Identification Evaluations. Environmental Toxicology and Chemistry 25:973-984.
Wren, C.D., C.A. Bishop, D.L. Stewart, and G.C. Barrett, 1997. Wildlife and Contaminants in Constructed Wetlands and Stormwater Ponds: Current State of Knowledge and Protocols for Monitoring Contaminant Levels and Effects in Wildlife. Technical Report Series Number 269. Canadian Wildlife Service, Environment Conservation Branch, Ontario Region, Environment Canada, Ontario, Canada.
Yousef, Y.M., M. Wanielista, J. Dietz, L. Yin, and M. Brabham, 1990. Final Report-Efficiency Optimization of Wet Detention Ponds for Urban Stormwater Management. Florida Department of Environmental Regulation, Orlando, Florida, 200 pp.

JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
Vol. 46, No. 2 AMERICAN WATER RESOURCES ASSOCIATION April 2010

WATER-QUALITY PERFORMANCE OF A CONSTRUCTED STORMWATER WETLAND FOR ALL FLOW CONDITIONS[1]

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ABSTRACT: Results from a multiyear study demonstrate that a constructed stormwater wetland (CSW) improves urban stormwater runoff quality mitigating downstream impacts. Best management practices, such as CSWs, can comprehensively treat the various scales of stormwater runoff issues. Discrete sample analysis was used to investigate the CSW effect for storm events and base-flow periods on water-quality parameters [i.e., total suspended solids, total dissolved solids, total nitrogen, phosphorous (total and reactive), chloride, heavy metals (zinc, lead, and copper), and *Escherichia coli*]. The primary finding was that stormwater sediment load was removed through the CSW for all flow conditions during all seasons. The mechanisms responsible for the removal of suspended solids, including slower flow velocity, longer retention times, and vegetative contact, also reduced the mass of nutrients discharged downstream throughout the year. Exceedance probabilities were used to evaluate the expected pollutant reductions of nutrients and to incorporate the effect of natural flow variation on quality. Other findings included the observation that there was no significant difference in the performance of the CSW over two-year-long periods four years apart, indicating that a CSW is effective for an extended period.

(KEY TERMS: nutrients; nonpoint source pollution; best management practice; storm water management; constructed stormwater wetland; green infrastructure.)

Wadzuk, Bridget M., Matthew Rea, Gregg Woodruff, Kelly Flynn, and Robert G. Traver, 2010. Water-Quality Performance of a Constructed Stormwater Wetland for All Flow Conditions. *Journal of the American Water Resources Association* (JAWRA) 46(2):385-394. DOI: 10.1111/j.1752-1688.2009.00408.x

INTRODUCTION AND BACKGROUND

Stormwater runoff is a leading cause of water-quality degradation in receiving waters in the United States (USEPA, 1990; Lee *et al.*, 2002; NRC, 2008). Urbanization and added impervious surfaces increase runoff rates and volumes with higher pollutants loads (e.g., suspended solids, nutrients, bacteria, and metals) (Brown *et al.*, 1999). Suspended solids are perhaps the most critical pollutant in urban stormwater runoff (Mulhern and Steele, 1989; Sansalone and Cristina, 2004), as other pollutants adhere to the solids. Therefore, if solids are removed, then the pollutants that adhere to the solids will also be removed, such as phosphorous. Aside from solids, nutrients and metals are pollutants of concern, as nutrients in receiving

[1]Paper No. JAWRA-09-0033-P of the *Journal of the American Water Resources Association* (JAWRA). Received February 16, 2009; accepted October 14, 2009. **Discussions are open until six months from print publication.**
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waters can lead to algal blooms, fish kills, and human health impacts, and metals may accumulate in sediment and bio-accumulate in the food chain (NRC, 2008).

Beginning in the 1970s, runoff from large events was managed by detention basins, without regards to smaller rainfall events or water quality (Emerson *et al.*, 2005; USEPA, 2005). Small events (<25.4 mm) comprise the majority of annual events (e.g., in southeastern Pennsylvania) (Prokop, 2003) and current stormwater best management practices (BMPs) are designed to treat small events for quantity and quality (NRC, 2008). One stormwater management tool, constructed stormwater wetlands (CSWs), treats polluted stormwater through biological, chemical, and physical interactions between plants and water flow (USEPA, 1977; Coleman *et al.*, 2001). Unlike other stormwater BMPs, CSWs have continuous flow as base flow and storm flows, while most other BMPs only treat stormwater.

Nutrients, suspended solids, and bacteria tend to be removed as water passes through the CSW, and dissolved constituents, such as chloride, pass through the system unaltered (Carlisle and Mulamoottil, 1991). Several studies have attempted to characterize CSWs by removal efficiency and there tends to be a large range in reported pollutant removal efficiencies (e.g., suspended solids range from 70 to 97% removal; Brown, 1984; Yousef *et al.*, 1986; Hvitved-Jacobsen *et al.*, 1989; Mashauri *et al.*, 2000). The range in removal efficiencies may be due to a seasonal effect, treatment time (Yousef *et al.*, 1986; Hvitved-Jacobsen *et al.*, 1989), and when in the CSW's operational life the study was conducted. In the present study, a combination of effluent quality, mass load removal, the Li and Davis' (2009) method of exceedance probability, and statistical significance was used to report and analyze CSW performance (Strecker *et al.*, 2001). Many past studies on CSW performance report on overall performance and only storm events. The present study evaluated CSW performance over seasons for two different study periods and all flow conditions.

The main objective of the present study was to investigate a CSW's ability to treat flows during storm events and base flow consistently over time. The present work uses discrete sample analysis to evaluate CSW performance for storm events and base-flow periods for total suspended solids, total dissolved solids, total nitrogen, phosphorous (total and reactive), chloride, lead, copper, and *Escherichia coli*. The sampling periods were 2003-2004 and 2007-2008; sampling occurred over this extended time period to evaluate the CSW's performance and longevity through its life cycle.

METHODS

Water samples were taken from a CSW located on the Villanova University campus at the headwaters of a tributary to a high-priority stream outside of Philadelphia, Pennsylvania. The Villanova CSW (Figure 1) treats an 18.2-ha suburban watershed, with 9.7 ha of impervious surfaces and predominantly turfed pervious areas. The 0.4-ha CSW is completely vegetated with the exception of a 0.02-ha open water sediment forebay. Twenty species of wetland vegetation were originally planted in 1999. There was no maintenance done and, by 2003, approximately 85% of the vegetation was *Phragmites australis* (Type M), a salt-tolerant opportunistic species (Weisner and Ekstam, 1993). A control plan of a harvest and continued glyphosate sprays was started in 2006. As the control plan was implemented, *P. australis* growth and density are less around the CSW perimeter; however, there is still dense *P. australis* growth in the interior. A vegetation survey was conducted in 2008 and *P. australis* accounts for 53% of the CSW vegetation and was located mostly in the interior. During base- and low-flow events, most flow is through the CSW interior, whereas larger events inundate the perimeter.

Data Collection

There were two sampling periods where base flow and storm events were measured: 2003-2004 represented the early part of the CSW's design life and 2007-2008 represented the middle part of the CSW's design life. Sampling occurred in all seasons (herein, winter = December-February, spring = March-May, summer = June-August, fall = September-November). Flow in the CSW was assumed to be base flow after at least 48 hours with no rainfall. A storm event was defined when there was 1 mm of rain in 25 min. At least three base-flow samples and three storm event samples were taken each season. Influent samples were taken as a composite of the two inlet pipes just downstream of their junction and effluent samples were taken at the outlet (Figure 1). Flow was recorded at 5-min intervals with an American Sigma 950 Flow Meter (American Sigma-Hach Company, Loveland, Colorado). An American Sigma Model 2149 tipping bucket rain gauge recorded rainfall in 5-min intervals. For each base-flow water-quality sampling event, three 250-ml grab samples were taken at the inlet and at the outlet. The samples were collected simultaneously and assumed to be representative of the average base-flow condition. Storm event samples were automatically taken at prescribed intervals throughout a storm event with an American Sigma 900 Automated Sampler. Each sample interval was a composite sample for that interval. For the 2003-2004 events, samples were taken at the start of precipitation and then at 5, 10, 20, 30, 50, and 80 min, and then every 60 min thereafter at each sampling location; for the 2007-2008 samples, the sampling interval lasted 36 hours after the beginning of the storm at the inlet and 87 hours after the beginning of the storm at the outlet. The storm sampling intervals were short early in the storm and increased later in the storm, so the peak and entire recession limb of the storm hydrograph were captured.

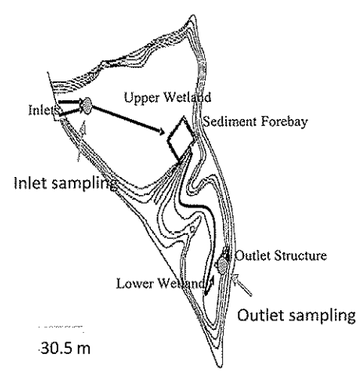

FIGURE 1. Schematic of Villanova Constructed Stormwater Wetland. Contour interval is 0.6 m. The sampling locations are noted by the gray circles.

Pollutants [i.e., total suspended solids (TSS), total dissolved solids (TDS), chloride, total phosphorous (TP), reactive phosphorus (RP), total nitrogen (TN), lead (Pb), copper (Cu), and *Escherichia coli* (*E. coli*) (metals and bacteria for base-flow conditions only)] were analyzed using standard methods and suggested methods by equipment manufacturers. Analysis of TN, TP, and RP used a Hach DR 4000 spectrophotometer (Hach Company, Loveland, Colorado) to measure light absorbance, which is related to concentrations. Chloride was tested using a High Pressure Liquid Chromatograph/Ion Chromatograph, which measures the conductivity of the ions to determine concentration. The TDS and TSS analysis sample was filtered (1.5-μm pore size filter) and APHA Standard Methods 2540C and 2540D were followed to measure the concentration, respectively (Clesceri *et al.*, 1998). Metals were collected, preserved by acidification with nitric acid to pH of <2 (following USEPA Method 7010) (USEPA, 2007), and tested with a PerkinElmer 2380 Atomic Absorption Spectrophotometer (PerkinElmer, Waltham, Massachusetts) plus graphite furnace. Coliform bacteria sampling was performed once a week for the 2003-2004 sampling year and followed USEPA-approved Method 10029 for Membrane Filtration of Coliforms, *Enterococci*, and Pseudomonas. Filtered samples in Hach's m-Coli Blue broth were incubated and counted for colony forming units. Because metals and bacteria were generally below water-quality standards during the 2003-2004 portion of the study, they were not measured during the 2007-2008 portion. More details on methods and analysis are presented in Rea (2004), Woodruff (2005), and Flynn (2008).

Data Analysis

The water-quality results are presented by mass and concentration. A pollutant's mass inlet and outlet loading for a storm event (M_s) was calculated by

$$M_s = \sum_{i=\text{begin}}^{\text{end}} C_i Q_i \Delta t, \tag{1}$$

where C_i is the concentration of a sample for an interval (i), Q_i is the volumetric flow rate for an interval, and Δt is the time interval. The time interval is 5 min, which matches the sampling interval and was selected to capture the flow's fluctuations. The C_i was linearly interpolated at 5-min intervals between measured sample concentrations. The mass loading of a pollutant under base flow (M_b) was calculated by

$$M_b = \overline{C}\overline{Q}\Delta t, \tag{2}$$

where $\overline{C}$ is the average concentration of all observed base flow samples taken in a season, $\overline{Q}$ is the average base flow rate for a season, and Δt is a season (three months).

The traditional percentage removal method tends to bias the perceived performance of a CSW if the inlet pollutant concentration is extremely high or extremely low (Strecker *et al.*, 2001) and it does not account for the system's hydrology (Davis, 2007). Exceedance probability (Li and Davis, 2009) was used here to analyze inlet and outlet pollutant concentrations, on the recommendation of Strecker *et al.* (2001). Using the exceedance probability clearly shows how often it is expected for a specific effluent quality to be achieved or exceeded. This method provides a direct comparison between flow from varying sized storm events, as well as a comparison between storm and base flows, with a focus on the treatment outcome (i.e., effluent quality). Additionally, it clearly shows how the pollutant concentration is changing from inlet to outlet, is sensitive to a system's hydrology and design, and is not biased to large storm flows. The exceedance probability was

calculated for this study using the Gumbel method, which ranks each pollutant's observed concentration and assigns a probability to each concentration based on the total number of observations made. The event mean concentration (EMC) was used for the analysis of storm events. The EMC is the total pollutant mass (M_s) divided by the total volume passing through the CSW for a storm event. The average concentration of base-flow samples within a season ($\overline{C}$) was used for base-flow analysis. The Mann-Whitney U-test was used to calculate the statistical significance between mean inlet and outlet pollutant concentrations.

The annual mass load (M_{annual}) for each pollutant is the sum of the mass load under base-flow and storm-flow conditions. The average annual base-flow mass load for each pollutant was calculated from the median base-flow concentration corresponding to 50% exceedance ($C_{base,50\%}$; Figures 2 and 3), the yearly average base-flow rate ($Q_{average\ base}$), and the number of days with base flow ($t_{base\ days}$).

$$M_{annual,base,in} = C_{base,in,50\%} \times Q_{average\ base} \times t_{base\ days} \quad (3)$$

The annual storm-flow mass load for each pollutant was calculated from the EMC corresponding to 50% exceedance ($EMC_{storm,50\%}$; Figure 2) for each pollutant and the annual volume of storm flow (V_{storm}).

$$M_{annual,storm,in} = EMC_{storm,in,50\%} \times V_{storm} \quad (4)$$

The V_{storm} was calculated by multiplying the drainage area by the average annual rainfall in southeastern Pennsylvania (1,143 mm; Prokop, 2003). The M_{annual} is the sum of $M_{annual,base}$ and $M_{annual,storm}$.

STORM EVENTS

A total of 19 storm events were sampled and analyzed; these storm events represented a wide range of depth, duration, and intensity. The hydrology of the watershed and within the CSW varies based on the depth, duration, and intensity of the storm event;

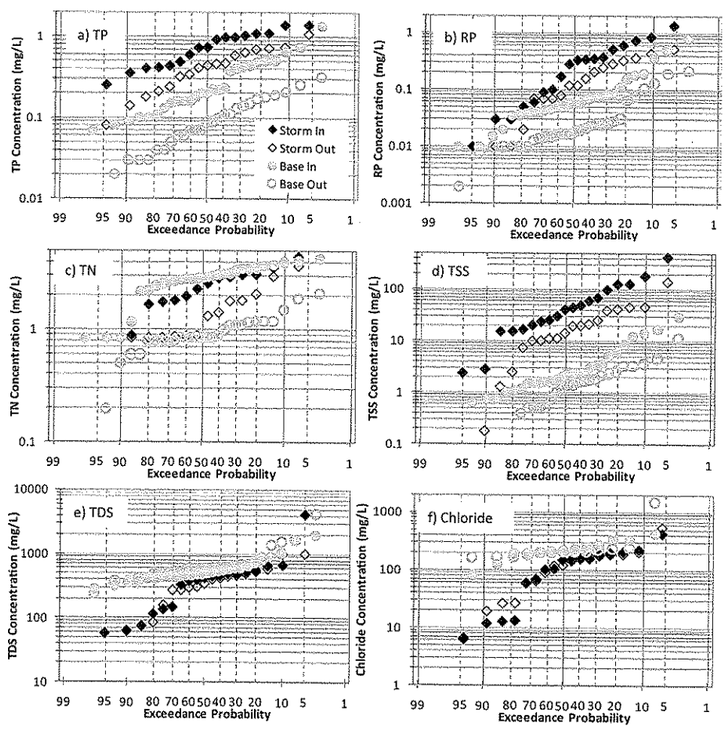

FIGURE 2. Inlet and Outlet EMCs for Storm Events and Average Concentrations for Base-Flow Events for (a) Total Phosphorous, (b) Reactive Phosphorous, (c) Total Nitrogen, (d) Total Suspended Solids, (e) Total Dissolved Solids, and (f) Chloride.

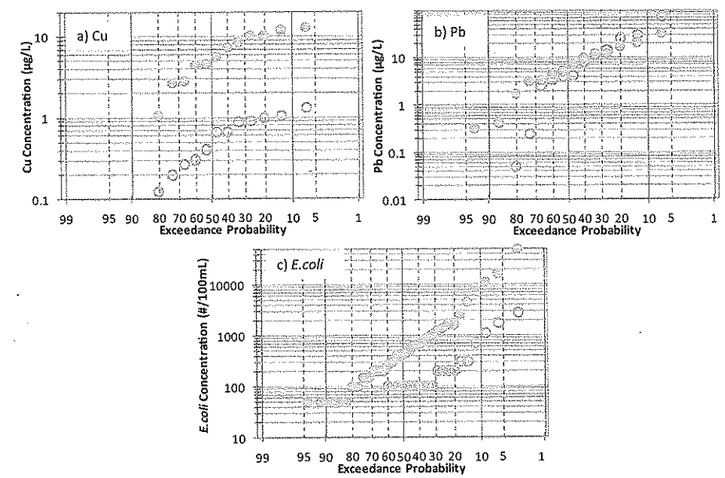

FIGURE 3. Inlet and Outlet Average Concentrations for Base-Flow Events for (a) Lead, (b) Copper, and (c) *Escherichia coli*. Similar to Figure 2, a closed circle is Base In and an open circle is Base Out.

generally during a storm, the retention time within the CSW is on the order of 1-3 hours. Generally, the mass (Figures 4a-4d) and concentration (Figures 2a-2d) of TP, RP, TN, and TSS decreased from inlet to outlet. The inlet and outlet EMCs were statistically different ($p = 0.05$) for TP, TN, and TSS, but not for RP. The inlet and outlet mass load of TDS and chloride on average decreased between inlet and outlet, except in fall 2003-2004 (Figures 4e and 4f). On a storm by storm basis, the inlet and outlet EMCs were statistically similar (Figures 2e and 2f).

The storms were assessed for a seasonal influence and over the monitoring years. The greatest removal of each pollutant varied by season and year. Overall, there was no seasonal trend with regards to concentration, but there were some interesting patterns in terms of mass. Although the mass removal was accompanied by a reduction in EMC from inlet to outlet for RP, TP, TN, and TSS, the TDS and chloride mass removal were not necessarily associated with a decrease in EMC, as the inflow and outflow EMC was nearly the same (Figures 2e and 2f), but had different flow rates (Q). The 2007-2008 sampling period had higher TP, TDS, and chloride mass loads than the 2003-2004 period. The inlet and outlet mass loads of TN were relatively consistent over all seasons in both study periods. There were no consistent trends in mass loading over seasons or study periods for RP or chloride. Chloride concentrations were the greatest in the winter, followed by the summer and fall, with the lowest concentrations in the spring; the largest mass removal was in the winter.

BASE FLOW

Thirty base-flow samples were collected and analyzed over the study periods. The base-flow travel time through the CSW is approximately 58 hours, depending on the actual flow rate (Wadzuk *et al.*, 2006). In all seasons, there was a statistically significant ($p = 0.05$) decrease in concentration from inlet to outlet for TP, RP, TN, TSS, Cu, and *E. coli*, but not for TDS, chloride, or Pb. There was mass removal of TP, RP, TN, TSS, and Cu for all seasons, except spring 2007-2008 (Figure 4). The mass addition in spring 2007-2008 is due to uncharacteristically low inflows during this period, most likely due to construction at the CSW's inlet. Similar to the storm samples, the greatest concentration reduction and mass removal of each pollutant varied per season.

For the three sampling seasons in which metals were analyzed (analysis was not carried out in summer 2004 or 2007-2008), copper concentration and mass were reduced, with the greatest reduction in the fall (Figures 3a and 4g). [All metal concentrations were below the Pennsylvania water-quality human health standard (Table 1, Figures 3a and 3b).] The overall effect on metals treatment through the CSW is negligible due to the small input loading. There did not appear to be any leaching of metals from the CSW soil.

There was a reduction in *E. coli* in all seasons except summer (Figure 3c). The Pennsylvania water-

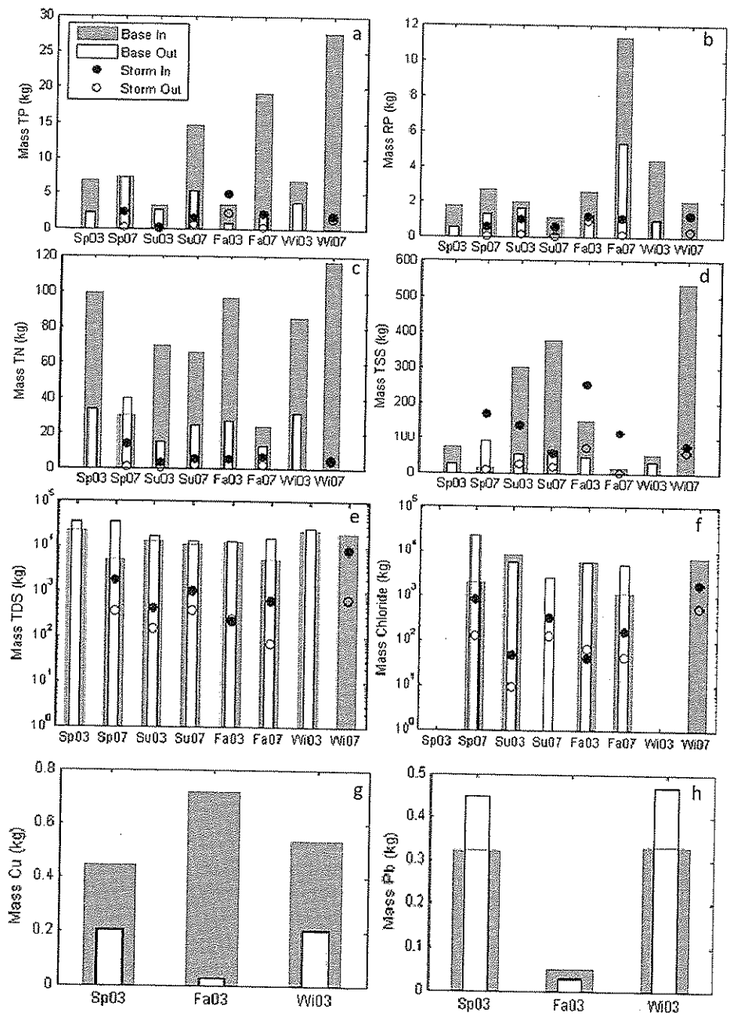

FIGURE 4. Seasonal Inlet and Outlet Mass Where a–h Show the Different Pollutants Analyzed (TP, RP, TN, TSS, TDS, Chloride, Cu, and Pb, respectively). There was no base outflow for winter 2007 so the mass is 0 kg. No storms were sampled in winter and spring 2003. Where the inlet and outlet mass are nearly the same, the symbols lie over each other (e.g., TN winter 2007).

quality standard for Fecal coliform (200/100 ml for summer) (PA Code, 2009) may be used for comparison of *E. coli*. The summer sampling season had an outlet *E. coli* count greater than the Pennsylvania Fecal coliform standard, but winter observations were below the Pennsylvania water-quality standard for Fecal coliform (Table 1). The summer net input of *E. coli* could be because of the ideal environmental growing conditions and abundance of wildlife activity and waste. Warmer daily temperatures foster near 24-hour reproductive capability for *E. coli* colonies already present in the water column. The night temperatures of the fall, winter, and spring would repress, if not stop, *E. coli* reproduction and metabolic activities (Pote *et al.*, 2009). This observation would indicate that, in terms of the abundance of *E. coli*, temperature is the driving force in removal rather than CSW design characteristics.

TABLE 1. Pennsylvania Water-Quality Standards (PA Code, 2009) and the Percent That the Storm Event Mean Concentration (EMC) and Base-Flow Concentration Exceeded the Standard.

Pollutant	PA Code (mg/L)	Inlet EMC % Exceed	Outlet EMC % Exceed	Sig	Inlet Base C % Exceed	Outlet Base C % Exceed	Sig
TSS	25	70	30	Sig	5	0	Sig
TDS	750	7	12	NSig	19	20	NSig
TN	4.9	0	0	Sig	0	0	Sig
TP	0.14	100	11	Sig	73	29	Sig
RP	NS	-	-	NSig	-	-	Sig
Chloride	250	9	9	NSig	32	10	NSig
Cu	1.0	-	-	-	0	0	Sig
Pb	0.05	-	-	-	0	0	NSig
E. coli (summer)	200/100 ml	-	-	-	70	30	Sig
E. coli (winter)	2,000/100 ml	-	-	-	20	3	Sig

Notes: Cu, copper; *E. coli*, *Escherichia coli*; NS, no standard or reference value given; NSig, no significant difference between inlet and outlet concentration; Pb, lead; RP, reactive phosphorus; Sig, significant difference between inlet and outlet concentration; TDS, total dissolved solids; TN, total nitrogen; TSS, total suspended solids; TP, total phosphorous.

COMPARING STORM EVENTS AND BASE-FLOW PERIODS

Total phosphorous includes both particulate and dissolved phosphorous. Total phosphorous concentrations were greater for storm events than base-flow periods (Figure 2a), as the flow entering the CSW during a storm may be nutrient enriched due to accumulation of surface contaminants. The probability of exceedance for the inlet and outlet concentrations under both flow conditions is depicted in Figure 2a and Table 1. The base-flow outlet concentration had a 29% probability of exceeding the Pennsylvania water-quality standard; this was the highest base-flow outlet exceedance probability for all pollutants except *E. coli* for the summer standard. The annual transport of phosphorous through the CSW during base-flow conditions was calculated according to Equation (3) and was 90% of the annual total load (Table 2). Reactive phosphorus is a dissolved form of phosphorus and is the form that is available for use by plants. Interestingly, there was significant RP reduction under base flow in the fall and winter when there is plant decay, so there must be other mechanisms besides plant uptake that capture or degrade RP. The concentration of RP was greater during storm events than base flow about 70% of the time (Figure 2b). The mass load of RP was greater under base-flow conditions than storm events (80% of the total load).

TABLE 2. Average Base, Storm, and Annual Load of Pollutants.

Pollutant	Base Load (kg)	Storm Load (kg)	Annual Load (kg)
TN	230.9	6.0	236.9
TP	12.8	1.3	14.1
RP	4.6	0.7	5.3
TSS	100.4	120.1	220.5
TDS	−9,890.8	363.2	−9527.6
Chloride	953.1	73.5	1,026.7
Pb	0.2	-	0.2
Cu	0.3	-	0.3

Notes: A positive value indicates load retained within the constructed stormwater wetland (CSW), a negative value indicates load that is discharged from the CSW. Cu, copper; Pb, lead; RP, reactive phosphorus; TDS, total dissolved solids; TN, total nitrogen; TP, total phosphorous; TSS, total suspended solids.

Although phosphorous and nitrogen are often grouped together as nutrients of concerns, their fate through a CSW does differ. The CSW's watershed was fertilized and assumed to be the major nitrogen source to the CSW, but the CSW was effective at reducing TN loads. All observed concentrations of TN were below the Pennsylvania standard (Table 1). The total nitrogen inlet concentration was significantly reduced and mass was removed through the CSW during storm events and base-flow periods, except spring 2007-2008 (Figure 4c). Inlet TN concentrations under base-flow and storm conditions were similar, but the outlet concentrations for base flow were generally less than outlet concentration for storm events. The annual mass load of TN was due mostly (97% of the load) to load under base-flow conditions.

The concentration of TSS was greater for storm events than for base flow (Figure 2d). The TSS storm outlet concentration had the highest probability of exceeding the water-quality standard at 30%, but met the standard under base-flow conditions 100% of the time (Table 1). The annual mass load of TSS during base flow and storms was about the same. Total dissolved solids concentrations were virtually unchanged as flow passes through the CSW, which is consistent with literature. The TDS concentrations were lower for storm events than base flow (Figure 2e). Despite little treatment of flow through the CSW, the water-quality standard was exceeded 12% of the time

for storms and 20% for base flow (Table 1). Mass of TDS was added through the CSW over the year under base flow, but removed during storms; however, the net effect was an addition (Table 2).

Chloride moved through the CSW as a dissolved substance and did not significantly interact with the CSW vegetation. Base-flow chloride concentrations were greater than storm concentrations. Storm event chloride concentrations had no significant difference from inlet to outlet (Figure 2f) and were greater than the standard 9% of the time (Table 1). The base flow chloride concentration had a slight decrease from inlet to outlet and the outlet concentration exceeded the standard 10% of the time. There was overall annual mass removal.

EVALUATION OF PERFORMANCE

The CSW is effective at reducing loads and concentrations of nutrients, TSS, and Cu under all flow conditions and over time. This was true despite the construction immediately adjacent to and within the CSW, variable pollutant loading to the CSW, and a *Phragmites australis* control plan during the 2007-2008 study period. Pollutant removal did vary depending on flow condition. The major difference between the CSW's performance during storm events and base flow is the residence time. Inflow stormwater can pass through the system in a few hours, whereas the residence time under base-flow conditions is two to three days (Wadzuk *et al.*, 2006). The increased residence time allows for additional settling and contact with the CSW vegetation, which increases the potential for pollutant removal.

There were several interesting observations made regarding the fate of the pollutants studied. The portion of TP that adsorbs to suspended solids was removed as the CSW flow slows and TSS settles, demonstrated by a statistically similar removal of TP and TSS. The end product for nitrogen removal is the gaseous state via nitrifying bacteria activity, which has more time to occur under base-flow conditions. High loads of TN out of the CSW were expected in the fall and winter seasons as plants decay and return nearly 80% of the nitrogen taken up (Peterjohn and Correll, 1984); this was not observed. There was significant reduction in all seasons. This leaves the question as to how much TN gets released into the CSW by decaying matter and are there other mechanisms to remove TN? Like TP, there was a correlation between TN and TSS removal. Although the primary mechanism for TN removal is not adsorption to solid particles, as the flow velocity slows, solids settle and the water has increased contact time with the plants for biological and chemical reactions. Thus, there was correlation without causation between TN and TSS. Additionally, there were low TN levels entering the CSW, yet high reduction was still achieved (i.e., only 10% of the time outlet base-flow concentrations were >1.5 mg/l). Thus, a lower limit on TN removal was not apparent.

Many pollutants adsorb to solid particles, so removing suspended solids from the flow is beneficial for water-quality improvement. There was TSS concentration reduction for storm-flow and base-flow periods, even though the TSS in base flow was composed of fine material that does not easily settle. Plant density may be a factor for TSS removal as the greatest removal was in the summer when plant density was the highest. High plant density blocks and slows flow to allow for settling to occur (Nepf, 1999; Burke and Wadzuk, 2009). Additionally, the elongated path from inlet to outlet allows particles to settle. Throughout the 2007-2008 study period, there was construction adjacent to and within the CSW that caused high TSS measurements at the inlet, yet overall the CSW was able to significantly remove TSS before the flow exited the CSW.

The observation that base-flow levels of chloride were greater than storm event levels for all seasons was unexpected as the authors thought the chloride levels would be high during winter and spring storm events when de-icing salts washed into the CSW. If chloride moved into the CSW during a storm event when de-icing activity was prevalent and then released during storm events, then most chloride would be gone by late summer. As this was not the case, it was hypothesized that: (1) chlorides move into the CSW during the winter and spring through surface runoff, (2) chlorides move into the ground and enter the CSW via groundwater flow, (3) chlorides accumulate within the storm pipes and get washed into the CSW during storms throughout the year, and (4) chlorides stored within the CSW become concentrated with lower flow volumes in the summer (Kaushal *et al.*, 2005; Kelly *et al.*, 2008).

Although no consistent seasonal trends were observed over the course of this study, there were definite water-quality differences between base-flow or storm-flow conditions. This finding can guide designers and evaluators when interpreting data on any CSW site. In addition to the seasonal observations, the CSW was analyzed at different points within its life cycle. There were some differences between study periods, however, the CSW's performance did not significantly change from 2003-2004 to 2007-2008 proving that the treatment longevity of CSWs is not a concern. In addition, although there were some seasonal variations, there was removal of

nutrients and TSS nearly year-round, indicating that CSW facilities can perform effectively at all times.

SUMMARY AND CONCLUSIONS

The Villanova CSW, due to its large area and high plant density, removes suspended solids and nutrients during storm events and base-flow conditions throughout the year. Effluent quality was used as an analytical tool to compare storm event and base-flow periods, which is important as pollutant removal during base-flow periods can be substantial. Unlike other stormwater BMPs that solely treat storm flows, the CSW treats influent and improves the quality of flow entering the receiving body every day under all flow conditions.

A significant ($p = 0.05$) reduction in the load and concentration of total phosphorus, which is correlated to the removal of suspended solids, reactive phosphorous, total nitrogen, and copper was observed. Regardless of inlet concentration, the nutrients all had removal indicating that the volume, flow path, and nature of the vegetation within a CSW drives the removal capacity. Chlorides and dissolved solids are not significantly removed as flow passes through the CSW. Generally, storm events had about an order of magnitude lower concentration and loading than base flows for chlorides and dissolved solids. Part of the chloride loading throughout the year could be from the groundwater, storage within the watershed, or the concentrated effect due to lower CSW volumes in the summer. With regards to metals, the increased retention time under base flow does not appear to lead to any significant leaching of metals from the underlying soil complex to the water column. The necessary microbiological conditions are established within the CSW to remove *E. coli* bacteria during the fall, winter, and spring; however, the high summer temperatures override the CSW's ability to process *E. coli* bacteria.

The observations from this study indicate that CSW design and hydrodynamic conditions contribute to the pollutant reductions and the ability to achieve design standards, although the physical design may be the key in pollutant removal. By altering CSW design, flow may be slowed and retained longer, which would allow for more base-flow-like conditions to aid in pollutant removal. The broader impact of this study is a demonstration of the variations in pollutant fate through a CSW in different seasons and flow conditions and that a CSW maintains its water-quality benefit over a decade of operation. The research presented here can be used to further the state-of-the-art of stormwater BMPs and their application by water resources engineers, planners, and managers in designing a holistic approach to stormwater management.

ACKNOWLEDGMENTS

The project was funded in part by the United States Environmental Protection Agency and the Pennsylvania Growing Greener Program. The authors would also like to thank Dr. Metin Duran for his assistance on the *E. coli* analysis.

LITERATURE CITED

Brown, R.G., 1984. Effects of an Urban Wetland on Sediment Loads in Runoff. Wetlands 4:147-158.

Brown, S., S. Shrestha, and S.J. Riley, 1999. The Allocation of Resources to Stormwater Pollution Control. IAHS Publication, Wallingford, Oxfordshire, pp. 381-389.

Burke, E.N. and B.M. Wadzuk, 2009. The Effect of Field Conditions on Low Reynolds Number Flow in a Wetland. Water Research 43:508-514.

Carlisle, T.J. and G. Mulamoottil, 1991. Artificial Wetlands for the Treatment of Stormwater. Canadian Water Resources Journal 16(4):331-343.

Clesceri, L.S., A.E. Greenberg, and A.D. Eaton, 1998. Standard Methods for the Examination of Water and Wastewater (20th Edition). American Public Health Association, Washington, 1325 pp.

Coleman, J., K. Hench, K. Garbutt, A. Sexstone, G. Bissonnette, and J. Skousen, 2001. Treatment of Domestic Wastewater by Three Plant Species in Constructed Wetlands. Water, Air, and Soil Pollution 128:283-295.

Davis, A.P., 2007. Field Performance of Bioretention: Water Quality. Environmental Engineering Science 24(8):1048-1064.

Emerson, C., C. Welty, and R.G. Traver, 2005. A Watershed-Scale Evaluation of a System of Stormwater Detention Basins. Journal of Hydrologic Engineering 10(3):237-242.

Flynn, K., 2008. Pollutant Removal Efficiency of a Mature Constructed Stormwater Wetland Over the Course of a Year. Thesis, Villanova University, Villanova, Pennsylvania, www3.villanova.edu/VUSP, *accessed* June 9, 2009.

Hvitved-Jacobsen, T., Y.A. Yousef, and M.P. Wanielista, 1989. Rainfall Analysis for Efficient Detention Ponds, Engineering Foundation Conference on Current Practice and Design Criteria for Urban Quality Control, Potosi, Missouri, USA, July 10-15, 1988. *In:* L.A. Roesner, B. Urbonas, and M.B. Sonnen (Eds.), Design of Urban Runoff Quality Controls, ASCE (American Society of Civil Engineers) publication, pp. 214-222.

Kaushal, S.S., P.M. Groffman, G.E. Likens, K.T. Belt, W.P. Stack, V.R. Kelly, L. Band, and G.T. Fisher, 2005. Increased Salinization of Fresh Water in the Northeastern United States. Proceedings of the National Academy of Sciences of the United States of America 102:13517-13520.

Kelly, V.R., G.M. Lovett, K.C. Weathers, S.E.G. Findlay, D.L. Strayer, D.J. Burns, and G.E. Likens, 2008. Long-Term Sodium Chloride Retention in a Rural Watershed: Legacy Effects of Road Salt on Stream Water Concentration. Environmental Science and Technology 42:410-415.

Lee, J.H., K.W. Bang, L.H. Ketchum, J.S. Choe, and M.J. Yu, 2002. First Flush Analysis of Urban Storm Runoff. The Science of the Total Environment 293(1-3):163-175.

Li, H. and A.P. Davis, 2009. Water Quality Improvement Through Reductions of Pollutant Loads Using Bioretention. Journal of Environmental Engineering 135(8):567-576.

Mashauri, D.A., D.M.M. Mulungu, and B.S. Abdulhussein, 2000. Constructed Wetland at the University of Dar Es Salaam. Water Research 34(4):1135-1144, Great Britain.

Mulhern, P.F. and T.D. Steele, 1989. Water Quality Ponds – Are They the Answer? *In:* Design of Urban Runoff Quality Control, L. Roesner, B. Urbonas, and M. Sonnen (Editors). ASCE, New York, p. 11.

Nepf, H.M., 1999. Drag, Turbulence, and Diffusion in Flow Through Emergent Vegetation. Water Resources Research 35(2):279-289.

NRC (National Research Council), 2008. Urban Stormwater Management in the United States. The National Academies Press, Washington, D.C., 624 pp. http://books.nap.edu/openbook.php?record_id=12465&page=R1, *accessed* June 9, 2009.

Pennsylvania Code (PA Code), 2005. Title 25–Environmental Protection. Chapter 93–Water Quality Standards, http://www.pacode.com/secure/data/025/chapter93/chap93toc.html, *accessed* on June 9, 2009.

Peterjohn, W.T. and D.L. Correll, 1984. Nutrient Dynamics in an Agricultural Watershed: Observations on the Role of a Riparian Forest. Ecology 65:1466-1475.

Pote, J., L. Haller, R. Kottelat, V. Sastre, P. Arpagaus, and W. Wildi, 2009. Persistence and Growth of Feacal Culturable Bacterial Indicators in Water Column and Sediments of Vidy Bay, Lake Geneva, Switzerland. Journal of Environmental Science – China 21:62-69.

Prokop, M.J., 2003. Determining the Effectiveness of the Villanova Bio-Infiltration Traffic Island in Infiltrating Annual Runoff. Thesis, Villanova University, Villanova, Pennsylvania. www3.villanova.edu/VUSP, *accessed* June 9, 2009

Rea, M., 2004. Pollutant Removal Efficiency of a Stormwater Wetland BMP During Base Flow and Storm Events. Thesis, Villanova University, Villanova, Pennsylvania. www3.villanova.edu/VUSP, *accessed* June 9, 2009.

Sansalone, J.J. and C.M. Cristina, 2004. First Flush Concepts for Suspended and Dissolved Solids in Small Impervious Watersheds. Journal of Environmental Engineering 130(11):1301-1314.

Strecker, E.W., M.M. Quigley, B.R. Urbonas, J.E. Jones, and J.K. Clary, 2001. Determining Urban Stormwater BMP Effectiveness. Journal of Water Resources Planning and Management 127(3):144-149.

USEPA (U.S. Environmental Protection Agency), 1977. Alternatives for Small Wastewater Treatment Systems. USEPA Report 625/4-77-011. USEPA, Washington, D.C.

USEPA (U.S. Environmental Protection Agency), 1990. National Water Quality Inventory-1988 Report to Congress. Office of the Water Program Operations, Water Planning Division, Washington, D.C.

USEPA (U.S. Environmental Protection Agency), 2005. National Management Measures to Control Nonpoint Source Pollution From Urban Areas. USEPA Report EPA-841-B-05-004. USEPA, Washington, D.C.

USEPA (U.S. Environmental Protection Agency), 2007. Graphite Furnace Atomic Absorption Spectrophotometry. http://www.epa.gov/osw/hazard/testmethods/sw846/pdfs/7010.pdf, *accessed* August 30, 2009.

Wadzuk, B.M., W.C. Heasom, and R.G. Traver, 2006. Modeling and Optimizing the Design of Villanova University's Constructed Stormwater Wetland. Proceedings of the AWRA 2006 Annual Water Resources Conference, Baltimore, Maryland, 292 pp.

Weisner, S.E.B. and B. Ekstam, 1993. Influence of Germination Time on Juvenile Performance of *Phragmites Australis* on Temporarily Exposed Bottoms—Implications for the Colonization of Lake Beds. Aquatic Botany 45:107-118.

Woodruff, G., 2005. Pollutant Removal Efficiency and Seasonal Variation of a Storm Water Wetland BMP. Thesis, Villanova University, Villanova, Pennsylvania. www3.villanova.edu/VUSP, *accessed* on June 9, 2009.

Yousef, Y.A., M.P. Wanielista, and H.H. Harper, 1986. Best Management Practices – Effectiveness of Retention/Detention Ponds for Control of Contaminants in Highway Runoff. Florida Department of Transportation, Gainesville, Florida.