TREATMENT EFFICIENCIES FOR RESIDENTIAL STORMWATER RUNOFF IN A HARDWOOD WETLAND

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ABSTRACT

The fate of nutrients and heavy metals contained in stormwater runoff was investigated in a 3 ha hardwood wetland near Orlando, Fla. The wetland receives stormwater runoff from a large residential community through a small shallow canal and provides treatment prior to discharge to Hidden Lake. Field investigations begun in 1984 were divided into the following tasks: (1) assessing the quantity of nutrients and heavy metals entering the wetland by stormwater runoff, (2) attenuation of the pollutants during travel through the wetland, (3) monitoring movement of nutrients and heavy metals in ground water, and (4) accumulation of nutrients and heavy metals in the sediments of the wetland. During continuous flow, the wetland system was found to be very effective in removing heavy metals but less effective in removing nutrients. Heavy metals appear to be tightly bound into the upper sediment layers. Treatment of runoff by infiltration through wetland soils resulted in good removal of nutrients as well as heavy metals. The results suggest that treatment schemes involving infiltration or retention are possible and more effective than flow-through systems.

INTRODUCTION

Nonpoint sources of pollution have long been recognized to contribute significantly to receiving water loadings of both nutrients and toxic elements such as heavy metals, oil, and grease (Wanielista et al. 1982). As a means of protecting surface waters from further deterioration, many states have established regulations requiring new developments to treat stormwater runoff before discharge from the property. In most cases this treatment involves retention or detention of specified amounts of runoff volume in shallow ponds. Recently, interest has risen in natural treatment systems, such as wetland areas, for assimilating stormwater pollutants to minimize the loss of valuable land in meeting these regulations.

Numerous studies have been conducted on the treatment efficiency of controlled inputs of secondary effluent in wetland systems, but few detailed studies have examined the feasibility of wetland systems in treating sporadic inputs of stormwater runoff although many wetland areas are currently being used for this purpose. This research focused on the fate and movement of runoff-related inputs of nutrients and heavy metals in a hardwood wetland north of Orlando, Fla.

STUDY AREA

The natural wetland site investigated in this research was a 48.4 ha hardwood hammock located adjacent to Hidden Lake north of Orlando (Fig. 1). The dominant canopy vegetation is divided between sweetbay, red maple, and swamp ash with an understory of ferns, greenbriar, and blackberry. Soils within the wetland area are poorly drained organic soils characterized by a surface layer of dark reddish-brown muck 10–20 cm thick over a loose 1 m thick peat layer underlain by a dense sand or clay base.

This hammock has been receiving residential runoff since 1975 from an 18.6 ha drainage basin of single and multifamily residences. Both curb and gutter as well as grassed swales convey the runoff waters to a single, small vegetated canal that flows into the wetland (Fig. 1). Although other residential areas discharge into the perimeter of the wetland at various locations, most of the inputs remain localized and do not produce a noticeable flow through the wetland area. As a result, the small canal represents the major input into the wetland. Stormwater inputs into the wetland generally observe the flow patterns indicated in Figure 1. Approximately 3 ha of the total 48.4 ha area come into contact with runoff flow.

During the winter and spring months (December–June) the water table is generally slightly beneath the wetland surface, although the soil remains wet. Stormwater inputs during this period are usually infiltrated into ground water. However, during the summer months, standing waters ranging from 1 to 20 cm are common, and occasionally the wetland becomes hydraulically connected to Hidden Lake following heavy rain events.

METHODS

Both base flow and runoff into the wetland were monitored continuously at a weir installed across the input canal, using an ISCO flowmeter and flow totalizer. An ISCO sequential refrigerated sampler also installed at the weir collected flow-weighted composite runoff samples over the hydrographs of selected storm events to estimate water quality characteristics of inputs to the system.

Surface water samples were collected biweekly at seven fixed stations within the wetland at 25 m intervals along the dominant flow path to a distance of 150 m. This distance was observed to be the extent of runoff movement into the wetland during most storm events. A fixed control station was also established in an area of the wetland removed from runoff influence. Fixed sample ports were installed at each station as indicated in Figure 2 with sample tubing extending to areas away from the flow path. Field measurements of pH, specific conductivity,

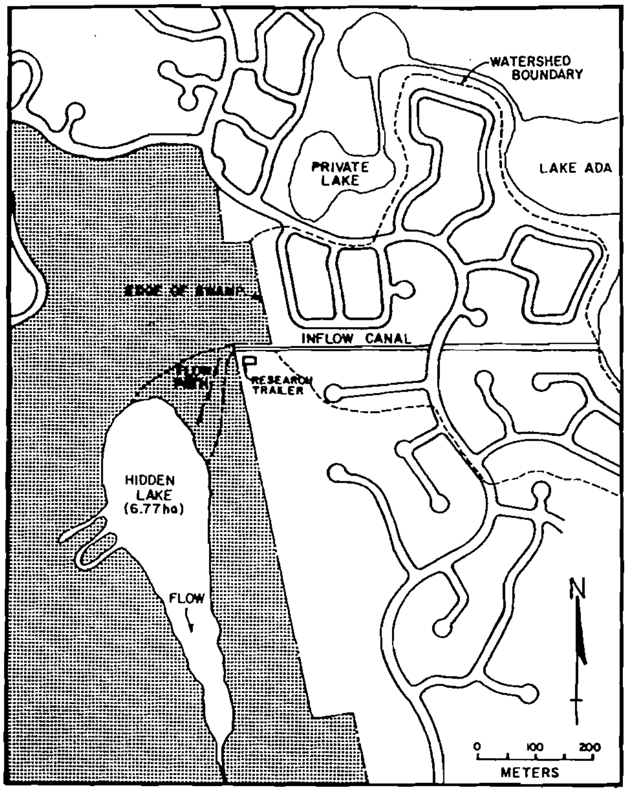

Figure 1.—Study site at Hidden Lake, Fla.

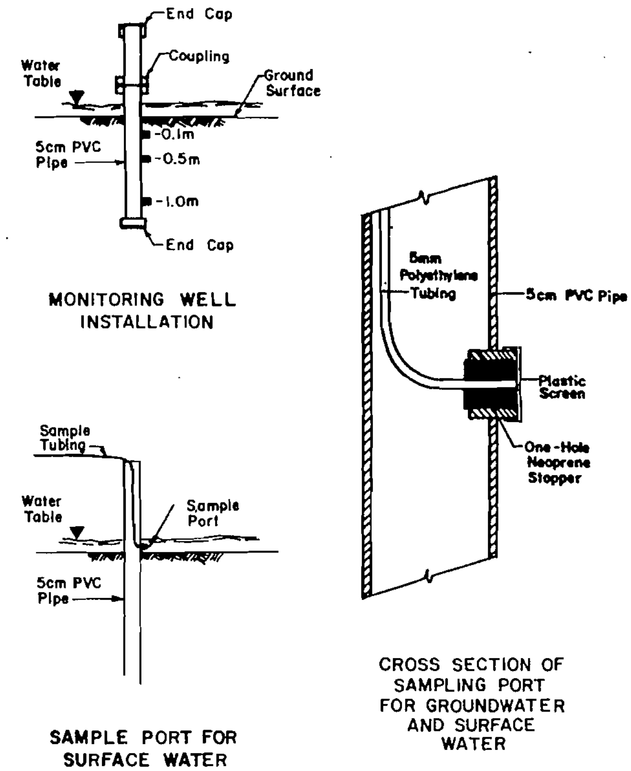

Figure 2.—Schematic diagram of sample collection devices for ground water and surface waters.

water temperature, dissolved oxygen, and oxidation reduction potential were collected simultaneously with the water samples, using a flow-through cell attached to a Hydrolab model 8000 water quality monitor.

Multiport groundwater sampling devices were constructed and installed with sample ports 0.1 m, 0.5 m, and 1.0 m beneath the soil surface (Fig. 2). Three monitoring wells were installed: one upstream of the wetland, one in the major flow path, and one in the control area. Water samples and measurements of piezometric surface were collected on a monthly basis.

Sediment analyses were conducted on core samples collected near the sample stations in the flow path and control areas to characterize the deposition and attenuation of heavy metals. Each core sample was divided into the following layers: (1) 0–1 m, (2) 1–5 cm, (3) 5–10 cm, (4) 10–15 cm, and (5) 15–20 cm. Three 5 cm diameter samples were collected at each fixed station and combined to form a single sample. Each layer was analyzed for acid extractable heavy metals, moisture content, and organic content.

FLOW-THROUGH EFFICIENCIES

A summary of mean water quality characteristics at fixed

Table 1.—Summary of mean water quality characteristics at fixed sample locations in the wetland flowpath from December 1984 to August 1985.

PARAMETER	STORM-WATER INPUTS[1]	FLOW-WEIGHTED INPUTS[2]	MEAN VALUES AT WETLAND LOCATIONS[3]							
			10 M	25 M	50 M	75 M	100 M	125 M	150 M	CONTROL
pH	6.00	6.07	6.51	6.24	6.22	6.17	6.03	5.95	5.71	5.83
Sp. Cond. (μmho/cm)	148	158	177	178	134	100	115	106	86	81
Diss. O_2 (mg/L)	–	7.5	7.0	3.8	3.2	3.3	2.3	2.7	3.3	1.8
ORP (mv)	–	451	470	400	379	354	342	352	363	266
Alkalinity (mg/L)	71.1	73.0	67.7	68.5	53.6	36.2	41.8	40.3	30.6	10.8
NH_3-N (μg/L)	54	53	51	79	136	64	111	78	52	95
NO_3-N (μg/L)	65	60	49	41	53	53	42	52	46	49
Organic-N (μg/L)	486	463	285	513	226	243	350	454	563	766
Total-N (μg/L)	605	576	385	633	415	360	503	584	661	910
Ortho-P (μg/L)	25	26	21	27	41	65	75	55	78	155
Total-P (μg/L)	73	72	59	94	104	133	145	128	160	201
TOC (mg/L)	13.0	13.2	13.0	13.7	12.2	9.7	16.0	10.4	11.8	42.5
BOD (mg/L)	2.9	2.7	2.3	2.6	2.7	3.3	2.5	2.1	3.0	1.8
Color (Pt. Co Units)	86	82	78	95	115	155	180	151	241	508
S.S. (mg/L)	7.2	6.4	7.0	7.8	9.0	11.8	7.9	8.7	13.0	4.0

[1] n = 18 storm events
[2] includes stormwater plus background flow
[3] n = 18 samples

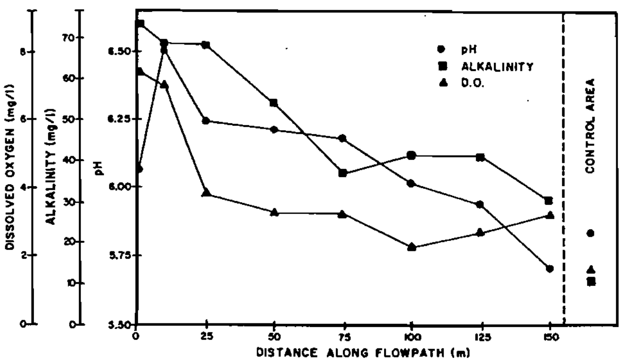

Figure 3.—Changes in pH, conductivity, and dissolved oxygen during flow through the wetland at Hidden Lake.

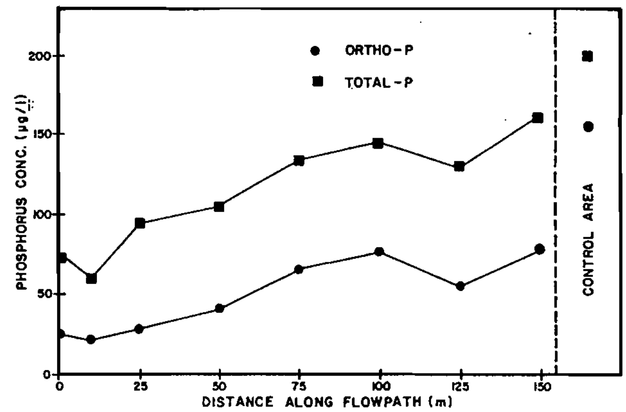

Figure 5.—Changes in phosphorus concentations during flow through the wetland at Hidden Lake.

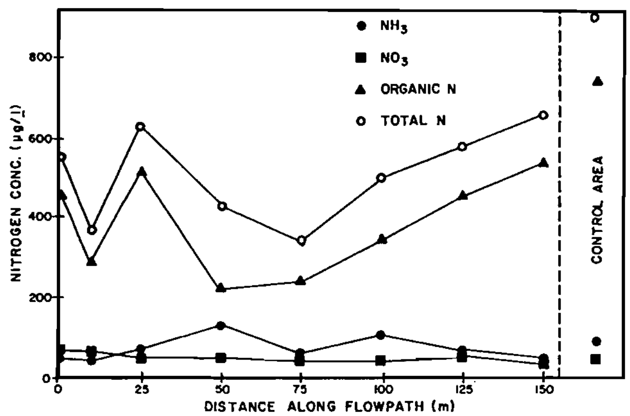

Figure 4.—Changes in nitrogen species during flow through the wetland at Hidden Lake.

sample locations in the wetland flow path is presented in Table 1 for the period of December 1984 to August 1985. Stormwater inputs into the wetland during this period were characterized by relatively low levels of soluble nitrogen and phosphorus. Approximately 80 percent of the total nitrogen inputs was organic in nature, and 66 percent of the total phosphorus inputs was particulate in nature.

After entering the wetland treatment system, stormwater inputs were observed to exhibit general reductions in pH, specific conductivity, dissolved oxygen, oxidation reduction potential, and alkalinity with increasing flow distance (Fig. 3). The rather rapid decreases in both dissolved oxygen and oxidation reduction potential with increasing distance from the input canal are presumably related to the increased stagnant nature of the surface waters as the flow spreads out during travel.

Nitrogen forms of ammonia, nitrate, and organic nitrogen were not removed to any significant degree during flow through the wetland, although fluctuations were

Table 2.—Summary of heavy metal concentrations measured at fixed sample locations in the wetland flowpath from December 1984 to August 1985.

Heavy metal	Types of species	Storm-water inputs[1]	Flow-weighted inputs[2]	Mean values at wetland locations[3]							
				10 m	25 m	50 m	75 m	100m	125 m	150 m	Control
Cadmium	Diss.	4.3	4.4	2.8	3.1	3.5	4.2	2.2	4.3	4.6	2.1
	Particulate	1.2	1.0	2.2	0.3	0.3	0.3	0.6	0.3	0.3	0.6
Zinc	Diss.	4.5	4.5	7.8	5.4	4.7	4.7	4.0	3.5	5.5	3.5
	Particulate	1.0	0.9	1.7	0.2	0.0	0.0	0.0	0.0	0.0	10
Manganese	Diss.	2.7	2.8	2.3	3.4	3.0	4.3	4.0	2.0	6.5	4.5
	Particulate	1.6	1.5	0.5	0.4	0.3	0.3	0.3	0	0.4	1.5
Copper	Diss.	16	15	16	18	10	6.3	15	16	13	15
	Particulate	7	6	5	1	1	0.0	1	0	0	11
Iron	Diss.	67	66	69	120	136	211	206	174	222	224
	Particulate	49	45	20	28	24	21	27	35	15	44
Lead	Diss.	30	30	24	19	19	16	17	17	17	12
	Particulate	3	3	1	4	0	2	0	1	1	3
Nickel	Diss.	3.2	3.2	2.7	2.7	2.2	2.2	1.7	2.1	1.6	0.6
	Particulate	0.6	0.6	0.5	0.2	0.2	0.1	0.2	0.1	0	0.5
Chromium	Diss.	3.3	3.4	3.1	3.0	2.8	2.5	2.2	2.4	2.3	1.2
	Particulate	0.6	0.5	0.9	0.3	0.2	0.4	0.3	0.2	0.5	0.5

[1] n = 18 storm events
[2] includes stormwater plus background flow
[3] n = 18 samples

measured both above and below input values at certain sample locations (Fig. 4). Concentrations of both orthophosphate and total phosphorus generally increased during flow through the system (Fig. 5). Increases in orthophosphate were closely correlated with decreases in oxidation reduction potential ($r = -0.90$) and decreases in pH ($r = -0.83$). Although fluctuations were measured in concentrations of total oxygen concentration, biochemical oxygen demand, and suspended solids, at various sample sites, no significant trends of increase or decrease in concentrations were observed for any of these parameters. The control site, located in an isolated area unaffected by runoff inputs, was generally lower in pH, specific conductivity, dissolved oxygen, oxidation reduction potential, alkalinity, biochemical oxygen demand, and suspended solids and higher in concentrations of organic and total nitrogen, orthophosphorus and total phosphorus, total oxygen concentration, and color than wetland areas affected by runoff inputs.

A summary of heavy metal concentrations measured at each sample site in the wetland flow path is presented in Table 2. The wetland appeared to be very effective in removing particulate forms with most metal species exhibiting a removal rate of 60–85 percent in the first 10–25 m. Dissolved forms of heavy metals were removed to a lesser degree than particulate species. Dissolved concentrations of lead, chromium, and nickel apparently decreased during travel through the wetland, while cadmium, zinc, manganese, and copper remained unchanged and iron increased substantially.

The agitation and circulation of surface waters along the flowpath caused by inputs of base flow and stormwater are important in explaining the better water quality characteristics of the treatment area over the stagnant control area. The more reduced environment found in the control area increases the release of phosphorus, nitrogen, organic compounds, and iron from the sediments to the water phase. This behavior suggests that treatment by continual input of base flow may be more effective than by sporadic stormwater input.

Measured concentrations of dissolved metal species in the runoff inputs were extremely low compared to concentrations measured in other residential sites in the Central Florida area (Wanielista et al. 1982). Dissolved concentrations of all metal species except copper, iron, and lead measured in runoff inputs were less than 5 μg/L. These low concentrations are presumably related to pretreatment efficiencies obtained in the grassed swales and canals used as part of the stormwater conveyance system. Yousef et al. (1984) reported that swales very effectively remove dissolved metal species in runoff water.

GROUNDWATER EFFECTS

A summary of mean water quality characteristics in shallow ground waters in the wetland area is presented in Table 3 for a monitoring well upstream of the wetland (Well 1), a well in the general flowpath (Well 2), and the stagnant control area. In general, water quality characteristics in Wells 1 and 2 appear similar for many parameters, particularly at the 1.0 m sample ports. Notable exceptions are the increased concentrations of all nitrogen forms at Well 2.

Water quality characteristics in ground waters beneath the flow path were also very similar to surface water characteristics listed in Table 1, except for increased concentrations of ammonia in the former. Ground waters in the stagnant control area exhibited significantly elevated concentrations of ammonia, organic nitrogen, orthophosphorus, total organic carbon, color, and iron compared to ground waters in other locations.

The increased concentrations of these parameters in ground waters is thought to be related to the release of ions from the sediments under stagnant and reduced conditions. Apparently, treatment systems that minimize stagnant conditions will improve groundwater quality as well as surface water quality.

FATE OF HEAVY METALS

Patterns of deposition and accumulation of heavy metals along the wetland flow path were investigated by examining metal concentrations in the 0–1 cm sediment layers at each of the fixed sample stations. A summary of these

Table 3.—Summary of mean water quality characteristics in shallow ground waters in the wetland area from samples collected December 1984 to August 1985 (n = 9 samples).

	WELL 1/UPSTREAM OF WETLAND		WELL 2/IN WETLAND FLOWPATH		CONTROL AREA WELL	
PARAMETER	0.1 M	1.0 M	0.1 M	1.0 M	0.1 M	1.0 M
pH	5.09	5.18	5.95	5.31	4.96	5.26
Sp. Cond. (μmho/cm)	127	111	251	129	106	138
Diss. O_2 (mg/L)	0.4	0.2	5.0	0.0	0.0	0.0
ORP (mv)	115	99	203	79	98	57
Alkalinity (mg/L)	29.4	44.2	111	41.3	19.0	32.6
NH_3-N (μg/L)	127	126	494	366	522	1,073
NO_3-N (μg/L)	59	44	71	97	14	22
Organic-N (μg/L)	538	195	330	460	1,694	1,411
Ortho-P (μg/L)	24	53	26	45	385	412
TOC (mg/L)	32.9	9.7	17.2	18.1	43.7	46.1
BOD (mg/L)	3.2	2.2	4.1	3.3	4.5	6.5
Color (Pt. Co Units)	371	433	216	180	639	546
Diss. Metals (mg/L):						
Cadmium	2.3	3.2	5.2	3.3	4.5	5.9
Zinc	40	47	22	24	24	40
Manganese	7.6	5.9	23	8.7	8.3	21
Copper	43	35	24	29	32	46
Iron	6,827	1,080	1,140	1,256	1,877	2,922
Lead	21	22	35	20	25	43
Nickel	4.2	3.1	6.4	2.6	3.5	4.8
Chromium	3.1	5.1	4.3	3.1	3.2	3.5

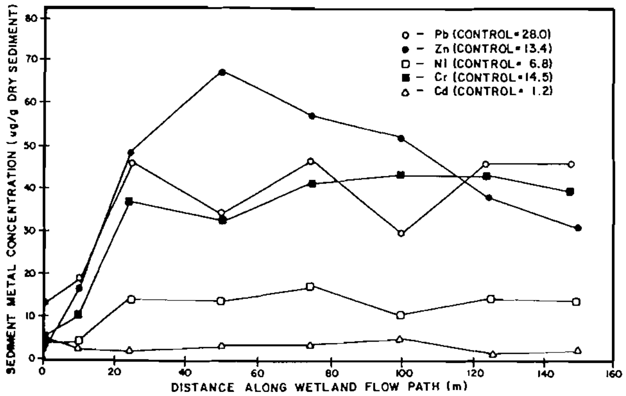

Figure 6.—Accumulation patterns of heavy metals in the wetland treatment system.

patterns is given in Figure 6 for lead, zinc, nickel, chromium, and cadmium. All of these metals reach peak sediment concentrations at a distance of 25–50 m from the input canal followed by constant or slightly fluctuating concentrations with increasing distance into the wetland.

Mean vertical accumulations of heavy metals in the top 20 cm of the wetland and control areas are presented in Table 4. Sediment concentrations of cadmium, zinc, aluminum, iron, lead, nickel, and chromium in the flow area appear elevated compared to sediment concentrations in the control area, while sediment concentrations of copper and manganese appear similar in both areas. This behavior implies that the sediments are accumulating and retaining certain metals while not retaining others.

The second important pattern that is apparent in the wetland flow path for all metal species except copper is the rapid attenuation of metal concentrations with increasing depth. That this rapid attenuation is much less pronounced or absent in the sediments of the control area suggests that metals are predominantly retained in the surface layers and that the sediment-bound metal concentration front is moving downward at a slow rate. However, elevated concentrations of all metal species except manganese were observed in the wetland area to depths exceeding 20 cm when compared to the control area.

The attenuation of sediment metal concentrations with increasing depth fit almost equally well both semilog and linear regression models, although slightly higher values of R-square were obtained for some metals with the semilog model. The sediments are clearly the primary sink for metal species entering the wetland. Concentration factors, calculated as the mean sediment metal concentration in the 0–1 cm sediment layer in µg/L divided by the mean surface water concentration in µg/L, were 165 for cadmium, 1,835 for zinc, 1,030 for manganese, 101 for copper, 7,682 for iron, 449 for lead, 1,262 for nickel, and 2,662 for chromium.

EFFICIENCIES DURING INFILTRATION

The effectiveness of wetland soils in removing pollutants during infiltration was investigated in undisturbed 10 cm diameter core samples 1 m long using a simulated stormwater solution. Flow rates were varied at approximately 2 cm/day and 5.5 cm/day, corresponding to detention times of 50 to 18 days, respectively. Infiltration through the core columns resulted in substantial reductions in all parameters measured except total organic carbon, iron, and ammonia, although total nitrogen decreased (Table 5). In general, removal efficiencies were improved by infiltration at the slower rate. Wetland soils appear very effective in removal of pollutants during infiltration, especially phosphorus and heavy metals.

RETENTION CAPACITY OF THE WETLAND

One method of improving the relatively poor removal efficiencies measured for nitrogen and phosphorus during flow through the wetland is to provide total retention for a portion of the runoff inputs. Assuming infiltration to be negligible, the major losses would be from evaporation and transpiration. From March to September, evaporation was measured in the wetland using a recording evaporimeter, and transpiration was estimated from changes in piezometric surface after allowing for direct precipitation and inputs through the canal.

From April to September, evaporative losses under the wetland canopy ranged from 0.75–1.48 mm/day with an average of 1.00 mm/day. Transpiration ranged from 8.4–17.3 mm/day with an average of 12.5 mm/day for a combined average evapotranspiration loss of 13.5 mm/day. During the same six month period approximately 91.5 cm of rain fell (70 percent of the yearly total), and the wetland evapotranspired 243 cm of water for a net loss of 151.5 cm from the wetland. The average retention capacity of the wetland during this period would be 91.5/151.5

Table 4.—Comparison of mean heavy metal concentrations in various layers within wetland and control areas at Hidden Lake, Fla.

	SEDIMENT METAL CONCENTRATION (µG/G DRY WT)								
SAMPLE	CD	ZN	CU	AL	FE	PB	NI	CR	MN
Wetland Area[1]									
0 – 1 cm	2.74	39.3	5.91	43,377	5,698	35.4	11.9	32.1	16.3
1 – 5 cm	2.78	37.5	5.06	33,468	4,342	30.9	9.73	26.0	13.1
5 – 10 cm	2.13	25.6	5.88	20,311	3,903	36.2	7.93	17.4	12.1
10 – 15 cm	1.80	12.4	5.10	7,849	2,581	28.5	5.92	9.38	9.16
15 – 20 cm	1.86	8.58	4.27	5,818	2,758	22.5	5.28	9.48	7.18
Control Area[2]									
0 – 1 cm	1.21	13.4	6.93	16,273	3,452	28.0	6.81	14.5	15.7
1 – 5 cm	0.86	11.4	5.94	8,791	2,592	26.6	4.79	8.75	14.8
5 – 10 cm	0.85	5.52	2.74	2,819	2,463	12.6	2.16	2.91	7.17
10 – 15 cm	0.87	8.00	4.31	3,334	1,963	21.7	3.51	4.44	13.2
15 – 20 cm	0.96	6.93	3.76	2,713	2,191	18.4	3.67	4.38	12.9

[1] n = 21 samples
[2] n = 6 samples

Table 5.—Comparison of removal efficiencies for simulated stormwater solutions passing through undisturbed 1 m long wetland core samples at various flow rates for a three month period.

		FLOW RATE = 1.99 CM/DAY		FLOW RATE = 5.54 CM/DAY	
PARAMETER	INPUT	OUTPUT	% CHANGE	OUTPUT	% CHANGE
pH	6.09	5.77	−5.3	6.03	−1.0
Sp. Cond. (μmho/cm)	255	137	−46	209	−18
Alkalinity (mg/L)	84.8	20.7	−76	72.6	−14
NH_3-N (μg/L)	266	986	+271	1,829	+588
NO_3-N (μg/L)	4,622	47	−99	50	−99
Organic-N (μg/L)	696	262	−62	270	−61
Total-N (μg/L)	5,584	1,295	−77	2,149	−62
Ortho-P (μg/L)	269	25	−91	343	+28
TOC (mg/1)	4.9	12.5	+155	15.9	+225
BOD (mg/L)	3.3	0.8	−76	1.1	−67
Diss. Metals (mg/L):					
Cadmium	21	7.5	−64	6.3	−70
Zinc	908	26	−97	80	−91
Manganese	155	4.3	−97	12	−92
Copper	139	34	−76	31	−78
Iron	103	184	+79	375	+264
Lead	107	20	−81	41	−62
Nickel	43	4.5	−90	4.8	−89
Chromium	9.1	3.6	−60	4.0	−56

= 0.6 ha of wetland/ha of impervious area, or for a residential area with a runoff coefficient of 0.5 a retention requirement of 0.3 ha of wetland/ha of development. These suggested design criteria are for average rainfall conditions, and extreme rain events or prolonged periods of rainfall would result in discharges to the receiving water. However, retention of mass inputs on a yearly basis for this site would exceed 80 percent.

SUMMARY

The effectiveness of a hardwood wetland in removing pollutants in residential runoff was investigated at a site near Orlando, Fla. Flow through 150 m of the wetland removed as much as 50–80 percent of particulate metal species, less of dissolved species. Metal species settled very quickly after entering the wetland, forming relatively stable metal–sediment associations with the majority of metals retained near the surface layers. No significant removal of total nitrogen was observed in the system. Dissolved orthophospshorus increased during travel through the wetland and was closely correlated to decreases in both oxidation reduction potential and pH. A stagnant control area exhibited elevated concentrations of total nitrogen and phosphorus as well as total organic carbon and color. The column studies indicated that removal efficiencies for nitrogen, phosphorus, and heavy metals were substantially greater during infiltration than during a flow-through situation.

Wetland systems appear better suited for removing heavy metals than nutrients, suggesting that wetlands may be particularly effective in treating highway runoff where heavy metals are the primary pollutants. Systems designed for removal of nutrients should avoid long detention times and stagnant conditions; both can decrease oxidation reduction potential and pH and reduce the efficiency of phosphorus removal. Discharges through infiltration should be encouraged to increase removal efficiencies. This can be achieved by creating hydraulic gradients between wetlands and receiving waters during periods of high rainfall.

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