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Wetland networks for stormwater management in subtropical urban watersheds[1]

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Abstract

A quantitative method suitable for planning wetland stormwater treatment at the regional, multibasin scale was developed based on simple zero order kinetics (uptake rates) and average nutrient loading conditions. The method was applied to urbanized watersheds south of Miami, FL and yielded a hierarchically organized network of wetlands for processing stormwaters. Coastal watersheds in Dade county, FL, varying in intensity of development from heavily urbanized to almost completely undeveloped and ranging in size from 38600 ha to 700 ha were analyzed. Watersheds were divided into three spatial scales: basin (> 1000 ha), sub-basin (1000–100 ha) and neighborhood (100–10 ha). The methods used to calculate wetland area were based on: (1) reducing nutrient and sediment concentrations to background levels of the receiving water body (Biscayne Bay); and (2) retaining storm runoff to attenuate pulses of freshwater discharge. At each spatial scale, the wetland area needed to treat nitrogen, phosphorus, suspended sediment, biological oxygen demand and the water quantity was calculated. The constituent requiring the largest treatment area determined the amount of wetland area necessary. Results indicated that at the neighborhood scale, phosphorus runoff, generated by a 5-year 24-h design storm, required the largest wetland treatment area, needing between 2.3 and 10.8% of total basin area. At the sub-basin scale, the loading of total suspended solids, derived from land use specific criteria, needed the largest treatment area, ranging from 0.2 to 4.5% of basin area. The basin scale treatment,

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based on retaining drainage canal discharge for at least 72 h, needed between 0.1 and 2.5% of basin area. This methodology is useful for feasibility analysis and leads to design principles for planning basin-scale, stormwater management systems in urbanized watersheds.

Keywords: Wetland restoration; Urban stormwater; Wetland networks; Watershed planning; Landscape restoration; Constructed wetlands; Stormwater wetlands

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1. Introduction

Historically, urban stormwater management was only concerned with collecting and distributing stormwater to minimize flooding (Chow et al., 1988). More recently, in the USA, amendments to the Clean Water Act have addressed the impacts of non-point pollution sources, such as municipal stormwater runoff, on receiving water bodies (33 US Code, Section 1251a, 1989, US Congress (1989)). This has forced stormwater management efforts of many municipalities to focus on providing treatment and modifying the discharge pattern of urban runoff so that it more closely resembles stormwater coming from undeveloped landscapes (40 C.F.R. Section 131b, 1995, US Code of Federal Regulations (1995)).

Applying wastewaters to wetlands for water purification has been investigated in the USA since the late 1960s (Odum, 1985). Since that time research on the effectiveness of created and natural wetlands to process wastewaters from a diverse array of sources has flourished (Hammer, 1989; Moshiri, 1993; Kadlec and Knight, 1995; Harberl et al., 1997). Several researchers have shown that wetlands were effective at reducing nutrient, sediment, organic carbon and heavy metal loadings of urban stormwater runoff (Martin and Smoot, 1985; Harper et al., 1986; Oberts and Osgood, 1991; Ethridge and Olson, 1992; Johengen and LaRock, 1993; Carr and Rushton, 1995; Reinelt and Horner, 1995; Rushton et al., 1995; Rochfort et al., 1997; White and Myers, 1997). Rushton et al. (1995) tested the effect of hydraulic residence time on the removal rate of various pollutants in a constructed wetland receiving urban runoff in Tampa, FL. They found that the sediment load (TSS) was reduced by 94% and total phosphorus (TP) by 90% for the wetland with the 14-day residence time but sediment was only reduced by 67% and phosphorus by 57% when residence time was 5 days. Reinelt and Horner (1995) observed that the percent removal of the TP load to a wetland was 8% when the residence time was only 3.3 h but that a wetland with a 20 h residence time removed 82%. Moustafa et al. (1996) monitored the nutrient dynamics of a freshwater marsh in central Florida, USA for 9 years and found that the removal efficiency of TP was consistently around 80%. Kadlec and Hey (1994) reported that re-constructed wetlands receiving diverted water from a river draining a watershed that was 80% agricultural and 20% urban land use reduced sediment loads by an average of approximately 90% and total phosphorus loads by about 80% over a 2-year period. Others have observed how constructed wetlands recondition industrial wastewaters

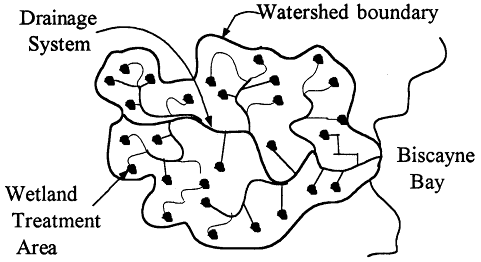
(Kadlec et al., 1997), acid-mine drainage (Tyrell et al., 1997), landfill leachate (Bulc et al., 1997) and runoff from intensive livestock operations (Cronk, 1996; Siever, 1997).

While wetlands are effective at treating urban stormwater runoff, appropriate methods for determining stormwater wetland area requirements at a regional, multi-basin scale that provide criteria for feasibility studies and planning efforts are needed. De Laney (1995) reviewed the approaches suggested for incorporating treatment wetlands into an agricultural landscape. When discussing how to select sites for wetlands created for intercepting agricultural runoff, van der Valk and Jolly (1992) suggested that placing small wetlands in the headwater sub-basins or locating a large wetland in the downstream reach were practical alternatives. van der Valk and Jolly (1992) went on to add that the choice of landscape location should hinge on construction costs as well as the logistics of involving landowners. Knight (1993) proposed that the location of treatment wetlands within the landscape should be driven by the goal chosen for the wetland; if water quality or attenuation of 'normal' flooding was desired, then many small upstream sites were likely the best choice but if concern existed for controlling large episodic flow volumes or for creating wildlife habitat, then a large downstream wetland would prove the most useful. However, Moler and Franz (1987) highlighted the need to protect and restore small, isolated, ephemeral wetlands because they provide a unique breeding and foraging habitat for many amphibians and birds. Baker (1993) suggested that that headwater wetlands, by slowing the floodwaters upstream, would decrease streambank and channel erosion downstream. However, modelling efforts of Ogawa and Male (1983) showed not only that larger wetlands provided more flood attenuation but that the further downstream they were positioned, the more effect there was on decreasing stream discharge. Therefore, general principles that provide a rational basis for siting constructed wetlands within the entire watershed for the purpose of managing urban stormwater are needed.

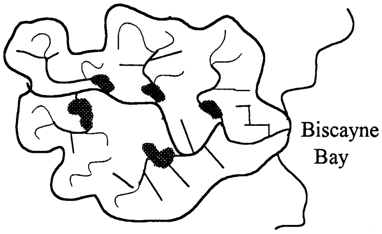
While several alternatives (SWMM, POND, etc.) exist for modelling the hydraulics and pollutant dynamics of urban stormwaters, "clear guidelines on the design and operation of urban runoff treatment wetlands need to be established" (Shutes et al., 1997). A simple method which yields suitable, yet conservative estimates of wetland treatment area requirements but does not entail extensive modelling or manpower inputs is needed. Such a method should provide criteria for: (i) judging the feasibility of modifying already urbanized watersheds; or (ii) planning newly developing watersheds.

In this paper a methodology for sizing stormwater wetland requirements at the watershed scale is demonstrated. The method is suggested as a 'first cut' analysis tool for determining wetland area requirements at the watershed scale and assumes that zero-order kinetics (constant uptake rates) are appropriate for planning purposes. While it is understood and has been shown, that the pollutant removal efficiencies of wetland systems are variable and depend on loading rates, input concentrations, wetland types, etc. it is believed that conservative methods, using a simple technique for sizing wetlands based on average inputs and uptake rates, are appropriate during initial planning efforts. More detailed analysis and simulation modelling of individual wetlands using actual rainfall and higher order kinetics may be more suitable for final design planning (and is the subject of a paper to follow) but are impractical for planning at the watershed scale because of time, energy and monetary constraints. A wetland model which incorporated phosphorus dynamics, such as that developed by Kendall (1997) or Mitsch and Reeder (1991), could be useful for final design planning.

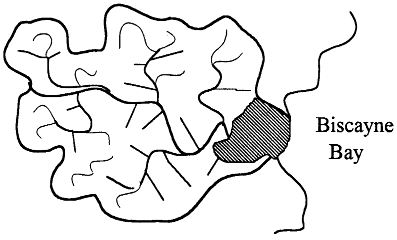
Application of the methodology indicated that a network of constructed wetlands integrated into the urban landscape (Fig. 1) may be appropriate for simultaneously improving water quality by reducing the flow of nutrient and sediments and dampening the pulses of freshwater discharge. The spatial configuration of the wetland network is similar to what was observed for undeveloped watersheds of Florida; many small wetlands were scattered throughout basins contributing flow to several medium sized wetland sloughs which in turn converged waters to a few large wetlands (Sullivan, 1986).



a) Neighborhood Treatment Wetlands



b) Sub-basin Treatment Wetlands



c) Basin Treatment Wetland

Fig. 1. Schematic diagrams showing spatial arrangement of: (a) Neighborhood; (b) Sub-basin; and (c) Basin treatment wetlands within a watershed.

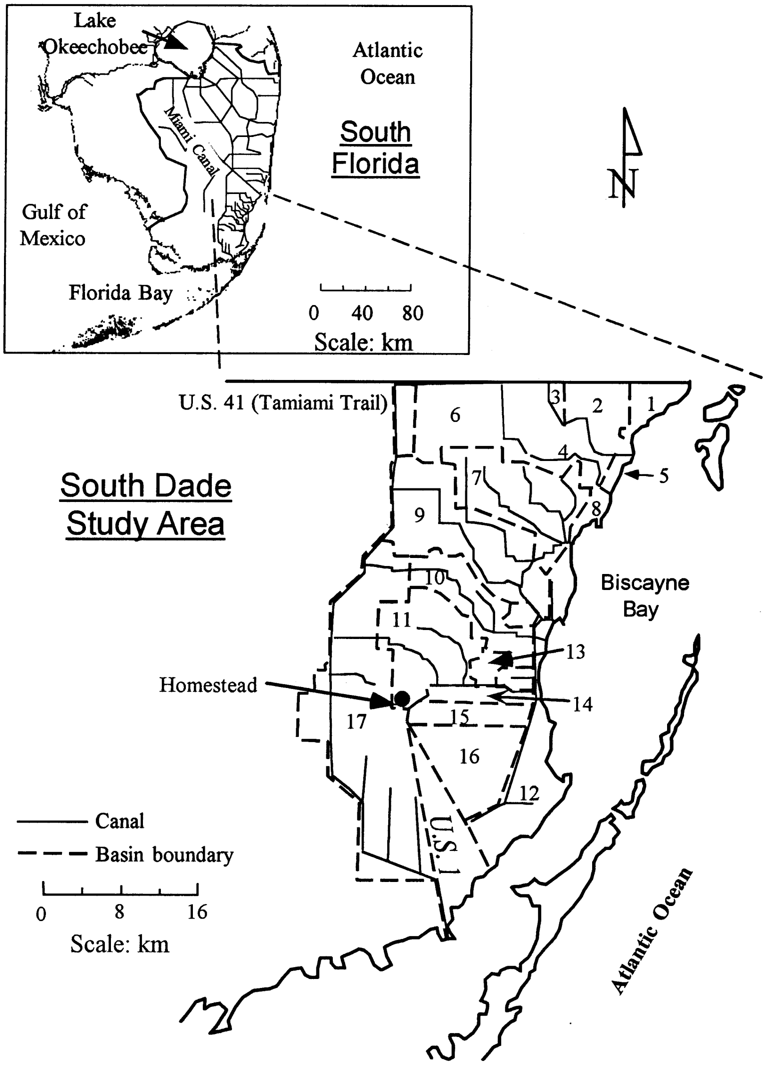


Fig. 2. Location and drainage system of South Dade Study Area with basins numbered (1–17) in Northwest-Southwest orientation for use with charts given (SFWMD, 1994).

2. Description of Study Site

A total of 17 coastal watersheds in south Dade county, FL, varying in intensity of development from heavily urbanized to almost completely undeveloped were used to develop principles for designing wetland treatment systems at the watershed scale. South Dade county, located on the extreme southeast coast of Florida, immediately south of the rapidly urbanizing metropolitan Miami area, (Fig. 2) covers 347000 ha. It is bounded on the north by Miami, on the east by Biscayne Bay, on the south by Florida Bay and on the west by the Everglades.

2.1. Land use

Prior to the modern settlement of south Dade, the cover of land consisted of six broad types: (a) coastal ridge; (b) rocky glades; (c) transverse glades; (d) everglades; (e) mangrove swamps; and (f) coastal marshes (Fig. 3). The transverse glades were tidal channels, formed during the Pleistocene, which cut through the coastal ridge to drain the interior land. With the receding of the sea, the tidal channels became wetland sloughs that conveyed surface water from the Everglades, eastward to Biscayne Bay during the wettest parts of the year. As a result of drainage activities to accommodate agricultural and urban development, the majority of the transverse glades were bisected longitudinally by drainage canals (USGS, 1973).

A land use map of the south Dade study area for 1988 is shown in Fig. 4. Urban land uses dominate in the northern portions of the study area giving way to increasing agricultural uses toward the south. The eastern, southern and coastal sections of the study area are dominated by wetlands.

2.2. Climate

The climate of south Dade county is sub-tropical with a mean July temperature of 28°C and a mean January temperature of 19°C. The average annual rainfall is 1473 mm year^{-1}. There exists a distinct seasonality to the annual rainfall pattern

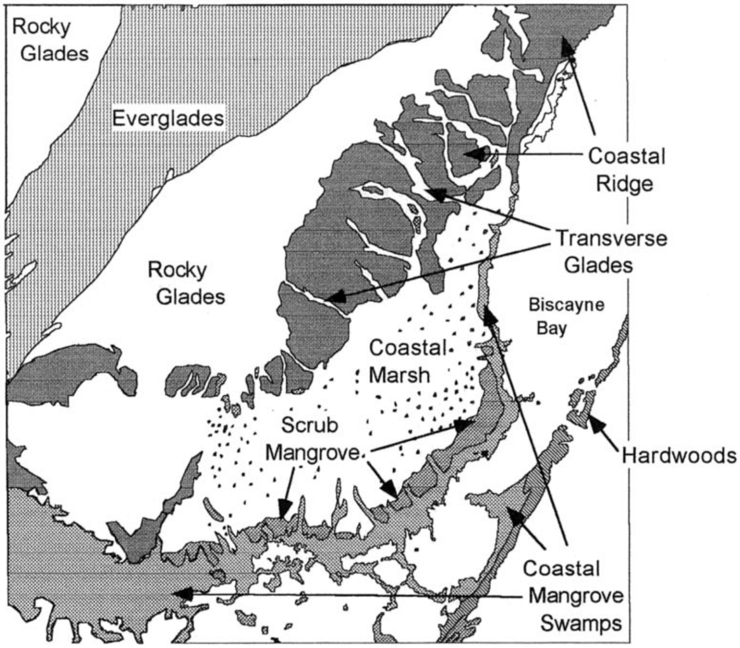


Fig. 3. Map of South Dade land types prior to human development. Adapted from Lopez Barba (1995).

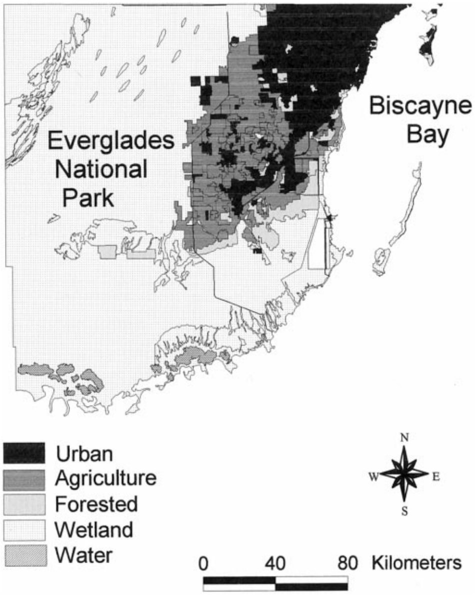


Fig. 4. Map of land use for South Dade Study Area in 1988.

with 2/3 (982 mm) occurring during the period from May to October and 1/3 (491 mm) falling during the drier season from November to April (Sculley, 1986).

3. Materials and methods

Guidelines for designing stormwater wetlands have been largely based on the experiences of developing municipal wastewater wetlands (Somes and Wong, 1994). However, one of the most common methods available for sizing a constructed wetland receiving a 'constant' load of wastewater, based on the flow rate and the difference in logarithms of the influent and effluent concentrations, does not account for stochastic processes (Kadlec et al., 1997). Thus, this sizing model is likely inappropriate for sizing stormwater wetlands which receive highly variable input.

Since the objective at this preliminary phase was to determine the feasibility of retrofitting an artificial drainage network of an entire urban landscape with a more natural network of stormwater wetlands and in lieu of there not being a tried and true method for sizing stormwater wetlands the following method was developed. Procedures were developed for designing watershed-scale, stormwater management systems in urban areas which rely on hierarchically organized networks of constructed wetlands to process nutrients and sediments and to dampen abrupt pulses of freshwater discharge. The watersheds were divided, spatially, to encompass three hierarchical scales (Fig. 1): basin (> 1000 ha), sub-basin (1000–100 ha) and neighborhood (100–10 ha), resembling the natural Florida landscape (Brown and Tighe, 1991). Treatment wetlands at each scale were sized to retain storm runoff for 72 h and to reduce nutrient and sediment concentrations to background levels of Biscayne Bay.

The basin scale relied on drainage canal water quality and discharge quantity to determine pollutant loads and wetland treatment size. For the sub-basin scale, a method based on land use and the mean concentration of storm events was used to evaluate pollutant generation. At the neighborhood scale, pollutant generation was estimated based on the 5-year 24-h design storm. Treatment wetlands at each scale were sized based on processing the estimated pollutants and water flow. The rate at which treatment wetlands remove nutrients and sediments at the three scales were assumed constant and based on values reported for constructed wetlands.

3.1. Pollutant loadings and wetland treatment area

It is recognized that the frequency distribution of storm event intensities exhibits hierarchical properties with many small storms and fewer large ones. Further, it was realized that forcing functions (driving energies) change with changes in scale. As a result, different hydrologic parameters were used along with different measures of water quality to size wetland areas at each scale (see Table 1). Positions within the watershed where stormwater pollutant loadings were evaluated for each scale are shown in the energy systems (Odum, 1996; Odum and Odum, 1998) diagram in Fig. 5. At the basin scale, the hydrologic and stormwater constituent parameters driving wetland size requirements, were annual hydrographs of basin discharge and average monthly concentrations of constituents in the discharge waters. At the sub-basin scale the forcing functions were the mean annual runoff and the land use specific event mean concentration of stormwater constituents averaged over the year (US EPA, 1993). The hydrologic input at the neighborhood scale was a 5-year 24-h design storm and regression models devised by Driver and Troutman (1989) determined the concentrations of stormwater constituents.

The geographic information system (GIS) software, ARC/Info and 1988 Dade county land use coverages supplied by the South Florida Water Management District (SFWMD, 1994) were used to generate land use coverages of each drainage

Table 1
Methodology for evaluating size of wetland treatment areas at the three spatial scales

	Forcing functions	
Watershed scale	Hydrologic	Concentrations of stormwater constituents
Basin	Mean annual hydrograph of discharge from basin	Mean monthly discharge concentrations in canals
Sub-basin	Land use specific annual runoff	Land use specific event mean concentrations
Neighborhood	5-year 24-h design storm	Event concentrations derived from regression models (Driver and Troutman, 1989)

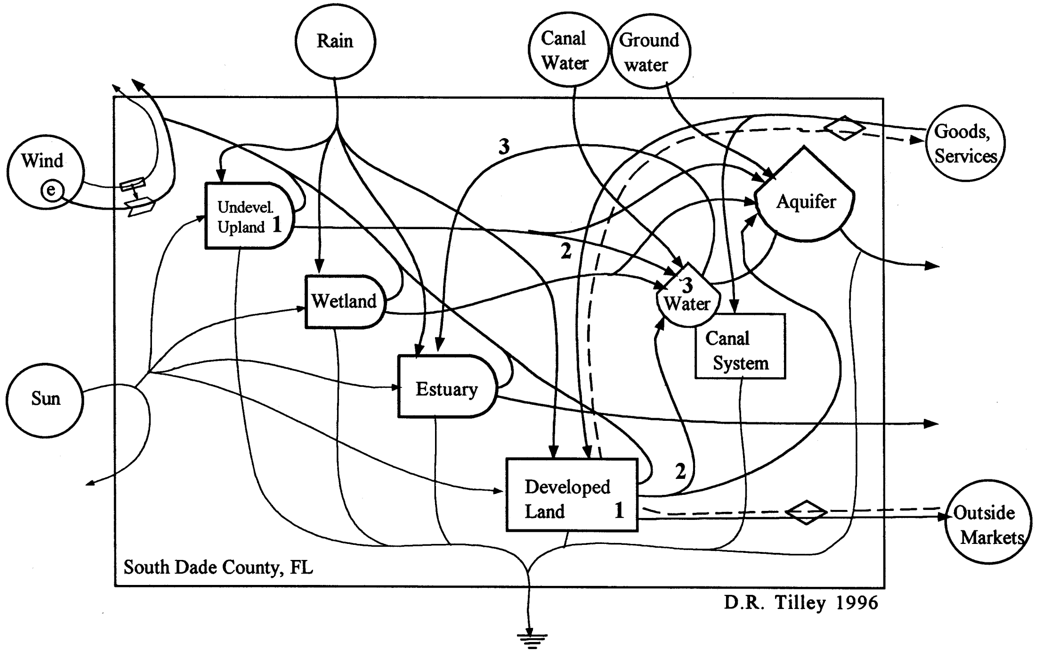


Fig. 5. Overview diagram of present stormwater flows in South Dade Study Area showing evaluation locations for each landscape scale (1. Neighborhood treatment wetlands, 2. Sub-basin treatment wetlands and 3. Basin treatment wetlands).

Table 2
Land use specific concentrations of stormwater constituents and runoff

Land use	Source	BOD	TSS concentration	TN (mg l^{-1})	TP	Runoff^e (mm y^{-1})	Specific use
Agriculture/rangeland	a	3.8	55	2.32	0.32	**93**	
	b	9.4	120	2.32	0.35		
	c	8.7	313	2.75	0.64		
	d	**5.1**	**94**	**2.48**	**0.48**		Pasture
	d	n/a	n/a	2.68	0.56		Crop
	d	2.6	16	2.05	0.14		Citrus
Industrial	a	9.1	74	1.42	0.21	**1077**	
	b	9.4	91	1.42	0.21		
	c	11.4	191	1.70	0.49		
	d	**9.6**	**94**	**1.79**	**0.31**		
Residential	a	10.1	45	1.55	0.40	**588**	
	b	10.1	47	1.68	0.40		
	c	11.7	197	1.95	0.44		
	d	7.4	27	2.29	0.30		Single family
	d	**11.0**	**72**	**2.42**	**0.49**		Multi-family
Transportation	a	6.7	39	1.39	0.31	**322**	
	b	9.0	56	1.42	0.25		
	c	9.0	96	1.29	0.27		
	d	**5.6**	**50**	**2.08**	**0.34**		
Commercial	a	9.5	77	1.61	0.24	**1177**	
	b	9.5	77	1.61	0.24		
	c	10.3	114	1.68	0.25		
	d	8.2	81	1.18	0.15		Low intensity
	d	**17.2**	**94**	**2.83**	**0.33**		High intensity
Institutional	a	9.5	77	1.61	0.24	**840**	
	b	9.5	77	1.61	0.24		
	c	**9.5**	**77**	**1.61**	**0.24**		
Other	a	14.8	119	1.43	0.29	**716**	
	b	8.0	90	1.43	0.23		
	c	**8.5**	**97**	**1.47**	**0.22**		

Table 2 (continued)

Land use	Source	BOD	TSS concentration	TN (mg l^{-1})	TP	Runoff[e] (mm y^{-1})	Specific use
Barren land	a	14.8	119	1.43	0.29	**91**	
	b	8.0	90	1.43	0.23		
	c	8.5	97	1.47	0.22		
	d	**1.5**	**11**	**1.25**	**0.05**		
Urban open	a	1.5	32	1.25	0.11	**85**	
	b	1.5	32	1.25	0.11		
	c	1.5	32	1.25	0.11		
	d	**1.5**	**11**	**1.25**	**0.05**		
Forested uplands	a	n/a	n/a	n/a	n/a	**91**	
	b	1.7	83	0.52	0.07		
	c	**1.7**	**83**	**0.52**	**0.08**		

BOD, biological oxygen demand; TSS, total suspended solids; TN, total nitrogen; TP, total phosphorus.

a Provided by Metro-Dade DERM (Department of Environmental Resources Management).

b Median of National Stormwater Quality Database.

c Mean of National Stormwater Quality Database.

d Overall mean of database for Central/South Florida compiled by Harper, 1994.

[e] Runoff supplied by Metro-Dade DERM and supplemented by Mattraw and Miller, 1981.

Locations and sources for National Stormwater Quality Database: Anchorage, Alaska. Brabets, 1986; Broward, FL. Mattraw and Miller, 1981; Chesapeake Bay, Correll et al., 1974; Dade County, Waller et al., 1984; Data from State of Florida, South/Central Florida and Dade county given by Dorian K. Valdes, Metro-Dade DERM Stormwater Monitoring and Evaluation Section King County, Wash. Pyrch and Brenner, 1983; Nationwide Urban Runoff Program. Summarized in Stockdale, 1991; Near Rochester, NY. Kappel et al., 1986; Northeastern Illinois, Polls and Lanyon, 1980; South Dakota. Dornbush et al., 1974; Southern New York, Haith and Doughtery, 1976; Viginia, North Carolina border, Bliven et al., 1980.

Table 3
Design criteria used to size stormwater wetlands

Constituent	Wetland uptake rate used in sizing stormwater wetlands kg ha^{-1} d^{-1}	Concentration of outflow from stormwater wetland mg l^{-1}
Total suspended solids	20	18
Biological oxygen demand	8	5.0
Total nitrogen	2	1.0
Total phosphorus	0.2	0.05
	Water storage capacity Mean (m)	Maximum (m)
Wetland depth	0.5	1.5

Rate of uptake and outflow concentrations of constituents and water storage capacities of wetlands.

basin within the South Dade Study Area. The literature values for the concentration of each stormwater constituent and surface runoff depth were assigned to each land use type (Table 2). Land use categories included residential, institutional, industrial, commercial, transportation, agriculture, barren land, rangeland, forested upland, wetland and open water. The percentage of land in each category for each drainage basin was extracted and used to develop hydrologic and stormwater constituent loading rates at the neighborhood and sub-basin scales. Wetland treatment area requirements were calculated based on: (a) wetland uptake rates of biological oxygen demand (BOD); (b) total suspended solids (TSS); (c) total nitrogen (TN); and (d) total phosphorus (TP) and water storage retention properties of a shallow marsh (Table 3).

3.2. Evaluation of storm water quality

3.2.1. Neighborhood treatment wetlands

Treatment wetlands for the neighborhood scale (1 in Fig. 5) were sized based on surface runoff and pollutant loadings generated during a 5-year 24-h design storm (rainfall = 190 mm). Empirically derived regression models with drainage basin characteristics as parameters (Driver and Troutman, 1989) were used to determine the pollutant loading for a 5-year 24-h storm event. These regression models were based on measurements from over 2800 storm events at 173 urban stations in 30 metropolitan areas, including Miami. The ability of these regression equations to explain the observed variability was admittedly low for both total nitrogen and total phosphorous ($R^2 = 0.35$, 0.54; standard error of estimate (%) = 165, 192, respectively). The resulting pollutant load was then used to size a wetland treatment area assuming a 72 h residence time.

The regression models were used to estimate the total phosphorus (TP) and total nitrogen (TN) loadings as well as runoff volume. The general form for these models is shown in Eq. (1):

$$\mathrm{TL} = B_0 \cdot X_1{}^{B_1} \cdot X_2{}^{B_2} \cdot X_n{}^{B_n} \cdot \mathrm{BCF} \quad (1)$$

Where, TL is the total loading (lbs.); B_0 is the regression constant; X_i is the basin characteristics, e.g. drainage area, total storm rainfall; B_i is the regression coefficients; n is the number of basin characteristics in equation; BCF is the bias correction factor.

Basin characteristics used depended upon the constituent modelled. The following basin characteristics served as model parameters:

- drainage area (mi^2)
- impervious area as a percent of drainage area (%)
- industrial land use as a percent of drainage area(%)
- residential land use as a percent of drainage area (%)
- non-urban land use as a percent of drainage area (%)
- total storm rainfall (in)
- mean annual rainfall (in)
- mean annual nitrogen in rainfall (lb-N/ac)
- mean January temperature (°C)

3.2.2. Sub-Basin treatment wetlands

The land use based event mean concentration or unit load method (US EPA, 1993) was applied to size sub-basin treatment wetlands (2 in Fig. 5). The pollutant loadings for individual basins were calculated using Eq. (2):

$$\mathrm{TL}_j = \sum\nolimits_{i=1\ to\ n} 10 \cdot A_i \cdot \mathrm{RO}_i \cdot \mathrm{EMC}_{ij};\ j = 1\ \ to\ \ m \quad (2)$$

Where, TL is the total loading of pollutant j from a basin (kg/year); i is the land use type i, e.g. residential, commercial, etc.; j is the pollutant j, e.g. BOD, TSS, TN, etc.; n is the number of land uses within the basin; m is the number of pollutants to estimate; A_i is the total basin area in land use i (hectares); RO_i is the annual runoff from land use i (m/y); EMC_{ij} is the event mean concentration for pollutant j from land use i (mg/l).

The total runoff volume (TRO) for a basin (ha m year^{-1}) was calculated using Eq. (3):

$$\mathrm{TRO} = \sum\nolimits_{i=1\ to\ n} A_i \cdot \mathrm{RO}_i \quad (3)$$

Eq. (2) and Eq. (3) were used to estimate the pollutant loadings and runoff volumes for 1988 land use data. Values for area (A_i) were taken from the land use coverages provided by SFWMD. Values for annual runoff (RO_i) were obtained using Eq. (4):

$$\mathrm{RO}_i = 147\ \mathrm{cm\ year}^{-1} \cdot F_i \quad (4)$$

Where, F_i is the fraction of rainfall that becomes runoff from land use i; 147 cm year^{-1} is the average annual rainfall for south Dade county.

In Eq. (2), the EMC_{ij}'s were means in the database compiled by Harper (1994) for sites in central and south Florida, while in Eq. (4), F_i's were mean values from the nationwide literature review (see Table 2).

3.2.3. Basin treatment wetlands

Design of the basin treatment wetlands (3 in Fig. 5) was based on processing the pollutant load estimated by multiplying, separately, the mean monthly concentrations of total phosphorus and total nitrogen in the drainage canals by the mean monthly discharge from the canals, as reported in the Biscayne Bay SWIM (Surface Water Improvement and Management) Plan (SFWMD, 1994). The derived loading was taken to be representative of the quality and quantity of water that a basin treatment wetland, located near the mouth of the watershed, would be required to treat and store. The loadings of total suspended solids (TSS) and biological oxygen demand (BOD) were not used at this scale since Metro-Dade Department of Environmental Resource Management monitored neither the canals nor Biscayne Bay for their presence.

The annual pollutant loadings per basin were calculated using Eq. (5):

$$\mathrm{TL}_j = 0.001 \cdot \textstyle\sum_{i=1}^{12} \mathrm{CC}_{ij} \cdot Di; \; j = 1 \;\; to \;\; m \tag{5}$$

Where, TL_j is the total annual loading of pollutant j (kg); CC_{ij} is the canal concentration for month i and pollutant j (mg/l); $\mathrm{D_i}$ is the average canal discharge for the period of record for month i (m^3); m is the number of pollutants.

3.3. Evaluation of wetland uptake rates

Information on how effectively constructed wetlands process urban runoff waters was not nearly as abundant as that for municipal systems but the data are increasing (see above). Additionally, nutrient and sediment retention rates in wetlands have typically been found to be sensitive to loading rate, residence time, water depth, climate and season, to name a but a few. Therefore, the database of uptake rates for constructed wetlands receiving municipal wastewater compiled by Knight et al. (1993) was used as a reference point for estimating uptake rates for stormwater wetlands. Uptake rates for treatment wetlands receiving intermittent loads of nutrients and sediments due to the nature of storms, cannot be simply extrapolated from a database on treatment wetlands receiving a much more consistent input of municipal wastewater. However, to proceed with the study some assumptions about a treatment wetland's ability to remove nutrients and sediments were made.

For TP, the database contained 34 sites with loading rates less than 1.1 kg ha^{-1} day^{-1}. For those 34 sites, the range of removal rates was from 0.0 to 0.45 kg ha^{-1} day^{-1}. Thus, an approximate mid-point was used, 0.20 kg ha^{-1} day^{-1} as the estimate of TP uptake. For the Des Plaines River Wetlands Demonstration Project Kadlec and Hey (1994) reported that mean TP uptake rates for four wetlands receiving diverted river water ranged from 0.015 to 0.040 kg ha^{-1} day^{-1} while the loading rates ranged from 0.017 to 0.056 kg ha^{-1} day^{-1}. There were 20 sites listed in the database for which the TN load was less than 4.0 kg ha^{-1} day^{-1}. A total of 95% of the variation in removal rate was explained by the loading rate, revealing that on average 78% of the load was removed within this range. The uptake rate that was assumed for TN (2.0 kg ha^{-1} day^{-1}) was in close agreement with an experimental rate (1.3 kg ha^{-1} day^{-1}) observed by Johengen and LaRock (1993) in a marsh receiving urban runoff from Tallahassee, FL. The assumed removal rate for TP (0.2 kg ha^{-1} day^{-1}) was about 1/6 of that observed by Johengen and LaRock (1993). For TSS uptake, a value slightly higher than the mean reported in Knight et al. (1993) was used since the average percent removal (68%) seemed valid for input loadings as high as 45 kg ha^{-1} day^{-1}. Assuming a conservative input loading of 30 kg ha^{-1} day^{-1} and a percent removal of 68%, gave the 20 kg-TSS ha^{-1} day^{-1} uptake rate used. Data on BOD for 49 sites were included in the database. Removal rates ranged from -0.05 to 83.0 kg ha^{-1} day^{-1}, with a mean of 8.9 kg ha^{-1} day^{-1}. A total of 93% of the variation in removal rate was explained by the loading rate, revealing that on average 59% of the load was removed over this range. Therefore, since statistics on BOD removal by treatment wetlands covered such a broad range an uptake rate of 8.0 kg ha^{-1} day^{-1} was assumed valid for the purposes. The uptake rates assumed for TSS, BOD, TN and TP are shown in Table 3.

3.4. Calculation of wetland treatment area

Treatment wetland areas were first figured based on reducing the incoming concentration of each pollutant to at least the background concentration of the receiving water body, Biscayne Bay (Table 3), since the Florida legislature required that Biscayne Bay's trophic state not be altered (SFWMD, 1994). However, the mean annual background concentration of total phosphorus (0.007 mg l^{-1}) reported for Biscayne Bay was slightly less than the lowest attainable concentration (0.01 mg l^{-1}) reported by Kadlec and Knight (1995) for emergent marshes and more than an order of magnitude less than the mean value (0.10 mg l^{-1}). Instead of targeting a seemingly unachievable concentration, a level (0.05 mg l^{-1}) attained by a few wastewater wetlands (Knight et al., 1993) was used. Similarly, the prescribed level (0.10 mg l^{-1}) for total nitrogen (TN) was an order of magnitude less than the concentration (1.0 mg l^{-1}) normally achieved by wastewater wetlands. Therefore, for the TN 1.0 mg l^{-1} was used as the goal for the outflow concentration. The total suspended solids (TSS) was based on background concentrations reported by SFWMD (1994) for that section of Biscayne Bay encompassed by the South Dade Study Area. The target goal for BOD was based on the typical outflow limits of wastewater wetland systems.

The following method was used to estimate the required wetland treatment area. The target outflow concentrations were used in combination with the runoff volumes for each drainage basin to calculate the allowed outflow pollutant mass, Eq. (6).

$$O_{ij} = 0.001 \cdot \mathrm{TC}_i \cdot \mathrm{RO}_j; \tag{6}$$

Where, O_{ij} is the targeted mass output for pollutant i and basin j (kg/d); TC_i is the targeted concentration for pollutant i (mg/l); RO_j is the runoff volume for basin j (m^3 day^{-1}).

The mass to be removed is then simply the input minus the targeted output, Eq. (7).

$$R_{ij} = I_{ij} - O_{ij}; \tag{7}$$

Where, R_{ij} is the mass to be removed of pollutant i and basin j (kg day^{-1}); I_{ij} is the mass input for pollutant i and basin j (kg day^{-1}).

For the sub-basin and basin scales, the required wetland treatment area was calculated by dividing the mass to be removed by the uptake rate, Eq. (8). At the neighborhood scale, to account for a 72 h residence time, the mass to be removed was divided by three times the daily uptake rate.

$$\mathrm{WTA}_{ij} = \frac{R_{ij}}{U_i}; \tag{8}$$

Where, WTA_{ij} is the required wetland treatment area for pollutant i and basin j (ha); U_i is the uptake rate for pollutant i (kg ha^{-1} day^{-1}).

Additionally, Eq. (9) was used to determine wetland treatment area needed at each scale based on retaining the runoff volume. Treatment wetlands were assumed to have characteristics similar to a shallow marsh and thus an average depth of 0.5 m and a maximum water depth of 1.5 m for single pulsed events.

$$\mathrm{WTA}_j = \frac{\mathrm{RO}_j \cdot t}{d}; \tag{9}$$

Where, WTA_j is the wetland area treatment for basin j (ha); RO_j is the runoff volume (ha m day^{-1}); d is the depth (0.5 m); t is the residence time (3 days).

3.5. Sensitivity analysis

Since the area necessary for processing TSS with the sub-basin treatment wetlands was generally only 1.5 times that of TP, a sensitivity analysis was performed. The sensitivity of the size of sub-basin treatment wetlands to uptake rate, loading rate and target outflow concentration was tested for all 17 basins.

The uptake rates and outflow concentrations representing the high and low extremes of typically observed values for stormwater and wastewater wetlands were tested for both TSS and TP. Uptake rates (kg ha^{-1} day^{-1}) tested were 5, 10, 20 and 45 for TSS and 0.05, 0.10, 0.20 and 0.30 for TP. These minimum values were in line with observations made by Mitsch (1992) for a constructed wetland receiving stormwater runoff where the retention rates of TSS and TP were 5.5 kg ha^{-1} day^{-1} and 0.06 kg ha^{-1} day^{-1}, respectively. The higher TSS value tested, corresponded to the near limit of that reported in the database compiled by Knight et al. (1993). The larger TP uptake rate was double the median value found in Knight et al. (1993).

The outflow concentrations (mg l^{-1}) tested were 3, 9, 18 and 30 for TSS and 0.05, 0.10, 0.15 and 0.20 for TP. The wastewater wetland database compiled by Knight et al. (1993) contained only four sites with inflow concentrations of TP less than 1.0 mg l^{-1}. These four sites had outflow concentrations of 0.05, 0.10, 0.11 and 0.19 mg l^{-1}. Since it was estimated that the runoff concentration for the Black Creek basin was less than 0.50 mg l^{-1}, the outflow numbers similar to that found in the database of Knight et al. (1993)were tested.

A total of three sources of data were used to estimate land use specific event mean concentrations (Table 2). These included the compilation of a nationwide literature review into a national stormwater quality database (NSQD), Metro-Dade Department of Environmental Resource Management's (DERM) assessment of stormwater quality in Dade county and Harper (1994) compilation of observations in central and south Florida.

4. Results

The spatial configuration of a system of constructed wetlands, intended to process urban runoff, was evaluated using estimates of pollutant generation and wetland uptake at three different landscape scales. First, wetland areas were determined as if small wetlands were scattered throughout basins acting as stormwater treatment wetlands for single rainfall events at the neighborhood scale (<100 ha). Second, wetlands were sized assuming they were located at the sub-basin scale, where they treat stormwaters from a sub-basin area representing roughly 100–1000 ha. Finally, the wetland treatment area requirements for entire basins (>1000 ha) were calculated assuming that stormwaters were routed to wetlands at the downstream ends of watersheds (an 'end-of-pipe' treatment wetland).

4.1. Neighborhood scale

The total phosphorus was the constituent which required the largest area of stormwater wetland treatment at the neighborhood scale in all basins (Fig. 6). The treatment area required for retaining storm runoff was the next largest, while no area was needed for processing total nitrogen since the estimated runoff concentrations were less than 1.0 mg l^{-1} in all basins.

The size of treatment areas, based on processing total phosphorus loads, ranged from 2.3% to 10.8% of the total basin area, based on 1988 land use. A total of 65% (11 of 17) of the watersheds needed less than 5% of basin area as wetland treatment, while only one basin needed more than 10% (Fig. 6).

4.2. Sub-basin scale

Estimates of land use specific pollutant generation at the sub-basin scale were taken from Harper (1994) (Table 2). For every sub-basin treatment wetland within the study area, the pollutant requiring the largest treatment area was total suspended solids (TSS). Total phosphorus (TP) removal required the next largest wetland treatment area (Fig. 7). Removal of TSS was estimated to need wetland treatment area ranging from 4.5 to 0.2% of total basin area. In almost every basin, treatment area for TSS was 50% more than that needed for processing TP. The wetland area required for treatment of TP was always less than 3.0% of basin area.

4.3. Basin scale

The mean monthly outflow concentration of total phosphorus and total nitrogen and the annual discharge hydrograph of the drainage canals were used to calculate the size of treatment wetlands in basins for which there were data. Given in Fig. 8 are the requirements for the area of the basin treatment wetlands. The hydraulic loading required the largest wetland treatment area (all basins less than 2.5% of total area), except in one basin which was controlled by total nitrogen.

4.4. Sensitivity analysis

At the sub-basin scale the sensitivity of the required treatment area to uptake rate, loading rate and target outflow concentration was evaluated for all 17 basins. However, reporting the results for all basins would be confusing since the intensity of development across basins varies widely. Instead, the Black Creek watershed (9 in Fig. 2) was chosen as a representative basin credible for reporting results since it

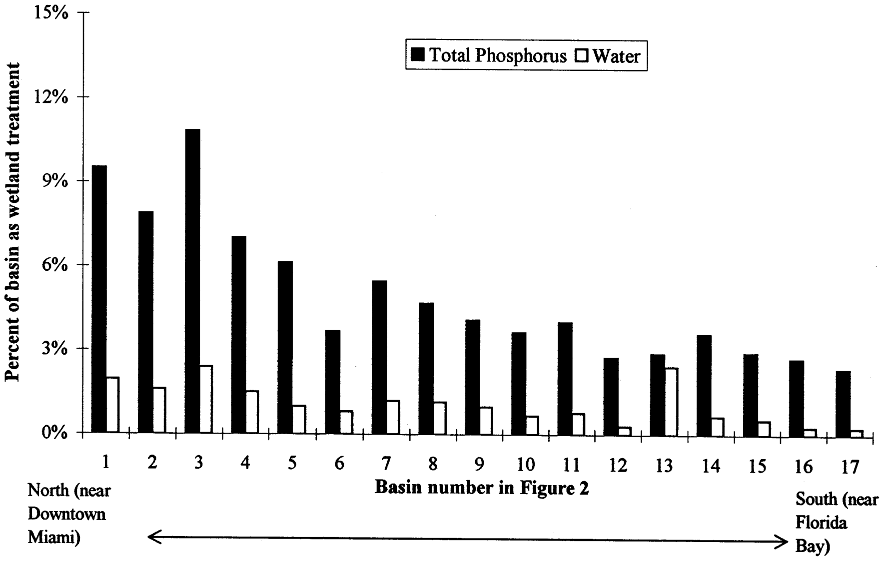


Fig. 6. Percent of basin area needed for neighborhood treatment wetlands based on total phosphorus (TP) loading and water runoff generated using the 5-year 24-h design storm.

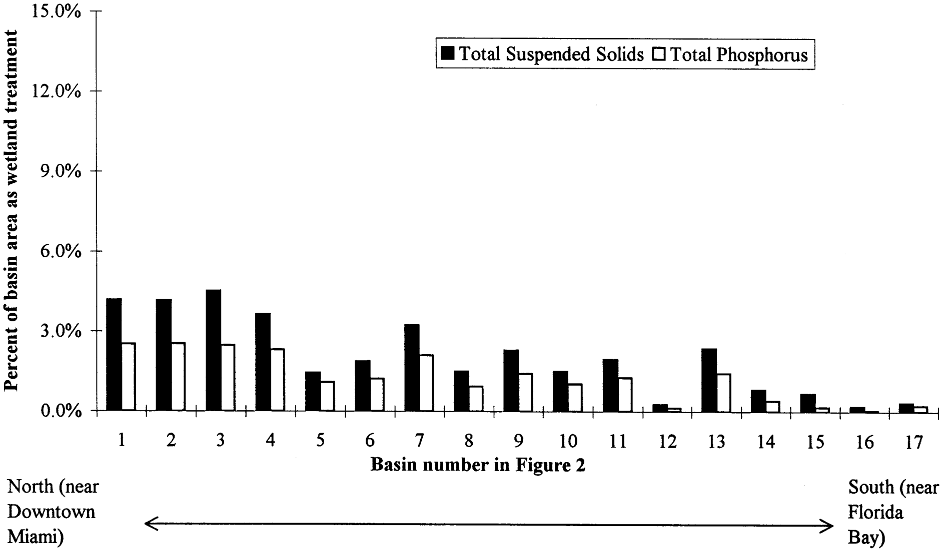


Fig. 7. Percent of basin area needed for sub-basin treatment wetlands based on loadings of total suspended solids (TSS) and total phosphorus (TP) estimated using the event mean concentration (EMC)—land use method (US EPA, 1993).

was centrally located within the study area and had a broad, even distribution of land use types.

The area of the watershed needed as sub-basin treatment wetland for processing both TSS and TP was most sensitive to the uptake rate (Fig. 9). The area required was inversely proportional to uptake rate, i.e., doubling the uptake rate halved the area needed. The range of values estimated for TSS and TP in the Black Creek basin were 9.2–1.0% and 5.6–0.8%, respectively. The higher values represented approximately half of the maximum of the 17 basins (TSS, 18.1%; TP, 11.5%), while the lower estimates for the Black Creek were ~ 1% greater than the lowest estimates for the complete basin set (TSS, 0.1%; TP, 0.0%).

Conversely, the treatment area needed for processing TSS and TP was not very sensitive to the outflow concentration (Fig. 9). The treatment area demanded for reducing TSS, as a percentage of total basin area, varied by only ±0.5% for the Black Creek basin, while retaining TP called for an area within 0.6% of the results obtained in the analysis.

The area of sub-basin treatment wetland needed for processing TSS and TP did not show the same response when loading rates from the different databases were tested (Fig. 9). The area required for sufficiently reducing TSS varied from 5.3% of total watershed area when the overall mean of the national stormwater quality database (NSQD) was employed to 1.9% when the median of the NSQD was applied. In comparison, the analysis deemed necessary a commitment of 2.3% of the total basin area to properly reduce TSS. There was no noticeable difference for the area needed to process TP (Fig. 9) when different loading data were applied.

5. Discussion

The ecological engineering of urban stormwater wetlands is best achieved by embracing a watershed perspective, positioning wetlands into urbanized watersheds much like they occur in undeveloped landscapes. When size rank distributions of wetlands in central Florida were analyzed they exhibited hierarchical properties where there were many small wetlands and fewer large wetlands (Sullivan, 1986; Brown and Sullivan, 1988). When viewed spatially, the small wetlands were scattered throughout the watershed, receiving only rainfall and minor overland flows; their hydrology influenced by an intimate contact with surficial groundwaters. Medium sized wetlands were more centrally located in watersheds, dominated more by storm runoff and baseflow of streams. Large wetlands were often associated with lower reaches, receiving pulses of runoff and dampening outflows to receiving bodies of water.

In this paper, stormwater wetlands were sized based on the premise that to both achieve treatment of stormwaters and maximize the use of water on the landscape, a hierarchical distribution of wetland sizes was required. Further, methods for sizing stormwater wetlands were developed to account for their position and main function along the watershed gradient. Small wetlands, scattered throughout a basin were designed as 'nutrient sinks' and therefore, the method used to size them relied on treating the pulses of nutrients that result from individual storm events. Medium sized wetlands, located at intermediate positions within the basins, were sized for their sediment retention capabilities. Large wetlands located at the basin

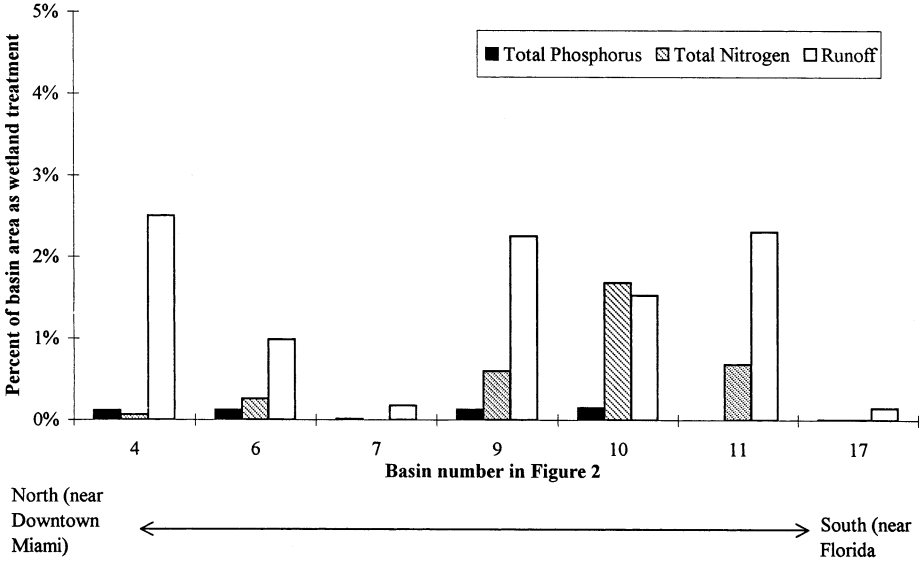


Fig. 8. Area needed for basin treatment wetlands to process total phosphorus (TP), total nitrogen (TN) and discharge quantity based on loadings derived from historical records (1980's) of drainage canal water quality and discharge quantity.

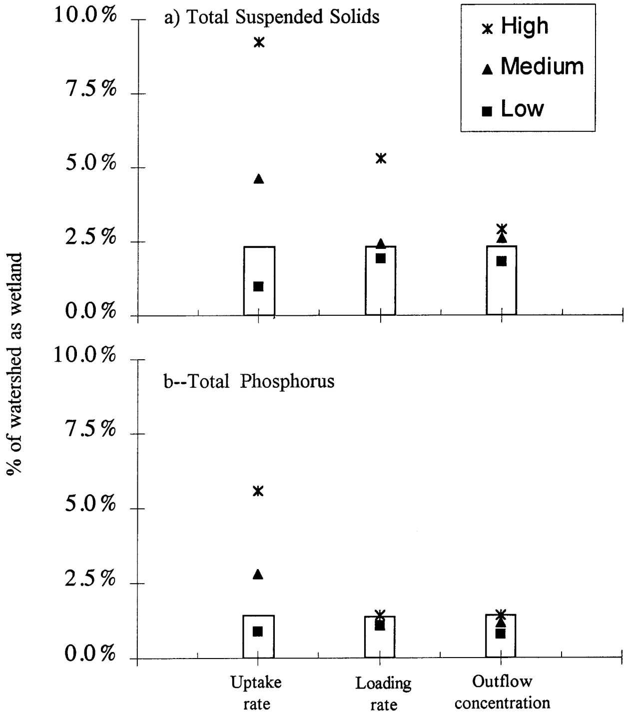


Fig. 9. Sensitivity of Sub-basin treatment wetland size to estimates of uptake rate, loading rate and outflow concentration for: (a) total suspended solids (TSS); and (b) total phosphorus (TP). Uptake rates (kg/ha/d): TSS, 5, 10, 20*, 45; TP, 0.05, 0.10, 0.20*, 0.30; loading rates: mean and median of national stormwater quality database, Metro-Dade DERM and Harper (1994)* (see Table 2); outflow concentrations (mg/l): TSS, 3, 9, 18*, 20; TP, 0.05*, 0.10, 0.15, 0.20. (*) used for analysis. Analysis shown is for Black Creek basin (9 in Fig. 2).

outfall were sized for dampening large rainfall pulses and providing any necessary nutrient and sediment retention.

5.1. Stormwater wetlands for nutrient uptake

If small treatment wetlands, placed throughout the watershed at the neighborhood scale were used for managing stormwater, then they need to be designed for treating phosphorus runoff. For all basins included in the study area, the percent of the basin required as a neighborhood treatment wetland ranged from 2.6 to 10.8%. Halcrow Environmental Services (1993) suggested that the wetland surface area occupy between 0.5 and 5.0% of the catchment area. The five basins nearest downtown Miami, in the northeast section of the study area, required the largest percentage of the basin area; all greater than 7% (Fig. 6). The other 12 basins required less than 7% of basin area for treatment wetlands.

5.2. Stormwater wetlands for sediment retention

Sub-basin treatment wetlands, placed at ‘mid-basin’ locations within the watershed, were designed based on handling the average annual sediment load generated from the landscape. For the entire study area, treatment area requirements ranged from 0.2 to 4.5% of basin area (Fig. 7). As with area requirements for the neighborhood wetlands, the basins needing the largest wetland area were the ones in the more urbanized, northeast portion of the study area, closest to downtown Miami (see Fig. 7).

5.2.1. Sensitivity analysis

The sensitivity analysis emphasized that the area of the treatment wetlands at the sub-basin scale was influenced by pollutant uptake rate but not loading rate data nor target outflow concentrations. Though the wetland treatment area was sensitive to uptake rate, the sensitivity analysis revealed that TSS required more area than TP when the highest estimates were compared to each other as well as when the lowest estimates were compared. Designing the treatment wetland for TSS and TP required 9.2 and 5.6%, respectively of the total basin area when the lowest uptake rate was tested. Applying the highest uptake rate, 1.0 and 0.9% of total basin area was required for TSS and TP, respectively (Fig. 9).

5.3. Basin stormwater wetlands for salinity stabilization in Biscayne Bay

The large and erratic pulses of freshwater discharge to Biscayne Bay, caused in part by the canal drainage system, likely hinder estuarine productivity, since, as Montague and Ley (1993) found, high salinity fluctuation correlated with reduced benthic productivity, especially for seagrasses. Spatial requirements for a basin treatment wetland based on current discharge records indicated that from 0.1 to 2.5% of total basin area was necessary in order to store the mean discharge for at least 3 days (Fig. 8). This agreed with computer simulations completed for the same study area, showing that allocating just 1% of basin area to stormwater wetland decreased the daily maximum discharge by at least 50% (Tilley, 1996). Novitzki (1985), studied watersheds in Illinois and determined that the peak flood period was cut in half when 4–5% of the catchment area was preserved as wetland as opposed to having no wetlands.

Assuming that the estuarine system is organized to take better advantage of a smooth continuous input of freshwater, rather than an abruptly pulsing, discontinuous flow, a regional wetland system would improve the timing of discharge to the estuary and perhaps the productivity of the system.

6. Conclusions

As the intensity of land use activity increases within a watershed, so does the need for stormwater treatment wetlands (Fig. 10). Every 1% increase in urban area required that roughly 0.1% of the watershed area be used as wetland for treating stormwater runoff, according to fitted estimates of the ratio of area of the neighborhood treatment wetlands to urban area (Fig. 10). The ratio of wetland treatment area to urban area for the basin scale was an order of magnitude less (~ 0.01% wetland area per 1% urban area), while at the sub-basin scale the ratio of wetland treatment area to urban area was in between the estimates for the neighborhood and basin treatment wetlands (~ 0.05% per 1%). Perhaps, these ratios indicate general guidelines useful for planning stormwater management systems in urban development. However, one must realize that the need for

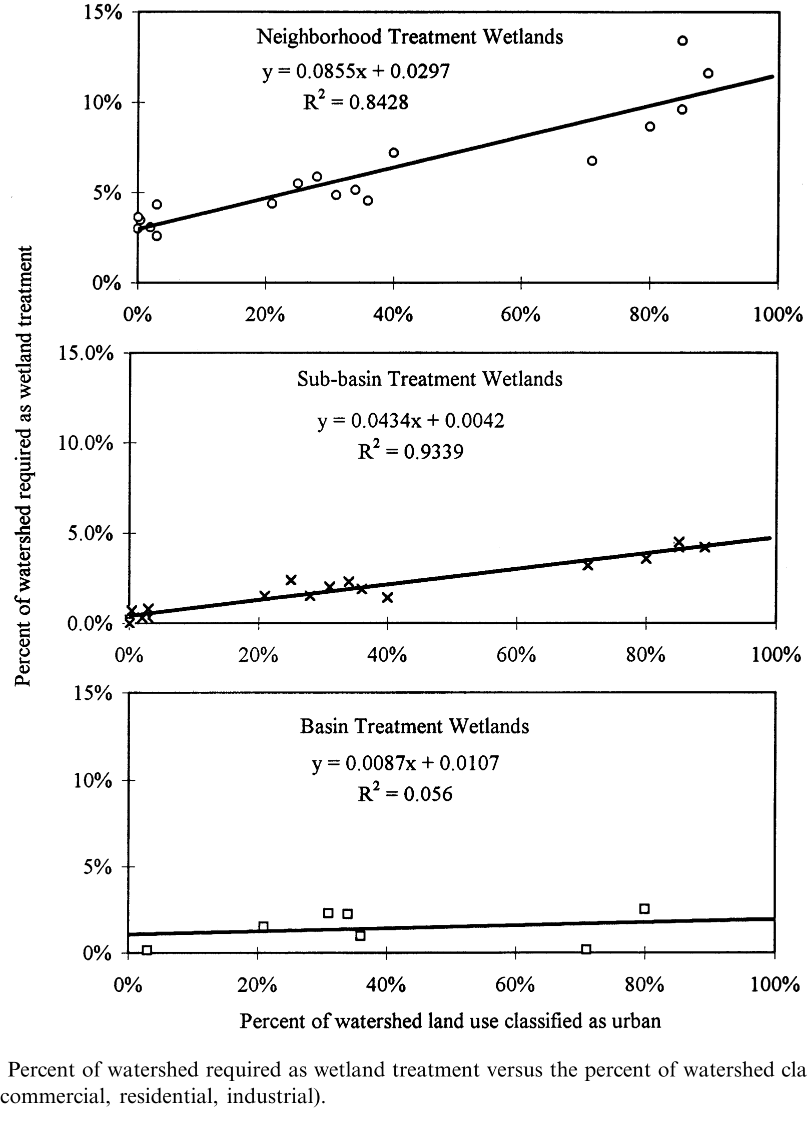


Fig. 10. Percent of watershed required as wetland treatment versus the percent of watershed classified as urban (commercial, residential, industrial).

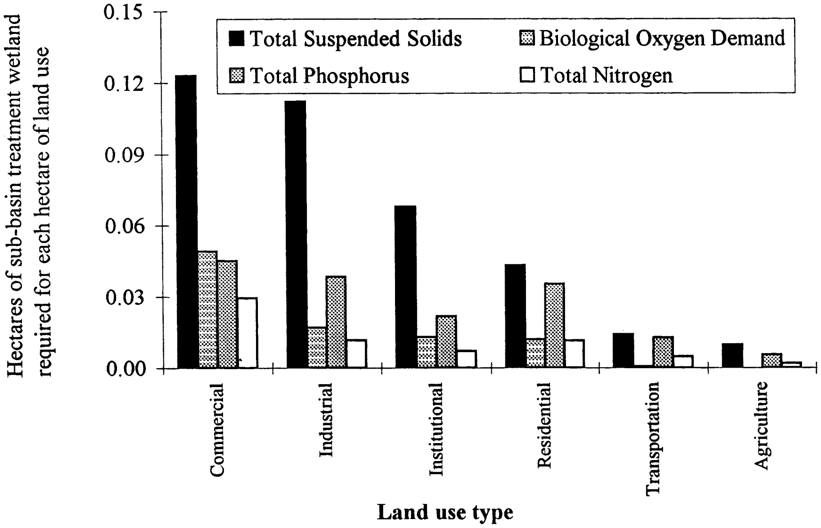


Fig. 11. Area needed as sub-basin treatment wetland for processing TSS, TP, TN and BOD for every one unit of the specified land use type.

stormwater treatment not only varies with the level of urbanization but that it also changes with the intensity of the urban use (Fig. 11). If, for example, the classification of urban area is more heavily weighted towards industrial or commercial land, then the need for stormwater treatment would be higher than if the mix of land were more weighted towards residential. As shown in Fig. 11, if sub-basin treatment wetlands were sized to retain suspended sediments, then every one unit of land classified as commercial would require 0.12 units of stormwater wetland but each one unit of residential land would only require 0.045 units.

Since each size class of wetland was designed for a particular purpose (i.e. nutrient sink, sediment trap, hydrologic pulse dampening) it stands to reason that all three size classes are necessary to achieve effective stormwater management. If the wetland areas for the three scales are simply summed, then for the most urbanized basins (urban area > 60% of total), the total wetland area needed for treatment is approximately 25% of the total basin; for basins of medium intensity (10% > urban area < 60%) the wetland area is about 10% of basin area, while for the least urbanized (urban area < 10%) the area required is less than 5% of the basin (see Fig. 10). However, if treatment wetlands were incorporated at each scale, then some synergism between the scales would likely emerge, leading to a smaller overall demand for land area. Therefore, the next step in evaluating the benefits of a network of stormwater wetlands, organized according to hierarchical principles, should be to investigate the cumulative or synergistic effects of including all three levels of the network together. This hierarchical arrangement could, by employing such computer simulations as given by Kendall (1997), be compared to previously proposed landscape configurations, such as locating treatment wetlands only in the headwaters or only at basin outlets.

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