Environmental Engineering and Management Journal September 2018, Vol.17, No. 9, 2221-2228
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

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NUTRIENT REMOVAL IN A WET DETENTION POND WITH BAFFLE DIKE – A CASE STUDY OF THE CEDAR RIVER PROJECT

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Abstract

The City of Jacksonville, Florida USA is in the midst of an important program to reduce nutrient load from its municipal storm water system. New regulations promulgated by the US EPA and State of Florida have targeted nutrient reduction within the St. Johns River watershed which includes most of the City of Jacksonville. In order to reduce overall nutrient loads to the St. Johns River, the City of Jacksonville and its consultant team have begun a construction program to build a series of wet detention storm water reservoirs designed to attenuate storm runoff and reduce nutrient discharge. One such facility lies within the Cedar River watershed which is connected downstream to the St. Johns River. This paper describes the layout of the facility and its nutrient removal performance over a period of more than one year. The storage and treatment facility is unique in its design since it includes a longitudinal baffle dike designed to extend the flow path and increase the overall residence time of the facility. The actual nutrient removal performance of the specially-designed facility greatly exceeded its design goals and outperformed other typical wet detention facilities in Florida as well as many storm water treatment wetlands. Overall, the pond removed approximately 31% of total nitrogen, 59% of total phosphorus, and 83% of total suspended solids during the study period.

Key words: storm water detention, baffle dike, nutrient removal, wet pond

Received: November, 2015; Revised final: July, 2016; Accepted: October, 2016; Published in final edited form: September, 2018

1. Introduction

Urban storm water runoff has long been recognized as a major contributor to water quality impairment of rivers and lakes (USEPA, 1990). Nutrients, in particular, can be problematic. The removal of nutrients is a continuing environmental engineering challenge. The Cedar River, located in Jacksonville, Florida USA is watershed with nutrient problems. Jacksonville, Florida USA has a sub-tropical climate with an annual precipitation of about 132 cm spread across a five month wet season (May through September) and a seven month dry season; usually a majority of the annual precipitation falls in the wet season (https://rainfall.weatherdb.com/l/64/Jacksonville-Florida). The Cedar River Outfall regional storm water facility, located at the intersection of Highway Avenue and Cynthia Street in Jacksonville, Florida USA (Fig. 1), is a 5.67 hectare wet-detention pond that treats approximately 608 hectares of tributary area (mixed residential, commercial and industrial) that currently do not receive storm water quality treatment, with the exception of a few individual properties (CDM Smith, 2007). Wet-detention ponds are storm water control facilities that provide both retention and treatment of contaminated storm water runoff (USEPA, 1999), as well as flood control. By capturing and retaining storm water runoff during storm events, wet-detention ponds allow physical, biological, and

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chemical processes to remove particulates, organic matter, metals, dissolved metals, and nutrients (Istenic and Justin, 2012; USEPA, 1999). The further optimization of wet-detention ponds for nutrient removal is a current area of great research interest in Florida, USA and elsewhere (Hartshorn et al., 2016; Lynch et al., 2015; Wang et al., 2014). The simple reason for this renewed interest in these commonplace storm water management features is that they are numerous and, if optimized, could be a great resource for further nutrient reduction. At the same time, they are simple to construct and operate. However, in most cases, they are simply designed to primarily attenuate floods and include little thought regarding water quality treatment which is considered of secondary importance (Tsihrintzis and Hamid, 1997). This study will show how a simple design optimization, inclusion of long, interior baffle dike, can lead to improved nutrient removal performance for a moderate additional cost. Koch et al. (2014) call for “a select number of long-term flux-based best management practices (BMP) studies that rigorously measure rainfall, hydrology, and site conditions could improve BMP implementation.” This study is consistent with that calling.

The Cedar River wet detention pond has long been envisioned to improve the water quality of the study area. The Cedar River watershed has had significant sediment contamination from a number of historical industrial sites as well as a history of high fecal coliform counts. In the mid-1990s, over 75% of all samples analyzed for fecal coliform were found to exceed the single sample Florida limit (800 CFU per 100 mL of water sample) and the mean value was about 10 times the permissible limit (UNF and JU, 2011). The Cedar River watershed additionally has been recognized since at least 1983 as having been burdened by years of discharges from wastewater treatment plants and runoff from small, poorly managed industries, and from identified and unidentified hazardous waste sites (UNF and JU, 2011). Fig. 1 shows the general location of the project site in Florida, USA and Fig. 2 is a detailed aerial photo showing the general project features.

Due to the water quality issues within the watershed, the City of Jacksonville (COJ) cooperated with the St. Johns River Water Management District and the Florida Department of Environmental Protection (FDEP) to develop a regional storm water treatment area within the watershed, which was completed in January of 2008. The facility features an unconventional design in which the flow, during normal operation, is diverted around a long baffle dike and is discharged through a single 152 cm diameter reinforced concrete pipe culvert located under the maintenance berm at the northwest corner of the facility. This is due to the geometry of the parcel available for the project which only abuts the Cedar River at one location, forcing the facility intake and outfall to be co-located, and a circuitous flow path established via baffle dike to prevent short circuiting.

Fig. 1. General project location in Florida, USA

The bottom elevation of the pool varies from -0.61 to -1.22 m National Geodetic Vertical Datum of 1929 (NGVD29). In the case of a larger than average storm event, some of the flow may bypass the facility by way of a bypass weir that is at elevation 2.22 m NGVD29; any flow that bypasses the facility is assumed to have received no treatment. The total area of the facility is about 2 hectares.

Fig. 2. Detailed project features

In order to fulfil the requirements of FDEP Grant S-0271 designated for nutrient remediation in the watershed and funds of which were used to construct the facility, an integral water quality monitoring program was included as part of the overall project to measure facility function and performance. The monitoring program was begun in February 2011 and was completed in October 2012 under the direction of CDM Smith Inc. (CDM Smith) and the University of North Florida (UNF). Further monitoring of the facility is being considered by the COJ or others. The monitoring program consisted of water quality sampling in order to estimate the long-term pollutant removal efficiency of the storm water facility for 14 water quality constituents. These water quality constituents included: ammonia as N, cadmium, chromium, copper, lead, nickel, nitrate/nitrite as N, orthophosphate as P, total phosphorous (TP), total Kjeldahl nitrogen (TKN), total suspended solids (TSS), zinc, oil and grease, and fecal coliform bacteria. The summed concentrations of nitrate/nitrite as N and TKN will collectively be referred to as total nitrogen (TN) for the remainder of the paper (USEPA, 2009). This paper only focuses upon the removal of TSS and nutrients (TN and TP).

The sampling work was completed in accordance with the Quality Assurance Project Plan and was focused upon 9 precipitation-generating storm events; a tenth storm event, occurring in the dry-season, was removed from the scope due to an extended period of drought and project setbacks including equipment theft and extensive telemetry issues. Storm events were targeted that produced a rainfall depth between about 13 and 76 cm. This paper provides a detailed description of the sampling site equipment, storm selection, methodology, and storm sampling procedures as well as analytical results from each storm event, details on the water mass balance used to assess each storm event, and finally the nutrient removal efficiency achieved by the storm water facility during the project as compared to the original design goals and similar facilities elsewhere in Florida.

2. Materials and methods

Composite surface water quality samples were taken for each event by automatic samplers installed at the influent (CRV1) and effluent (CRV2) station locations of the facility (Fig. 2). Oil and grease sampling was conducted via grab sample because the automatic sampler intakes were submerged and would therefore not sample the pond surface where oil and grease accumulate. The automatic samplers were programmed using site-specific criteria and expected water quality conditions seen at similar storm water treatment areas (Harper and Baker, 2007).

Station CRV 1 was located at the influent end of the facility. Fig. 3 and Fig. 4 show the stilling well containing the autosampler influent station and the actual sampling equipment stored in a secure cage. The sampling equipment was installed in a secure cage on a concrete slab at the top of the maintenance berm. The use of the secure cage was important as the project location is located in an area where vandalism is common. The sampling equipment was initially enclosed by chain-link fencing and later heavy-duty metal bars to prevent theft. The pond influent location CRV1 was located at the bridge, just south of the confluence of two channels. Station CRV2 was located at the effluent end of the facility. The sampling equipment was installed, similar to CRV1, on a concrete slab on top of the maintenance berm. The sampling equipment was enclosed identically to CRV1. The sampling at the effluent location was performed at the outfall of the facility within the RCP culvert that allows treated storm water to drain from the facility as fresh storm water enters the facility at the influent end. Stations CRV1 and CRV2 contained the following equipment:

1. Stormbox (Precision Systems);
2. Full-size portable automatic sampler (ISCO model 6712);

3. Area velocity flow module (ISCO model 750);
4. Tipping bucket rain gauge (ISCO model 674) – only at CRV1;
5. Digital cellular modem system (ISCO model SPA 1489);
6. 40-watt solar panel (ISCO model SPA 1347);
7. Standard 12V marine battery;
8. Sample intake strainer; and
9. 0.019 cubic meter or 19 L composite sampling bottle.

Fig. 3. Sampling station

Fig. 4. Sampling equipment

Sampling of the influent storm water took place near the edge of the channel inside of a custom-built stilling basin. The stilling well was built to mitigate disturbance to the area velocity sensor by floating debris, animals, etc., in order to measure water levels more accurately and prevent false triggering of sampling due to water surface disturbances. The automatic sampler was connected to the area velocity sensor and sample intake strainer by a length of data cable and sampling tubing that were buried just below the ground surface. CRV1 contained a two-part (A and B) sampling program which initiated part A upon both of the following criteria being met:

• Measured rainfall must be greater than 2.54 mm in 1 hour; and
• Pond level must rise more than 15.2 mm in 1 hour.

Once part A was initiated a 500 mL water sample was taken every 15 minutes until a total of 4 samples had been taken. Part B would initiate after the following criteria were met:

• Part A had been completed; and
• Pond level continued to rise to 30.5 mm in 1 hour (2^{nd} hour consecutively).

Once part B was initiated a 500 mL water sample was taken every 15 minutes until either the pond level ceased rising at the specified rate or there were a total number of 30 samples taken from parts A and B.

Sampling at CRV2 was performed differently than at CRV1. A 33-point discharge versus stage rating curve was developed that relates the surface elevation (e.g. stage) of the pond to an instantaneous outflow rate through the culvert. The rating curve was developed using a previously-developed and calibrated Environmental Protection Agency Stormwater Management Model (EPA SWMM). The SWMM hydraulic model of the facility (CDM Smith, 2007; personal communication from CDM Smith, 2012) and related confirmatory field measurements were used to relate outflow to the stage for the purposes of simplifying field measurements by only recording stage (rather than both stage and flow). Actual velocity measurements were also recorded, however, the outflow velocity sensor was determined to be unreliable at low outflow rates. Therefore, for the effluent measurements the stage was recorded continually and then related to estimated outflow rate using the developed rating curve. CRV2 contained a one-part program that was initiated upon both of the following criteria being met:

• Pond level must rise more than 91.4 mm in 1 hour; and
• Velocity measured in the RCP outlet culvert must exceed 52 cm per second.

Once the program was initiated, a 500 mL water sample was taken for every 708 cubic meters of water passing through the RCP outfall culvert until either there were a total of 30 samples or sampling staff determined the composite bottle needed to be changed. Sampling was ended by sampling staff once it was determined that the water level within the pond had recovered from the increase due to the storm event; targeting a 90% or better depth recovery or pond recession.

In order to ensure that the sampling equipment was prepared to sample a storm event, a preventative maintenance program was developed for the project. Routine site visits were made to ensure maintenance and testing was performed on sampling devices such as the rain gauge, automatic samplers, battery, solar panels, sample strainers, tubing, clamps, electrical connections, and sampler programming.

The field team had to continually track project site weather conditions and frequently reviewed available digital Internet resources and published forecasts. Once a potential storm system was identified as possibly meeting required storm conditions for the project, the sampling staff mobilized to prepare for the candidate storm. Once the storm was identified, the predicted amount of precipitation was obtained from the National Weather Service Southeast River Forecast Center (SERFC, 2012) in order to better anticipate if the storm would produce adequate runoff to allow sample collection. Mobilization procedures included checking sampler equipment and supplies prior to the event.

Once precipitation exceeded 12.7 mm of rain measured at the rain gauge location, the sampling staff mobilized to the detention pond in order to collect samples. Composite sampling bottles were collected and replaced as they were filled and were transported to the COJ laboratory to be processed and placed into the appropriate containers for analysis until the conclusion of the sampling event. They were then transported on wet-ice from the COJ laboratory to the Environmental Quality Division (EQD) Analytical Laboratory located in Jacksonville, Florida.

3. Results and discussion

A total of nine storm events were sampled during this project; three in the dry season (from about November to June each year) and six in the wet season (June thru October). Mass balance and removal efficiency estimates were calculated for each event. A general water budget equation (Eq. 1) was developed for the facility, and was used to perform water balance calculations for each storm event. Groundwater recharge and bank loss during storm events was assumed to be negligible and was not included in the budget formulation. The overall error of the water budget was found to be within 3 to 8 percent for most storm events, but was as high as 18 percent for the eighth event which included overflow out the emergency overflow or spillway. The equation considers the potential storm water inputs and outputs of the facility and relates them to the actual storage capacity of the facility. Potential inputs identified included the storm water runoff entering the facility and the direct rainfall on the pond. Potential outputs from the facility include the normal discharge of treated storm water through the culvert, evaporation of water from the pond surface, and (in the case of high-flow events) bypass weir overflow. The bypass emergency overflow was only engaged during extremely high inflows but when it was used the amount of water quality treatment and nutrient removal was reduced for that event. Under normal operating conditions flow through the facility is attenuated, allowing suspended particles to settle out of the water column. Instead, during emergency overflow events the untreated storm water is directed over the bypass emergency weir and directly into the facility effluent ditch.

Influent Storm water + Direct Rainfall - Effluent Storm water - Evapotranspiration - Bypass Weir Flow = Change in Pond Storage (1)

Data that were collected by the automatic samplers for each storm event was analyzed and compared. Both onsite instrumentation data and model simulations were used in the overall analysis. The project team was fortunate that an existing EPA SWMM storm water hydraulic model had been previously developed and calibrated for the entire City of Jacksonville service area (CDM Smith, 2007) including the project site. Therefore, the model proved useful in refining estimates of basin performance, especially in cases of lower flow rates where the model provided better estimates of the water budget as compared to the instrumentation. Analysis consisted of utilizing rainfall measurements taken by CRV1 and developing a simulation for each storm. Each simulation produced a modelled inflow and outflow volume, as well as a modelled pond stage. Graphical comparisons made between the modelled and measured flow and stage data demonstrated that the hydraulic model of the site was generally accurate and provided better estimates of the outflow than using onsite instrumentation alone (see Fig. 5 with an estimated r^2 value of 0.95 for measured versus modelled inflow as an example).

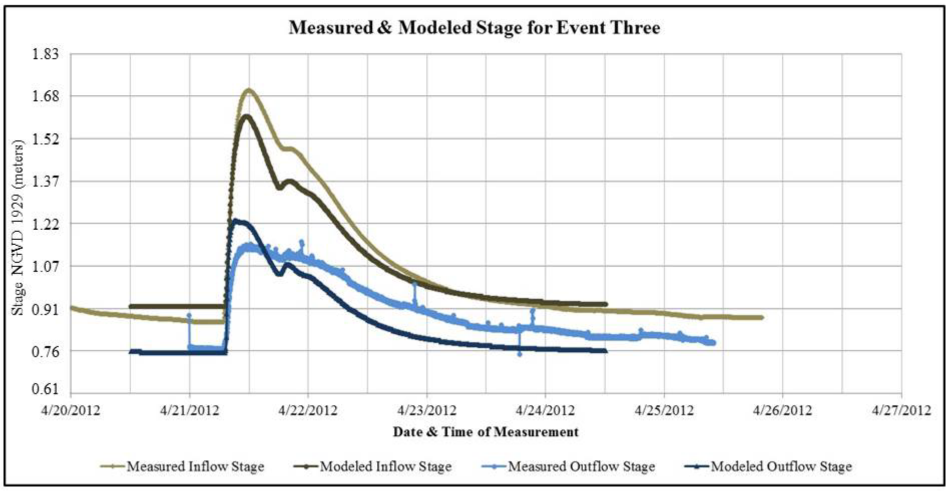

Fig. 5. Comparison of measured and modeled inflow and outflow for event 3

Table 1. Nutrient removal percent (%), comparison

	TN	*TP*	*TSS*
Design Goal Removal %	8%	23%	68%
Typical Performance of Florida wet detention ponds with 7-day residence times (Harper and Baker, 2007)	27%	53%	Not Available
Cedar River Project Removal %	31%	59%	83%

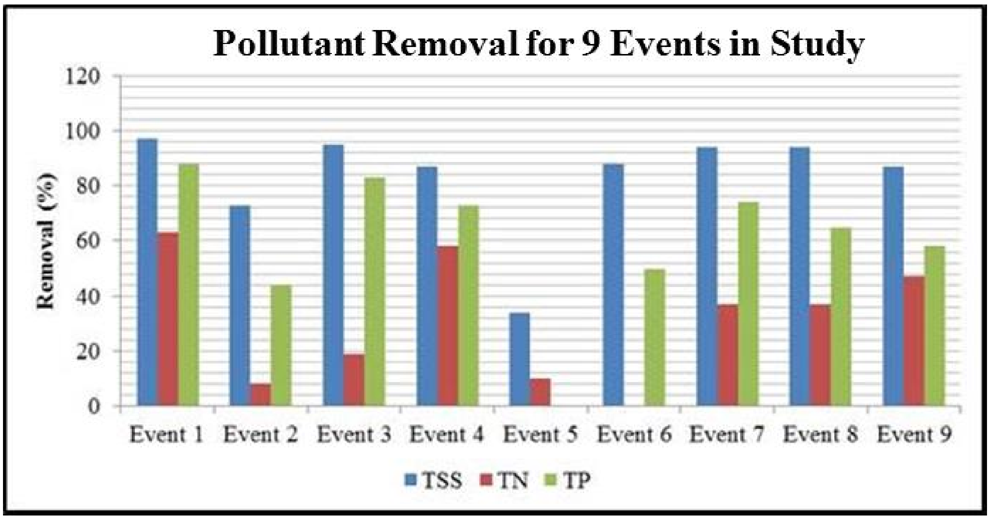

Fig. 6. TSS and nutrient removal performance for all events

Once this determination was made and the model results and field data analyzed, the water budget for each event was calculated. The stage data recorded by both CRV1 and CRV2 were first plotted to determine the appropriate starting and ending time for the event consistent with sampling event trigger criteria. Then field data and model simulations were used to calculate the overall inflows and outflows plus check the event water budget. The influence of direct rainfall on the pond as well as evaporation from the pond was also included in the overall analysis. Regional daily evaporation estimates were used (Fernald and Purdum, 1998) while the onsite rain gauge was used to determine direct precipitation on the detention pond. A stage-area curve was developed for the detention pond to determine the appropriate area for the calculation of daily evapotranspiration and precipitation. The “Bypass Weir Flow” component of the general water budget equation was used in the case of high-flow events when bypass weir flow had occurred; otherwise it was assumed to be zero.

Overall the TSS and nutrient removal performance of the innovative wet detention pond was satisfactory and exceeded design goals. Table 1 compares the original performance design goals and typical wet detention pond performance in Florida versus the actual arithmetic mean measured nutrient removal efficiencies for the project. The mean removal efficiencies were used instead of the median values to be conservative in the performance comparisons as the median values were higher. The Cedar River pond greatly outperformed its conservative design goals with more than triple the removal efficiency for TN, more than double for TP, and 22% better for TSS.

In comparing the Cedar River wet pond performance to Florida-wide values, it is clear that the project performed well. In fact, it performed considerably better than typical wet detention ponds in Florida. Harper and Baker (2007) provided estimates of wet pond performance after seven days of residence time which is probably somewhat higher than typical residence time durations of most Florida ponds. So in a sense, these benchmark values probably represent reasonable maximum removal efficiencies one would expect for a typical wet pond in Florida, USA. The Cedar River wet pond had a median residence time during the nine storm events of about 2.5 days or only 36% of the residence time of the benchmark. Therefore, it should have performed considerably worse than the benchmark; it actually performed as well for TN and slightly better for TP removal. The Cedar River wet pond also performed well in regards to TSS and TP removal compared to urban ponds in agricultural basins as reported by Chretien et al. (2016) who reported TSS, TN, and TP removal percentages of 50-56%, 42-52%, and 48-59%, respectively. Fig. 6 shows the TSS and nutrient removal performance during each event. The median influent concentration for the nine events for TSS, TN and TP were 91, 0.91, and 0.22 mg/L, respectively. Of the nine events, events 5 and 8 were somewhat unique. During event 8 almost 2.5 cm of precipitation fell during a relatively short duration and another 4 cm of precipitation had fallen over the previous 48 hours; therefore, the pond stage rose precipitously and flow was recorded out the emergency spillway. Event 5 was unique due to the spread of precipitation across the event. During this event precipitation intensity peaked five times during the sampling event but still resulted in the smallest inflow volume to the pond. In addition, the pond was slow to drain resulting in a truncated sampling duration as compared to the other events. This may have resulted in an underestimation of nutrient mass removal during this event.

Besides the actual analytical results collected for the study, overall project performance is also easily recognized by visually comparing the color of the influent and effluent. Fig. 7 shows storm water before and after wet detention treatment.

Fig. 7. Influent (left) and effluent (right) water samples collected during the study

The analytical data and visual results clearly show above average nutrient removal and TSS removal performance. Storm water treatment wetlands are increasingly being considered for the same purpose (Carleton et al., 2001). Treatment wetlands have also been studied extensively for use in cleaning municipal wastewater (Fazlolahi and Eslamian, 2014). There are many types of treatment wetlands being used and studied. The use of submerged plants (Brown et al., 2014), emergent plants (Vymazal, 2007), and floating plants (Chang et al., 2013) are being studied in detail. The TSS and nutrient removal efficiencies of such systems vary widely from net nutrient addition (e.g. negative pollutant removal) to up to 87% TP removal (Carleton et al., 2001).

The vast Everglades Construction Project in South Florida, USA covers thousands of hectares and has a long-term TP removal efficiency of 67% (RTI International, 2012). In order to compare the Cedar River wet pond TP removal efficiency to those of comparable treatment wetlands, the authors calculated the volumetric removal rate constant for each storm event and then calculated the mean and median values for the rate constant (Dortch, 1996). Then the authors compared the present results to calculated rate constants of 16 gravity flow treatment wetland systems discussed in Carleton et al. (2001). The results clearly demonstrate the excellent performance of the Cedar River wet pond. Table 2 compares the mean and median volumetric removal rate constants for TP from Cedar River project to Carleton et al. (2001).

Table 2. TP Volumetric removal rate constant (per year) comparison

	TP Mean	***TP Median***
Carleston et al. (2001)	93.1	30.6
Cedar River Project Removal	147.7	127.4

The results clearly show the Cedar River Project with both higher mean and median TP volumetric removal rate constants. A Mann-Whitney statistical test of medians was completed for each dataset to determine if the outperformance noted in the Cedar River Project was significant. The results show that the Cedar River median volumetric rate constant is indeed significantly better at the $p = 0.05$ significance level. The Cedar River pond with baffle dike has an approximate length to width ratio of about 12 to 1 while Khan et al. (2013) noted that an 8 to 1 ratio was optimal in their studies of floating treatment wetlands. Overall, the designers included the baffle dike to increase the overall pond length to width ratio which has been discussed by several investigators (Sonderup et al., 2016) since the area of the pond could not be further optimized as recommended by Park and Roesner (2013).

Therefore, the above average nutrient removal performance of the pond was not totally surprising. Based upon the study results, it appears that the primary treatment mechanism of the Cedar River pond is most likely the sedimentation of sand and silt particles and particulate nutrients which is similar to what was reported by Chretien et al. (2016). Further studies are warranted on this innovative design to further validate this study and the hydraulic design features. Determining the optimal baffle length would also help minimize future pond costs while maximizing nutrient removal. Also, studies are warranted to determine if performance is degraded over time without periodic pond volume maintenance as noted in Sonderup et al. (2016). Lastly, including more wet detention ponds in combined storm sewer systems my help reduce nutrient loads at overflow points (Casadio et al., 2013).

4. Conclusions

The nutrient and TSS removal efficiencies of the wet detention pond with the long interior baffle dike have demonstrated that the water quality of the storm water runoff improves significantly after being routed through the storm water facility. The removal efficiencies for total nitrogen, phosphorus, and suspended solids exceed the predicted removal efficiencies assumed for this facility during design as well as those seen at other typical storm water wet ponds in Florida, USA. In addition, the Cedar River pond had higher TP volumetric removal rates than 16 storm water treatment wetlands in Florida, USA. The project team attributes the superior project performance to its specialized geometry which is very different from typical Florida wet detention pond designs.

Further studies considering interior baffle dikes in wet detention ponds to assess the trade-off between added cost versus improved nutrient and suspended solids removal are warranted. Wet detention ponds are ubiquitous in Florida, USA and around the globe. This study is evidence that simple, low-cost design improvements to the layout and geometry of these everyday structures can result in significantly more nutrients being kept out of critical surface water bodies.

The removal of nutrients by including submerged or floating wetland plants within wet detention has recently also been investigated in Florida and shown to have promise. Perhaps, the future of wet-detention best management practices (BMPs) will focus on hybrid systems where the hydraulic design of the facility is optimized, and then, the use of plants for nutrient removal can be implemented to enhance the overall hydraulic design.

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