A comparative study of the effectiveness of wetlands and ponds in the treatment of stormwater in subtropical Australia

Margaret Greenway and Graham Jenkins

School of Environmental Engineering, and Cooperative Research Centre for Catchment Hydrology, Faculty of Environmental Sciences, Griffith University, Brisbane, Queensland 4111, Australia

(Email: m.greenway@griffith.edu.au)

Abstract

Urban stormwater can be a potential pollution source to waterways and may impact aquatic ecosystem health. In urbanised residential areas, major pollutants are sediment and nutrients. Stormwater Best Management Practice is aimed at reducing potential downstream impacts. Wetlands and ponds incorporated into the urban landscape can assist in the removal of sediment and nutrients, but how effective are these treatment devices in subtropical climates which experience intense storm events? Researchers at Griffith University have been investigating the performance of two stormwater treatment trains (a wetland system and a pond system) having similar catchment size and urban land use in Brisbane, Australia. Our study found that detention time was a major factor in pollutant removal capability. During large storm events, suspended solids increased in the wetland system due to resuspension caused by the high flow velocities, lack of dense emergent macrophytes, and very short retention times. TSS was reduced in the pond system due to longer retention time and by allowing stormwater overflows from Pond 1 to bypass the pond system. Removal of NO_3 and PO_4 occurred in both systems during wet and dry weather, but was greater in the pond system, with mean outlet concentrations of 0.10 mg L^{-1} NO_3-N and 0.02 mg L^{-1} PO_4-P. Wetland mean outlet concentrations were 0.25 mg L^{-1} NO_3-N and 0.05 mg L^{-1} PO_4-P. During dry weather, NH_4 increased in the wetland system to 0.08 mg L^{-1}. In the pond system, there was substantial removal of NH_4 in Pond 1 from 0.58 mg L^{-1} to 0.10 mg L^{-1} NH_4-N. NH_4 increased in Ponds 2 to 5, but mean outlet concentrations were 0.11 mg L^{-1} NH_4-N. Suspended solids increased in both systems during the inter-event dry periods, either due to resuspension by water birds and/or phytoplankton blooms (ponds only).

Keywords

Stormwater, wetlands, ponds, water quality, subtropical climate

Introduction

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. Land use can be indicative of types and concentrations of pollutants. In agricultural areas, sediment, nutrients and pesticides are likely to be major pollutants in runoff. In urbanised residential areas, major pollutants are sediment and nutrients. Highway and road runoff will include heavy metals and hydrocarbons. 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.

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), Ponds (open water) and Wetlands (dominated by wetland plants) (effective sediment and nutrient removal by aquatic ecosystems).

Wetlands and ponds

Constructed wetlands and ponds are two stormwater treatment devices used to treat diffuse non-point source runoff from roofs and roads in urban areas. The main structural difference between wetlands and ponds is the extent of vegetation. Vegetation is the dominant and most conspicuous feature of wetlands, whereas open water is the dominant feature of ponds. Wetlands support a variety of vegetation types: emergent macrophytes, floating-leaved attached macrophytes, submerged macrophytes and floating macrophytes (Greenway, 2003; IWA, 2000). Shallow water is crucial for the survival of most macrophytes. Thus, water depth in constructed wastewater wetlands varies between 20 cm and 120 cm (Greenway, 2003). In stormwater wetlands, macrophytes have to be able to cope with periodic drying and flooding (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 1.5 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 may cover the surface. Phytoplankton communities are important in 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; Greenway, 2004); hydrology and hydraulics (Shutes *et al.*, 1997; Wong *et al.*, 1999); available area for construction, and community opinion and benefits including aesthetic value, recreational value, wildlife habitat, water storage and reuse.

Frequently asked questions are: “How effective are these stormwater treatment devices in improving water quality?” and “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, rural); pollutant characteristics; climate, in particular rainfall), under both wet weather and dry weather conditions, is essential. Although literature and case studies have documented the performance of various Best Management Practices (Urbonas, 1994; Lawrence *et al.*, 1996; Shutes *et al.*, 1997; Mehler and Ostrowski, 1999; Braune and Wood, 1999), there is limited information and case studies pertaining to the effectiveness of wetlands versus ponds for stormwater quality improvement (Bartone and Uchrin, 1999; Bavor *et al.*, 2001).

Our research efforts have focused on two field sites in Brisbane: (1) a stormwater treatment train consisting of a sediment basin, two constructed wetlands, a natural riparian wetland, a natural downstream channel and lagoons; (2) a stormwater treatment train consisting of a series of six ponds.

Methods

Site description

Golden Pond Wetland, Calamvale. Located 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 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 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 *Perscicaria* 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 *Perscicaria 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, 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, organic debris (leaf litter) and very coarse sediment-gravel pebbles. 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.

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, 2003). 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.

BCC (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. BCC monitoring indicates that only 59% of flow recorded upstream of the wetland passes through (Ponds 2 to 6).

Water-quality monitoring

Sampling: Grab samples were collected during and after storm events. Wet-weather (WW) samples collected within 12 hours of a storm were categorised as 12 h WW, and those collected 24 hours after an event as 24 h WW. Dry-weather (DW) samples were categorised as “dry-weather samples” if there had been no rainfall for a period of 72 hours or longer. DW samples represent base flow.

Water-quality analysis: Water samples were routinely analysed for: total suspended solids and total volatile solids; total nitrogen, ammonium-N, nitrate-N, nitrite-N; total phosphorus, soluble reactive phosphate-P.

At Golden Pond Wetland, water quality was monitored on a regular basis over a period of 22 months (November 2000 to August 2002). At Bridgewater Creek Wetland, water quality has been monitored on a regular basis since January 2002 (two months after completion of the wetland) until present. 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).

Results

Golden Pond Wetlands

Suspended Solids. Water-quality data for total suspended solids (TSS) and total volatile solids (TVS), i.e. the organic fraction, are given in Table 1. 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.

Table 1. Summary of TSS and TVS (mg/L) at Golden Pond Wetlands treatment train

Site	12-hour wet weather			24-hour wet weather			Dry weather		
	n	TSS	TVS	n	TSS	TVS	n	TSS	TVS
		Mean ± SD	Mean ± SD		Mean ± SD	Mean ± SD		Mean ± SD	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

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.

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 up to 12 hours and 24 hours after a storm event are given in Table 2. The water-quality data for nutrients from dry-weather samples are summarised in Table 3.

Table 2. Summary of nutrient water quality for 12-hour and 24-hour wet-weather samples (mean ± SD)

Site	NH_4-N (mg/L)		NO_3-N (mg/L)		PO_4-P (mg/L)	
	12 hour	**24 hour**	**12 hour**	**24 hour**	**12 hour**	**24 hour**
In Sediment Basin	0.10 ± 0.10	0.07 ± 0.04	0.44 ± 0.33	1.23 ±0 .48	0.06 ± 0.05	0.11 ± 0.09
Out Sediment Basin	0.09 ± 0.09	0.06 ± 0.05	0.38 ± 0.28	0.98 ± 0.38	0.06 ± 0.06	0.08 ± 0.04
Top Wetland 1	0.12 ± 0.10	0.05 ± 0.04	0.47 ± 0.28	0.39 ± 0.36	0.08 ± 0.07	0.05 ± 0.04
Bottom Wetland 1	0.08 ± 0.07	0.08 ± 0.06	0.28 ± 0.18	0.43 ± 0.46	0.06 ± 0.06	0.05 ± 0.06
Stormwater Outlet 1	0.11 ± 0.05	0.12 ± 0.05	1.92 ± 1.47	2.67 ± 1.89	0.24 ± 0.15	0.24 ± 0.19
Bottom Wetland 2	0.07 ± 0.04	0.12 ± 0.05	0.22 ± 0.16	0.37 ± 0.28	0.05 ± 0.05	0.05 ± 0.04
Stormwater Outlet 2	0.11 ± 0.08	0.05 ± 0.06	0.74 ± 0.51	1.07 ± 0.68	0.09 ± 0.08	0.10 ± 0.09
Riparian Wetland	0.05 ± 0.04	0.04 ± 0.04	0.30 ± 0.18	0.61 ± 0.45	0.04 ± 0.03	0.07 ± 0.08
Downstream	0.06 ± 0.03	0.03 ± 0.03	0.18 ± 0.13	0.42 ± 0.17	0.05 ± 0.04	0.04 ± 0.02

Table 3. Summary of nutrient 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: In both the 12 h WW and 24 h WW samples, 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 increase in NH_4-N in the 24 h WW samples and a decrease in all soluble nutrients in dry weather. Removal of nutrients in dry weather would be 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 in all soluble nutrients in the 24 h WW samples and an increase for NH_4-N and PO_4-P in the DW samples. The increase appears to be due to the high concentrations of nutrients entering Wetland 2 in stormwater from the CDS outlet. Aquatic plants, algae and periphyton would remove soluble nutrients. However, their demand for nitrogen is greater than phosphorus, which probably explains the greater reduction in NO_3-N.

Bottom Riparian Wetland: A reduction in soluble nutrients was found in the 24 h WW samples at the bottom of the 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 had consistently lower soluble nutrients than in the receiving waters.

Chlorophyll-a: This was only measured in the dry base-flow periods, and 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).

Bridgewater Creek Wetland — ponds

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 4. 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 5, and for dry weather in Table 6. 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 5. Summary of nutrients for Bridgewater Creek 12 h WW and 24 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)	
	12 h WW	24 h WW	12 h WW	24 h WW	12 h WW	24 h WW	12 h WW	24 h WW	12 h WW	24 h WW
Creek Inlet	0.14 ± 0.12	0.03 ± 0.02	0.43 ± 0.17	1.13 ± 0.73	0.14 ± 0.16	0.13 ± 0.08	4.68 ± 2.70	1.69 ± 0.76	0.70 ± 0.38	0.18 ± 0.07
Piped Inlet	0.12 ± 0.10	0.14 ± 0.11	0.42 ± 0.32	1.76 ± 0.77	0.10 ± 0.09	0.14 ± 0.07	3.62 ± 3.36	2.48 ± 0.56	0.31 ± 0.22	0.18 ± 0.05
Pond 1 Out	0.13 ± 0.11	0.06 ± 0.05	0.46 ± 0.37	0.51 ± 0.38	0.15 ± 0.21	0.14 ± 0.08	2.69 ± 3.12	1.33 ± 0.60	0.21 ± 0.19	0.26 ± 0.13
Pond 2	0.31 ± 0.03	0.05 ± 0.08	0.13 ± 0.07	0.59 ± 0.76	0.04 ± 0.02	0.10 ± 0.07	1.14 ± 0.19	1.38 ± 0.70	0.20 ± 0.03	0.25 ± 0.12
Pond 3	0.10 ± 0.10	0.04 ± 0.04	0.13 ± 0.14	0.17 ± 0.18	0.08 ± 0.05	0.07 ± 0.06	1.84 ± 0.87	1.37 ± 0.61	0.30 ± 0.14	0.24 ± 0.11
Pond 4	0.20 ± 0.27	0.06 ± 0.07	0.16 ± 0.10	0.21 ± 0.19	0.04 ± 0.03	0.07 ± 0.05	1.73 ± 0.37	1.15 ± 0.56	0.26 ± 0.18	0.25 ± 0.14
Pond 5	0.28 ± 0.06	0.05 ± 0.08	0.16 ± 0.10	0.20 ± 0.22	0.02 ± 0.02	0.07 ± 0.06	1.42 ± 0.31	1.15 ± 0.34	0.19 ± 0.06	0.22 ± 0.08
Pond 6 Out	0.13 ± 0.22	0.11 ± 0.10	0.10 ± 0.08	0.12 ± 0.07	0.02 ± 0.02	0.05 ± 0.04	0.84 ± 0.21	1.27 ± 0.37	0.12 ± 0.08	0.26 ± 0.10

Higher concentrations of NO_3-N in stormwater runoff occurred in the 24 h WW samples, particularly from the piped inlet. Reductions occurred in Pond 1 to 0.51 ± 38 mg L^{-1}. Between Pond 2 and Pond 6, there was a further reduction to 0.12 ± 0.07 mg L^{-1} (77%). There was no reduction in PO_4 in Pond 1, but between Pond 1 and Pond 6, PO_4-P was reduced from 0.14 mg L^{-1} to 0.05 mg L^{-1} (64%). NO_3 and PO_4 removal both suggest biological processes. By contrast, NH_4 increased. TN and TP increased in the ponds, indicating the addition of particulate and/or soluble organic N and P in the water column.

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 6. Summary of 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

Chlorophyll-a: In dry weather, algal blooms occurred in Ponds 1 and 2, but chlorophyll-a was reduced in Ponds 3 to 6 (Table 7). 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 and Greenway, 2004). 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.

Table 7. A comparison of chlorophyll-a (µg 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

Discussion

Table 8. Comparison of outlet nutrient and suspended solid concentrations (mg L^{-1}) in the wetland and pond systems

Event detention	Wetland system outlet			Pond system outlet		
	12 h WW	24 h WW	Dry	12 h WW	24 h WW	Dry
	3-16 h	2-4 days	16-20 days	36 h – 6 days	2.5 – 7 days	> 20 days
NO_3-N	0.22 ± 0.16	0.37 ± 0.28	0.25 ± 0.23	0.10 ± 0.08	0.12 ± 0.07	0.10 ± 0.14
NH_4-N	0.07 ± 0.04	0.12 ± 0.05	0.08 ± 0.09	0.13 ± 0.21	0.11 ± 0.10	0.11 ± 0.11
TN	0.83 ± 0.40	1.02 ± 0.41	0.97 ± 0.50	0.84 ± 0.21	1.27 ± 0.37	1.04 ± 0.36
PO_4-P	0.05 ± 0.05	0.05 ± 0.04	0.05 ± 0.08	0.02 ± 0.02	0.05 ± 0.04	0.02 ± 0.01
TP	0.12 ± 0.07	0.10 ± 0.04	0.14 ± 0.07	0.12 ± 0.08	0.26 ± 0.10	0.17 ± 0.07
TSS	24 ± 12	13 ± 9	13 ± 7	34 ± 33	25 ± 10	16 ± 8
TVS	5 ± 3	6 ± 5	7 ± 5	8 ± 7	10 ± 5	7 ± 4

TSS in stormwater runoff was highest at both sites in samples collected during or within 12 hours of a storm event. At Golden Pond, TSS increased as the stormwater passed through Wetlands 1 and 2, indicating resuspension of sediment due to increased flow velocities. Discharge rates calculated for stormwater leaving the sediment basin and entering Wetland 1 during and up to 12 hours after a storm event ranged from 0.35 $m^3 s^{-1}$ to 0.015 $m^3 s^{-1}$.

Assuming steady-state plug flow, retention times in Wetland 1 would range from 1 hour to 16 hours respectively. However, short-circuiting occurs through the middle during high flows, due to the positioning of a single V-notch weir and the lack of dense emergent macrophytes. Between Wetland 1 and Wetland 2, the water flows over a wide concrete sill and flat platform. Short-circuiting has not been observed in Wetland 2. Furthermore, 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 storm events would be between 3 and 5 hours, and between 5 and 32 hours for less intense rainfall events.

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, all sites showed a large range in TSS, with minimum values less than 5 mg L^{-1} and maximum values up to 30 mg L^{-1} bottom Wetland 2 and 35 mg L^{-1} bottom riparian wetland. Despite detention times of 16 to 20 days in the wetlands in dry weather, Wetland 1 and, to a much greater extent, Wetland 2 are adding TSS to the water column. Resuspension of fine sediment by wind and ducks has been observed in the shallower Wetland 1.

Nutrient concentrations of NH_4, NO_3 and PO_4 were higher in the 24 h WW than DW samples. The 24 h WW samples show that NH_4 was highest at the bottom of Wetland 2, suggesting ammonification. However, downstream concentrations were almost undetectable. NO_3 and PO_4 were substantially reduced in the wetlands, suggesting removal by plants and autotrophic micro-organisms. Downstream had the lowest concentrations, indicating the effectiveness of the natural stream channel, lagoons, and aquatic vegetation in removing soluble nutrients.

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}.

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.

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.

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.

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 *Perscicaria* would remove these from the water column. In dry weather, an increase in NH_4 again suggests amination and ammonification.

Conclusion

In comparing the performance of the wetlands at Golden Pond and the ponds at Bridgewater Creek during storm events, 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.

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.

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, and 0.07 mg L^{-1} TP), neither the wetlands nor the ponds were able to consistently achieve these guidelines. The only site where the Water Quality Objectives were achieved was the downstream site at Golden Pond during dry weather. Thus, this 600 m stretch of natural stream channel, lagoons, and associated wetland and riparian vegetation was the most effective treatment train.

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References

Bartone D. M. and Uchrin C. G. (1999). Comparison of pollutant removal efficiencies for two residential stormwater basins. *J. Eng. Eng.*, **125**, 674–677.

Bavor H. J., Davis C. M., Sakadevan K. (2001). Stormwater treatment: Do constructed wetlands yield improved pollutant management performance over a detention pond system? *Wat. Sci. Tech.*, **44**(11/12), 565–570.

BCC (2003). *Brisbane City Council. Stormwater Quality Treatment Devices*. Report No. 6.

Braune M. J. and Wood A. (1999). Best management practices applied to urban runoff quantity and quality control. *Wat. Sci. Tech.*, **39**(12), 117–121.

Carleton J. N., Grizzard T. J., Godrej A. N. and Post H. E. (2001). Factors affecting the performance of stormwater treatment wetlands. *Wat. Res.*, **35**(6), 1552–1556.

Greenway M., Jenkins G. and Le Muth N. (2002). Monitoring spational and temporal changes in stormwater quality through a treatment train. A case study — Golden Pond, Brisbane, Australia. *ASCE 9th International Conference on Urban Drainage*, Portland Oregon, USA, 8-13 September 2002.

Greenway M. (2003). Suitability of macrophytes for nutrient removal from surface flow constructed wetlands receiving secondary treated effluent in Queensland, Australia. *Wat. Sci. Tech.*, **48**(2), 211–218.

Greenway M. (2004). Constructed wetlands for water pollution control - processes, parameters and performance. *Dev. Chem. Eng. Mineral Process.*, **12**(5/6), 1–14.

Greenway M. and Polson C. (2004). Macrophyte survival in stormwater wetlands: coping with flash flooding and fluctuating water levels. *9th IWA Conference on Wetland Systems for Water Pollution Control*, Avignon, France, September 2004.

IWA (2000). *Constructed Wetlands for Pollution Control — Processes, Performance, Design and Operation*. IWA Specialist Group on Use of Macrophytes in Water Pollution Control. International Water Association (IWA) Publishing, London, UK.

Kasper T. and Jenkins G. (2004). Background concentrations of suspended solids in a constructed stormwater treatment wetland. *9th IWA Conference on Wetland Systems for Water Pollution Control*, Avignon, France, September 2004.

Larm T. (2000). Stormwater quantity and quality in a multiple pond-wetland system: Flemingsbergsviken case study. *Ecol. Eng.*, **15**, 57–75.

Lawrence A. L., Marsalek J., Ellis J. B. and Urbonas B. (1996). Stormwater detention and best management practices. *J. Hydraulic Res.*, **34**(6), 799–813.

Nairn R. W. and Mitsch W. J. (2000). Phosphorus removal in created wetland ponds receiving river overflow. *Ecol. Eng.*, **14**, 107–126.

Scholes et al. Metals in wetlands no comparison with ponds, no nutrient removal.

Shutes R. B. E., Revitt D. M., Munger A. S. and Scholes L. N. L. (1997). The design of wetland systems for the treatment of urban runoff. *Wat. Sci. Tech.*, **35**,19–25.

Somes, Fabian, Wong (2000). Tracking pollutant detention in constructed stormwater wetlands. *Urban Water* **2**, 29-37.

Urbonas B. (1994). Assessment of stormwater BMPs and their technology. *Wat. Sci. Tech.*, **29**, 347–353.

Wong T. H. F., Breen P. F., Somes N. L. L. and Lloyd S. D. (1998). *Managing Urban Stormwater Using Constructed Wetlands*. Industry Report 98/7. Cooperative Research Centre for Catchment Hydrology.