Evaluating Four Storm-Water Performance Metrics with a North Carolina Coastal Plain Storm-Water Wetland

Hayes A. Lenhart[1] and William F. Hunt III, M.ASCE[2]

Abstract: Storm-water best management practices (BMPs) are typically assessed using the performance metric of pollutant concentration removal efficiencies. However, debate exists whether this is the most appropriate metric to use. In this study, a storm-water wetland constructed and monitored in the coastal plain of North Carolina is evaluated for water quality and hydrologic performance using four different metrics: concentration reduction, load reduction, comparison to nearby ambient water quality monitoring stations, and comparison to other wetlands studied in North Carolina. The River Bend storm-water wetland was constructed in spring 2007 and was monitored from June 2007 through May 2008. Twenty-four hydrologic and 11 water quality events were captured and evaluated. The wetland reduced peak flows and runoff volumes by 80 and 54%, respectively. Reductions were significant. Concentrations for the following pollutants *increased*: total kjeldahl nitrogen (TKN), NH4–N, total nitrogen (TN), and total suspended solids (TSS); inflow and outflow concentrations did not change for total phosphorus (TP), while only $NO_{2\text{-}3}$–N and orthophosphorus (OP) concentrations were lower at the outlet. Using a load reduction metric, results were strikingly different, showing positive load reductions of 35, 41, 42, 36, 47, 61, and 49% for these respective pollutants: TKN, $NO_{2\text{-}3}$–N, NH_4–N, TN, TP, OP, and TSS. When comparing the effluent concentrations from the wetland to ambient water quality in the Trent River, all effluent nitrogen species concentration were either similar or lower. TP and TSS concentrations leaving the wetland were higher than ambient water quality data. Finally, by comparing pollutant concentrations among different North Carolina wetlands, it is apparent the River Bend wetland received relatively "clean" water and released water with pollutant concentrations comparable to all other studies examined. Major conclusions from this study include: (1) storm-water wetlands sited in sandier soils (such as those of the North Carolina coastal plain) should be considered a low impact development tool and (2) the selection of performance metric has a pronounced bearing on how a BMP's performance is perceived. Sole reliance on a concentration reduction metric is discouraged.

DOI: 10.1061/(ASCE)EE.1943-7870.0000307

CE Database subject headings: Stormwater management; Runoff; Water quality; Watersheds; Wetlands; North Carolina.

Author keywords: Storm-water management; Runoff; Water quality; Watersheds; Wetlands; North Carolina.

Introduction

Storm-water runoff has been identified as one of the largest sources of water pollution by the U.S. EPA. Storm water has been shown to transport pesticides, oils, heavy metals, nutrients, and a variety of other contaminants (Bannerman et al. 1993; Flint and Davis 2007; U.S. EPA 1996). In the Chesapeake Bay and North Carolina's Albemarle and Pamlico Sounds, excess nutrient loads, in part associated with urbanization, have negatively impacted fishery health (Abler et al. 2002; Stanley 1993). As a result, a variety of storm-water best management practices (BMPs) has been approved by the states like North Carolina [North Carolina Department of Environmental and Natural Resources (NCDENR) 2007] to treat storm-water runoff. One such BMP is a constructed storm-water wetland.

The actual assessment of how storm-water BMPs perform is a topic of much discussion in the storm-water community. Strecker et al. (2001) listed many of the inconsistencies associated with evaluating BMP performance including sample collection techniques, water quality constituents, tributary watershed information, efficiency estimation techniques, and statistical validation of results. Currently, all of the measures of effectiveness are based on the differences between concentration and loading from influent and effluent storm water. Strecker et al. (2001) further stated that biological and downstream habitat assessment may need to be explored as an evaluation technique as well. Essentially, putting storm-water BMPs in context of the environment in which they are located may be as valid a way of measuring how well BMPs are functioning than the currently used concentration and load basis (McNett et al. 2010).

To better assess the performance of the storm-water wetland at River Bend, North Carolina and potentially provide support to the conclusions drawn in Strecker et al. (2001), the effectiveness of a constructed wetland was evaluated using the following four metrics:

[1]Water Resources Engineer, Wright Water Engineers, 2490 W. 26th Ave., Suite 100A, Denver, CO 80211.

[2]Associate Professor and Extension Specialist, Dept. of Biological and Agricultural Engineering, North Carolina State Univ., NCSU P.O. Box 7625, Raleigh, NC 27695-7625 (corresponding author).

Note. This manuscript was submitted on January 3, 2009; approved on July 13, 2010; published online on July 16, 2010. Discussion period open until July 1, 2011; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Environmental Engineering***, Vol. 137, No. 2, February 1, 2011. ©ASCE, ISSN 0733-9372/2011/2-155–162/$25.00.

Table 1. River Bend Wetland Design Parameters

Parameter	Details
Wetland location	River Bend, Craven County
Latitude and longitude	N 35° 4′ 21.67″, W 77° 9′ 2.17″
Wetland area	0.14 ha (0.34 acre)
Watershed area	46.5 ha (115 acre)
Watershed CN	55
Rainfall event captured	3.3 cm (1.3 in.)
Ponding depth	15.3 cm (6 in.)
Capture volume	122 m^3 (4,300 ft^3)
Vegetation included in original planting plan	*Nyphaea odorata* (Water lily), *Nuphar luteum* (Spatterdock), *Pontederia cordata* (Pickerel weed), *Saururus cernuus* (Lizard tail), *Peltandra virginica* (Arrow arum), *Sagittaria lancifolia* (Duck potato), *Juncus effuses* (Common rush), *Scirpus cyperinus* (Wool grass), *Kosteletzkya virginica* (Marsh mallow), *Lobelia cardinalis* (Cardinal flower), *Lyonia lucida* (Pink fetterbush), *Clethera alnifolia* (Pepperbush), and *Schoenoplectus tabernaemontani* (Softstem bulrush)

1. Determine the percent reduction between influent and effluent concentrations based on the following equation:

$$\%\text{Reduction} = (\text{Inflow}_x - \text{Outflow}_x)/(\text{Inflow}_x) \times 100 \quad (1)$$

where Inflow_x and Outflow_x=respective concentrations.
2. Determine the percent reduction between influent and effluent loads based on Eq. (1), where Inflow_x and Outflow_x are the respective loads;
3. Compare influent and effluent pollutant concentrations with ambient stream concentrations in the surrounding river basin; and
4. Compare influent and effluent pollutant concentrations with those from other storm-water wetland studies in North Carolina.

The four measures of effectiveness were evaluated for total kjeldahl nitrogen (TKN), nitrate and nitrite (NO_x–N), ammonium (NH_4–N), total nitrogen (TN), total phosphorus (TP), orthophosphorus (OP), and total suspended solids (TSS).

Site Description

The research site was a 0.14 ha (0.34 acre) storm-water treatment wetland constructed in River Bend, N.C., in the relatively sandy and low relief coastal plain (Table 1). The wetland was sized to capture runoff from the 3.3 cm (1.3 in.) rainfall event and store approximately 122 m^3 (4,300 ft^3) of water and followed design recommendations of Hunt et al. (2007), including a shallow (5–10 cm) ponding depth for most of the wetland at normal pool.

Built in March 2007, the wetland treats storm water from a 46.5 ha (115 acre) watershed consisting of 0.2 ha (0.5 acre) residential lots, a small industrial area and a golf course. The hydrologic response of the watershed, as described by the Natural Resources Conservation Service curve number (CN) method, was calculated to be 54, reflecting a very permeable watershed. Five different soil series were within the watershed: the Conetoe, Goldsboro, Masontown, Tarboro, and Udorthents series. The primary series, Conetoe, present in 75% of the watershed, is a well drained loamy sand with slopes ranging from 0 to 10%, and an elevation range from 3 to 22 m (10 to 70 ft) [Natural Resources and Conservation Service (NRCS) 2002].

After a late-season frost killed the majority of 3,200 plants planted in early spring, another 1,000 plants (primarily herbaceous species) were again planted in June 2007, upon which time monitoring commenced. Fig. 1 shows the River Bend wetland

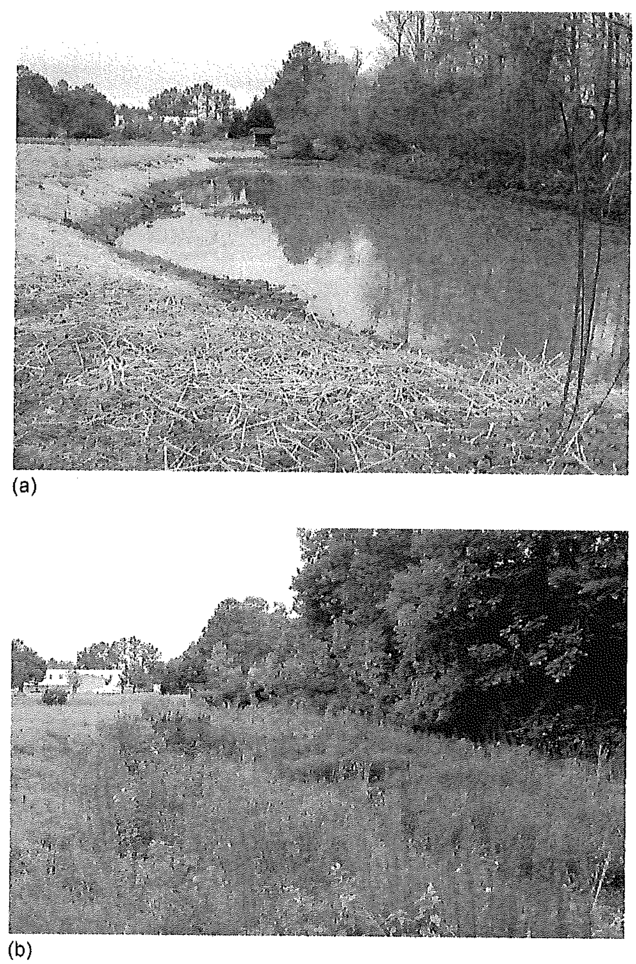

Fig. 1. (a) River Bend wetland post resizing and planting (April 2007); (b) the River Bend wetland in July 2008

Table 2. CAAE Laboratory Analysis Methods

Parameter	Method	Instrument
TKN	EPA[a] 351.1	QuAAtro (since October 2007), TrAAcs 800 Continuous Flow Analyzer (prior to October 2007)
NO_{2-3}–N	SM[b] 4500-NO3-F	QuAAtro (since October 2007), TrAAcs 800 Continuous Flow Analyzer (prior to October 2007)
NH4–N	SM 4500-NH3-H	QuAAtro (since October 2007), TrAAcs 800 Continuous Flow Analyzer (prior to October 2007)
TP	SM 4500-P-E	Lachat QuikChem 8000 FIA (flow injection analysis)
Ortho P	SM 4500-P-F	Lachat QuikChem 8000 FIA (flow injection analysis)
TSS	SM 2540 D	Vacuum filtered on glass fiber filters, dried at 104°C

[a]EPA—U.S. EPA (1983).

[b]SM—Standard Methods for the Examination of Water and Wastewater (1998).

immediately after resizing and planting and approximately 14 months later.

Based on historical averages from meteorological station number 316108, New Bern Craven Co. Airport (N 35.067°, W 77.05°), which is 8.9 km (5.5 mi) east of the River Bend wetland, the average annual temperature is 16.8°C (62.3°F) ranging from a normal monthly minimum temperature of 1.1°C (33.9°F) in January to a normal monthly maximum of 31.3°C (88.3°F) in July. Average annual precipitation is 1387 mm (54.6 in.), ranging from a monthly mean of 86 mm (3.4 in.) in April to 174 mm (6.84 in.) in August [North Carolina Climate Office (NCCO) 2008].

Materials and Methods

In June 2007, the inlet and outlet of the wetland were instrumented with ISCO model 6712 portable samplers and associated ISCO model 720 bubblers to collect water quality samples and monitor runoff during storm events. A contracted rectangular weir was constructed at the inlet, while a compound weir consisting of a contracted v-notch and rectangular weir was constructed at the outlet. Starting in June 2007 and ending in May 2008 water quality samples were collected for storm events and analyzed for TKN, nitrate and nitrite (NO_{2-3}–N), ammonium (NH_4–N), TP, OP, and TSS. During storm events, the ISCO flow monitoring equipment collected 200-mL samples after each 6.5 m^3 (230 ft^3) and 5.1 m^3 (180 ft^3) of water passed over the inlet and outlet, respectively, resulting in a flow weighted composite sample for each event. The automatic samplers were set so that precipitation events between 6.4 mm (0.25 in.) and 50.8 mm (2 in.) were captured and analyzed. All samples, which were unrefrigerated, were retrieved within 24–48 h of the events' completion. All samples exceeding a 48-h hold time were discarded.

The collection of a sample for pollutant analysis involved three separate bottling techniques. First, the 10-L glass jar which stored the entire sample was vigorously shaken to resuspend any settled solids. For TSS a 1-L plastic bottle was filled immediately after shaking with sample water. For OP analysis, 20 mL of sample water was drawn into a syringe and passed through a Whatman Puradisc sterile and endotoxin free 0.45 μm PES filter media into a glass sample bottle. For NO_{2-3}–N, NH_4–N, TKN, and TP analysis a preacidified 250-mL glass bottle with 0.25 mL of sulfuric acid was filled with sample water. Once sample collection was complete, the 10-L jar was emptied, rinsed with deionized water, and returned to its respective sampler unit. Collected sample bottles were placed on ice and delivered to the North Carolina State University Center for Applied Aquatic Ecology (CAAE) laboratory for analysis. Analysis procedures used by CAAE are given in Table 2.

Statistics were analyzed using the SAS System for Windows version 9.1. A one-way ANOVA table was used to determine whether the wetland significantly reduced flow peaks, flow volumes, pollutant concentrations, and pollutant loads (SAS 2008). Concentration and load values proved to be normally distributed based on SAS residual plots, justifying the use of a one-way ANOVA. To determine if there was a difference between growing season and nongrowing season runoff volumes and peak flows, a completely randomized split-block design was developed. A confidence level (α) of 0.05 was used.

Results and Discussion

Water Quantity

Peak inflow and outflow rates from 24 rain events varied in size from 0.001 cm (0.04 cfs) to 0.22 cm (7.65 cfs). The wetland reduced outflow peaks by an average of 80%. The wetland reduced runoff volumes by an average of 54% (Table 3). The difference in peak flows and runoff volumes were both significant. There was no significant difference between growing and nongrowing season runoff volumes or peak flows. This was likely due to the drought conditions that impacted the watershed during the course of this study. Due to this drought, the volume of outflow was not dependent on storm size as much as it was on the antecedent dry period.

Fig. 2 shows the relationship between inflow and outflow volumes on a log-log scale. From the graph there is a positive correlation between the inflow and outflow volumes. Moreover, a reduction in outflow volumes compared to inflow volumes almost always occurred. This wetland substantially reduced runoff volumes, a hallmark of low impact development (LID) [Davis 2005; Maryland Department of Environmental Resources (MDDER) 1999]. The wetland was able to retain portions of inflow in part due to the drought and the seepage and evapotranspiration (ET) losses during the interevent period. Using the Thornthwaite and Mather (1957) equation and actual rainfall and temperature records [State Climate Office of North Carolina (SCO-NC) 2009], ET losses were estimated to be approximately 5% of the total volume lost (350 m^3). While not conclusive due to the drought, it appears that the coastal plan, sandy in situ soil, wetlands may be considered as an LID tool.

Table 3. Rain Events with Respective Runoff Values, Flow Peaks, and Reductions

Number	Storm date	Rainfall (cm)	Inflow (m^3)	Outflow (m^3)	Peak inflow (cm)	Peak outflow (cm)	Runoff reduction (%)	Peak flow reduction (%)
1	July 7, 2007	3.73	615.7	547.3	0.10	0.04	11.1	65.8
2	July 10, 2007	1.96	309.8	178.6	0.05	0.01	42.3	82.7
3	July 11, 2007	1.80	596.5	587.5	0.06	0.02	1.5	64.9
4	July 13, 2007	2.51	1,132.5	976.7	0.21	0.10	13.8	50.3
5	July 28, 2007	2.16	293.6	127.7	0.07	0.01	56.5	88.0
6	August 10, 2007	1.42	0.0	0.0	0.00	0.00	na	na
7	August 31, 2007	3.63	0.0	0.0	0.00	0.00	na	na
8	September 15, 2007	1.80	56.0	0.0	0.01	0.00	100.0	100.0
9	September 20, 2007	1.35	0.0	0.0	0.00	0.00	na	na
10	October 25, 2007	1.24	7.4	0.0	0.00	0.00	100.0	100.0
11	October 27, 2007	3.38	365.9	150.2	0.06	0.01	59.0	88.5
12	December 21, 2007	1.07	4.7	0.0	0.00	0.00	100.0	100.0
13	December 30, 2007	1.32	147.0	0.0	0.02	0.00	100.0	100.0
14	January 19, 2008	2.92	1,240.2	1,153.5	0.05	0.02	7.0	51.5
15	February 13, 2008	3.00	631.3	419.0	0.05	0.02	33.6	65.6
16	February 18, 2008	1.17	47.3	28.8	0.01	0.00	39.2	96.7
17	February 22, 2008	2.57	992.0	716.9	0.05	0.02	27.7	59.4
18	March 7, 2008	1.78	560.6	251.1	0.05	0.01	55.2	81.1
19	March 15, 2008	1.65	196.9	60.1	0.04	0.00	69.5	95.5
20	April 1, 2008	3.00	817.3	413.0	0.16	0.02	49.5	86.2
21	April 5, 2008	5.13	5,021.3	1,427.4	0.17	0.06	71.6	67.6
22	April 22, 2008	3.00	449.4	93.9	0.03	0.00	79.1	93.5
23	May 6, 2008	4.37	1,169.5	528.8	0.22	0.06	54.8	70.8
24	May 11, 2008	1.83	504.8	160.5	0.05	0.01	68.2	82.6
Mean							54.3	80.5

Note: na=not applicable.

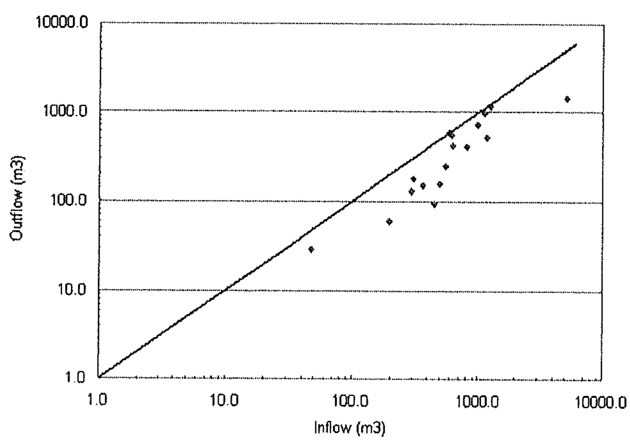

Fig. 2. Log-log inflow volumes versus outflow volumes

Water Quality

Four alternative methods for assessing water quality performance are examined; the first two are "traditional" and the latter two have been previously suggested by Strecker et al. (2001), but are not currently employed: (1) concentration removal efficiency; (2) load removal efficiency; (3) comparing wetland effluent concentrations to ambient water quality in nearby receiving waters; and (4) comparing effluent concentrations to those of other North Carolina storm-water wetlands. For water quality analysis, 11 storms were used to compare concentrations and loadings of TKN, NO_{2-3}–N, NH_4–N, TN, TP, OP, and TSS.

Using the conventional measure of comparing inflow concentrations to outflow concentrations, there were no significant differences for all but one (OP) pollutant. However, mean pollutant concentrations increased for TKN, NH_4–N, TN, and TSS by the following percentages respectively: 70, 53, 51, and 30%. TP con-

Table 4. Mean Water Quality Concentrations, Loads, and Reductions

Pollutant	Mean inflow concentration (mg/L)	Mean outflow concentration (mg/L)	Mean reduction (%)	Mean inflow load (kg)	Mean outflow load (kg)	Mean reduction (%)
TKN	0.55	0.94	−70	0.51	0.33	34.9
NO_{2-3}–N	0.18	0.17	9	0.08	0.05	40.7
NH_4–N	0.05	0.08	−53	0.06	0.03	41.6
TN[a]	0.73	1.11	−51	0.60	0.38	35.7
TP	0.23	0.23	0	0.18	0.09	47.2
Ortho P	0.15	0.09	39	0.12	0.05	60.9
TSS	31.2	40.5	−30	24.8	12.6	49.2

[a]TN=calculated by adding TKN and NO_{2-3}–N.

centrations did not change. All results are listed in Table 4. Clearly, using concentration reduction efficiency as an evaluation metric would lead to the conclusion that this wetland performed quite poorly, negatively impacting water quality.

When using the pollutant load removal efficiency metric, strikingly different results were found. Due to the large amount of between storm infiltration and evapotranspiration losses, pollutant loads were substantially reduced. However, the reduction was typically not significant. TKN, NO_{2-3}–N, NH_4–N, TN, TP, OP, and TSS loads were reduced by 35, 41, 42, 36, 47, 61, and 49%, respectively. Inflow loads for OP and NH_{2-3}–N were significantly greater than outflow loads. Pollutant loads during the growing season (March 14 to November 18) were not significantly different than loads during the nongrowing season.

While the intent of the article is to show how different evaluation metrics lead to substantially different conclusions regarding this BMP's performance, a brief rationale for the increases in pollutant concentrations is provided. Due to the late-season frost that killed the majority of vegetation planted in late March 2007, the delayed replanting (June 2007) and the extended drought, two things occurred. First, vegetation did not quickly establish and large algal mats flourished during the summer. Much of the increase in nutrient concentrations is suspected to be associated with flushing of algal mats from the wetland system during the rain events that did occur. Nutrient effluent concentrations decreased after October 2007, coinciding with the decline of algal presence, better vegetative coverage, and the ending of the drought. Because the wetland remained in an undervegetated, and therefore less stable, state, some internal erosion was observed. The wetland initially served as a source for suspended sediment that was captured at the outlet monitoring station, but not present at the inlet. As with nutrient concentrations, TSS effluent concentrations decreased as the wetland became more stable in late autumn 2007.

The River Bend, N.C. storm-water wetland influent and effluent concentrations were compared with water quality concentrations from three NCDENR stream and river monitoring sites in the same river basin as the River Bend, N.C. wetland. Comparing these concentrations put the results of this study into context with natural or typical background pollutant concentrations in the area. All three monitoring stations were located along the Trent River (Fig. 3). Station number J8690000 (N 35.06364°, W 77.46107°) was located approximately 13 km (8 mi) W of the River Bend wetland. Between September 27, 2000 and August 24, 2005, 53 samples were analyzed for nutrient concentrations and 19 samples for TSS concentrations by NC DENR. Station number J8730000 (N 35.00993°, W 77.21891°) was located approximately 10 km (6 mi) SW of the River Bend, N.C. wetland. Between October 17, 2000 and August 30, 2005, 134 water samples were analyzed for nutrient concentrations, but no TSS concentrations were analyzed. The final stream monitoring location, station number J8770000 (N 35.07502°, W 77.11627°) was located approximately 3 km (2 mi) E of the River Bend wetland. Between September 20, 2000 and August 16, 2005, 58 water samples were analyzed for nutrient concentrations and 18 for TSS concentrations. The first two stations were assigned a bioclassification (bioclass) of Moderate. Bioclass ratings range from poor to excellent. These ratings are given to monitoring locations per benthic sampling; the more intolerant Ephemeroptera, Plecoptera, and Trichoptera insects are present, the higher the bioclass [North Carolina Department of Environmental and Natural Resources (NCDENR) 2006]. No rating was assigned to the third station.

Tables 5 and 6 (nitrogen species and phosphorus and TSS,

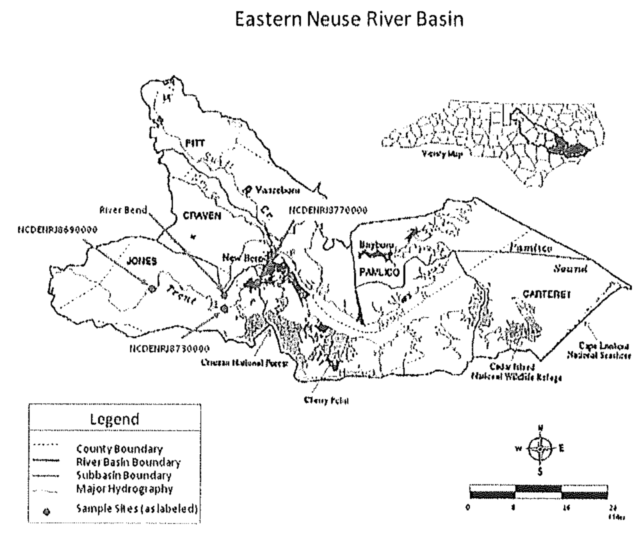

Fig. 3. Location of NCDENR water quality monitoring locations

respectively) compare the minimum, mean, and maximum influent and effluent pollutant concentrations from River Bend, N.C. with the 10th, 50th, and 90th percentile pollutant concentrations at the Trent River ambient monitoring stations. River Bend wetland mean inflow and outflow concentrations for NO_{2-3}–N were 0.18 and 0.16 mg/L, respectively, much lower than the neighboring stream concentrations of 0.64, 0.61, and 0.34 mg/L. River Bend wetland NH_4–N concentrations were similar to those of the nearby monitoring stations. Concentrations of TKN appear to be similar when comparing inflow concentrations; however, outflow TKN concentrations from River Bend, N.C. are greater than those of background streams. River Bend, N.C. mean inflow and outflow TN concentrations were 0.73 and 1.11 mg/L, similar to or slightly lower than the 1.30, 1.18, and 0.95 mg/L concentrations at the NC DENR monitoring stations. By comparing TN, the River Bend wetland is both receiving and exporting low concentrations of TN, evidence to support the possibility of irreducible concentrations (Kadlec and Knight 1995; Schueler and Holland 2000). An evaluator would potentially draw sharply different conclusions on the wetland's TN performance when the ambient water quality method is compared to the concentration "reduction" metric. However, for TP and TSS similar (poor) assessments would be made using either the concentration reduction metric or the ambient water quality metric, as evidenced in the following section.

The River Bend wetland tended to receive and release higher concentrations of TP and TSS when compared to streams in the surrounding watershed. Mean TP inflow and outflow concentrations at the River Bend, N.C. wetland were greater than the 90% high concentrations at the ambient monitoring stations. The minimum TSS inflow and outflow concentrations at the River Bend wetland were approximately equal to the 90th percentile instream concentrations. However, it should be noted that the sampling technique used to measure TSS in streams (such as the Trent River) will not have any bed load influence; whereas, some bed load was captured by the River Bend wetland monitoring apparatus.

The final method of assessing the River Bend wetland's performance was to compare its influent and effluent concentrations to those of other wetlands studied in North Carolina. Bass (2000) evaluated the performance of an in-stream constructed wetland in

Table 5. Comparison of River Bend Influent/Effluent N Concentrations and Local Stream Concentrations

	TKN (mg/L)			NO_{2-3}–N (mg/L)			NH4-N (mg/L)			TN (mg/L)[a]		
Location	10	50	90	10	50	90	10	50	90	10	50	90
NCDENR[b] J8690000	0.35	0.66	0.90	0.22	0.64	1.22	0.02	0.03	0.21	0.57	1.30	2.12
NCDENR J8730000	0.41	0.57	0.76	0.38	0.61	0.89	0.02	0.04	0.07	0.79	1.18	1.65
NCDENR J8770000	0.45	0.61	0.81	0.02	0.34	0.63	0.02	0.04	0.18	0.47	0.95	1.44
	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum
River Bend inflow	0.40	0.55	0.66	0.01	0.18	0.57	0.02	0.06	0.18	0.41	0.73	1.23
River Bend outflow	0.47	0.95	2.46	0.10	0.16	0.55	0.03	0.08	0.17	0.57	1.11	3.01

[a]TN calculated as the sum of TKN and NO_{2-3}–N.

[b]Data from NCDENR sites is from North Carolina Department of Environmental and Natural Resources (NCDENR) (2006).

Edenton, North Carolina, another coastal plain location. The wetland received drainage water from a 240 ha (600 acre) watershed consisting of both urban and agricultural land uses. Water quality samples were collected from August 1997 through December 1999.

Johnson (2006) evaluated the performance of a storm-water wetland located in Charlotte, North Carolina. The wetland received storm-water from a 6.4 ha (15.8 acre) watershed consisting of residential development and school property. Water quality samples were collected from September 2004 to December 2005.

Line et al. (2008) studied the effectiveness of two storm-water wetlands in North Carolina. The first wetland, CMS, was located in Raleigh, North Carolina. The wetland received storm water from a 9.6 ha (23.7 acre) watershed consisting of a large school building, parking lots, and hardwood tree stands. Water quality samples were collected from April to August 2006. The second Line et al. (2008) wetland, named UNC, was located in Asheville, North Carolina. The wetland received storm water from a 4.1 ha (10.1 acre) watershed consisting of a parking lot, manicured lawn, and hardwood tree stands.

Finally, the International Storm-water Best Management Practices Database (http://www.bmpdatabase.org/) provides performance analysis and information, including inflow and outflow pollutant concentrations, for various types of storm-water BMPs. Summary influent and effluent mean concentrations of various pollutants for 19 different constructed wetlands in the database are presented along with the four previously mentioned wetland studies (Tables 7 and 8).

There is a clear difference between the River Bend study and all other wetlands presented with respect to inflow concentrations. The River Bend wetland received lower concentrations compared to other studies for a majority of the pollutants. For TKN, NH_4–N, and TN, influent concentrations at River Bend were lower than the *effluent* concentrations from all other sites. Only

Table 6. Comparison of River Bend Influent/Effluent P and TSS Concentrations and Local Stream Concentrations

	TP (mg/L)			TSS (mg/L)		
Location	10	50	90	10	50	90
NCDENR[a] J8690000	0.04	0.08	0.21	2	4	7
NCDENR J8730000	0.07	0.12	0.16	NA	NA	NA
NCDENR J8770000	0.08	0.13	0.18	2	4	10
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
River Bend inflow	0.14	0.23	0.53	8	31	96
River Bend outflow	0.13	0.23	0.48	11	40	89

Note: NA=not applicable.

[a]Data from NCDENR sites is from North Carolina Department of Environmental and Natural Resources (NCDENR) (2006).

Table 7. Mean N Concentrations for Various Wetland Studies

	Mean TKN (mg/L)		Mean NO_{2-3}–N (mg/L)		Mean NH4–N (mg/L)		Mean TN (mg/L)	
Writer	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Bass (2000)	2.1	1.9	0.6	0.2	0.6	0.4	2.7	2.1
Johnson (2006)	1.57	0.87	0.74	0.5	0.31	0.12	2.31	1.37
Line et al. (2008) CMS	0.96	0.87	0.15	0.13	0.21	0.14	1.11	1.00
Line et al. (2008) UNC	0.33	0.79	0.33	0.15	0.14	0.08	0.66	0.94
BMP database	1.11	1.05	0.37	0.13	na	na	1.48	1.18
River Bend	0.55	0.94	0.18	0.17	0.05	0.08	0.73	1.11

Note: na=not applicable.

Table 8. Mean P and TSS Concentrations for Various Wetland Studies

Writer	Mean TP (mg/L)		Mean Ortho P (mg/L)		Mean TSS (mg/L)	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Bass (2000)	0.37	0.57	0.27	0.42	na	na
Johnson (2006)	0.44	0.2	na	na	71	24
Line et al. (2008) CMS	1.68	0.99	na	na	38	18
Line et al. (2008) UNC	0.27	0.12	na	na	100	31
BMP database	0.27	0.11	na	na	31	13
River Bend	0.23	0.23	0.15	0.09	31	41

Note: na=not applicable.

one mean inflow concentration (TKN at UNC) was lower than those at River Bend, N.C. For NO_3–N and TP, the River Bend wetland's influent concentrations were less than that of the effluent concentrations from two of the five other studies. This explains why the River Bend wetland does not perform as well as other constructed wetlands when a concentration reduction efficiency metric is used. River Bend outflow concentrations of TKN, NO_{2-3}–N, NH_4–N, TN, and TP were also less than outflow concentrations from at least two of those from other wetlands. Some influent concentrations measured at the River Bend wetland could be considered irreducible concentrations. It is arguable whether the River Bend wetland should be expected to reduce nutrient concentrations by a significant or substantial amount.

The mean TSS outflow concentration of 41 mg/L for River Bend was higher than all of the other studies. However, no study had a lower inflow concentration (31 mg/L) either. Based on the previous TSS discussion (high internal erosion and a difference in sampling methods), it is not surprising that the effluent TSS concentrations for River Bend were higher than those from more established wetlands.

Based on both assessing a BMP's performance relative to background concentrations in nearby waters and by comparing influent and effluent concentrations among similar practices, it is apparent that calculating percent reduction values for storm-water BMPs is not always the best metric for evaluating how well BMPs function. This is an important point, as many jurisdictions use removal efficiencies as *the sole* BMP performance metric. Even though the River Bend wetland was exporting many pollutants using a concentration reduction metric, it still reduced pollutant loads and had effluent concentrations similar to ambient river conditions for most pollutants.

Conclusions and Recommendations

Based on the results from this study, some general conclusions are drawn regarding a storm-water wetland's inclusion as an LID technology and selection of water quality performance metrics. Please note that (1) this study took place during one of the most severe droughts in NC history and (2) monitoring began before vegetation had fully established.

The wetland reduced peak flows and runoff volumes by 80 and 54%, respectively. Considering LID is in great part predicated on runoff volume reduction, it appears select storm-water wetlands, particularly those situated in sandier soils, should be considered a viable LID option. Storm-water wetlands currently are not on the "LID menu."

The water quality performance greatly varied depending upon the performance metric used. Assessing the River Bend storm-water wetland by the commonly employed concentration reduction efficiency metric, one would conclude the River Bend wetland performed quite poorly. Outflow concentrations for TKN, NH_4–N, TN, and TSS were increased by 70, 53, 51, and 30%, respectively, while TP concentrations did not change.

Assessing performance from a load reduction metric, the storm-water wetland performed well. The total load reduction from 11 storms for TKN, NO_{2-3}–N, NH_4–N, TN, TP, Ortho P, and TSS were 35, 41, 42, 36, 47, 61, and 49%, respectively. The primary reason for the positive load reduction was the wetland's ability to significantly reduce inflow volumes.

Assessing the BMP performance using an ambient water quality metric, the wetland's performance was mixed. Nitrogen species' effluent concentrations were generally at or less than those of nearby streams. TP and TSS effluent concentrations were both somewhat higher than those in the Trent River. Finally, the River Bend, N.C. wetland was assessed by comparing its influent and effluent concentrations to those of other wetlands monitored in North Carolina. River Bend's mean influent concentrations for TKN and TN were consistently lower than effluent concentrations in nearly all of the referenced studies. Influent nitrogen concentrations to the River Bend wetland may have been close to irreducible concentrations. Perhaps this wetland should not be expected to reduce concentrations that are already low.

Assessing this wetland only on pollutant concentration reduction would be insufficient and not accurately reflect the somewhat unique situation occurring at the River Bend wetland. In summary, this case study shows that storm-water BMPs should not solely be evaluated on a percent reduction metric and should also be examined within the context of their environment to better evaluate their impact on water quality.

Acknowledgments

This research was funded by the NC Ecosystem Enhancement Program and the North Carolina Department of Environmental and Natural Resources-Division of Water Quality. We would like to thank the following faculty, staff, and students at North Carolina State University for their substantial help: Dr. Mike Burchell, Mr. Shawn Kennedy, Mr. Ryan Smith, Mr. Jon Hathaway, Mr. Charlie Humphrey, and Mrs. Adrienne Cizek. The willingness of the town of River Bend, and Mayor John Kirkland, to host the project is greatly appreciated.

References

Abler, D., Shortle, J., Carmichael, J., and Horan, R. (2002). "Climate change, agriculture, and water quality in the Chesapeake Bay region."

Clim. Change, 55(3), 339–359.
Bannerman, R. T., Owens, D. W., Dodds, R. B., and Hornewer, N. J. (1993). "Sources of pollutants in Wisconsin stormwater." *Water Sci. Technol.*, 28(3–5), 241–259.
Bass, K. L. (2000). "Evaluation of a small in-stream constructed wetland in North Carolina's coastal plain." MS thesis, North Carolina State Univ., Raleigh, N.C.
Davis, A. P. (2005). "Green engineering principles promote low impact development." *Environ. Sci. Technol.*, 39(16), 338A–344A.
Flint, K. R., and Davis, A. P. (2007). "Pollutant mass flushing characterization of highway stormwater runoff from an ultra-urban area." *J. Environ. Eng.*, 133(6), 616–626.
Hunt, W. F., Burchell, M. R., Wright, J. D., and Bass, K. L. (2007). *Stormwater wetland design update: Zones, vegetation, soils and outlet guidance*, North Carolina Cooperative Extension, Raleigh, N.C.
Johnson, J. L. (2006). "Evaluation of stormwater and wet pond forebay design and stormwater wetland pollutant removal efficiency." MS thesis, North Carolina State Univ., Raleigh, N.C.
Kadlec, R. H., and Knight, R. L. (1995). *Treatment wetlands*, Lewis, Boca Raton, Fla.
Line, D. E., Jennings, G. D., Shaffer, M. B., Calabria, J., and Hunt, W. F. (2008). "Evaluating the effectiveness of two stormwater wetlands in North Carolina." *Trans. ASABE*, 51(2), 521–528.
Maryland Department of Environmental Resource (MDDER). (1999). *Low-impact development design strategies*, MDDER Programs and Planning Div., Largo, Md.
McNett, J. K., Hunt, W. F., and Osborne, J. A. (2010). "Establishing storm-water BMP evaluation metrics based upon ambient water quality associated with benthic macroinvertibrate populations." *J. Environ. Eng.*, 136(5), 535–541.
Natural Resources and Conservation Service (NRCS). (2002). *Official series description—CONETOE series*, Raleigh, N.C.
North Carolina Climate Office (NCCO). (2008). *1971–2000 climate normals | State climate office of North Carolina*, Raleigh, N.C.
North Carolina Department of Environmental and Natural Resources (NCDENR). (2006). "Basinwide assessment report Neuse River basin." *Rep. Prepared for NCDENR*, Raleigh, N.C.
North Carolina Department of Environmental and Natural Resources (NCDENR). (2007). *Stormwater best management practices manual*, N.C. Div. of Water Quality, Raleigh, N.C.
SAS. (2008). *SAS user's guide: Statistics*, Cary, N.C.
Schueler, T. R., and Holland, H. K. (2000). "Article 65: Irreducible pollutant concentrations discharged from stormwater practices." *The practice of watershed protection, The Center for Watershed Protection, Ellicott City*, The Center for Watershed Protection, Ellicott City, Md., 377–380.
Standard Methods, American Public Health Association (APHA), American Water Works Association (AWWA), and Water Environment Federation (WEF). (1998). *Standard methods for the examination of water and wastewater*, 20th Ed., American Public Health Association, Alexandria, Va.
Stanley, D. W. (1993). "Long-term trends in Pamlico River Estuary nutrients, chlorophyll, dissolved oxygen, and watershed nutrient production." *Water Resour. Res.*, 29(8), 2651–2662.
State Climate Office of North Carolina (SCO-NC). (2009). "Data and Products." ⟨http://www.nc-climate.ncsu.edu/dynamic_scripts/cronos/query.php⟩ (Dec. 31, 2009).
Strecker, E. W., Quigley, M. M., Urbonas, B. R., Jones, J. E., and Clary, J. K. (2001). "Determining urban storm water BMP effectiveness." *J. Water Resour. Plann. Manage.*, 127(3), 144–149.
Thornthwaite, C. W., and Mather, J. R. (1957). *Instructions and tables for computing potential evapotranspiration and the water balance*, Drexel Institute of Technology, Laboratory of Climatology, Centerton, N.J.
U.S. EPA. (1983). "Methods for chemical analysis of water and wastes." *Rep. No. EPA-600/4-79/020*, Office of Research and Development, Washington, D.C.
U.S. EPA. (1996). "Nonpoint source pollution: The nation's largest water quality problem." *Rep. No. EPA-841-F-96-004A*, Washington, D.C.