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Wetlands and Ponds for Stormwater Treatment in Subtropical Australia: Their Effectiveness in Enhancing Biodiversity and Improving Water Quality?

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Abstract: Stormwater best management practice is aimed at reducing potential downstream impacts on aquatic ecosystem health. Sediment basins, wetlands and ponds are commonly used in subtropical Australia for water-quality improvement; they also have the potential to enhance aquatic biodiversity in urbanised catchments. Two retrofit field sites in Brisbane, Australia were monitored for water quality and ecosystem health. The Golden Pond "wetland system" treatment train consisted of a sediment basin and two wetlands. The Bridgewater Creek "pond system", consisted of a sediment basin and five ponds. Suspended solids were reduced during wet weather, but increased during dry weather due to resuspension by ducks. NO_3-N decreased in both wet and dry weather. NH_4-N increased probably due to ammonification of organic matter. PO_4-P decreased. The removal of soluble NO_3 and PO_4 is indicative of biological uptake by phytoplankton submerged pond weeds and periphyton attached to aquatic macrophytes. Macroinvertebrate species richness increased, and mosquitoes were not a problem due to predation of larvae by macroinvertebrates. Macrophyte survival was adversely affected by flash flooding and increased inundation. Although water quality objectives were not consistently achieved, both systems were effective in reducing suspended solids and nutrients from stormwater runoff and provided a habitat for aquatic organisms.

Keywords: *Ecosystem health, wetland, stormwater treatment*

Urban stormwater runoff is recognized as a potential pollution source for downstream waterways and aquatic ecosystems. The amount and types of pollutants carried in stormwater runoff will vary according to land use, the intensity and duration of rainfall events, and the time between rainfall events. Rainfall intensity can influence the quantity of pollutants transported in stormwater. The time between rainfall events also affects the quality and quantity of stormwater runoff due to the build up of contaminants on impervious surfaces. As the time between events increases, the more pollutants accumulate. Most of these pollutants are dislodged into the receiving waters at the beginning of a rain event. Both intensity and duration of rainfall events aid in dislodging and transporting pollutants into water courses.

Major pollutants in urban runoff 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 are a high proportion of organic particles, then biochemical oxygen demand (BOD) increases. These organic particles provide a food source for microorganisms that 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 localized and their impacts on aquatic ecosystem health are usually not acute.

As noted by the European Union Framework Directive on eutrophication (SCOPE 2006) "quality status" should be assessed on the basis of observed changes in biological factors in aquatic ecosystems not simply on the basis of nutrient concentrations. However, regulatory authorities set water quality thresholds based on nutrient concentrations, but do these criteria adequately assess "poor," "moderate," or "good" quality status in terms of ecological disturbance and aquatic health? Sheeder and Evans (2004) compared water quality and aquatic ecosystem health in impaired and unimpaired watersheds in Pennsylvania and found concentrations thresholds of 2.01 mg/L N and 0.07 mg/L P, whereas EPA concentrations were set at 0.5 mg/L N and 0.02 mg/L P. Furthermore, most unimpaired watersheds based on biological assessment did not meet EPA nutrient criteria. Sheeder and Evans point out that variability in climate and landscape characteristics between ecoregions will also affect the variability and causes of eutrophication suggesting that nutrient and sediment threshold are localized.

Nevertheless, regulatory authorities continue to set threshold water quality objectives for broad geographical regions. 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 to meet legislative requirements to improve the quality of urban stormwater runoff into receiving waters that ultimately flow into Moreton Bay: 15 mg/L TSS, 5 mg/L TVS, 0.65 mg/L TN, 0.035 mg/L NH_4-N, 0.13 mg/L NO_3-N, 0.07 mg/L TP, 0.035 mg/L PO_4-P, and 8 µg L^{-1} chlorophyll a. But are these water quality objectives realistic? And can they be achieved using the range of stormwater treatment devices and technologies that we are incorporating into water sensitive urban design in subtropical and tropical areas?

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 and reduction. Commonly used stormwater treatment devices include: gross pollutant traps (to catch coarse sediment and trash), retention sediment basins (to capture coarse and fine sediment), vegetation buffer strips (sediment and nutrient removal by sheet flow across wide natural vegetation strips), infiltration and bioretention systems (sediment and nutrient removal by filtration and biological processes), porous pavements (sediment and nutrient removal by filtration to treat impervious area runoff), vegetation filter strips/grass swales (sediment and nutrient removal along concentrated flow paths), wetlands (dominated by wetland plants) and ponds (open water) (effective sediment and nutrient removal by aquatic ecosystems).This paper will focus on wetlands and ponds.

Research Objectives

Frequently asked questions are: "How effective are these stormwater treatment devices in improving water quality?," "What are the ecological impacts of stormwater runoff on ecosystems health?"; "Do constructed stormwater wetlands and ponds enhance aquatic biodiversity?"; "Is the retention of natural stream channels and adjacent riparian vegetation an effective treatment?" 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; and climate) 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 — a climatic region with high intensity summer rainfall events and prolonged inter-event dry periods. Our research efforts have focused 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.

Wetlands and Ponds

Wetland and pond ecosystems are composed of abiotic (non-living) components (sediment, water, air) and biotic (living) components (aquatic plants or macrophytes, aquatic organisms including macroinvertebrates and vertebrates, and micro organisms). Plants are often the most conspicuous feature but microorganisms are the most diverse and abundant. Vegetation (usually emergent macrophytes) is the dominant feature of wetlands, whereas open water is the dominant feature of ponds. Wetlands are shallow water bodies (less than 50 cm) and support a variety of vegetation types: emergent reeds and rushes, water lilies, aquatic creepers, and submerged pond weeds. Ponds, lagoons, and lakes are deeper (often greater than one meter) open water bodies. 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. Periphyton (biofilm) communities are an important component covering the sub-merged portion of stems and leaves in either wetlands or ponds.

Macrophytes

Aquatic plants, known as macrophytes, can be classified into two functional types: rooted plants and floating plants. Rooted plants can be further classified as emergent macrophytes such as reeds (Phragmites), bulrush (Typha), sedges (Baumea, Eleocharis, Schoenoplectus), submerged macrophytes such as pond weeds (Ceratophyllum, Potamogeton), and floating leafed macrophytes such as water lilies. Rooted emergent macrophytes are restricted to shallow water from a few centimetres to a maximum depth of 1.5m. The depth distribution of submerged plants is restricted by turbidity and light availability. Floating plants have surface leaves and roots which hang in the water such as duckweed (Lemna, Azolla).

Water depth plays a critical role in the distribution of the types and species of aquatic plants. In natural wetlands, zonation is common, with emergent seasonally inundated species occurring at the landward interface and submerged species occurring in deeper permanent water. Ephemeral wetlands or wet meadows are dry or waterlogged areas that experience regular inundation which may be seasonal and support emergent macrophytes. Marshes are shallow wetlands (20-50 cm), typically dominated by emergent macrophytes. However, floating-leaved attached macrophytes such as water lilies, submerged macrophytes and floating macrophytes (e.g. duck weed) may occur, particularly where there is permanent water. Deeper (50-200 cm) open ponds may support floating-leaved attached macrophytes, floating macrophytes or submerged macrophytes if there is sufficient light for growth.

Macroinvertebrates

Wetlands and ponds support a diversity of aquatic animals including microcrustaceans (copepods, ostracods, claderans) shrimps, crayfish; insects (dragonfly larvae, water beetles, water boatman); pond snails, tadpoles, frogs and fish. These organisms are a crucial component of wetland and pond ecosystems providing invaluable food web linkages between plants, microorganisms and other animals. Predator-prey relationships are important in the control of mosquitoes (Greenway et al. 2003).

Wetland plant diversity is important for determining macroinvertebrate associations (De Szalay and Resh 2000) 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 (p. 5).”

Microorganisms

Microorganisms, although inconspicuous, are the most abundant and diverse group of living organisms in wetland systems. They include bacteria, fungi, unicellular, and filamentous algae and protozoans. Microorganisms occur in the water column as "plankton"; attached to plant surfaces as "epiphytes" and biofilms; attached to other surfaces as "periphyton" and biofilms; and on or in the sediment as "microbenthos." Anaerobic bacteria occur in low-oxygen environments in the sediment. They are crucial for biogeochemical cycles of carbon, nitrogen, sulphur, and phosphorus.

Wetland Functions

Natural wetlands and ponds perform a wide range of hydrological, ecological, and social functions that directly or indirectly result in benefits to human society. Hydrological functions include: water quality improvement by filtering suspended particles and by removing, recycling or immobilising environmental contaminants and nutrients; flood mitigation by storing and detaining precipitation and runoff thus reducing downstream flood rates and peak floods; and ground water recharge. Ecological functions include: temporary and permanent habitats for a variety of aquatic and terrestrial organisms; breeding areas for fish, frogs, and waterbirds; roosting sites and feeding grounds for birds; refuges for wildlife during drought periods. Social functions include: landscape and recreational amenity; biological resources such as fisheries; education and research. Recognition of the beneficial values of wetlands and ponds has lead to the creation of constructed wetlands and ponds (also referred to as sediment basins, lagoons or lakes in an urban area – depending on their size) for stormwater management including water storage for reuse and water-quality improvement.

Stormwater Wetlands and Ponds

The decision to use ponds or wetlands, or a combination of both, depends on several factors: 1) pollutant characteristics of the stormwater, 2) treatment performance expectations, 3) pollutant loading, and the ability of the system to remove pollutants by physical, biological or chemical processes (Table 1); 4) hydrology and hydraulics (Carleton et al. 2001; Jenkins and Greenway, 2005; 2007); 5) available area for construction, and 6) community opinion and benefits – including aesthetic value, recreational value, wildlife habitat, water storage, and reuse.

Mitsch and Gosselink (2007) state that "Hydrology is probably the most important determinant of the establishment and maintenance of specific types of wetlands and wetland processes (p. 108)." The duration of flooding or substrate saturation, the depth of flooding, the frequency and season of flooding and drying, can all have an effect on plant establishment and growth. Wetlands that are permanently flooded support different plant species compared to wetlands that are only seasonally flooded or subjected to extended drought periods. While the hydroperiod (i.e. duration of inundation or substrate saturation) of municipal wastewater treatment wetlands can be regulated and controlled by a steady inflow of effluent, stormwater runoff is highly variable due to the erratic nature of storm events in both intensity and duration. Thus, wetland plants growing in stormwater wetlands would experience a range of water depths and periods of inundation. The duration of inundation, drought, the depth of water, or the frequency of flooding will affect plant growth, establishment, and survival. Long periods of flooding are stressful to some wetland plants (Greenway 2007(a); Greenway et al. 2007). Bonilla-Warford and Zedler (2002) express concern about the lack of native wetland plants in stormwater wetlands in the United States, and list Typha spp., Phragmites australis, Scirpus spp., Juncus spp. and Phalaris arundinacea as the most commonly used species. They suggest that limited knowledge of plant tolerances to fluctuating water levels is one reason for the lack of variety of native species in stormwater wetlands.

Zonation of macrophytic vegetation is particularly important in stormwater wetllands (Greenway 2004; Greenway 2007(a); Greenway et al. 2007; Jenkins and Greenway 2007). In the design of stormwater wetlands, it is important to allow for variations in water depth, thereby accommodating both flooding and intermittent flows. Stormwater wetlands should support a zonation of wetland plants, each adapted to a specific hydroperiod (i.e. the extent of periodic or permanent inundation). "Ephemeral wetland" zones, which in natural wetlands occur around the landward margins of lakes or on floodplains,

Table 1. Comparison of treatment processes in wetlands and ponds.

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

can be established in locations where they would only be inundated during the wet season. This could include the upper margins of the deeper, open-water ponds or specially created shallow areas within the macrophyte zones which would completely dry out. Ephemeral species can include a variety of trees and shrubs, as well as smaller herbaceous plants. "Shallow wetland" zones should be designed to maintain water depths of at least 10 cm during the dry season and up to 50 cm of permanent water. "Deep wetland" zones should maintain water depths of at least 20 cm during the dry season.

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 per year greater than 50 mm rainfall. Intense rainfall events (10 y ARI 1-hour duration intensity of 71 mm/h), are common in the rainy season. The constructed wetland system and pond system are retrofit structures located within existing residential areas (70 percent impervious area) in Brisbane (Table 2). For more detailed description of these field sites refer to Greenway (2007 b) for Golden Pond and Jenkins and Greenway (2007 b) for Bridgewater Creek.

Golden Pond "Wetland System," Calamvale. The stormwater treatment train consists of a small sediment basin and two constructed wetlands. The sediment basin and wetlands were constructed within an existing concrete stream channel. The wetlands are unusual in that they are dominated by water lilies, aquatic creepers, and submerged pond weeds – rather than emergent sedges, rushes, or reeds (Greenway 2007b). Downstream, riparian vegetation fringes a 600m length of natural stream channel with lagoons.

Bridgewater Creek Wetland "Pond System," Coorparoo. This treatment "wetland" consists of six interconnected ponds. Pond 1 is a large sediment basin with a narrow littoral zone of Schoenoplectus validus. 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 2007(b); Greenway et al. 2007; Jenkins and Greenway 2007). Thus all ponds are dominated by open water, dramatically decreasing their intended functional role as "wetlands." During high-intensity storm events stormwater from Pond 1 overflows into an "bypass channel" which flows around the "wetland" and re-enters Bridgewater Creek downstream of the Pond 6 outlet. This retrofit system replaced a narrow concrete channel. The downstream section for a length of 200m has been reconstructed to resemble a shallow natural stream channel.

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

	Golden Pond (2 percent catchment)		Bridgewater Creek (4 percent catchment)	
	Sediment basin	**Wetlands 1 and 2**	**Sediment basin**	**Ponds 2-6**
Area Vegetation	284 m^2	2600 m^2	1000 m^2	7000 m^2
Vegetation	Absent	Water lillies, aquatic creepers, submerged pond weeds	Littoral emergent sedges	
% cover	0	75-90 percent	1 percent	0.1 percent
Depth	1.5m	0.2 - 1.2 m	2 m	0.2 - 1.5 m
Volume (Standing Water Level)	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			
Storm events	4.22 - 0.15 m^3/s			2.33 - 0.33 m^3/s

Water Quality Monitoring

Grab samples were collected during and after storm events. Samples collected within 12 hours of a storm were categorized as 12 h wet, and those collected 24 hours after an event as 24 h wet. Wet samples were collected after six storm events at Golden Pond and 26 storm events at Bridgewater Creek. 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 during 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. The objective of this study was to observe stormwater treatment within a pond system and during inter-event periods to investigate the processes which influence and determine background concentrations (Kasper and Jenkins 2004).

Ecological Health Monitoring

Ecosystem 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 looked at the following properties of ecosystem health: macrophytes distribution and abundance; chlorophyll a as an indicator of phytoplankton biomass; macroinvertebrate species richness and their sensitivity to pollution; and mosquito larvae abundance. The study was conducted within the first four years after construction.

Macrophytes. Macrophytes are crucial for wetland function and biodiversity. Thus, the success of a stormwater wetland depends on successful plant establishment and survival. At Golden Pond, the wetlands were marked out by a 5 × 5 m grid system.The extent of cover in each grid was estimated. This was aided by both photographic records and field survey. At Bridgewater Creek, a series of permanent transects were established from either the landward edge of the ponds or the ephemeral zone between the ponds and into the open water. Species abundance was recorded in quadrats placed at 50cm intervals along each transect every 6 months.

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 of the constructed wetland or pond 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. Macroinvertebrate sensitivity to pollution can be measured using a variety of biotic indices. We used the Stream Invertebrate Grade Number – Average Level : SIGNAL-2 scoring system, commonly used in Australia, to grade macroinvertebrate families according to their pollution sensitivity (Chessman 2003). Grades are on a scale of 1 to 10, with 10 being the most sensitive to pollution. Mosquito larvae were sampled using a 200 mL scoop (Greenway et al. 2003).

Results and Discussion

Ecosystem Health

Macrophytes. ***Golden Pond Wetlands***. Tables 3 and 4 provide an indication of the changes in macrophytes plant cover between October 2000 and February 2002. Unfortunately, both wetlands were dredged of all vegetation in March 2002 by maintenance workers instructed to "tidy up and get rid of the weeds," so monitoring was discontinued.

When Wetland 1 (Table 3) was first surveyed in October 2000 (12 months after planting), it was dominated by waterlilies (Nymphoides and Nymphaea). Clumps of Schoenoplectus validus were restricted to the littoral margins. No plants of Baumea nor Lepironia were found, suggesting the unsuccessful survival of these species that were planted in deeper water. The greatest change in macrophyte cover occurred between October 2000 and February 2001 with the spread of the native aquatic creeper Ludwigia peploides, which took advantage of the floating-leaved species to assist in spreading from the banks towards the center. Between February 2001 and March 2001, there were two major storm events with rainfall of 86 mm and 161 mm. Flash flooding had three major impacts on the vegetation. Firstly, a large sediment load (mostly sand) "overflowed" from the small sediment basin and was deposited at the top of the wetland, smothering stands of Schoenoplectus. Secondly, scouring occurred in the flow path, causing the uprooting of Hydrilla and some Nymphoides. Thirdly, the high velocities washed away creeping stems of Ludwigia. Rapid recolonization of both Hydrilla and Ludwigia occurred post-storm. Ludwigia continued spreading. However, its smothering effect may have restricted the spread of both Nymphaea and Nymphoides. There was limited spread of emergent species along the landward margins due to continual brush cutting by maintenance workers seeking a "manicured lawn" effect (even as much as 1m into the water)!

Wetland 2 (Table 4) supported 90 percent surface cover in October 2000, dominated by Nymphaea and Nymphoides; beneath were dense stands of Ceratophyllum. Between October and February 2001, an increase in the creepers Ludwigia, Paspalum and Persicaria smothered the Nymphoides around the shallower margins. The storm events had a lesser impact due to the evenly distributed flow at the top of Wetland 2. However, some of the aquatic creepers (Paspalum, Ludwigia and Persicaria) were washed away. Post-storm recovery was rapid, and during the next 10 months, Persicaria (attenuatum and strigosa) spread to occupy 30 percent of the surface area, smothering, and displacing Nymphaea or Nymphoides.

Bridgewater Creek "Wetland" - Ponds

Table 5 provides a comparison of the temporal changes in extent of distribution of plant species in the different macrophyte zones from the initial planting in November 2001 until May 2006. The original planting scheme for the different macrophyte zones is shown in column 1 (Nov 2001). The "wetland" was designed to achieve 80 percent macrophyte cover in Ponds 2-6. However, several species did not survive the first three months: Eleocharis sphacelata and Lepironia articulata (planted in the deep marsh) and Eleocharis equisetina and Philydrum lanuginosum (planted in the marsh). Poor plant establishment occurred in all marsh zones following planting, but was worse in the deep marsh resulting in only two percent area cover. Thus, by May 2002 open water was 56 percent of the total wetland area (Ponds 2-6). Hence the wetland in effect became a pond system dominated by open water with a fringing littoral zone. During the next four years, the extent of open water increased to 80 percent as plants failed to establish and spread in the marsh zones, whereas the loss of plants in the ephemeral zone resulted in bare mud.

Table 3. Percentage cover of macrophytes in Wetland 1. Below-surface cover for *Hydrilla*. October 1999 was the original planting scheme.

	October 1999	**October 2000**	**February 2001**	**March 2001**	**July 2001**	**February 2002**
Open water	20	52	30	42	18	10
Submerged species:						
Hydrilla verticillata	+	(20)	(20)	(12)	(15)	(15)
Ceratophyllum demersum	+	-	-	-	-	-
Floating-leaved species:						
Nymphaea caerulea	4	10	12	12	15	15
Nymphoides indica	20	20	20	19	20	22
Aquatic creepers:						
Ludwigia peploides	-	1	20	15	28	35
Paspalum distichum	-		1	1	2	2
Emergent species:						
Alisma plantago	5	+	+	+	+	+
Baumea articulata	20	-	-	-	-	-
Leporina articulata	5	-	-	-	-	-
Schoenoplectus validus	-	14	15	8	10	10
Schoenoplectus macronatus	20	1	1	1	1	1
Juncus usitatus	6	1	1	1	4	2
Typha orientalis	-	1	1	1.5	2	3

Table 4. Percentage cover of macrophytes in Wetland 2. Below-surface cover for *Ceratophyllum*.

	October 2000	**February 2001**	**March 2001**	**July 2001**	**February 2002**
Open Water	10	5	9	5	2
Ceratophyllum	(60)	(60)	(55)	(60)	(40)
Nymphea capensis	30	30	30	30	23
Nymphoides indica	45	33	32	33	23
Ludwiga peploides	4	10	9	10	15
Paspalum distichum } *Persicaria attenuatum* }	1	7	6	7	8
Persicaria strigosum	10	15	13	15	30
Typha orientalis				1	4

From December 2005 until mid April 2006 the wetland had been inundated by water depths of up to 75cm above the ephemeral zone (Relative Level 5.0m). The cause was a blockage in the outlet riser orifice that prevented draining. This extended period of inundation caused the loss of Baumea articulate and Schoenoplectus validis. Only Bolboschoenus fluviatilis survived by landward migration into the terrestrial zone. A decline in Potamogeton also occurred during this period of increased water depths.

Monitoring macrophyte establishment in these two stormwater "wetlands" has identified many hurdles facing plant survival. The greatest challenge for stormwater wetlands is successful establishment, and the hydroperiod is the key factor. The failure of macrophyte establishment at the Bridgewater Creek Wetland was due to deeper water in the marsh zones and prolonged inundation in the ephemeral zones. Thus, careful consideration must be given not only to water depth, but also to the duration of inundation. Riser and weir levels must ensure that water levels recede to the appropriate Relative Level post storm/flood event to prevent extended periods of inundation. More research needs to be undertaken into understanding the tolerance of different species to periods of inundation. Scouring, erosion and loss of topsoil also contribute to poor plant establishment. Exposure of the clay base also prevented the spread of rhizomatous species. At the Golden Pond Wetland, submerged species and aquatic creepers were washed away in large storm events. However, once established, emergent macrophytes (Schoenoplectus validus) and floating-leaved attached macrophytes (Nymphaea and Nymphoides) withstood very high flow rates without becoming uprooted and washed away. Nevertheless, the incorporation of a high flow bypass channel in wetland design can minimize the impact of increased velocities within the wetland.

Phytoplankton: Chlorophyll a. At Golden Pond, chlorophyll a values were low (3.5 ± 0.6 µg L^{-1} in the sediment basin, 5.5 ± 3.2 µg L^{-1} in Wetland 1, and 3.2 ± 0.8 µg L^{-1} in Wetland 2). These values are below water quality objectives (8 µg/L^{-1}).

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 6). 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 compared to 0.08 mg/L 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. Phytoplankton species diversity changed with seasons and following rain events (Bayley 2008). Many of the genera identified are noted for their occurrence in eutrophic waters.

Chlorophyll a exceeded water quality objectives of 8 µg/L. During the first two years of operation dissolved oxygen profiles were similar in all ponds. However, due to the large quantities of organic matter (mostly leaf litter that has washed into Pond 1), it has now become anaerobic, with surface dissolved oxygen of 1.2 mg/L and bottom dissolved oxygen of 0.2 mg/L. These conditions are 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 7, it is very evident that the constructed stormwater wetlands and ponds increased species richness compared with the channelized 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. Macroinvertebrate species richness showed an increase during the four years since construction at Bridgewater Creek from 12 taxa to 86 taxa with 28 percent of the families having a sensitivity grade greater than five. Golden Pond Wetland maintained approximately 60 taxa with 24 percent families having a sensitivity grade of greater than 5.

Table 5. Temporal changes in wetland zones (percent area) in Ponds 2-6 and species survival in Bridgewater Creek Wetland. (N.B. RL outlet overflow weir is 5.01m AHD). Nov 2001 represents original planting scheme. (*denotes that species survived by spreading into shallower zones).

Wetland Zone/Species	Nov 2001	May 2002	Nov 2002	Nov 2003	May 2004	Nov 2004	Aug 2005	May 2006
	Percent							
Ephemeral, RL 4-4.25	14	14	14	11.5	10	8	8	1
Carex appressa	+	+	+	+				
Isolepis nodosa	+	+	+					
Juncus usitatus	+	+	+	+	+	+	+	+
Juncus kraussii	+	+	+	+	+	+	+	+
Philydrum lanuginosum	+	+	+	+				
Bolboschoenus fluviatilis				+	+	+	+	+
Shallow marsh, RL 3.75 - 4	23	10	14	7	7	7	7	0.1
Baumea rubiginosa	+	+	+					
Cyperus polystachys	+	+						
Juncus Kraussii	+	+	+	+	+	+	+	+
Isolepis nodosa	+	+						
Philydrum lanuginosum	+	+	+	+				
*Bolboschoenus fluviatilis**			+	+	+	+	+	+
Schoenoplectus validus			+	+	+	+	+	+
Baumea articulata			+	+	+	+	+	
Marsh, RL 3.5 - 3.75	24	15	6	6	0.2	0.2	0.2	0.05
Baumea rubiginosa	+	+	+					
Bolboschoenus fluviatilis	+	+				+	+	
Eleocharis equisetina	+							
Schoenoplectus mucronatus	+	+	+	+				
Lepironia articulata	+	+	+	+	+	+	+	+
Schoenoplectus validus		+	+	+	+	+	+	+
Baumea articulata			+	+	+		+	
Deep Marsh RL 3 - 3.5	20	2	2	0.5	0.2	0.2	0	0
*Baumea articulata**	+	+	+	+	+	+		
Eleocharis sphaceleta	+							
*Schoenoplectus validus**	+	+	+	+	+	+		
Open Water	19	56	64	72	80	80	80	85
Potamogeton in open water						8	18	10
Bare Mud	0	0	0	0	2.6	4.6	4.8	13.9

Table 6. A comparison of chlorophyll-a (μgL^{-1}) as an indicator of phytoplankton biomass in the ponds at Bridgewater Creek "Wetland."

Pond 1 (Sediment Basin)	Pond 2	Pond 3	Pond 4	Pond 5	Pond 6
64 ± 80	54 ± 60	15 ± 20	12 ± 12	10 ± 5	12 ± 10

Table 7. Major macroinvertebrate taxa at Golden Pond and Bridgewater Creek Stormwater Systems.

Macroinvertebate Taxa	**Golden Pond "Wetland System"**				**Bridgwater Creek "Pond System"**			
	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
Gastropoda	5	8	8	8	4	4	2	4
Microcrustaceans	4	5	3	4	1	4	1	1
Acarina	3		1			2	1	3
Epiproctophora	5	11	6	3	6	4	3	11
Zygoptera	1	3	3	5	1	2	5	4
Ephemeroptera	1	1	1	0	1	0	1	2
Hemiptera	1	4	4	1	2	3	8	6
Diptera	3	3	4	2	6	6	5	8
Coleoptera	1	0	0	4	3	0	8	6
Trichoptera	0	1	1	1	0	0	2	3
Total taxa	23	43	37	34	27	34	39	53
Families	12	20	16	18	18	19	25	26

It is interesting to note that, although water quality objectives 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 TN, 8 mg/L NO_x-N, 12 mg/L NH_4-N, 0.2 mg/L TN, and 0.02 mg/L PO_4-P). This demonstrates that a wide variety of macroinvertebrate species can tolerate high nutrient concentrations.

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 (Table 8), less than five percent of sampling dips during a 12-month period contained mosquito larvae. When present, they were in very low numbers (less than 10/200 mL scoop). Pond 1 recorded more larvae (14 percent of dips), but these occurred among 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.

A constructed wetland with a diversity of plant

Table 8. Relative abundance of mosquito larvae.

Location	Golden Pond Wetland	Bridgewater Creek Wetland	
		Ponds 1-5	Pond 6
Number of Dips	130	190	30
Percent NO larvae present	95.2	86.3	96.6
Percent less than 10 larvae	4.0	11.3	3.4
Percent greater than 1-40 larvae	0.8	2.4	0

species and macrophyte zones subjected to wetting and drying cycles, as well as open water zones, will maximize water treatment efficiency. It will also support a greater diversity of aquatic organisms. Deeper water zones will function as refuge habitats for these organisms during dry periods and allow rapid recolonization of newly inundated zones. This is particularly important for the management of potential mosquito breeding since predators of mosquito larvae will already be present.

Water Quality

Golden Pond "Wetland System" Treatment Train. ***Suspended Solids***. Water-quality data for total suspended solids (TSS) and total volatile solids (TVS), such as the organic fraction, are given in Table 9. The 12 h wet samples showed considerable variation in TSS. This reflected 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 wet were two-to-threefold higher than the 24 h wet. Dry weather samples were similar to 24 h wet weather samples at most sites. Higher TSS and TVS were recorded at Wetland 1 outlet, 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 wet 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.

Wetland 1 and 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 accumulated sediment in the culverts and particles in Wetland 2. TVS was always higher at the bottom of Wetland 2 than Wetland 1, indicating an export of organic particulates.

Downstream. Water at the last sampling site, 600 m downstream from Wetland 2 consistently had the lowest TSS (below 15 mg/L) in the 24 h wet weather and dry weather samples. However, the 12 h wet weather samples showed little reduction in TSS. High-water velocities probably precluded filtration and settlement.

Nutrients. Water-quality data for nutrients for wet-weather samples (collected up to 12 hours after a storm event) are given in Table 10. The water-quality data for nutrients from dry-weather samples are summarized in Table 11.

Sediment Basin. The wet weather samples show that soluble nutrients leaving the sediment basin were generally lower than the receiving upstream 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. At the bottom of Wetland 1 there was a slight decrease in all soluble nutrients, suggesting uptake by plants, algae, and periphyton.

Wetland 1 and Wetland 2. A comparison between the bottom of Wetland 1 and Wetland 2 shows a decrease in the wet but an increase for NH_4-N and PO_4-P in the dry. The increase appears to be due to particularly high concentrations of nutrients entering Wetland 2 from a piped stormwater outlet.

Downstream. Water at the downstream site consistently had the lowest soluble nutrient concentrations, again indicating removal by aquatic plants, algae, and periphyton.

Bridgewater Creek Wetland "Pond System." ***Suspended Solids***. Water-quality data for TSS

Table 9. 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 Wetland 2).

Site	12-hour wet			24-hour wet			Dry Weather		
		TSS	TVS		TSS	TVS		TSS	TVS
	n	Mean ± SD	Mean ± SD	n	Mean ± SD	Mean ± SD	n	Mean ± SD	Mean ± SD
Upstream	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
Out Wetland 2	6	24 ±12	5 ± 3	8	13 ± 9	6 ± 5	13	13 ± 9	7 ± 5
Downstream	6	21 ± 16	5 ± 4	8	8 ± 5	4 ± 2	12	5 ± 2	3 ± 3

and TVS are given in Table 12. The 12 h wet samples show that TSS in stormwater in the main Bridgewater Creek inlet is very high compared to Golden Pond stormwater. Between Pond 1(the Sediment Basin) and Pond 6, there is only a 20 percent 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 wet samples show a 56 percent reduction in TSS in Pond 1 compared to the 12 h samples. Nevertheless, the Pond 6 outlet concentrations still exceeded water quality objectives (15 mg/L). TSS in dry-weather samples were highly variable in the stormwater entering Pond 1, but almost 50 percent reduction occurred in the sediment basin to produce good water clarity (9.6 ± 5.6 mg/L TSS). However, between Pond 1 and Pond 6, TSS increased to produce an average outlet concentration of 15.6 ± 7.8 mg/L TSS (within the same magnitude as the bottom of Wetlands 1 and 2 at Golden Pond) again indicating re-suspension of sediment. Of particular note is the high (75 percent) organic proportion (TVS) in Pond 1 due to phytoplankton growth (Kasper and Jenkins 2004).

Nutrients. Water-quality data for nutrients for the wet-weather samples are given in Table 13, and for dry weather in Table 14. 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 percent) and PO_4-P (87 percent) 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.

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. NO_3 and PO_4 were both reduced in Pond 1. PO_4 was further reduced from 0.08 mg/L PO_4-P in Pond 1 to 0.02 mg/L in Pond 6, but there was only a small reduction in NO_3. NH_4 increased suggesting ammonification of organic matter.

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 for extreme (greater than 20 y ARI) storm events, and from 0.15 - 0.8 m^3/s for high-intensity rain squalls. At discharge rates greater than 0.45 m^3/s, 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

Table 10. 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)
Upstream	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
Out Wetland 1	0.08 ± 0.07	0.28 ± 0.18	1.19 ± 0.58	0.06 ± 0.06	0.13 ± 0.07
Out Wetland 2	0.07 ± 0.04	0.22 ± 0.16	0.94 ± 0.51	0.05 ± 0.05	0.11 ± 0.06
Downstream	0.06 ± 0.03	0.18 ± 0.13	0.90 ± 0.42	0.05 ± 0.04	0.13 ± 0.08

Table 11. 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
Upstream	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
Out Wetland 1	0.03 ± 0.03	0.25 ± 0.49	0.63 ± 0.33	0.02 ± 0.02	0.07 ± 0.02
Out Wetland 2	0.08 ± 0.09	0.25 ± 0.23	0.97 ± 0.50	0.05 ± 0.08	0.14 ± 0.07
Downstream	0.03 ± 0.03	0.09 ± 0.11	0.60 ± 0.28	0.02 ± 0.02	0.05 ± 0.03

Table 12. Summary of TSS and TVS (mg/L) for Bridgewater Creek Pond System (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

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 three and five hours, and between five 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 six 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 three to five 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 to 0.0003 m^3/s. Thus, minimum retention time would be eight 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.

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 during four storm events with export loads exceeding input loads. They attributed this 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.

Table 13. Nutrients for Bridgewater Creek Pond System 12 h wet weather samples (x ± SD).

Site	NH_4-N	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 6 Out	0.13 ± 0.22	0.10 ± 0.08	0.02 ± 0.02	0.84 ± 0.21	0.12 ± 0.08

Table 14. Nutrients for Bridgewater Creek Pond System, dry-weather samples (x ± SD).

Site	NH_4-N (mg/L)	NO_3-N (mg/L)	PO_4-P (mg/L)	TN (mg/L)	TP (mg/L)
Creek Inlet	0.08 ± 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 6 Out	0.11 ± 0.11	0.10 ± 0.14	1.04 ± 0.36	0.02 ± 0.01	0.17 ± 0.07

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 (less than 2 µm) with attached microorganisms. They also found that most of the nitrogen and phosphorus associated with sediments is associated with the less than 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 of organic partiles. 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 9 and TVS 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. 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. The highest chlorophyll values were 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 macrophyte stems and leaves for biofilm attachment.

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 stormwater outlet.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.

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 15. Comparison of outlet nutrient and suspended solid concentrations (mg/L) in the constructed wetland and pond systems (*indicates meeting water quality objectives).

	Wetland system outlet		Pond sytem 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

During storm events, there was a small reduction in soluble inorganic nutrients in the wetlands, but the short retention times (three to five 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 the 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 is due to wetland processes including direct uptake by plants, algae and microorganisms. Higher NH_4 at Wetland 2 outlet compared with Wetland 1 was probably due to additional contributions from a piped stormwater outlet and some ammonification in Wetland 2. The natural stream channel was also effective in removing NO_3-N, reducing concentrations from 0.22 ± 0.28 mg/L to 0.08 ± 0.11 mg/L.

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

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