical oxygen demand (BOD) increases. These organic particles provide a food source for micro-organisms which use up oxygen in aerobic respiration, and this may lead to oxygen depletion. Nutrients are essential for plant (and animal) growth. However, excess nutrients, in particular soluble inorganic nitrogen and phosphorus, can increase the growth of unicellular algae and cyanobacteria causing algal blooms. Dense blooms can also increase turbidity and BOD, and some cyanobacteria are toxic.

Other potential stormwater pollutants include heavy metals, pesticides/herbicides, oils/grease and microbial pathogens. These substances are often more localised and their impacts on aquatic ecosystem health are usually not acute. Given the potential detrimental impacts of increased suspended solids and nutrients on aquatic ecosystems, it is not surprising that today most stormwater management strategies relate to sediment and nutrient control (Urbonas, 1994; Lawrence *et al.*, 1996; Shutes *et al.*, 1997; Bartone and Uchrin, 1999; Braune and Wood, 1999; Mehler and Ostrowski, 1999; Carleton *et al.*, 2001).

In Queensland, Australia, the Environmental Protection Act (1994) and the Environmental Protection (Water) Policy (1977) require local authorities to manage the impacts of stormwater on receiving waters. A study into decline of seagrass beds in Moreton Bay, a RAMSAR-listed marine park with significant ecological and fisheries value, identified increased turbidity from stormwater and increased nutrients from sewage effluent as the primary causes of seagrass loss. In response, the Brisbane City Council has set the following Water Quality Objectives (WQO) to meet legislative requirements to improve the quality of urban stormwater runoff into receiving waters which ultimately flow into Moreton Bay: 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, and 8 μg L^{-1} chlorophyll-a.

Wetlands and ponds

Constructed wetlands and 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. Wetlands are shallow water bodies (< 50 cm) and support a variety of vegetation types - emergent reeds and rushes, water lilies, aquatic creepers, submerged pond weeds (Greenway, 2004). Zonation is important in stormwater wetllands (Greenway, 2000; Greenway, 2004; Greenway and Polson, 2004). Ponds, which may also be referred to as sediment basins, lagoons or lakes in an urban area, depending on their size, are deep, open-water bodies, often greater than 1 m. Macrophytes are usually absent, except for the shallow littoral margins. Submerged species may occur if there is a suitable substrate and sufficient light. Floating species, including aquatic creepers, may cover the surface. Phytoplankton communities are important in open-water ponds. Periphyton (biofilm) communities are an important component covering the submerged portion of stems and leaves in either wetlands or ponds. The decision to use ponds or wetlands, or a combination of both, depends on several factors: pollutant characteristics of the stormwater, treatment performance expectations, pollutant loading, and the ability of the system to remove pollutants by physical, biological or chemical processes (IWA, 2000); hydrology and hydraulics (Shutes *et al.*, 1997; Somes *et al.*, 2000; Carleton *et al.*, 2001); available area for construction, and community opinion and benefits including aesthetic value, recreational value, wildlife habitat, water storage and reuse.

Table 1. Comparison of treatment processes in wetlands and ponds

	Wetlands	**Ponds**
Physical	Filtration/sedimentation **Facilitated by macrophytes** Adhesion of fine particles and colloids to biofilm surfaces of plant stems	Settlement/sedimentation **Passive-density dependent**
Biological	Nutrient uptake by macrophytes, attached periphyton and phytoplankton/bacterioplankton. **Macrophyte-dominated**	Nutrient uptake by phytoplankton/ bacterioplankton. **Phytoplankton dominated**
	Sediment microbial processes facilitate nutrient removal, transformations, recycling. Microbial hydrocarbon degradation, microbial predation of pathogens	
Chemical	Nutrient and metal adsorption onto sediment (or release) UV disinfection of pathogens	

Research objectives

Frequently asked questions are: "How effective are these stormwater treatment devices in improving water quality?", "Is the retention of natural stream channels and adjacent riparian vegetation an effective treatment?" and "What are the ecological impacts of stormwater runoff on ecosystems health?". In order to answer these questions, the evaluation of the performance of stormwater treatment devices for a range of conditions (catchment size, land use (percentage urban, industrial and rural); pollutant characteristics; climate, in particular rainfall) under both wet weather and dry weather conditions is essential. There is limited information and case studies pertaining to the effectiveness of stormwater-quality improvement devices in urban areas of south-east Queensland, Australia. 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 focussed on two field sites in Brisbane: (1) a wetland-system "treatment train" consisting of a sediment basin and two constructed wetlands, a natural riparian wetland, a natural downstream channel and lagoons; and (2) a "pond system" consisting of a sediment basin and five interconnected ponds.

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 are common in the rainy season. The constructed wetland system and pond system are both retrofit structures located within existing residential areas (70% impervious area) in Brisbane.

Table 2. Comparison of physical attributes of the Golden Pond wetland system and the Bridgewater Creek pond system

	Golden Pond (2% catchment)		Bridgewater Creek (4% catchment)	
	Sediment basin	**Wetlands 1 and 2**	**Sediment basin**	**Ponds 2–6**
Area	284 m^2	2600 m^2	1000 m^2	7000 m^2
Vegetation	Absent	Water lilies, aquatic creepers, submerged pond weeds	Littoral emergent sedges	
% cover	0	75-90%	1%	0.1%
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 $m^3\ s^{-1}$	

Golden Pond "Wetland System"

Located at Calamvale, 20 km south-west from the Brisbane CBD, urbanisation of this outer suburb occurred in the early 1990s. The catchment is predominantly residential land use, with 70% impervious surface. The stormwater treatment train consists of a sediment basin, two constructed wetlands, a natural riparian wetland, a natural downstream channel and lagoons; and two below-ground gross pollutant traps (Greenway *et al.*, 2002). The constructed wetlands are unusual in that they are dominated by water lilies, aquatic creepers and submerged pond weeds, rather than emergent sedges, rushes or reeds.

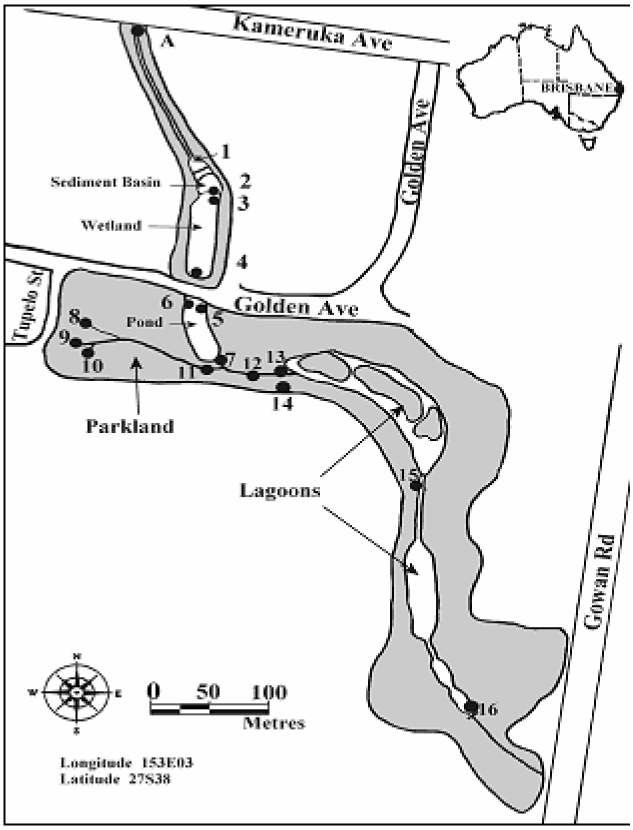

Figure 1. Golden Pond Wetland System and Kameruka Wetlands, Calamvale, Brisbane

The sediment basin and Wetland 1 are retrofit structures incorporating the lower 120 m of the channelised main stream and adjoining parkland. Wetland 2 was originally a small farm dam. Construction was completed in September 1999. The total area of the wetland system is 2% of the catchment.

The sediment basin is a trapezoidal concrete structure (21 m long × 13.5 m width) with 1-in-3 sloping slides and a maximum centre depth of 1.5 m. The volume of standing water level is 100 m^3. It receives water from the modified stream channel with a 160 ha catchment.

Wetland 1 is 80 m long × 15-20 m wide and is clay-lined. It has a surface area of 1550 m^2 with a volume of 1000 m^3 at the standing water level. The original design was a dumb-bell shape, with two deeper (100 cm) wetland ponds at the top and bottom separated by a shallow (50 m) macrophyte zone in the middle, and an outlet macrophyte zone. Percentage cover of vegetation varies between 60% (post storm event) to 90%, of which floating-leaved emergent species (*Nymphoides indica, Nymphaea caerulea, Ludwigia peploides)* account for 77%. Submerged pond weed (*Elodea)* is abundant. Wetland 1 receives water from the sediment basin.

Wetland 2 was excavated to its current dimensions: 52 m long × 20 m wide and up to 1.2 m deep. 95% is completely covered with floating-leaved emergent species. *Nymphaea* is rooted in the deeper water, whereas *Nymphoides* and the aquatic creepers *Ludwigia* and *Persicaria* extend from the banks. The submerged pond weed, *Ceratophyllum* is abundant even beneath the surface vegetation. Wetland 2 receives water from Wetland 1 after it has passed through road culverts, and stormwater from a piped drainage system (14 ha catchment) after it has passed through a below-ground GPT (Stormwater Outlet 1). At the bottom of Wetland 2, there is a narrow (1 m) outlet channel. The water then flows into the natural downstream channel.

The riparian wetland is a 90 m by 15 m band of riparian vegetation associated with an original tributary. The stream channel is poorly defined, but the entire band is permanently saturated, with ponding water towards the centre. It supports a dense cover of emergent aquatic plants including *Typha domingensis* and *Persicaria strigosa*, and ferns (*Blechnum indicum* and *Hypoclepis muelleria*). *Melaleuca* trees (*M. quinquenervia* and *M. linarifolia*) fringe the landward margins. It receives stormwater from a piped drainage system (40 ha catchment) after it has passed through a below-ground GPT (Stormwater Outlet 2). At the bottom of the riparian wetland, the water flows into the natural downstream channel.

The downstream channel is a 600 m length of the original stream channel, lagoons and associated aquatic vegetation and fringing riparian *Melaleuca* zone known as the “Kameruka Wetlands”. It receives water from the northern tributary (after passing through the sediment basin and constructed wetlands) and western tributary (after passing through the riparian wetland). It also receives stormwater from seven drainage pipes with intermittent (storm event only) flow.

Bridgewater Creek Wetland “Pond System”, Coorparoo

Located 10 km east of Brisbane CBD, urbanisation of this suburb occurred prior to 1950, though over the past 10 years, many lots have been subdivided for higher density housing. The catchment is predominantly residential land use with 70% impervious surface. The Bridgewater Creek Wetland is a retrofitted stormwater treatment train incorporating a 200 m concrete channel and adjoining parkland. Construction was completed in October 2001.

The “wetland” consists of six inter-connected ponds and receives stormwater from two tributaries. The main south-north flowing stream channel (Bridgewater Creek) has a catchment of 157 ha, whereas the piped drainage system from the west collects runoff from a 40 ha catchment. Before entering the “wetland”, the stormwater runoff from both tributaries passes through trash racks, i.e. above-ground gross pollutant traps, to collect trash and organic debris (leaf litter). The stormwater then passes into a sediment pond (Pond 1).

Pond 1, the sediment basin, is triangular in shape, with a surface area of 1000 m^2 and a depth of 2 m. It has steeply sloping sides and a concrete access ramp extending into the centre to facilitate removal of debris sediment. There is a 2-3 m littoral zone of *Schoenoplectus validus*.

Figure 2. Bridgewater Creek Wetland — Pond System

Ponds 2 to 6 were originally designed as “macrophyte zones” to include open water, deep marsh, shallow marsh and ephemeral zones. Unfortunately, the establishment of wetland vegetation has been poor and is largely restricted to narrow fringes along the shallow edges of the ponds (Greenway and Polson, 2004). Thus all ponds are dominated by open water, dramatically decreasing their intended functional role as “wetlands”.

Ponds 2 to 5 are oval-shaped, with dimensions of 40-50 m in length and 15-20 m in width. Pond 6 is triangular in shape. They have a combined surface area of 7000 m^2.

Water flow from Pond 1 to Pond 2 occurs via an underground pipe, whereas surface water flow occurs progressively between Pond 2 to Pond 6. The outlet structure in Pond 6 determines stormwater residence time in the wetland and has been designed to ensure stormwater is retained in the wetland for at least 48 hours (optimum detention time for treatment determined by Brisbane City Council). During periods of light rainfall and during dry weather, stormwater flows progressively through Ponds 1 to 6. In times of extended rainfall, heavy rainfall or storm events, the water levels rise rapidly so that Ponds 2 to 6 form a single lake-like water body.

During high-intensity storm events with high flow, the stormwater from Pond 1 can overflow into an “overflow bypass channel” which flows around the “wetland” and re-enters Bridgewater Creek flow path downstream of Pond 6 outlet. This bypass is designed to protect the wetland vegetation from being damaged during high flow events and to reduce resuspension of the sediment. The overflow pathway represents a grass swale, and therefore provides a certain degree of sediment retention as well.

Brisbane City Council (2003) studies suggest that when the wetland is “empty”, at least 15 mm of rainfall can be contained in the wetland before the bypass channel is activated. Brisbane City Council monitoring indicates that only 59% of flow recorded upstream of the wetland passes through (Ponds 2 to 6).

A rain squall (5 mm in five minutes) whilst on site at Golden Pond enabled the collection of a time series, taken approximately every 20 minutes up to two hours after the squall from the sediment basin and Wetland 1.

Water quality monitoring

Grab samples were collected during and after storm events. 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 when practical time series were collected after an event. Wet samples were collected after six storm events at Golden Pond and 26 storm events at Bridgewater Creek. Data are also presented here from samples collected at approximately 20-minute intervals after a rain-squall event (5 mm in five minutes). Dry-weather samples were collected when there had been no rainfall for three days or longer. Dry samples represent base flow. Water samples were routinely analysed for TSS, TVS, TN, TP, NH_4-N, NO_3-N and PO_4-P. At Golden Pond, water quality was monitored on a regular basis over a period of 22 months (November 2000 to August 2002). At Bridgewater Creek, water quality was monitored on a regular basis from January 2002 (two months after completion) until January 2005. In addition, a more intense sampling regime occurred between August 2002 and January 2003. The objective of this study was to observe a stormwater treatment wetland during inter-event periods to investigate the processes which influence and determine background concentrations (Kasper and Jenkins, 2004).

Ecological health monitoring

Ecosystems health can be a difficult concept to define, since it can incorporate a wide range of properties from loss of an individual species to complete ecosystem dysfunction. In our study, we have been looking at the following properties of ecosystem health: chlorophyll-a as an indicator of phytoplankton biomass, macroinvertebrate species richness, and mosquito larvae abundance.

Macroinvertebrates and mosquitoes

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. Both summer (wet season) and winter (dry season) sampling was conducted. Mosquito larvae were sampled using a 200 mL scoop (Greenway *et al.*, 2003).

Results and discussion

Golden Pond "Wetland System" treatment train

Suspended solids

Water-quality data for total suspended solids (TSS) and total volatile solids (TVS), i.e. the organic fraction, are given in Table 3. The 12 h WW samples showed considerable variation in TSS, 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. However, for any single event, there was consistency in TSS concentration throughout the treatment train. The mean values for 12 h WW were two to threefold higher than the 24 h WW. DW samples were similar to 24 h WW at most sites. Higher TSS and TVS were recorded at Bottom Wetland 1, whereas lower TSS and TVS were recorded Downstream.

Sediment Basin: TSS leaving the sediment basin was similar to the water entering the basin, indicating little or no settlement of finer particulates. During the 12 h WW sampling, there was resuspension at the top end due to the higher velocities of incoming water. TSS was consistently higher at the bottom of Wetland 1, indicating resuspension. During dry weather, this was caused by ducks which use the shallower bottom end.

Bottom Wetland 1 and Bottom Wetland 2: A comparison between the bottom of Wetland 1 and Wetland 2 shows that TSS is generally reduced during dry weather but increases during wet weather, probably due to resuspension of particles in Wetland 2 as well as 5. Probably due to resuspension of accumulated sediment in the culverts, TVS was always higher at the bottom of Wetland 2 than Wetland 1, indicating an export of organic particulates.

Bottom Riparian Wetland: During wet weather, the TSS in the water after it had passed through the riparian wetland was lower than in the receiving stormwater from Outlet 2, indicating a filtering effect in the densely vegetated riparian stream channel. However, during dry weather, TSS in water leaving the riparian wetland was often higher due to the export of organic particulates.

Table 3. Summary of TSS and TVS (mg/L) at Golden Pond Wetlands treatment train

(NB: 140 ha catchment drains into sediment basin; 14 ha catchment (piped) drains into Stormwater Outlet 1; 40 ha catchment (piped) drains into Stormwater Outlet 2)

Site	12-hour wet weather			24-hour wet weather			Dry weather		
	n	TSS Mean ± SD	TVS Mean ± SD	n	TSS Mean ± SD	TVS Mean ± SD	n	TSS Mean ± SD	TVS Mean ± SD
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
Top Wetland 1	5	22 ± 9	5 ± 3	6	8 ± 4	4 ± 2	14	7 ± 4	4 ± 2
Bottom 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
Bottom Wetland 2	6	24 ± 12	5 ± 3	8	13 ± 9	6 ± 5	13	13 ± 9	7 ± 5
Stormwater Outlet 2	4	18 ± 8	5 ± 2	7	10 ± 7	3 ± 1	13	12 ± 9	5 ± 4
Riparian Wetland	3	15 ± 8	4 ± 2	6	8 ± 5	5 ± 3	12	14 ± 11	6 ± 5
Downstream	6	21 ± 16	5 ± 4	8	8 ± 5	4 ± 2	12	5 ± 2	3 ± 3

Downstream: Water at the last sampling site, 600 m downstream from Wetland 2 outlet and the confluence with the riparian wetland tributary, consistently had the lowest TSS (below 15 mg L^{-1}) in the 24 h WW and DW samples. However, the 12 h WW samples showed little reduction in TSS. High-water velocities probably precluded filtration and settlement.

Nutrients

Water-quality data for nutrients for wet-weather samples, i.e. collected up to 12 hours after a storm event, are given in Table 4. The water-quality data for nutrients from dry-weather samples are summarised in Table 5.

Table 4. Summary of nutrients for wet-weather samples (mean ± SD)

Site	NH_4-N (mg/L)	NO_3-N (mg/L)	TN (mg/L)	PO_4-P (mg/L)	TP (mg/L)
In Sediment Basin	0.10 ± 0.10	0.44 ± 0.33	1.27 ± 0.63	0.06 ± 0.05	0.11 ± 0.05
Out Sediment Basin	0.09 ± 0.09	0.38 ± 0.28	1.23 ± 0.58	0.06 ± 0.06	0.08 ± 0.05
Top Wetland 1	0.12 ± 0.10	0.47 ± 0.28	0.89 ± 0.41	0.08 ± 0.07	0.18 ± 0.08
Bottom Wetland 1	0.08 ± 0.07	0.28 ± 0.18	1.19 ± 0.58	0.06 ± 0.06	0.13 ± 0.07
Stormwater Outlet 1	0.11 ± 0.05	1.92 ± 1.47	2.50 ± 1.22	0.24 ± 0.15	0.34 ± 0.22
Bottom Wetland 2	0.07 ± 0.04	0.22 ± 0.16	0.94 ± 0.51	0.05 ± 0.05	0.11 ± 0.06
Stormwater Outlet 2	0.11 ± 0.08	0.74 ± 0.51	1.52 ± 0.60	0.09 ± 0.08	0.13 ± 0.06
Riparian Wetland	0.05 ± 0.04	0.30 ± 0.18	0.88 ± 0.40	0.04 ± 0.03	0.09 ± 0.05
Downstream	0.06 ± 0.03	0.18 ± 0.13	0.90 ± 0.42	0.05 ± 0.04	0.13 ± 0.08

Table 5. Summary of nutrients for dry-weather samples (mean ± SD)

Site	NH_4-N (mg/L)	NO_3-N (mg/L)	TN (mg/L)	PO_4-P (mg/L)	TP (mg/L)
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
In Sediment Basin	0.03 ± 0.03	0.53 ± 0.67	0.57 ± 0.31	0.04 ± 0.04	0.08 ± 0.02
Out Sediment Basin	0.05 ± 0.05	0.56 ± 0.71	0.70 ± 0.33	0.03 ± 0.03	0.08 ± 0.01
Top Wetland 1	0.04 ± 0.03	0.43 ± 0.63	0.74 ± 0.33	0.03 ± 0.03	0.07 ± 0.01
Bottom Wetland 1	0.03 ± 0.03	0.25 ± 0.49	0.63 ± 0.33	0.02 ± 0.02	0.07 ± 0.02
Stormwater Outlet 1	0.07 ± 0.06	1.76 ± 0.78	2.35 ± 0.37	0.11 ± 0.06	0.19 ± 0.05
Bottom Wetland 2	0.08 ± 0.09	0.25 ± 0.23	0.97 ± 0.50	0.05 ± 0.08	0.14 ± 0.07
Stormwater Outlet 2	0.17 ± 0.36	1.10 ± 0.81	1.53 ± 0.79	0.04 ± 0.04	0.08 ± 0.02
Riparian Wetland	0.26 ± 0.43	0.28 ± 0.25	0.84 ± 0.25	0.02 ± 0.02	0.10 ± 0.05
Downstream	0.03 ± 0.03	0.09 ± 0.11	0.60 ± 0.28	0.02 ± 0.02	0.05 ± 0.03

Sediment Basin: The wet samples show that soluble nutrients leaving the sediment basin were generally lower than the receiving stormwater. However, during dry weather, some samples yielded an increase in NH_4-N and NO_3-N, possibly due to ammonification and nitrification of organic matter.

Top and Bottom of Wetland 1: A comparison between top and bottom shows a slight decrease in all soluble nutrients, possibly due to plant, algae and periphyton uptake.

Bottom Wetland 1 and Bottom Wetland 2: A comparison between the bottom of Wetland 1 and Wetland 2 shows an increase for NH_4-N and PO_4-P in the dry samples. The increase appears to be due to the high concentrations of nutrients entering Wetland 2 from the stormwater outlet. These soluble nutrients are significantly reduced in Wetland 2 due to removal by aquatic plants, algae and periphyton.

Bottom Riparian Wetland: During dry weather, NO_3 and PO_4 were reduced in the riparian wetland section, probably due to uptake by plants and periphyton, but NH_4 generally increased, probably due to ammonification of dead organic matter.
Downstream: Water collected at the last sampling site consistently had the lowest soluble nutrient concentrations.

Rain squall

Figure 3 reflects changes during a rain squall. The time series shows a lag response followed by a large peak in TSS (mostly inorganic particles) leaving the sediment basin at a flow rate of 0.35 m^3/s. While an increase in TSS occurs at the bottom of Wetland 1 after 30 minutes, there is substantial reduction in both TSS and TVS concentrations, confirming the effectiveness of the wetland in filtration.

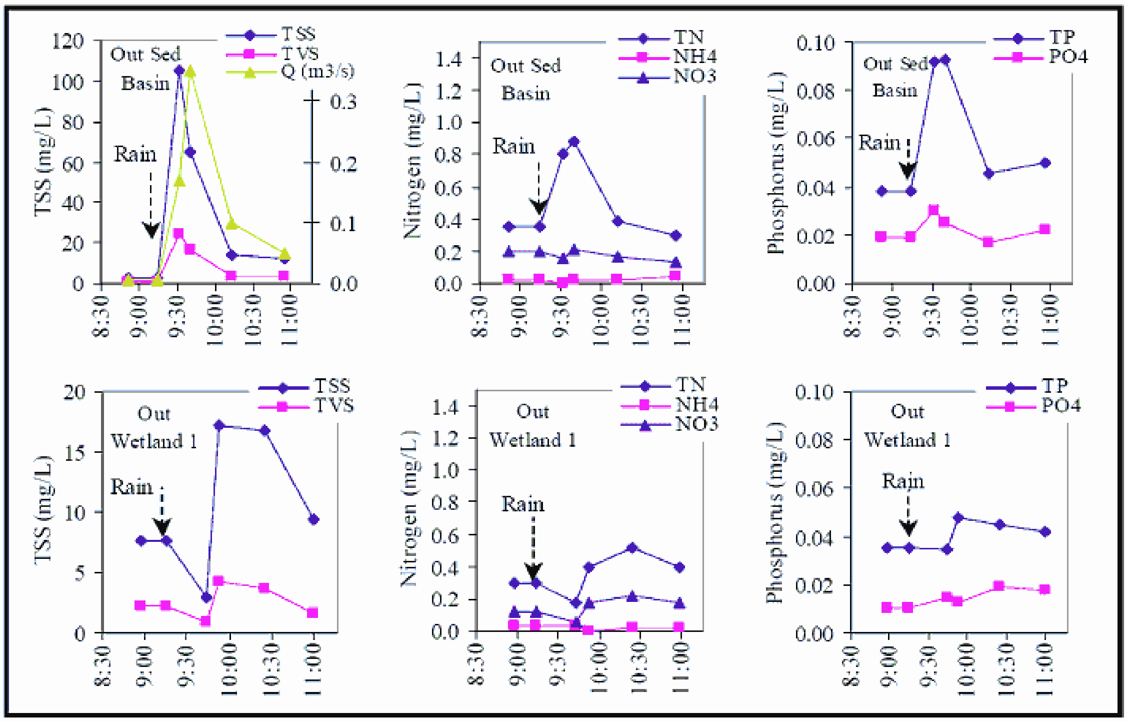

Figure 3. Time series for suspended solids and nutrients leaving the sediment basin and the bottom of Wetland 1, before and after a five-minute rain squall

Bridgewater Creek Wetland "Pond System"

Suspended solids

Water-quality data for TSS and TVS are given in Table 4. The 12 h WW samples show that TSS in stormwater in the main Bridgewater Creek inlet is very high compared to Golden Pond stormwater. Between Pond 1 outlet and Pond 6 outlet, there is only a 20% reduction in TSS concentration. Only two samples of stormwater entering Pond 1 after 24 hours were collected, and these are very low - perhaps indicating clear water following flushing. The 24 h WW samples show a 56% reduction in TSS in Pond 1 and a 30% reduction in TSS in Pond 2 compared to the 12 h WW samples. Nevertheless, the outlet concentrations still exceeded Water Quality Objectives (15 mg L^{-1}). TSS in dry-weather samples were highly variable in the stormwater entering Pond 1, but almost 50% reduction occurred in the sediment basin to produce good water clarity (9.6 ± 5.6 mg L^{-1} TSS). However, between Pond 1 and Pond 6, TSS increased to produce an average outlet concentration of 15.6 ± 7.8 mg L^{-1} TSS, i.e. within the same magnitude as the bottom of Wetlands 1 and 2 at Golden Pond, again indicating resuspension of sediment. Of particular note is the high (75%) organic proportion (TVS) in Pond 1 due to phytoplankton growth (Kasper and Jenkins, 2004).

Table 6. Summary of TSS and TVS (mg/L) for Bridgewater Creek treatment train (x ± SD)

Site	12-hour wet weather			24-hour wet weather			Dry weather		
	n	TSS	TVS	n	TSS	TVS	n	TSS	TVS
Creek Inlet	5	57.2 ± 17.8	25.0 ± 11.3	2	5.9 ± 4.8	1.9 ± 1.2	9	18.0 ± 16.9	4.6 ± 3.2
Piped Inlet	3	19.6 ± 8.4	8.1 ± 3.4	2	5.5 ± 4.8	1.7 ± 1.4	9	17.4 ± 15.8	4.6 ± 2.6
Pond 1 Out	7	41.4 ± 38.3	9.4 ± 5.1	6	18.5 ± 10.4	6.3 ± 3.0	75	9.6 ± 5.6	7.2 ± 4.7
Pond 6 Out	9	33.9 ± 33.4	8.3 ± 6.6	7	24.4 ± 9.8	9.5 ± 4.8	103	15.6 ± 7.8	6.6 ± 4.2

Nutrients

Water-quality data for nutrients for the wet-weather samples are given in Table 7, and for dry weather in Table 8. The 12 h WW samples show that NH_4-N and NO_3-N in the stormwater runoff are comparable to the stormwater flowing into the sediment basin at Golden Pond. However, PO_4-P was higher. TN and TP were also higher, indicating a greater particulate load. There was no reduction of soluble nutrients in Pond 1 but some reduction in TN and TP, suggesting settlement of particulates. Between Pond 1 and Pond 6, there was a large reduction in NO_3-N (78%) and PO_4-P (87%) concentrations, suggesting biological removal. TN and TP were also reduced, possibly due to further settlement of particulates. However, there was no reduction in NH_4-N concentrations. These trends were similar to the Golden Pond Wetlands.

Table 7. Nutrients for Bridgewater Creek 12 h WW samples (x ± SD) (March 2002 to July 2003)

Site	NH_4-N (mg/L)	NO_3-N (mg/L)	PO_4-P (mg/L)	TN (mg/L)	TP (mg/L)
Creek Inlet	0.14 ± 0.12	0.43 ± 0.17	0.14 ± 0.16	4.68 ± 2.70	0.70 ± 0.38
Piped Inlet	0.12 ± 0.10	0.42 ± 0.32	0.10 ± 0.09	3.62 ± 3.36	0.31 ± 0.22
Pond 1 Out	0.13 ± 0.11	0.46 ± 0.37	0.15 ± 0.21	2.69 ± 3.12	0.21 ± 0.19
Pond 2	0.31 ± 0.03	0.13 ± 0.07	0.04 ± 0.02	1.14 ± 0.19	0.20 ± 0.03
Pond 3	0.10 ± 0.10	0.13 ± 0.14	0.08 ± 0.05	1.84 ± 0.87	0.30 ± 0.14
Pond 4	0.20 ± 0.27	0.16 ± 0.10	0.04 ± 0.03	1.73 ± 0.37	0.26 ± 0.18
Pond 5	0.28 ± 0.06	0.16 ± 0.10	0.02 ± 0.02	1.42 ± 0.31	0.19 ± 0.06
Pond 6 Out	0.13 ± 0.22	0.10 ± 0.08	0.02 ± 0.02	0.84 ± 0.21	0.12 ± 0.08

The dry-weather samples showed similar base-flow nutrient concentrations to the Golden Pond catchment for nitrogen, but were higher for phosphorus. NO_3 was particularly high from the piped inlet, but was similar to NO_3 from the piped systems at Golden Pond (Stormwater Outlet 1 and Stormwater Outlet 2). NO_3 and PO_4 were both reduced in Pond 1. PO_4 was further reduced from 0.08 ± 0.06 mg L^{-1} PO_4-P in Pond 1 to 0.02 ± 0.02 mg L^{-1} in Pond 6, but there was only a small reduction in NO_3 from 0.12 ± 0.24 mg L^{-1} to 0.10 ± 0.08 mg L^{-1} NO_3-N. NH_4 increased in Ponds 2 to 5. TP increased in Ponds 2, 3 and 4 due to the particulate fraction.

Table 8. Nutrients for Bridgewater Creek, dry-weather samples (x ± SD) (March 2002 to July 2003)

Site	NH_4-N (mg/L)	NO_3-N (mg/L)	TN (mg/L)	PO_4-P (mg/L)	TP (mg/L)
Creek Inlet	0.08 ± 0.09	0.57 ± 0.60	1.84 ± 1.01	0.19 ± 0.18	0.26 ± 0.11
Piped Inlet	0.06 ± 0.05	1.10 ± 0.40	1.97 ± 0.28	0.16 ± 0.10	0.24 ± 0.09
Pond 1 Out	0.10 ± 0.09	0.12 ± 0.24	1.28 ± 0.45	0.08 ± 0.06	0.22 ± 0.10
Pond 2	0.22 ± 0.30	0.06 ± 0.10	1.46 ± 0.35	0.05 ± 0.04	0.27 ± 0.06
Pond 3	0.22 ± 0.29	0.07 ± 0.17	1.38 ± 0.50	0.04 ± 0.03	0.26 ± 0.08
Pond 4	0.15 ± 0.23	0.03 ± 0.04	1.14 ± 0.35	0.03 ± 0.02	0.23 ± 0.07
Pond 5	0.19 ± 0.23	0.08 ± 0.15	1.23 ± 0.38	0.02 ± 0.02	0.21 ± 0.08
Pond 6 Out	0.11 ± 0.11	0.10 ± 0.14	1.04 ± 0.36	0.02 ± 0.01	0.17 ± 0.07

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).

During dry weather, flows entering Wetland 1 at Golden Pond ranged from 0.0015 $m^3 s^{-1}$ to 0.0003 $m^3 s^{-1}$. Thus, minimum retention time would be 8 days in Wetland 1 and 16-20 days for both wetlands. At Bridgewater Creek during dry weather, retention times in the pond system were greater than 20 days.

Ecosystem health

Phytoplankton: Chlorophyll-a

At Golden Pond, chlorophyll-a was only measured in the dry base-flow periods, and values were low (3.5 ± 0.6 $\mu g\ L^{-1}$ in the sediment basin, 5.5 ± 3.2 $\mu g\ L^{-1}$ in Wetland 1, and 3.2 ± 0.8 $\mu g\ L^{-1}$ in Wetland 2).

At Bridgewater Creek, algal blooms occurred in dry weather in Ponds 1 and 2, but chlorophyll-a was reduced in Ponds 3 to 6 (Table 9). This indicates a reduction in phytoplankton biomass, despite similar soluble inorganic nitrogen concentrations in the ponds. Although the mean phosphate concentration in Pond 6 was only 0.02 mg L^{-1} compared to 0.08 mg L^{-1} in Pond 1, the N:P ratios are not limiting for phytoplankton growth (Wetzel, 2001; Bayley *et al.*, 2005). Similar light profiles in all ponds also suggest that light is not a limiting factor. Numerous microcrustaceans, in particular cladocerans, were found in Ponds 2 to 6, and may have been active predators on the phytoplankton. The higher chlorophyll-a values in Ponds 2 to 6 compared with Pond 1 in our wet-weather samples appear to be a flushing-out effect. Phytoplankton species diversity changed with seasons and following rain events. Many of the genera identified are noted for their occurrence in eutrophic waters.

Table 9. A comparison of chlorophyll-a ($\mu g\ L^{-1}$) as an indicator of phytoplankton biomass in the ponds at Bridgewater Creek Wetland (March 2002 to November 2003)

Pond	Pond 1	Pond 2	Pond 3	Pond 4	Pond 5	Pond 6
Dry	64 ± 80	54 ± 60	15 ± 20	12 ± 12	10 ± 5	12 ± 10
Wet	12 ± 15	22 ± 30	25 ± 30	22 ± 28	28 ± 22	33 ± 20

Chlorophyll-a exceeded WQO of 8 $\mu g/L^{-1}$. During the first two years, DO profiles were similar. However, due to the large quantities of organic matter (mostly leaf litter that has washed into Pond 1), it has recently become anaerobic, with surface DO of 1.2 mg/L and bottom DO of 0.2 mg/L. These conditions are now limiting phytoplankton growth.

Macroinvertebrates

Wetland plant diversity is important for determining macroinvertebrate associations and wildlife diversity (Knight *et al.*, 2001) because of the creation of habitats and food resources. (Wetzel, 2001) noted that the most effective wetland ecosystems “are those that possess maximum biodiversity of higher aquatic plants and periphyton associated with the living and dead plant tissue”. From Table 10, it is very evident that the constructed stormwater wetlands and ponds increased species richness compared with the channelised upstream creek bed. At Bridgewater Creek, the vegetated section of the modified creek downstream of the ponds had the highest species richness. At Bridgewater Creek, Pond 6 had the highest diversity of hemipterans and coleopterans. It is interesting to note that, although WQO were not being achieved, both wetland and pond treatment trains improved over all macroinvertebrate biodiversity. By comparison, Greenway *et al.* (2003) found 90 taxa in the Cooroy Wetland (Noosa Shire Council) which receives secondary-treated sewage effluent (25 mg L^{-1} TN, 8 mg L^{-1} NO_x-N, 12 mg L^{-1} NH_4-N, 0.2 mg L^{-1} TN, and 0.02 mg L^{-1} PO_4-P). This demonstrates that a wide variety of macroinvertebrate species can tolerate high nutrient concentrations.

Table 10. Major macroinvertebrate taxa at Golden Pond and Bridgewater Creek Stormwater Systems and Cooroy Sewage System

Macroinvertebrate Taxa	Golden Pond “Wetland System”				Bridgewater Creek “Pond System”				Cooroy Wetland
	Upstream Channel	Wetland 1	Wetland 2	Downstream Natural Creek	Upstream Channel	Pond 1	Pond 6	Downstream Modified Channel	
“Worms”	3	5	6	6	3	9	3	5	5
Gastropoda	5	8	8	8	4	4	2	4	8
Microcrustaceans	4	5	3	4	1	4	1	1	6
Acarina	3		1			2	1	3	1
Epiproctophora	5	11	6	3	6	4	3	11	19
Zygoptera	1	3	3	5	1	2	5	4	8
Ephemeroptera	1	1	1	0	1	0	1	2	3
Hemiptera	1	4	4	1	2	3	8	6	9
Diptera	3	3	4	2	6	6	5	8	12
Coleoptera	1	0	0	4	3	0	8	6	20
Trichoptera	0	1	1	1	0	0	2	3	6
TOTAL TAXA	23	43	37	34	27	34	39	53	97
FAMILIES	12	20	16	18	18	19	25	26	45

Mosquitoes

In aquatic ecosystems, 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 constructed wetlands will encourage mosquito breeding. While most mosquitoes are opportunistic breeders, they will only deposit eggs if a suitable body of water is available. A critical and significant issue for successful mosquito breeding is larval survival and whether adult mosquitoes emerge from pupae. If constructed wetlands and ponds are designed to function as ecosystems with a diversity of aquatic organisms, then natural predators would control mosquito breeding (Greenway *et al.*, 2003). In the wetlands at Golden Pond and Pond 6 at Bridgewater Creek, less than 5% of sampling dips over a 12-month period contained mosquito larvae, and when present, they were in very low numbers (< 10/200 mL scoop). Pond 1 recorded more larvae (14% of dips), but these occurred amongst dead vegetation, and most were only the very juvenile first and second instars. 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.

Overall discussion on water quality

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. This flushing-out effect when a detention system contains a permanent pond has been modelled by Somes *et* *al.* (2000). TSS was exported on two of the four events. Export also occurred in the non-vegetated basins, but to a lesser extent.

Bavor *et al.* (2001) found that reductions in bacterial concentrations in stormwater were significantly higher in a wetland system compared to a pond system, due to the more effective settling of fine particles (< 2 μm) with attached micro-organisms. They also found that most of the nitrogen and phosphorus associated with sediments is associated with the < 2 μm size fraction, and is therefore more likely to be effectively removed in wetlands.

As previously discussed, during dry weather, TSS (and TVS) increases in the wetland system due to resuspension. In the pond system, TSS decreases in Pond 1 due to settlement, but increases again in Ponds 2 to 6. Kasper and Jenkins (2004) have shown that an increase in TSS occurs after about 11 days following a storm event, possibly due to a combination of "biological growth" and resuspension. Resuspension appears to be largely caused by water birds which congregate in the shallows of Ponds 2, 3 and 4 to be fed by the local residents, though Kasper and Jenkins (2004) have also identified wind as playing a significant role in the resuspension and movement of suspended solids during inter-event periods.

Phytoplankton biomass was highly variable in the pond system, with the highest chlorophyll values in Ponds 1 and 2. This would explain the removal of NO_3 and PO_4 in Ponds 1 and 2. By contrast, nutrient removal by periphyton would be small in these ponds due to the lack of emergent macrophyte stems and leaves for biofilm attachment. During dry weather, most of the macrophytes are above the standing water level (Greenway and Polson, 2004), again diminishing both their physical and biological roles in water-quality improvement.

In the wetland system, phytoplankton biomass was low, but a large surface area for periphyton attachment was provided by the stems of water lilies, roots and stems of *Ludwigia peploides*, and the submerged pond weeds. The periphyton, submerged pond weeds, and the adventitious roots of *Ludwigia* and other aquatic creepers would all remove soluble nutrients from the water column. The dense *Ceratophyllum* in Wetland 2 probably accounts for most of the removal of NO_3 and PO_4 coming from the piped system and below-ground GPT (Stormwater Outlet 1). However, Wetland 2 and Ponds 2 to 6 were not effective in reducing NH_4 concentrations. In fact, the increase in NH_4 suggests amination and ammonification of organic matter.

Nairn and Mitsch (2000) compared phosphorus removal in vegetated and non-vegetated riparian wetland ponds and found both systems to be effective in decreasing turbidity, PO_4 and TP. They attributed the phosphorus removal to biological uptake due to productive algal cover.

The densely vegetated natural riparian wetland at Golden Pond was very effective in removing all soluble inorganic nutrients from Stormwater Outlet 2 in wet weather, and NO_3 and PO_4 in dry weather. Here the periphyton and adventitious roots of *Persicaria* would remove these from the water column. In dry weather, an increase in NH_4 again suggests amination and ammonification.

Conclusions

In comparing the performance of the wetland system at Golden Pond and the pond system at Bridgewater Creek, 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 ponds, considerable reduction in TSS occurred in Pond 1 (the sediment basin), but increased again in the other ponds, again largely due to resuspension caused by water birds.

Table 11. Comparison of outlet nutrient and suspended solid concentrations (mg L^{-1}) in the constructed wetland and pond systems (* indicates meeting WQO)

	Wetland system outlet		Pond system outlet	
Event	Wet	Dry	Wet	Dry
Detention	3-16 h	16-20 days	36 h - 6 days	> 20 days
TSS	24 ± 12	*13 ± 7	22 ± 12	16 ± 8
NO_3-N	0.22 ± 0.16	0.25 ± 0.23	0.07 ± 0.08	0.10 ± 0.14
NH_4-N	0.07 ± 0.04	0.08 ± 0.09	0.13 ± 0.15	0.11 ± 0.11
TN	0.83 ± 0.40	0.97 ± 0.50	1.08 ± 0.36	1.04 ± 0.36
PO_4-P	0.05 ± 0.05	0.05 ± 0.08	*0.03 ± 0.02	*0.02 ± 0.01
TP	0.12 ± 0.07	0.14 ± 0.07	0.19 ± 0.11	0.17 ± 0.07

During storm events, there was a small reduction in soluble inorganic nutrients in the wetlands, but the short retention times (3-5 hours) would limit biological uptake. In the ponds, no reduction of soluble inorganic nutrients occurred in Pond 1, but 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. However, the absence of dense macrophyte zones limits biological uptake to the phytoplankton community and attached periphyton in the narrow littoral zone. During dry weather, considerable reduction in soluble inorganic nutrients occurred in both wetlands and Pond 1, demonstrating the important roles of macrophytes and periphyton in the wetlands, and phytoplankton in Pond 1. Between Pond 2 and Pond 6, phytoplankton biomass was low and only PO_4 was significantly reduced.

During dry weather, NH_4 and NO_3 increased in the sediment basin but decreased in the wetlands. PO_4 also decreased in the wetlands. The removal of these soluble nutrients would be due to wetland processes including direct uptake by plants, algae and micro-organisms. Higher NH_4 at Wetland 2 outlet compared with Wetland 1 was probably due to additional contributions from Stormwater Outlet 1 and some ammonification in Wetland 2. NO_3-N concentrations were highest in the discharges from the stormwater outlets (Stormwater Outlet 1 and Stormwater Outlet 2) from the below-ground GPTs. However, concentrations were reduced as the stormwater passed through Wetland 2 and the riparian wetland respectively. The natural stream channel was also effective in removing NO_3-N, reducing concentrations from 0.22 ± 0.28 mg L^{-1} to 0.08 ± 0.11 mg L^{-1}.

In terms of achieving the Water Quality Objectives of Brisbane City Council (i.e. 15 mg L^{-1} TSS, 0.65 mg L^{-1} TN, 0.035 mg L^{-1} NH_4-N, 0.13 mg L^{-1} NO_3-N, 0.035 mg L^{-1} PO_4-P, and 0.07 mg L^{-1} TP), neither the wetlands nor the ponds were able to consistently achieve these guidelines. Nevertheless, both systems are important for increasing the biodiversity of aquatic organisms, water birds, aesthetics and passive recreation.

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