WETLANDS, Vol. 24, No. 2, June 2004, pp. 459–466

EFFICIENCY OF A CONSTRUCTED WETLAND IN REMOVING CONTAMINANTS FROM STORMWATER

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Abstract: As in most large capital cities, urban stormwater discharging into Port Jackson (Sydney) is highly enriched in a wide range of contaminants, which has resulted in degradation of the receiving basin waters and bottom sediments. The objective of the current investigation was to determine the removal efficiency of contaminants in urban stormwater by a wetland constructed in the Sydney catchment. The wetland (700 m^2) drains a residential urban catchment of about 480,000 m^2 comprising predominantly houses, streets, gardens, and street parking areas. Samples of stormwater influent and effluent were obtained during rainfall events between April and June 2000. Eight samples were collected at the inlet and outlet to the wetland during each event and analyzed for nutrients, trace metals, total suspended solids (TSS), and organochlorine pesticides and polycyclic aromatic hydrocarbons (PAHs). Water quality parameters (temperature, dissolved oxygen, pH, turbidity, conductivity) were measured concurrently. The average removal efficiency of trace metals Cr, Cu, Pb, Ni, and Zn was 64%, 65%, 65%, 22%, and 52%, respectively for the six events measured, whereas for Fe and Mn, removal efficiencies were negative for most events (mean−84% and−294%, respectively). The average removal efficiency of NO_x and TN was 22% and 16%, respectively. The average removal efficiencies of total Kjeldahl nitrogen (TKN) and total phosphorus (TP) were 9% and 12%, respectively. During four high-flow events, the removal efficiency of TSS in stormwater effluent from the wetland was between 9% and 46%; however, substantially higher TSS concentrations were observed in effluent than influent waters during two very high-flow events (removal efficiency−98% and−67%). Fecal coliform counts in the stormwater in this catchment are high (maximum: 620,000 cfu/100 ml), but mean removal efficiency was 76% (range 26% to 98%) during the four high-flow events monitored. Nevertheless, most samples from the outflow exceeded the Public Health criterion for secondary contact (e.g., boating) of 1000 cfu/100 ml. Concentrations of organochlorine pesticides and PAHs in stormwater were below analytical detection. Although highly variable, lower concentrations of Cr, Cu, Ni, Pb, Zn, NO_x, TN, and fecal coliform in the stormwater effluent compared to influent waters indicates that the wetland was moderately efficient in removing contaminants from urban stormwater.

Key Words: stormwater, wetland, heavy metals, nutrients, fecal coliform

INTRODUCTION

Anthropogenic activities within urban catchments generate pollutants, which are transported from street surfaces by stormwater runoff and are discharged into adjacent receiving waters. Pollution carried by urban stormwater contributes substantially to the degradation of water quality of receiving waters (Davis et al. 2001, Tilley and Brown 1998, Birch and Taylor 1999). Urban stormwater pollutants include gross pollutants, as well as trace metals, nutrients, and fecal coliforms, which are associated with suspended solids and the dissolved phase (Walker et al. 1999). Because of the well-documented adverse effects of increased toxicity and pathogen activity of polluted stormwater in urban waterways, local authorities are undertaking increased community-awareness programs on urban stormwater quality. Major public awareness campaigns encourage environmental sensitivity and the implementation of structural techniques to physically remove visible gross pollutants (Tilley and Brown 1998). Urban stormwater transports a variety of material, ranging from gross pollutants to fine particulates, but the majority of toxic substances are associated with the finer fraction which requires careful management (Walker et al. 1999).

Constructed wetlands as wastewater treatment system have become widespread in Australia and other parts of the world (Carleton et al. 2001). During the last three decades, the multiple functions and value of vegetated ponds or wetlands have been widely recognized (Schulz and Peall 2001, Walker and Hurl 2002). Constructed wetlands are used extensively for

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water quality improvement by reducing pollutant loads, as well as for ecological reasons (Wood and Shelley 1999, Schulz and Peall 2001). Wetlands were initially employed mainly to treat point-source wastewater, but more recently, an increased emphasis has been on urban and agricultural stormwater runoff (Carleton et al. 2001, Schulz and Peall 2001, Page et al. 2002).

Studies suggest that wetland performance in treating stormwater is generally a function of inflow, or hydraulic loading rate and detention time, which are functions of storm intensity, runoff volume, and wetland size (Carleton et al. 2001). A number of investigations have found significant levels of metals in stormwater runoff from urban areas, especially in highway runoff (Barbosa and Hvitved-Jacobsen, 1999, Davis et al. 2001, Walker and Hurl 2002). The efficiency of constructed wetlands for retention and reduction of heavy metals (Davis et al. 2001, Walker and Hurl 2002), pesticides (Schulz and Peall 2001), nutrients (Brezonik and Stadelmann 2002), and sediment (Backstrom 2002) have been investigated. However, only a few studies have been undertaken on the effectiveness of constructed wetlands for retention of sediments, nutrients, metals, and organic contaminants in a single investigation (Carleton et al. 2001, Schulz and Peall 2001).

Constructed wetlands are wastewater treatment systems that combine biological, chemical, and physical treatment mechanisms for water quality improvement (Crites 1992). The mechanisms for water quality improvement in wetlands include adsorption, complexation, chemical precipitation, and plant uptake (Reed et al. 1995). A substantial reduction of >97% of Cu, Pb, and Zn in wastewater passing through a constructed wetland has been observed previously, albeit for a hydraulic detention time of 5.5 days (Gersberg et al. 1985). Similarly, high removal efficiencies of Pb and Zn have been reported by Lenehan (1992), with a detention time of >7 days. A constructed wetland system commonly has two components: an upstream pond with relatively deep water and littoral macrophytes, and a downstream wetland with extensive macrophyte vegetation (EPA 1997). The principal water quality objective of a constructed wetland is the retention of fine sediment and nutrients. However, possible disadvantages include the required pre-treatment to remove coarse-grained sediment and the reliable inflow needed to keep the wetland 'wet' throughout the year, unless designed as an ephemeral wetland. A common system is the installation of a gross pollutant trap (e.g., a continuous deflective separation system or CDS) at the inflow to the wetland to remove the coarse-grained sedimentary particles and litter prior to the stormwater entering the wetland.

Degraded water and sediment quality demonstrated in investigations of Port Jackson and Parramatta River, Sydney, Australia during the 1990s were attributed to urban stormwater runoff (Irvine and Birch 1998, Birch et al. 1999, Birch and Taylor 1999, 2000, McCready et al. 2000). To minimize the input of sediments and stormwater contaminants into aquatic ecosystems, a wetland was constructed at Riverwood in the south of Sydney in May 1999 (WRCS 1997, 1998) (Figure 1). A continuous deflective separation (CDS) unit was installed at the inflow point to the wetland and releases flows up to the maximum expected daily rainfall for an average year (1:1 years average recurrence interval, ARI) to a sedimentation pond. Flows are released from the sedimentation pond to the reed bed when a level of 1.4 m Australian Height Datum (AHD) is reached. The area, mean depth, and volume of the reed bed in the wetland and the sedimentation pond downstream of the CDS unit are 700 m^2, 2.0 m, 290 m^3, and 100 m^2, 0.5 m, 105 m^3, respectively. The wetland catchment is approximately 480,000 m^2 and drains a mainly residential urban area of predominantly by houses, streets, gardens, and some street parking areas. The relative size of the wetland (0.1%) is thus probably less than optimum (0.5–2.0%) (Tilley and Brown 1998). Stormwater enters the sedimentation pond at the entrance of the wetland via a concrete pipe (70-cm diameter) and exits the wetland from a smaller pipe (20-cm diameter). The aims of the present study were to determine the efficiency of constructed wetland in controlling and removing sediments, nutrients, heavy metals, and fecal coliform from stormwater during flow events.

MATERIALS AND METHODS

Stormwater samples were collected at the wetland between April and June, 2000. During this period, high-flow events were sampled to characterize the efficiency of the wetland to retain total suspended solids (TSS), nutrients (TKN, NO_x, TP), trace metals, organochlorine pesticides (OCs), polycyclic aromatic hydrocarbons (PAHs), fecal coliforms, and total oil and greases. In addition, water quality parameters (pH, turbidity, dissolved oxygen, temperature, conductivity) were measured using a YSI Model 6920 Multiprobe with built-in data-logger at the inflow to the wetland to allow supplementary interpretation between total suspended solids and turbidity in stormwater runoff and provide additional information on TSS.

Sigma 900 MAX autosamplers were deployed at the inlet and outlet of the wetland. The water samples were collected via 9.5-mm-inner-diameter, teflon-coated sampling tubing and delivered directly into 1000-ml acid-washed polyethylene sample bottles (glass

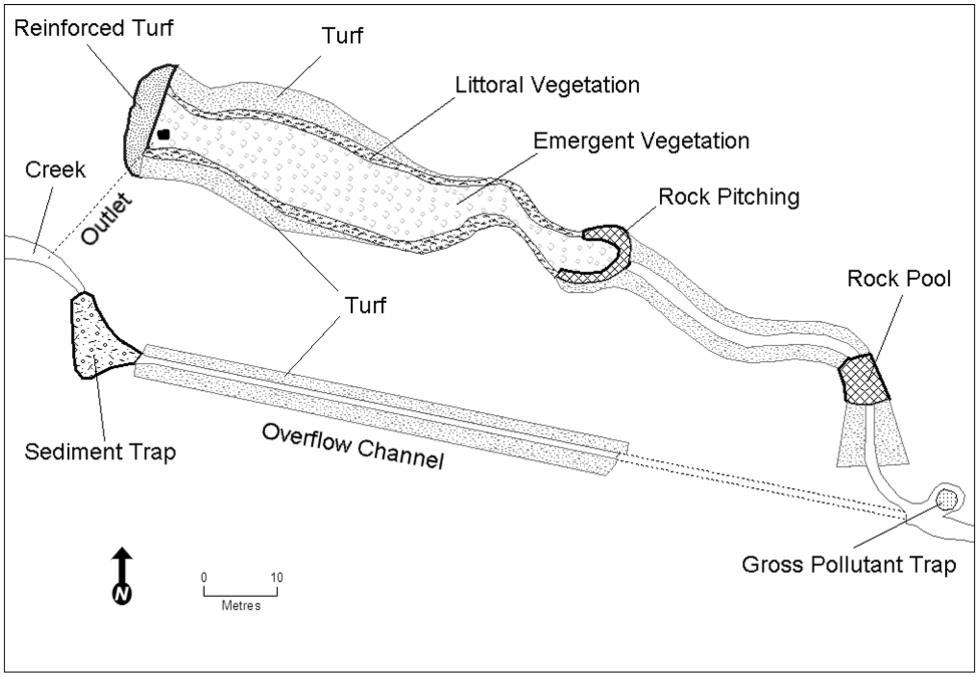

Figure 1. Design and components of wetland constructed in Hurstville, Sydney, Australia.

bottles for pesticide analyses) to minimize contamination. Flow level and velocity measurements were recorded every 2 minutes at the two monitoring sites throughout the monitoring period. The automatic sampler at the inflow location was triggered by the acoustic flow meter when the water level exceeded 180 mm. This level was reached within a few minutes of commencement of rainfall, ensuring that the first flush of stormwater runoff was captured. Rainfall for the initial 24-hour period of each event ranged between 1.0 and 15.25 mm. The rainfall intensity during the first hour of the high-flow events ranged between 0.75 mm and 6.50 mm.

Characterization of storm events included the determination of concentrations of TSS, trace metals (Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn) (all 6 high-flow events over the 3-month period of investigation), nutrients (TKN, NO_x, TP), and fecal coliform (four events) in stormwater sampled at inlet and outlet locations. A single rainfall event was sampled to determine the concentrations of OCs, PAHs, total oil and grease, and TSS by compositing four 350-ml samples obtained within 6 minutes after triggering to meet the minimum volume requirement for these analyses. Sampling was according to the hydrograph: two samples on the rising limb, two samples at peak flow, and four samples on the falling limb. Temperature, pH, dissolved oxygen, turbidity, and conductivity were measured at the inflow to the wetland during three events *in situ*, and samples were collected simultaneously to determine the relationship between turbidity and TSS.

The event mean concentration is the weighted average concentration (WAC) of a parameter measured in the stormwater samples (e.g., TKN, TP, Cu, TSS) over the sampling period (i.e., the time between the collection of the first and last samples). The sum of the average concentrations for each interval of known duration is divided by the total sampling interval to obtain the weighted average concentration (WAC) of the parameter during the storm event. The WAC of the event is calculated for inflow and outflow points. The removal efficiency of the stormwater remedial device is estimated by:

$$RE = WAC_{\text{inflow}}/WAC_{\text{outflow}} \times 100\%$$

where RE is the removal efficiency (in %), WAC_{inflow} is the weighted average concentration at the inflow point, and WAC_{outflow} is the weighted average concentration at the outflow point (Figure 2).

Chemical sample analyses were performed by a National Association of Testing Authorities (NATA) accredited Australian Laboratory Services (ALS) laboratory (Table 1). All analytical work meets strict NATA accreditation requirements for Quality Control/Quality Assurance. Analytical blanks were below detection for all parameters, ruling out laboratory contamination. Spike recoveries of control blanks, matrix-matched standards, and standard reference materials

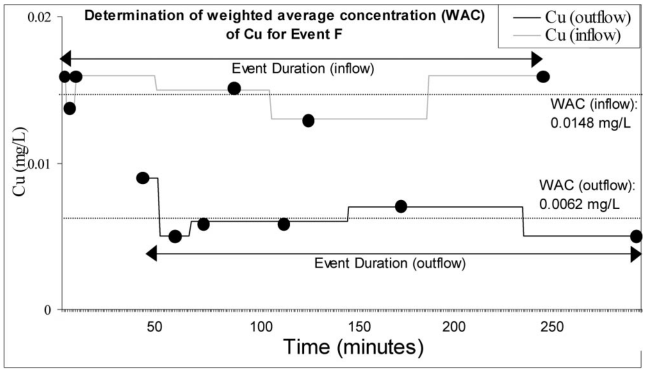

Figure 2. Estimation of weighted average concentration (WAC) during a high flow event, using Cu concentrations observed during Event RF.

(SRM) were all within the acceptance criteria of the NATA-accredited laboratory.

RESULTS AND DISCUSSION

In the current work, the mean removal efficiency of TSS by the wetland ranged between −98% and 46% (mean: −4%; SD: 63%; n = 6). The mean removal efficiencies of TP and TKN were 12% (range −14% to 39%) and 9% (range −34% to 58%), respectively, exemplifying the large variability in the removal of these contaminants from stormwater by the wetland. The reduction of NO_x was highly variable (mean 22%, range −20% to 75%) for the four high-flow events sampled, suggesting an important uptake of NO_x by the wetland. The mean removal efficiency of fecal coliforms was 98%, 83%, and 99% during three high-flow events but decreased to 26% during the largest high-flow event sampled. During the latter high-flow event, settling and removal of suspended particulates was substantially reduced and resuspended particulates likely contributed to the elevated TSS and fecal coliforms contents in outflowing stormwater during this event.

The mean removal efficiencies of trace metals from stormwater by the wetland were generally moderate to high but highly variable. Considerable Cr (67 to 84%) was removed during four of the six high-flow events monitored but decreased to 10% and was below dectection in the other two events (mean: 64%). The removal efficiency of Cu by the wetland was high for all events (56–86%), except during the largest event (21%), suggesting that Cu may be preferentially absorbed by plants in the wetland (Widerlund 1996). Pb and Zn also displayed substantial removal by the wetland during five of the six events monitored (Pb: 44–89%; Zn: 33–87%), but efficiencies were again markedly reduced during the highest flow event (Event RB)(Pb 27% and Zn −5%). The average removal efficiencies of Cu, Pb, and Zn during the six events monitored (including Event RB) were 65%, 65%, and 52%, respectively, supporting the moderate to high removal of these trace metals from stormwater. These results are supported by other investigators (Walker and Hurl 2002), who found 48%, 71%, and 57% reduction for Cu, Zn, and Pb, respectively. These authors determined that sedimentation is the primary process for the removal of heavy metals from stormwater, along with other biological and chemical processes. The removal of Ni was highly variable and ranged from −76% (Event RB) to 72% (mean: 22%; n = 5). However, the concentrations of Ni in stormwater were generally below 0.005 mg/L and do not represent a threat to aquatic biota (ANZECC/ARMCANZ, 2000). The close association of metals and TSS in the current investigation suggests that a substantial proportion of contaminants are associated with the particulate phase.

A surprising outcome of the current work is the identification of the wetland as a source of Fe and Mn over the three-momth period of the current invesiga-

Table 1. Analytical methods, minimum sample volumes and detection limits required for analysis of stormwater passing through wetland.

Analysis	Minimum Volume Required (mL)	Detection Limit (mg/L)	Method Reference
Nox	20	0.01	APHA 4500
TKN	200	0.1	APHA 4500
TP	50	0.01	USEPA 200.7 by ICP
FC	120	na	APHA 9222D
Trace metals	100	0.001 (Fe 0.1)	USEPA 200.7 by ICP
TSS	300	1	
Ocs & PCBs	400	0.01	USEPA 8081 by ICP
PAHs & 2-methylnaphthlene	400	0.0005–0.001	
Oil & grease	500	5	APHA 5520D

Nox = Oxidisable nitrogen; TKN = Total Kjeldahl nitrogen; TP = Total phosphorus; FC = Fecal coliforms; Trace metals = Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn; TSS = Total suspended solids; OCs = Organochlorine pesticides; PCBs = Polychlorinated biphenyls; PAHs = Polycyclic aromatic hydrocarbons.

tion. The mean removal efficiencies of Fe and Mn were −84% and −294%, respectively and although highly variable, the increased concentrations in effluent stormwater compared to influent water were reproducible for five of the six high-flow events monitored. Because Fe and Mn behave differently than the other metals studied, the export of these elements from the wetland cannot be explained by simple resuspension of bottom sedimnts during high-flow events. In particular, WACs of Mn are up to five-fold greater than influent concentrations, indicating that the wetland contributes, rather than removes, this element from stormwater. A possible explanation for this phenomenon is that the concentrations of Mn, and to a lesser extent Fe, are increased by the occurrence of medium- to coarse-grained Fe- and Mn-oxide coated grains. It is possible that these grains settle and accumulate in the wetland during low-flow conditions and are removed during periods of high flow when the resuspension threshold velocity for coarse grains is exceeded. Monitoring of grain-size spectra in influent and effluent samples may aid in solving the source of the Fe and Mn discharged from the wetland.

During the highest rainfall event (Event RB), the removal efficiency of trace metals and TSS was substantially lower than other events due to the intensity of rainfall (6.50 mm during the first hour of the event and peak intensity of 4.00 mm during a 10-minute period). The peak rainfall intensity was greater during this event than during other events monitored, and a maximum flow of 140 L/s was observed at the inflow point to the wetland. The rainfall intensity and the resulting large flow volumes through the wetland during this high-flow event may have contributed to the resuspension of fine-grained sediment and the transport of suspended particulates out of the wetland. Sediment in the wetland may require maintenance dredging to minimize the release of acid-volatile, sulfide-bound trace metals from the wetland during such periods of high flow and sediment resuspension.

There are often specific treatments for the many types of pollutants generated from urban land-use activities. Heavier sediment may be settled and floatable litter may be filtered readily by use of Gross Pollutant Traps (GPT), whereas the removal of fine-grained suspended solids requires the stormwater to flow through settling basins or more elaborate treatment mechanisms. Wetlands are not only efficient in the removal of particulate-bound contaminants, including trace metals and nutrients by sedimentation (Crites et al. 1997, Backstrom 2002, Walker and Hurl 2002), but also have the advantage of achieving water quality improvements in combination with biological and chemical treatment mechanisms. The water quality of in- and out-flowing stormwater collected during the six high-flow events is compared to the ANZECC/ARMCANZ (2000) water quality guidelines for freshwater in Table 2. No ANZECC guideline values are available for TSS, TKN, NO_x, and fecal coliforms. The mean concentrations of TKN and NO_x are therefore compared to the ANZECC/ARMCANZ (2000) guideline values for ammonia and nitrate, respectively. ANZECC (1992) guideline values for TN and TP are used to compare the mean concentrations of these two parameters in stormwater from the wetland catchment. The mean fecal coliform content in stormwater from this locality is compared to the level recommended for human health safety for secondary contact (LPRSWMP 1999).

The mean concentrations of trace metals (Cr, Cu, Mn, Ni, Pb, Zn) in stormwater obtained from the wetland inlet (n = 48) and outlet (n = 48) are compared to the guidelines and are expressed as a enrichment factor of the metal before and after treatment by the wetland. No water quality data are available for Fe, and Cd was below detection (<0.001 mg/L) in all samples. Mean concentrations of Cr exceed the ANZECC/ARMCANZ (2000) guideline value 3.3 times at the inflow point to the wetland but are similar to the recommended concentration at the outflow. Nickel also displays a moderate enrichment above ANZECC/ARMCANZ (2000) guideline values of 7.4 and 4.6 times in in- and out-flowing waters, respectively. The enrichments of Cu, Pb, and Zn in stormwater from the wetland catchment are substantially greater, ranging between 45 and 173 times above the recommended water quality guideline values for inflowing stormwater. Although the mean concentrations of these metals are substantially reduced at the outflow point from the wetland, the mean concentrations are still 34, 13, and 63 times above recommended ANZECC/ARMCANZ (2000) guidelines concentrations (Table 2). The mean concentrations of Mn in the in- and out-flowing waters are 3.7 and 9.6 times, respectively above the ANZECC/ARMCANZ (2000) water quality guideline for freshwater.

The overall removal efficiency of trace metal contaminants by the wetland is moderate to high, except for Fe and Mn. However, concentrations of trace metals (except Cr) in effluent stormwater from the wetland remains above the ANZECC/ARMCANZ (2000) guidelines for freshwater. Although the overall TSS content of the stormwater were slightly reduced from a mean content of 144 mg/L at the inflow point to the wetland to 121 mg/L at the outflow point, a further reduction of total suspended solids concentrations is desirable to reduce the effluent concentrations of trace metals.

The mean concentrations of TKN, NO_x, and TN in the inflowing stormwater exceeded the ANZECC/

Table 2. Weighted average concentrations (WAC) and removal efficiency (%) of heavy metals, total suspended solids (TSS), fecal coliforms and nutrients from stormwater runoff passing through wetland.

Event	WAC	Max. flow L/s	Cr	Cu	Fe	Pb	Mn	Ni	Zn	TSS	TP	FC	TKN	NOx	TN
RA	Inflow	9.9	0.003	0.021	1.4	0.013	0.26	0.004	0.47	61	0.07	1022851†	1.78	3.92	5.70
	Outflow	24.4	0.001	0.003	1.2	0.002	0.16	0.001	0.06	33	0.07	15608†	0.74	0.99	1.73
	Removal Efficiency (%)		84	86	10	85	37	62	87	46	−10	98	58	75	70
RB	Inflow	146.4	0.001	0.02	1.6	0.032	0.04	0.002	0.17	87	0.25	162050	1.04	1.34	2.38
	Outflow	50.3	0.001	0.016	3.7	0.023	0.23	0.004	0.18	172	0.16	120721	1.4	1.6	3.00
	Removal Efficiency (%)		10	21	−129	27	−406	−76	−5	−98	35	26	−34	−20	−26
RC	Inflow	73.4	bd	0.021	1	0.025	0.06	bd	0.22	48	0.06	18211	1.85	2.29	4.14
	Outflow	39.8	bd	0.009	3.6	0.014	0.36	bd	0.15	81	0.04	3151	1.83	2.05	3.88
	Removal Efficiency (%)		—	56	−269	44	−477	—	33	−67	39	83	2	11	6
RD	Inflow	13.6	0.003	0.025	1.7	0.051	0.13	0.003	0.38	58	0.2	24887	2.41	2.87	5.28
	Outflow	12.7	0.001	0.005	2.4	0.006	0.37	0.002	0.06	52	0.23	235	2.18	2.29	4.47
	Removal Efficiency (%)		84	79	−42	89	−183	38	84	9	−14	99	10	20	15
RE	Inflow	136.4	0.004	0.036	2.9	0.054	0.08	0.012	0.31	117	nd	nd	nd	nd	nd
	Outflow	48.3	0.001	0.012	3.9	0.020	0.38	0.003	0.2	64	nd	nd	nd	nd	nd
	Removal Efficiency (%)		77	66	−34	62	−392	72	34	45	nd	nd	nd	nd	nd
RF	Inflow	25.8	0.003	0.041	3.1	0.052	0.16	0.005	0.39	154	nd	nd	nd	nd	nd
	Outflow	13.7	0.001	0.009	4.3	0.009	0.7	0.004	0.09	95	nd	nd	nd	nd	nd
	Removal Efficiency (%)		67	79	−37	83	−342	12	77	38	nd	nd	nd	nd	nd
RA-RF	WAC (Inflow)		0.003	0.027	1.96	0.038	0.122	0.005	0.32	nd	0.14	68383	1.77	2.61	4.38
	SD (%)		0.001	0.009	0.87	0.017	0.08	0.004	0.11	nd	0.09	81187	0.56	1.08	1.48
	RSD (%)		37	33	44	45	66	76	35	nd	66	119	32	41	34
RA-RF	WAC (Outflow)		0.001	0.009	3.21	0.012	0.366	0.003	0.12	nd	0.12	41369	1.54	1.73	3.27
	SD (%)		0.0002	0.005	1.15	0.008	0.185	0.001	0.06	nd	0.09	68736	0.62	0.57	1.19
	RSD (%)		26	53	36	68	51	43	50	nd	69	166	40	33	36
RA-RF	Mean Removal Efficiency (%)		64	65	−84	65	−294	22	−52	−4	12	76	9	22	16
	ANZECC/ARMCANZ values		0.0001	0.00033	nd	0.0012	0.047	0.0007	0.0024	nd	0.1	1000††	0.032†††	0.12#	0.1–0.5##
RA-RF	n (number of events sampled)		6	6	6	6	6	6	6	6	4	4	4	4	4

nd = no data. All weighted average concentrations (WAC) in mg L^{-1}. RSD = Relative Standard Deviation; SD = Standard Deviation. See Table 1 for other abbreviations.

† Samples analyzed after 3 days, data not included in calculations, †† Human health safety for secondary contact (LPRSWMP, 1999). ††† ANZECC/ARMCANZ, 2000 guidelines for ammonia, #ANZECC/ARMCANZ, 2000 guidelines for nitrate, ## ANZECC, 1992.

ARMCANZ (2000) and ANZECC (1992) guideline values 92, 5.2, and 36 times, respectively. Although the mean concentrations of TKN, NO_x, and TN in the outflowing waters of the wetland were substantially reduced to 48, 14 and 32 times, respectively, above the recommended ANZECC (1999) values, the mean concentrations of TKN, NOx, and TN remained high. The mean concentration of TP decreased from 0.14 to 0.12 mg/L in the in- and outflowing stormwater, respectively. Although this represents an overall reduction of approximately 15%, the ANZECC/ARMCANZ (2000) guideline value was still exceeded slightly at the outflow point (1.2 times).

The number of fecal coliform colonies (FC) per 100 ml of stormwater was very high, particularly in inflowing stormwater. Mean FC contents at the inflow point were about 110,000 cfu/100 ml (excluding FC concentrations obtained during Event RA, which were analyzed after the 3 days required by the sampling and analytical protocol), representing a level that is 110 times above the recommended number for human health safety for secondary contact (e.g., boating). These levels of fecal coliform in influent waters may pose a substantial risk for human exposure (LPRSWMP 1999). Although fecal coliform counts in effluent water during high-flow events were below 5500 cfu/100 ml for two events (Events RC and RD), substantially greater FC contents of up to 220,000 cfu/100 ml were recorded during the largest of the high-flow events monitored. This indicates a high removal efficiency of FC during moderately intense high-flow events (~1.0 mm of rain per hour), but efficiency was substantially reduced during periods of intense rainfall (>4.0 mm of rain per hour). The source of fecal coliforms was probably sewage overflows in the catchment (NSW EPA 1995); however, no single point source was identified in the current work. Dog feces are also likely to contribute to the fecal coliform content in stormwater of the catchment, as the wetland is used as a recreational exercise area for dogs, and dog feces were observed within the wetland catchment. Additional work is required to establish the source of the fecal bacteria by quantifying the abundance of the human fecal indicator *Clostridium perfringens* Welch.

The quality of water entering the wetland determined during the current work was not significantly different from concentrations of metals (Cu, Pb, Zn), nutrients (TP, NO_x), and fecal coliform measured four years previously before construction of the wetland (i.e., 1996 and 2000) (HCC 2000). The continued high concentrations of trace metals in stormwater runoff in the wetland catchment emphasize the need for additional stormwater managment strategies to be implemented, and particularly source-control through community education programs. However, the concentrations of some of the water quality parameters investigated in the current study are substantially lower in effluent than influent stormwater (e.g., Cu, NO_x) and documents the advantageous application of wetlands for water quality remediation.

The wetland is located in a highly-urbanized area, and the main constraint on the wetland design was the limited space available. Due to this restriction, the wetland is smaller than optimum size and detention times are shorter than necessary for efficient operation (Tilley and Brown 1998, Carleton et al. 2001). No estimates have been made on the long-term sutainability of the wetland; however, the continued ability of the device to remove contaminants from stormwater is dependent mainly on its size relative to the catchment area and sedimentation rate (Smith et al. 1993). Although the catchment is mostly urbanized, the CDS device upstream from the wetland is expected to intersect a substantial proportion of the coarse-grained material, which otherwise would have entered the wetland. The wetland was completed in May 1999, and to date there is no appreciable siltation and no visible degradation of flora.

ACKNOWLEDGMENTS

The project was funded by Hurtsville City Council, the New South Wales Environmental Protection Authority, and the Stormwater Trust and staff from these organizations who assisted in the project are gratefully acknowledged. The authors thank the two anomolous reviewers for valuable suggestions made on the manuscript.

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Manuscript received 17 December 2002; revisions received 2 February 2004; accepted 8 March 2004.