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FACTORS AFFECTING THE PERFORMANCE OF STORMWATER TREATMENT WETLANDS

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Abstract—Data from 35 studies on 49 wetland systems used to treat stormwater runoff or runoff-impacted surface waters were examined and compared in order to identify any obvious trends that may aid future stormwater treatment wetland design efforts. Despite the intermittent nature of hydrologic and pollutant inputs from stormwater runoff, our analysis demonstrates that steady-state first-order plug-flow models commonly used to analyze wastewater treatment wetlands can be adapted for use with stormwater wetlands. Long-term pollutant removals are analyzed as functions of long-term mean hydraulic loading rate and nominal detention time. First-order removal rate constants for total phosphorus, ammonia, and nitrate generated in this fashion are demonstrated to be similar to values reported in the literature for wastewater treatment wetlands. Constituent removals are also demonstrated via regression analyses to be functions of the ratio of wetland area to watershed area. Resulting equations between these variables can be used as preliminary design tools in the absence of more site-specific details, with the understanding that they should be employed cautiously. © 2001 Elsevier Science Ltd. All rights reserved

Key words—wetland, BMP, nonpoint source, stormwater, runoff, literature

BACKGROUND

Wetlands constructed as wastewater treatment systems have become widespread in the US and other parts of the world. Interest in wetland treatment systems also extends to using them to treat urban and agricultural stormwater runoff, although the stochastic nature of the hydrologic and pollutant inputs makes performance prediction an inherently more difficult task than for wastewater. Little design guidance for stormwater wetlands is currently available, and there is an absence of comprehensive long-term mass balance data on existing systems. Nevertheless, there is a growing body of limited-scope performance data on individual stormwater wetlands, from which general inferences regarding the pollutant attenuation capabilities of these systems may be drawn. The purpose of this review is to analyze the available performance information on both natural and constructed wetlands that have been used to treat stormwater runoff or runoff-impacted surface water, and to identify any obvious trends in the data that may aid future design efforts. We hypothesized that long-term pollutant removals in stormwater wetlands could reasonably be described in terms of simple models commonly used to analyze wastewater treatment wetlands.

Studies suggest that wetland performance in treating stormwater is generally a function of inflow or hydraulic loading rate (HLR) and detention time (Dt), which are in turn functions of storm intensity, runoff volume, and wetland size (area and volume) (Barten, 1987; Hickok *et al.,* 1977; Meiorin, 1989; Scherger and Davis, 1982). Inflow rate presumably influences pollutant retention by affecting the degree of bottom scouring and resuspension of settled solids, and therefore the retention of solids and solids-associated pollutants. Wetland volume determines the fraction of a runoff event potentially captured, and therefore made available for treatment, especially during quiescent periods between events (Woodward-Clyde, 1986). The importance of proper sizing was recognized in early design guidelines published by the state of Maryland (MDE, 1987), which recommended that the surface area of a constructed stormwater wetland be at least 3% of the contributing watershed area. Since that time, other authors have suggested that the area ratio may not be as important as the volume ratio (ratio of average runoff volume to storage volume) in determining performance (Strecker *et al.*, 1992). More recent guidelines (Schueler, 1992) recommend both a

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*Author to whom all correspondence should be addressed. Tel.: +1-703-305-5736; fax: +1-703-305-6309; e-mail: carleton.jim@epa.gov minimum area ratio of 2% (or 1% for wetlands with extended detention), and a treatment volume large enough to capture 90% of all storm events. Despite the promulgation of these recommendations, little information has been presented to confirm their adequacy for attaining desired pollutant removals.

In recent years, a mathematical approach has been developed for the purpose of analyzing or predicting the performance of wastewater treatment wetlands, which treats these systems as steady-state, plug-flow reactors (Kadlec and Knight, 1996; Reed *et al.*, 1995). This approach ignores the mechanistic complexities involved in various removal processes and lumps them together into overall first-order rate constants. Because wastewater treatment wetlands are intended to be operated at fairly constant hydraulic and pollutant loading rates, the steady-state assumption is a reasonable approximation of flow conditions. The degree of plug-flow behavior varies with wetland length-to-width ratio and vegetation density among other things, but regardless of the degree of internal mixing, rate constants are maximally conservative when calculated under the assumption of plug-flow conditions. According to the "$k-C^*$" approach, concentration at the outlet of such a system is described by the following equation:

$$\ln\left(\frac{C - C^*}{C_\mathrm{i} - C^*}\right) = -\frac{k_\mathrm{a}}{q} \qquad (1)$$

where q is the hydraulic loading rate (e.g. in m/yr), C_i is the inlet concentration, C^* is the irreducible

Table 1. Wetland study citations

Name	Location	References
Gravity-fed systems		
Armstrong slough	Osceola County, FL	Goldstein (1986a, b)
Ash slough	Okeechobee County, FL	Goldstein (1986a, b)
B31	Bellevue, WA	Reinelt and Horner (1995)
Cache River	Gregory, AR	Dortch (1995), Dortch (1996)
Clear lake	Waseca, MN	Barten (1987)
Crestwood	Manassas, VA	Carleton *et al.* (2000)
Crookes	Victoria, Australia	Raisin *et al.* (1997)
DUST Marsh	Fremont, CA	Meiorin (1986)
E2	greater Minneapolis/St. Paul, MN	Willenbring (1985)
Fish Lake	Hennepin County, MN	Brown (1985a, b), Strecker *et al.* (1992)
Franklin County	Franklin County, OH	Niswander and Mitsch (1995)
Franklin Farms	Manassas, VA	OWML (1990)
Greenwood	Orlando, FL	McCann and Olson (1994)
Hidden Lake	Seminole County, FL	Harper *et al.* (1986a, b)
Hidden River	Tampa, FL	Carr and Rushton (1995), Carr (1995), Rushton (1996)
Island Lake	Seminole County, FL	Schiffer (1989)
Jones lake	greater Minneapolis/St. Paul, MN	Willenbring (1985)
Josephine	Roseville, MN	Willenbring (1985), Weidenbacher and Willenbring (1984)
Kingston	greater Minneapolis/St. Paul, MN	Willenbring (1985)
Lake Elmo	Washington County, MN	Brown (1985a), Strecker *et al.* (1992)
Lake McCarrons	Roseville, MN	Wotzka and Oberts (1988), Oberts and Osgood (1991)
Lake Munson	Tallahassee, FL	Maristany and Bartel (1989)
Lake Riley	Carver County, MN	Brown (1985a), Strecker *et al.* (1992)
Lake Tahoe	Lake Tahoe, CA	Reuter *et al.* (1992)
Lower Watkins	greater Minneapolis/St. Paul, MN	Willenbring (1985)
Mays Chapel	Baltimore, MD	City of Baltimore (1989)
PC12	King County, WA	Reinelt and Horner (1995)
Queen Anne	Centerville, MD	Athanas and Stevenson (1991)
Reedy Creek	Orlando, FL	German (1989)
Shop Creek	Aurora, CO	Urbonas *et al.* (1994)
Silver Star Road, original	Orlando, FL	Martin and Smoot (1986), Martin (1988)
Silver Star Road, modified	Orlando, FL	Gain (1996)
Spring Creek	Bowman, ND	Downer and Myers (1995)
Spring Lake	Scott County, MN	Brown (1985a), Strecker *et al.* (1992)
St. Joseph bog	Stearns County, MN	Stark and Brown (1988)
St. Joseph marsh	Stearns County, MN	Stark and Brown (1988)
Swift Run	Ann Arbor, MI	Scherger and Davis (1982)
Tampa Office Pond	Tampa, FL	Rushton and Dye (1993)
Wayzata	Wayzata, MN	Hickok *et al.* (1977)
Pumped systems		
Boney Marsh	Highlands County, FL	Moustafa *et al.* (1996)
Des Plains EWA3	Lake County, IL	Hey *et al.* (1994), Mitsch *et al.* (1995)
Des Plains EWA4	Lake County, IL	Hey *et al.* (1994), Mitsch *et al.* (1995)
Des Plains EWA5	Lake County, IL	Hey *et al.* (1994), Mitsch *et al.* (1995)
Des Plains EWA6	Lake County, IL	Hey *et al.* (1994), Mitsch *et al.* (1995)
ENR	Palm Beach County, FL	Moustafa (1999), Guardo (1999)
Lake Apopka reservoirs	Lake County, FL	Reddy *et al.* (1982)
Lake Apopka flooded fields	Lake County, FL	Reddy *et al.* (1982)
Olentangy W1	Columbus, OH	Spieles and Mitsch (2000), Nairn and Mitsch (2000)
Olentangy W2	Columbus, OH	Spieles and Mitsch (2000), Nairn and Mitsch (2000)

background concentration of the constituent, and k_a is the "areal" rate constant, expressed in units of length over time. For certain constituents, such as total phosphorus (TP), ammonia (NH_3), and nitrate (NO_3^{2-}), Kadlec and Knight (1996) consider C^* to be essentially zero, therefore equation (1) can be expressed in the following manner:

$$\frac{C}{C_i} = e^{-k_a/q} \qquad (2)$$

Equation (2) can also be expressed as

$$\frac{C}{C_i} = e^{-k_v\tau} \qquad (3)$$

where τ is the detention time, and k_v is the "volumetric" rate constant, with units of inverse time. Replacing the concentration terms in the above equations with the equivalent removal efficiencies (RE = percent of influent concentration or mass retained within the wetland), equations (2) and (3) become (after Dortch, 1996)

$$1 - \frac{RE}{100} = e^{-k_a/q} \qquad (4)$$

and

$$1 - \frac{RE}{100} = e^{-k_v\tau} \qquad (5)$$

Therefore, given estimates of percent removal for a constituent with negligible background concentration, and either q or τ, first-order rate constants k_a or k_v, respectively, can be calculated for a given wetland. In reviewing data from 82 emergent marsh treatment wetlands, Kadlec and Knight (1996) reported k_a values for TP ranging from 2.4 to 23.7 m/yr, with an average of 12.1 m/yr, and a standard deviation of 6.1 m/yr. Rate constants for NH_3 in 13 surface-flow marshes ranged from −2.8 to 22.1 m/yr, while constants for NO_3^{2-} ranged from 10.5 to 56.0 m/yr in seven systems.

Wong and Geiger (1997) suggested that the $k-C^*$ model could be adapted to develop design guidelines for extended detention stormwater treatment wetlands, and proposed a method wherein the wetland area required to achieve a given RE is calculated based on known C_i, C^*, k, and the "hydrologic effectiveness" of the facility, defined as the percentage of storm inflow subjected to treatment (a function of detention time and extended detention storage). They pointed out that use of this technique requires estimates of k for stormwater wetlands, which they expected to differ from values derived from wastewater wetlands due to the unsteady, intermittent nature of stormwater inflows.

METHODS

Thirty-five studies on pollutant removal in 49 separate wetland systems receiving urban or agricultural stormwater runoff or runoff-impacted surface waters were identified in which monitoring took place over a period of at least 6 months. Although our intention was to include data collected anywhere in the world, all but one of these studies took place in the US (Table 1). Many were conducted by entities such as municipalities, and were not published in peer-reviewed journals, but rather were published only as project reports. Two of the constructed wetlands were of the subsurface flow (SF) variety (Crooke's and Lake Tahoe); the remainder were free water surface (FWS) systems. In addition to constructed marshes, studies focused on natural wetland types ranging from cypress swamps to northern peatlands, some of which had been hydrologically modified with impoundments. Variables that differed between the wetlands studied include hydrologic conditions, vegetation, climate, source of runoff, and degree of pretreatment. Various monitoring and performance calculation procedures were also employed, making comparisons among studies difficult (Table 2).

In order to keep the amount of information manageable, our analysis was limited to constituents commonly of concern in stormwater, and for which there was a relatively large amount of data available (Table 4). These included orthophosphate phosphorus (OP), total phosphorus (TP), ammonia/ammonium (NH_3), nitrate (NO_3^{2-}), total suspended solids (TSS), and total (i.e. acid-extractable) forms of cadmium, copper, lead, and zinc (TCd, TCu, TPb, TZn). In order to estimate the removal rate constants, we focussed on the longest-term average data available at each site, including overall REs (Table 4) and long-term average hydraulic loading rates and detention times (Table 3) based on the total inflows including storm events and baseflow, over a period of several months or more, where this information was given. For REs we chose long-term load removal estimates where this information was available or derivable from the information presented in the study reports. Where this information was not available, we used long-term removals based on some kind of concentration reduction estimate (based on grab samples or event mean concentrations (EMCs)) instead. Where long-term detention times and hydraulic loading rates for these systems were not explicitly given in the study reports, we estimated these where possible based on other information, such as total inflow volumes over a defined interval, and wetland surface areas and volumes. For wetlands with varying ponded surface areas and volumes, such as constructed systems with extended detention, we based our calculations on the maximum values of these parameters, in order to generate maximally conservative (that is, minimal) estimates of k_a or k_v. Rate constant estimates were limited to TP, NH_3, and NO_3^{2-} because C^* for these constituents is negligible, and because relatively large numbers of REs were available for them.

Because it has been identified as a relevant design parameter, we also examined RE as a function of area ratio (AR), that is the ratio of wetland surface area to contributing watershed area. Inspection of the shape of the data for all the constituents examined suggested a general relationship of the form $\ln(1-RE/100) = -\alpha AR$ (Fig. 1). We therefore performed separate linear regressions of RE vs. AR, and ln-transformed RE (according to the above equation) vs. AR for each constituent.

RESULTS AND DISCUSSION

Removal rate constants for TP, NH_3, and NO_3^{2-} were remarkably consistent with values reported in the literature for wastewater treatment wetlands (Table 5). The mean k_a value for TP over all gravity-fed systems was 11.3 ± 17.6 m/yr, which is almost identical to the mean value (12.1 ± 6.1 m/yr)

Table 2. Wetland studies

Name	Wetland type[a]	Drainage[b]	Calculation based on
Gravity-fed systems			
Armstrong slough	C	A	Loads, 3 yr
Ash slough	N, impounded	A	Loads, 3 yr
B31	N	U	Loads, 2 yr
Cache River	N	A	Loads, 3 yr
Clear lake	C	U	Loads (from grab samples), 6 yr
Crestwood	C	U	Loads, 1 yr
Crookes	C	A	Loads, 1 yr
DUST Marsh	C	U, A	Loads (11 storms), 17 months.
E2	N, impounded	U	Conc. (mean grab sample (64)), > 2 yr (?)
Fish Lake	N, impounded	U	Conc. (flow-wt mean), 1 yr
Franklin County	C	U	Loads (modeled), 1 yr
Franklin Farms	C	U	Loads, 1 yr
Greenwood	C	U	Loads, 6 months.
Hidden Lake	N	U	Loads, 1 yr
Hidden River	N, impounded	U	Loads, 2.5 yr
Island Lake	N	U	Conc. (median grab sample, 2 storms), 7 months
Jones lake	N, impounded	U	Conc. (mean grab sample (11)), > 2 yr (?)
Josephine	N, impounded	U	Conc. (mean grab sample (43)), > 2 yr (?)
Kingston	N	A	Conc. (flow-wt mean grab samples (17)), 1 yr
Lake Elmo	N	A	Conc. (flow-wt mean), 1 yr
Lake McCarrons	C	U	Loads, 2 yr
Lake Munson	N, impounded	U	Conc. (mean EMC, 3 storms), 1 yr
Lake Riley	N	A	Conc. (flow-wt mean), 1 yr
Lake Tahoe	C	U (athletic field)	Loads, 1 yr
Lower Watkins	N	A	Conc. (flow-wt mean grab samples (21)), > 2 yr (?)
Mays Chapel	C	U	Conc. (median EMC), 1 yr
PC12	N	U (mostly forest)	Loads, 20 months
Queen Anne	C	U	Loads, 23 months
Reedy Creek	N	A	Loads, 1 yr
Shop Creek	C	U	Loads, 3 yr
Silver Star Road, original	N	U	Regression of loads (13 storms), 2 yr
Silver Star Road, modified	N	U	Conc. (geo. mean EMC(22 storms)), 16 months
Spring Creek	C	A	Loads, 2 yr
Spring Lake	C	U	Conc. (flow-wt mean), 1 yr
St. Joseph bog	N	U	Loads, 1 yr
St. Joseph marsh	N	U	Loads, 1 yr
Swift Run	N, impounded	U	Loads (5 storms), 2 yr
Tampa Office Pond	C	U	Loads, 2 yr
Wayzata	N	U	Loads, 1 yr
Pumped systems			
Boney Marsh	C	A	Loads, 1 yr
Des Plains EWA3	C	U, A	Loads, 2–3 growing seasons
Des Plains EWA4	C	U, A	Loads, 2–3 growing seasons
Des Plains EWA5	C	U, A	Loads, 2–3 growing seasons
Des Plains EWA6	C	U, A	Loads, 2–3 growing seasons
ENR	C	A	Loads, 3 yr
Lake Apopka reservoirs	C	A	Conc. (mean grab sample), 26 months
Lake Apopka flooded fields	C	A	Conc. (mean grab sample), 26 months
Olentangy W1	C	U, A	Loads, mean (conc. for TP), 2 yr
Olentangy W2	C	U, A	Loads, mean (conc. for TP), 2 yr

[a] C = constructed, N = natural.
[b] U = urban, A = agricultural.

reported by Kadlec and Knight for emergent marshes primarily receiving pumped wastewater. The higher standard deviation for stormwater wetlands reflects the greater variability in performance to be expected with stormwater treatment systems. Like for TP, calculated k_a values for NH_3 are consistent with the range of values reported for wastewater wetlands, while calculated k_a values for NO_3^{2-} are somewhat less than those reported for wastewater wetlands. The lower apparent performance for NO_3^{2-} in stormwater wetlands may in part reflect the episodic nature of their hydrologic inputs. Periodic partial drawdown and drying would tend to raise the redox potential in wetland sediments, thereby suppressing dentrification.

Wetland performance for TP is usually described in terms of areal rather than volumetric rate constants, consistent with the idea that phosphorus is primarily removed from the water column via settling of particles to which it is sorbed: k_a, with units of length over time, can be interpreted as an effective settling velocity for the constituent of interest. If the areal model is in fact a better model for TP removal than the volumetric model, then inverse hydraulic loading rate (equivalent to detention time divided by mean depth) should explain

Table 3. Hydrologic details of study wetlands

Name	Wetland volume $(10^3\,m^3)$	Wetland area $(10^3\,m^3)$	Drainage area $(10^6\,m^3)$	Area ratio	Volume ratio	HLR (cm/d)	Dt (day)
Gravity-fed systems							
Armstrong slough	*59.0*[a]	121	40.5	*0.0030*	*0.0015*	*34.65*	*1.4*
Ash slough	*12.3*	81.0	0.89	*0.0910*	*0.0139*	*1.43*	*10.6*
B31	*0.509*	20.0	1.87	*0.0107*	*0.0003*	*18.49*	*0.1*
Cache River		19,900	34,000	*0.0006*		*18.90*	*5.0*
Clear lake	*12.3*	214	4.33	*0.0494*	*0.0028*	*1.71*	*3.4*
Crestwood	0.133	0.70	0.029	*0.0241*	*0.0046*	*3.69*	*5.2*
Crookes	0.225	0.45	0.90	*0.0005*	*0.0003*	*21.83*	*2.3*
DUST Marsh	71.7	220	12.0	*0.0183*	*0.0060*		
E2		243	26.6	*0.0091*		*4.23*	
Fish Lake	*78.9*	64.0	2.84	*0.0225*	*0.0278*		
Franklin County		61.0	2.60	*0.0235*		10.60	
Franklin Farms	0.353	1.25	0.162	*0.0078*	*0.0022*	*17.16*	*1.6*
Greenwood	*81.4*	52.4	2.13	*0.0246*	*0.0382*	*2.57*	*60.6*
Hidden Lake		10.0	0.224	*0.0446*		*2.02*	
Hidden River		12.1	0.0619	*0.1961*		*1.04*	
Island Lake		417	1.45	*0.2887*			
Jones lake		93.0	9.07	*0.0103*		*3.68*	
Josephine		117	1.94	*0.0603*		*0.63*	
Kingston		2080	117	*0.0178*		*1.53*	
Lake Elmo	1110	910	8.35	*0.1090*	*0.1330*		
Lake McCarrons	11.6	25.0	0.38	*0.0658*	*0.0306*	*7.38*	*6.3*
Lake Munson	941	1030	94.7	*0.0109*	*0.0099*	*5.19*	*17.6*
Lake Riley	285	310	10.0	*0.0309*	*0.0284*		
Lake Tahoe		0.66	0.010	*0.0184*		*0.36*	
Lower Watkins		429	23.3			*1.43*	
Mays Chapel	1.21	2.40	0.393	*0.0061*	*0.0031*	*5.55*	*9.1*
PC12	*1.51*	15.0	0.87	*0.0172*	*0.0017*	*12.10*	*0.8*
Queen Anne	0.740	2.40	0.0064	*0.0375*	*0.0116*		
Reedy Creek		19700	399	*0.0494*		*1.18*	
Shop Creek		14.2	2.23	*0.0064*			
Silver Star Road, original	3.45	2.95	0.168	*0.0175*	*0.0205*		
Silver Star Road, modified	3.45	2.95	0.168	*0.0175*	*0.0205*	*2.45*	
Spring Creek	57.5	95.1				*0.22*	
Spring Lake	316	260	22.6	*0.0115*	*0.0140*		
St. Joseph bog		930	9.80	*0.0949*			*1.8*
St. Joseph marsh		930	9.80	*0.0949*			*3.1*
Swift Run	*74.2*	100	4.88	*0.0205*	*0.0152*		
Tampa Office Pond	0.389	1.29	0.0255	*0.0508*	*0.0153*	*8.16*	*3.7*
Wayzata		30.6	0.263	*0.1163*		*6.06*	
Pumped systems							
Boney Marsh	*186*	490				*2.11*	*18.0*
Des Plains EWA3	14.2	23.3				*7.46*	*8.2*
Des Plains EWA4	16.8	23.4				*1.45*	*49.7*
Des Plains EWA5	12.9	18.7				*5.16*	*13.4*
Des Plains EWA6	19.3	34.5				*1.97*	*28.5*
ENR	*10,700*	15,500				*3.45*	*20.1*
Lake Apopka reservoirs	3.22	3.72				*7.88*	*11.0*
Lake Apopka flooded fields	0.744	3.72				*3.59*	*5.6*
Olentangy W1	2.00	10.0				10.50	*2.7*
Olentangy W2	2.10	10.0				10.50	*2.7*

[a] Italicized values were calculated based on information in the study reports.

more of the variability in the quantity ln(1−RE/100) across systems than does detention time. In other words, ln(1−RE/100) should better fit a straight line when regressed against detention time divided by mean depth than when regressed against detention time alone. This did not prove to be the case for the data analyzed in this report (Figs 2 and 3), suggesting that for stormwater wetlands TP removal is a function more of mean detention time than of mean hydraulic loading rate. A possible partial explanation for this is that when intermittent high inflow rates occur, they may resuspend settled solids, offsetting the influence of a low mean hydraulic loading rate, and decreasing the removal of particulate-associated phosphorus.

Previous authors have concluded that stormwater wetlands tend to give better and more consistent performance as AR increases, but that the statistical relationships between RE and AR are not strong (Schueler, 1992; Strecker *et al.*, 1992). With a greater number of studies to draw on, our analysis suggests that the relationships between these variables are not linear, and that enough data now exist to begin to define them. For all constituents, linear regressions of ln(1−RE/100) vs. AR yielded higher r^2 values than was the case for regressions using untransformed RE.

Table 4. Long-term pollutant removal estimates

	Estimated pollutant removal (%)									
Name	OP	TP	NH_3	NO_3^{2-}	TN	TSS	TCd	TCu	TPb	TZn
Gravity-fed systems										
Armstrong slough	*39.7*[a]	*30.9*			5.9					
Ash slough	*39.7*	*39.7*			*17.3*					
B31		*7.5*				13.6				30.6
Cache River		3.0			21.4					
Clear lake	52.0	54.0	55.0			76.0				
Crestwood	35.8	45.9	54.7	39.4	21.7	57.9	28	65.5	74.7	29.2
Crookes		17			11					
DUST Marsh	56.0	48.0	10.0	15.0		64.0		31.0	88.0	33.0
E2		45.0				88.0				
Fish Lake		*37.0*	*0.0*		*−20.0*	*95.0*				
Franklin County		16.0								
Franklin Farms	23.6	14.9	−0.5	59.8		61.5				
Greenwood	76.7	61.5	10.2	−13.2	−11.0	68.3	0.0	58.9	59.7	68.9
Hidden Lake	−109.0	7.0	62.2	80.2	−1.6	82.9	70.7	39.9	54.8	40.9
Hidden River	67.0	70.0	79.0	94.0	46.0	86.0	88.0	79.0	83.0	84.0
Island Lake		*87.0*	*96.0*	88.8				*87.5*	*83.3*	*66.7*
Jones lake		9.0				56.0				
Josephine		59.0				92.0				
Kingston		38.0				27.0				
Lake Elmo		*27.0*	*50.0*		*38.0*	*88.0*				
Lake McCarrons		41.0		35.0	35.0	83.0			74.0	
Lake Munson	−70.3	62.7	−39.4	14.9	10.9	92.5		−4.3	55.5	59.2
Lake Riley		*−43.0*	*25.0*		*20.0*	*−20.0*				
Lake Tahoe			−53	85						
Lower Watkins		9.0				74.0				
Mays Chapel		−7.0	22.1	28.0		11.3				
PC12		82.4				56.5				23.2
Queen Anne	68.7	39.4	55.8	54.9	22.8	65.1				
Reedy Creek		33.0	88.0	62.0	36.0					
Shop Creek		36.0		21.0	41.0	25.0		−15.0		24.0
Silver Star Road, original	2.0	17.0	54.0	40.0	21.0	66.0			73.0	56.0
Silver Star Road, modified	−67.0	−55.0	40.0	−193.0	−49.0	−170.0		−67.0	−187.0	−14.0
Spring Creek		*39.6*		11.0		*77.7*				
Spring Lake		*−7.0*	*−86.0*		*−14.0*	*−300.0*				
St. Joseph bog		14.0				34.0				
St. Joseph marsh		18.0				44.0				
Swift Run		*49.0*				83			*83.0*	
Tampa Office Pond	67.0	65.0	39.0	65.0		55.0				51.0
Wayzata		78.0	*−44.0*			94.0	67.0	80.0	94.0	82.0
Pumped systems										
Boney Marsh		71.0			26.0					
Des Plains EWA3		*66.1*		*80.6*		*90.4*				
Des Plains EWA4		*88.4*		*49.8*		*85.1*				
Des Plains EWA5		*82.4*		*82.3*		*95.9*				
Des Plains EWA6		*89.1*		*98.8*		*99.6*				
ENR		82.0								
Lake Apopka reservoirs	75.1	60.9	57.5	68.1						
Lake Apopka flooded fields	16.7	7.3	51.9	64.2						
Olentangy W1		59.0		39.8						
Olentangy W2		54.0		36.7						

[a] Italicized values were calculated based on information in the study reports.

In general, this approach appeared to describe the general shape of the data, though substantial scatter is evident, especially at the lower end of the AR scale (Figs 4–12). With no information available other than wetland and watershed areas, the equations presented here can be used to make *a priori* best-guess estimates of expected wetland performance. Of course, this approach should be used cautiously, given the limited nature of the dataset from which the equations were derived, and the substantial variability in the data itself. Wetland performance is influenced by wetland structure and hydrology, and by climate, soils, vegetation, percent watershed imperviousness, and numerous other variables not accounted for in this simplistic approach. For example, the presence of plants, the nature of the rooting substrate, and the degree of pretreatment have all been demonstrated to influence removal rates (and associated areal removal rate constants) of OP, NH_4^+, and NO_3^{2-} in wetland mesocosm studies (Drizo *et al.*, 2000; Zhu, 1998). Nevertheless, the information summarized in this report appears to suggest that current sizing guidelines may not provide adequate treatment for some constituents: although the predicted RE for TSS using these equations is 61% with an AR of 0.02, the expected

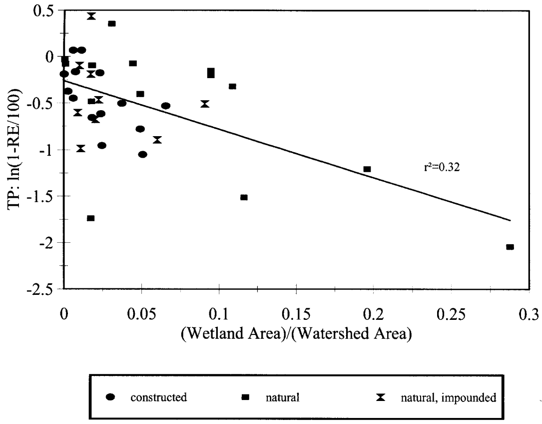

Fig. 1. Ln-transformed TP removal vs. wetland-to-watershed area ratio.

removals of TP and TN are only 30 and 10%, respectively.

CONCLUSIONS

Our analysis demonstrates that long-term pollutant removals in stormwater wetlands can be adequately described in terms of mean detention time and hydraulic loading rate using the same kinds of first-order steady flow design equations currently employed for wastewater treatment wetlands. Areal removal rate constants for TP, NH_3 and NO_3^{2-} calculated in this fashion are generally consistent with values given for wastewater in the literature, although the data for TP appear to be more consistent with the volumetric model. The rate

Table 5. Areal and volumetric removal rate constants

	TP		NH_3		NO_3	
Name	k_v (1/yr)	k_a (m/yr)	k_v (1/yr)	k_a (m/yr)	k_v (1/yr)	k_a (m/yr)
Gravity-fed systems						
Armstrong slough	*95.9*[a]	*46.7*				
Ash slough	*17.3*	*2.6*				
B31	*207.0*	*5.3*				
Cache River	*2.2*	*2.1*				
Clear lake	*84.3*	*4.9*	*86.7*	*5.0*		
Crestwood	*43.5*	*8.3*	*56.1*	*10.7*	*35.5*	*6.7*
Crookes	*29.7*	*14.8*				
DUST Marsh						
E2		*9.2*				
Fish Lake						
Franklin County		*6.7*				
Franklin Farms	*35.9*	*10.1*	*−1.1*	*−0.3*	*202.9*	*57.1*
Greenwood	*5.8*	*8.9*	*0.6*	*1.0*	*−0.7*	*−1.2*
Hidden Lake		*0.5*		*7.2*		*11.9*
Hidden River		*4.6*		*5.9*		*10.6*
Island Lake						
Jones lake		*1.3*				
Josephine		*2.0*				
Kingston		*2.7*				
Lake Elmo						
Lake McCarrons	*30.6*	*14.2*			*25.0*	*11.6*
Lake Munson	*20.5*	*18.7*	*−6.9*	*−6.3*	*3.4*	*3.1*
Lake Riley						
Lake Tahoe				*−0.6*		*2.5*
Lower Watkins		*0.5*				
Mays Chapel	*−2.7*	*−1.4*	*10.0*	*5.1*	*13.2*	*6.7*
PC12	*760.9*	*76.7*				
Queen Anne						
Reedy Creek		*1.7*		*9.1*		*4.2*
Shop Creek						
Silver Star Road, original		*1.4*		*5.8*		*3.8*
Silver Star Road, modified		*−3.9*		*4.6*		*−9.6*
Spring Creek		*0.4*				*0.1*
Spring Lake						
St. Joseph bog	*30.6*					
St. Joseph marsh	*23.4*					
Swift Run						
Tampa Office Pond	*104.1*	*31.3*	*49.0*	*14.7*	*104.1*	*31.3*
Wayzata		*33.5*		*−8.1*		
Pumped systems						
Boney Marsh	*25.1*	*9.9*				
Des Plains EWA3	*48.3*	*29.5*			*73.2*	*44.7*
Des Plains EWA4	*15.8*	*11.4*			*5.1*	*3.6*
Des Plains EWA5	*47.4*	*32.7*			*47.3*	*32.6*
Des Plains EWA6	*28.4*	*15.9*			*56.7*	*31.7*
ENR	*31.1*	*21.6*				
Lake Apopka reservoirs	*31.2*	*27.0*	*28.4*	*24.6*	*37.9*	*32.9*
Lake Apopka flooded fields	*5.0*	*1.0*	*48.0*	*9.6*	*67.4*	*13.5*
Olentangy W1	*120.5*	*34.2*			*68.6*	*19.4*
Olentangy W2	*105.0*	*29.8*			*61.8*	*17.5*

[a] Italicized values were calculated based on information in the study reports.

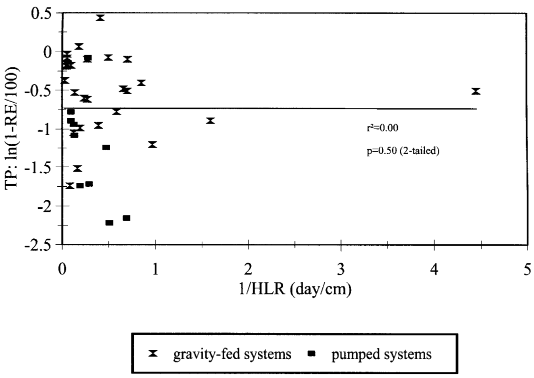

Fig. 2. Ln-transformed TP removals vs. mean hydraulic loading rate.

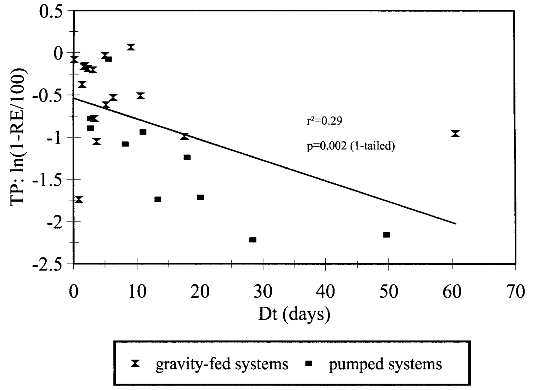

Fig. 3. Ln-transformed TP removal vs. nominal detention time.

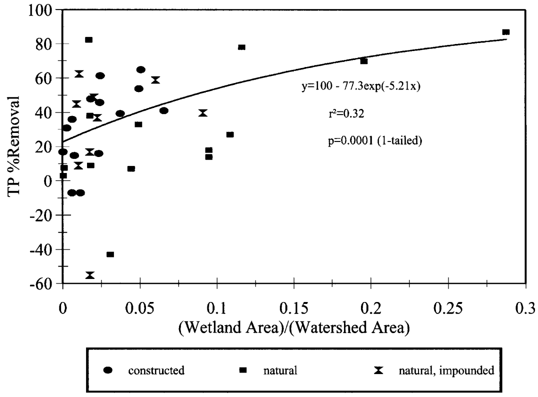

Fig. 4. TP removal vs. wetland-to-watershed area ratio.

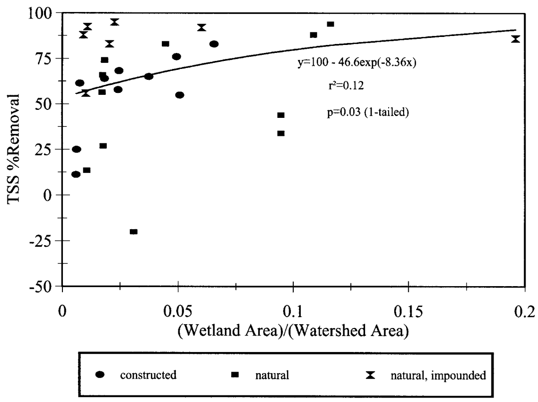

Fig. 5. TSS removal vs. wetland-to-watershed area ratio.

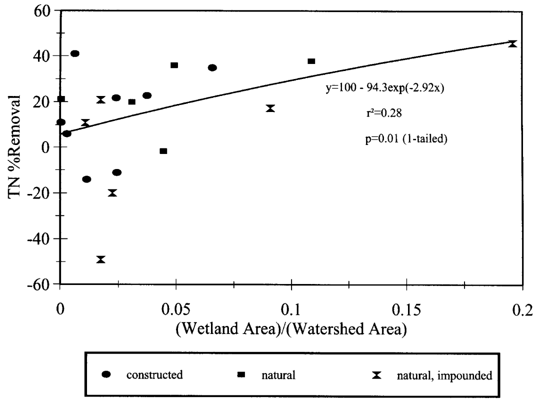

Fig. 6. TN removal vs. wetland-to-watershed area ratio.

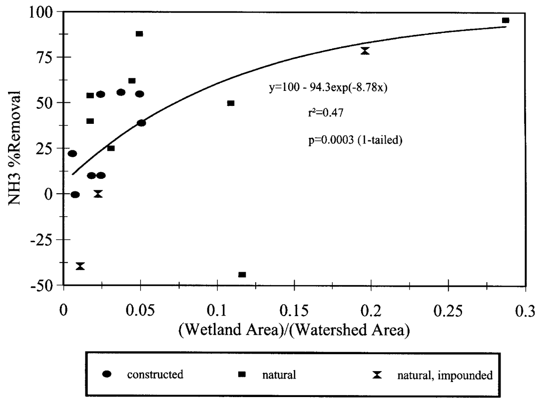

Fig. 7. NH_3 removal vs. wetland-to-watershed area ratio.

constants presented in this paper can be used together with a procedure such as the one suggested by Wong and Geiger (1997) to calculate the area necessary to achieve a given degree of treatment by a stormwater wetland. Our analysis also demonstrates that approximate long-term performance for common stormwater constituents can be predicted on the basis of the ratio of wetland surface area to

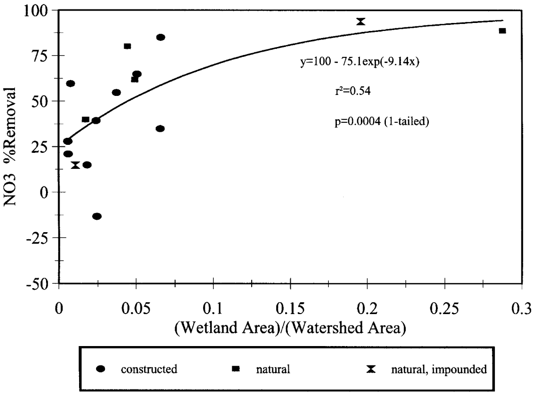

Fig. 8. NO_3^{2-} removal vs. wetland-to-watershed area ratio.

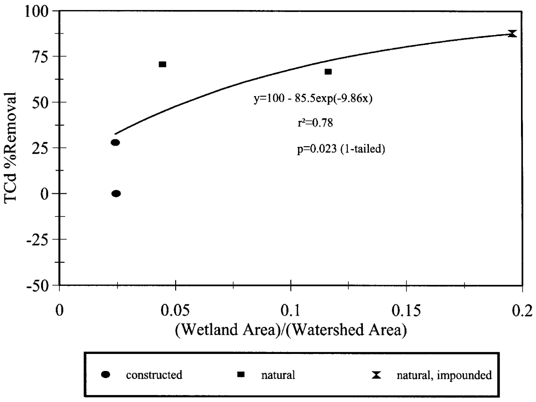

Fig. 9. TCd removal vs. wetland-to-watershed area ratio.

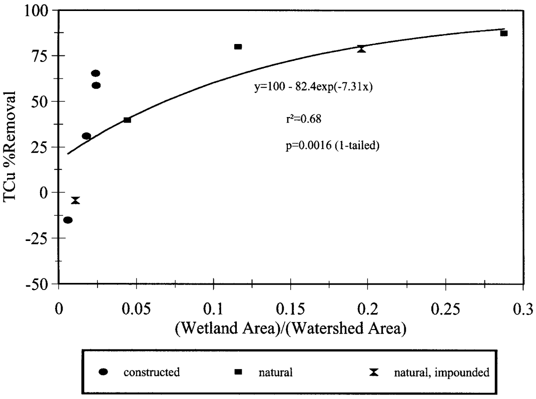

Fig. 10. TCu removal vs. wetland-to-watershed area ratio.

contributing watershed area. Regression equations derived with this approach can be used for preliminary wetland design purposes, but should be employed cautiously given the limited data set, and the substantial variability of the data about the regression lines.

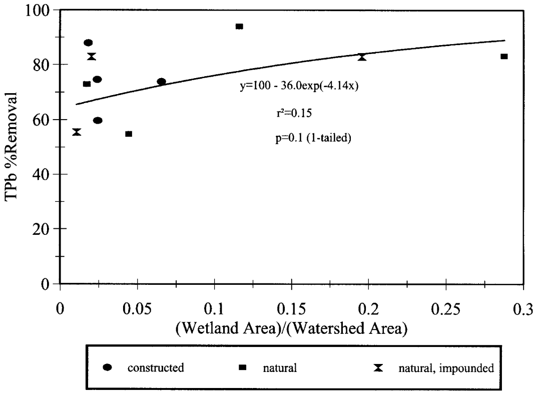

Fig. 11. TPb removal vs. wetland-to-watershed area ratio.

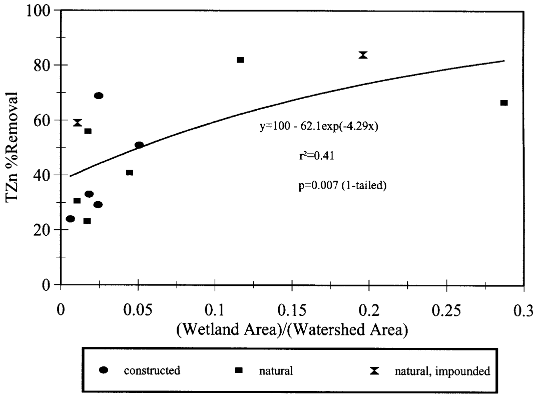

Fig. 12. TZn removal vs. wetland-to-watershed area ratio.

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