Water Quality Analysis of the Thorgren Naturalized Detention Basin

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ABSTRACT

This paper offers a study demonstrating an integrated stormwater best management practice for nutrient removal, runoff temperature reduction, suspended solids removal, enhanced hydraulic performance and runoff storage, and improved biological integrity. The study includes data collected from the Thorgren Detention Basin in Valparaiso, Indiana, originally designed as a dry-bottom detention basin and comparison data collected from the redesigned naturalized, wet-bottom, basin. Additional information is presented about the construction, finance, operation, and performance monitoring of the basin. We found a significant stormwater quality improvement due to the implementation of the detention basin naturalization effort.

Keywords: Naturalized detention basin; Water quality assessment; Benthic macroinvertebrates; Stormwater green infrastructure

INTRODUCTION

In 2013, the City of Valparaiso, Indiana, spent over $580,000 to naturalize the Thorgren Detention Basin. Because the authors had been monitoring the water quality inputs and outputs prior to the naturalization, this change provided us with a non-experimental opportunity to compare water quality output before and after the naturalization. Most land development projects are required to include stormwater runoff short-term storage facilities such as detention basins. Detention basins are traditionally designed as flood control measures in urbanized areas where stormwater runoffs are generated from streets, yards, and building roofs. They temporarily store, route, and slowly release stormwater runoff at a regulated rate. Traditionally, the main function of a detention basin was to control floods by reducing the peak runoff flow rates [1,2].

Unfortunately, a conventional dry-bottom detention basin does not usually contain wetland and native vegetation and the water quality benefits due to native vegetation are lost. Therefore, they have limited impact on removing pollutants associated with stormwater runoff from urbanized areas. Such pollutants typically include elevated concentrations of dissolved nutrients (nitrogen and phosphorus), dissolved heavy metals, and suspended solids.

Because increased urbanization over the years has resulted in increased flooding, soil erosion, pollutants loading to downstream receiving water bodies have caused poor water quality, degraded aquatic life habitats, and reduced ecosystems biodiversity [3-6]. The Federal Clean Water Act Amendments of 1987 mandated treating nonpoint source pollutants in stormwater runoff [7]. During the last twenty years, many states introduced additional stormwater management regulations and runoff treatment requirements. As a result, different Best Management Practices (BMPs), Low Impact Development (LID) measures, and new technologies were developed [8,9].

The United States Environmental Protection Agency (USEPA) has defined BMPs as "schedules of activities, prohibitions of practices, maintenance procedures, and other management practices to prevent or reduce the pollution of waters of the United States" [10]. As an alternative to traditional dry-bottom detention basins, one BMP is a naturalized detention basin that serves multiple functions including enhanced community flood control, improved water quality and pollutants removal efficiency, enhanced groundwater replenishment, created wildlife habitat and biodiversity, provided environmental educational opportunities for students and residents, provided natural beautification, and generated public appreciation [11]. The major distinctions between dry-bottom detention basins and naturalized basins include the utilization of wetland and native vegetation, and the varied topographic configuration of the basin.

Briefly, the Thorgren Detention Basin is located in the City of Valparaiso, Indiana. The treated stormwater runoff is then released into the Salt Creek watershed, one of Indiana’s Lake Michigan sub-watersheds comprising approximately 20055 hectares (49,557 acres) in Porter County. Salt Creek is tributary to the East Arm of the Little Calumet River. The watershed is made up of urban, agricultural, and forest lands and has over 157-kilometers (98-miles) of waterway. Salt Creek is designated as a salmonid waterway by the State, thus requiring colder and cleaner water to support these unique species. In 2013, approximately 47% of the 38.6-kilometers (24.0-mile) long creek was considered an impaired waterway for E. coli and impaired biotic communities. It was listed on the Indiana Department of Environmental Management (IDEM) 303(d) list which is part of the more comprehensive Indiana Integrated Water Monitoring and Assessment Report. In 2022, only 5.89 km (3.66 miles), approximately 15% of the Creek is considered impaired [12].

In recent years, local, state, and federal agencies, as well as many private organizations, have focused efforts on restoring water quality within Salt Creek by developing and implementing watershed management plans [13,14].

The City of Valparaiso expected to achieve a diverse set of outcomes with its investment in naturalizing the Thorgren Detention Basin. These included:

(1) Reducing downstream flooding and peak flow rates by increasing the detention time, (2) Filtering stormwater runoff by slowing the flow velocity through the basin, (3) Creating a natural habitat, (4) Creating a natural aesthetic landscape, (5) Reducing operation and maintenance costs, (6) Establishing partnerships with regional environmental groups, and (7) Providing educational environmental opportunities for the public students. While the overall project had multiple objectives, we focus on the first two objectives in this paper.

MATERIALS AND METHODS

In this study, we used two methods for monitoring water quality of the dry-bottom detention basin and the naturalized, wet-bottom, detention basin. First, a YSI Pro DSS digital multi parameter water quality meter equipped with four probes (for measuring pH/temperature, conductivity, dissolved oxygen, and nitrate) and a Global Positioning System (GPS) was used to measure temperature, pH, conductivity, dissolved oxygen, and nitrate. Water samples were collected and analyzed for Total Suspended Solids (TSS), Total Nitrogen (TN), Dissolved Phosphorus (DP) and Total Phosphorus (TP), and E. coli bacteria. Second, macroinvertebrate pollution tolerance indexes were calculated as bio-indicators of water quality. The macroinvertebrate index is divided into four Pollution Tolerance Groups. These four group levels (group 1, 2, 3, and 4) represent the different levels of pollution tolerance. The higher the group number, the higher the pollution tolerance level and the lower is its weighing factor with group 1 weighing factor of 4 and group 4 weighing factor of 1. We used the D-Net procedure [15] to perform the benthic macroinvertebrates sampling.

For each sampling event, we took a total of twenty jabs across the sampling area, counted the number of taxa in each pollution tolerance group, multiplied the total taxa number in each group with its weighing factor then totaled the four groups to obtain a Pollution Tolerance Index (PTI) score. The PTI score was used to rate the biological water quality of the basin as follows: excellent ≥ 23, $17<\text{good}<22$, $11<\text{fair}<16$, and poor ≤ 10.The benthic sampling consisted of collecting macroinvertebrates from three locations within the dry-bottom detention basin and using these samples to determine a score consistent with the PTI calculation procedure to determine the biological integrity of the basin [16].

Transforming the basin

The Thorgren Detention Basin is a community detention basin with an area of approximately two acres. It is one of multiple stormwater management components located in the City of Valparaiso, Indiana. It receives stormwater runoff from approximately 121 hectares (300 acres) of residential, industrial, and commercial land. The treated stormwater runoff is then released into Salt Creek at a regulated discharge rate through an outlet structure. Before the basin was naturalized in 2013, it was a dry-bottom detention basin with concrete channels leading from the two inlets at the north and east sides to the single outlet at the south end of the basin. The basin had grass coverage, maintained in a fair condition by regular mowing to keep it in a good aesthetic condition.

The naturalization and retrofitting design features of the reconstruction included removing existing concrete structures and installing meandering pathways, native plant and micro-topography zones, upland infiltration areas, sediment traps, clay-lined ponds, and stormwater runoff storage areas. The result was a basin with varied topography, landscaped sides, and plantings in the basin and sides of native vegetation. The naturalized basin has an approximate surface area of 0.77 hectares (1.9 acres), an average depth of 1.1 meters with the deepest point 2.44 meters, and a constant water volume of approximately 8437 cubic meters (6.84 acre-feet) as shown in Figures 1-3.

Figure 1. Dry-bottom detention basin.

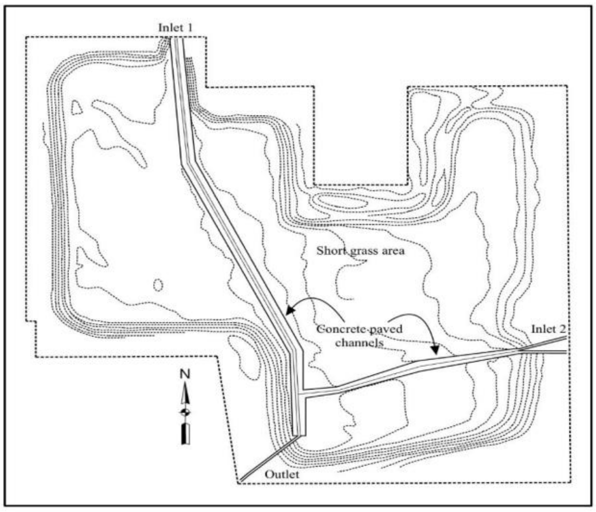


Figure 2. Wet-bottom, naturalized detention basin.

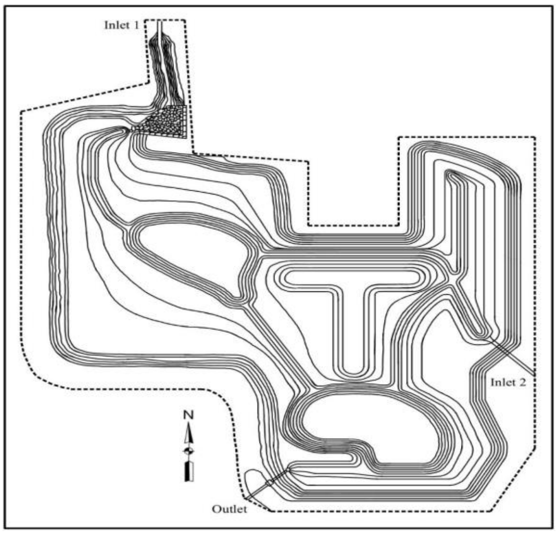
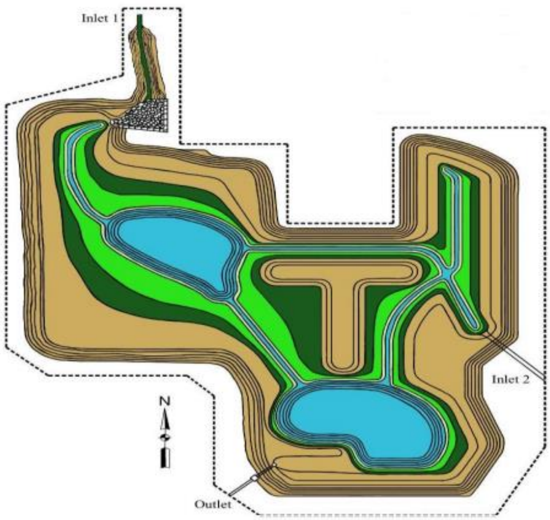


Figure 3. Wet-bottom plant zones. Note: ( ) Deep water zone; ( ) Floating leaf zone; ( ) Emergent zone; ( ) Wet meadow zone; ( ) Upland zone



The details of the naturalization process are important and significant. The process included the following activities:

- Re-engineering the topography of the flat dry-bottom detention pond to create two wet ponds, increase the travel paths of stormwater runoff, create a central island, regrade the banks of the basin to allow for a gentle safe slope, adding energy dissipation zones of a combination of riprap aprons and gabion walls at the two inlets to the basin and creating a sand filtration zone near the basin outlet.
- Rerouting the storm sewer to enter the basin at locations farthest from the outlet structure to allow for longer paths of travel.
- Creating multiple vegetation zones that included, deep water zone (16% of the basin area), floating leaf zone (5%), emergent zone (12.5%), wet meadow zone (12.5%), and an upland zone (54%) to simulate natural wetlands topography.
- The inlet zones to the basin were lined with one-foot-deep cobble stones over geotextile fabric membranes.
- For the basin outlet structure, a 48-inch diameter concrete standpipe with 8-inch in diameter protected inlet opening and 24-inch diameter outlet reinforced concrete pipe. The standpipe was covered using a grate to allow for additional stormwater passing and trash collection when the basin is at full capacity. In addition, the basin was equipped with an emergency spillway.
- Planting a variety of native plant species that included trees and a mixture of native grass and flowering plants. The tree species included autumn blaze maple (*Acer freemanii*), serviceberry multi-stem (*Amelanchier arborea*), river birch multi-stem (*Betula nigra*), eastern redbud multi-stem (*Cercis canadensis*), sweetgum (*Liquidambar styraciflua*), blackgum (*Nyssa sylvatica*), sycamore (*Platanus occidentalis*), bald cypress (*Taxodium distichum*), swamp white oak (*Quercus bicolor*), bur oak (*Quercus macrocarpa*), and tulip trees (*Liriodendron tulipifera*). The trees were planted in the upland zones of the basin.

Hydraulic performance

The hydraulic performance of the dry-bottom detention pond and the naturalized basin were simulated using the US Army Corps of Engineers Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) software. The simulated hydraulic performance of the dry-bottom basin before naturalization is shown in Figure 4 and the simulated hydraulic performance of the naturalized and retrofitted basin is shown in Figure 5.

These performance curves are based upon simulations which account for local rainfall distributions, the basin topography, and the outlet release rates. The Department of Agriculture Natural Resource and Conservation Service (NRCS) Type II rainfall distribution based on the United States National Oceanic and Atmospheric Administration (NOAA) Atlas 14 rainfall depths and durations was used in the simulation.

As shown in these figures, the stage elevation of the dry-bottom basin drops significantly within the 24 hours of each of the depicted 2 year, 5 year, and 1 year 24 hour storm events for the City of Valparaiso, Indiana [17]. While, the stage levels of the retrofitted and naturalized basin slowly dissipate over a 72 hour period after same storm events.

This intentionally designed slow hydraulic dissipation of the naturalized basin contributes to water quality improvement by allowing physical processes such as suspended solids settlement to be more thoroughly accomplished and allows chemical and biological processes such as plants intake of nutrients and decomposition of organics basin is shown in Figures 4 and 5.

Figure 4. Simulated hydraulic performance of dry-bottom basin. **Note:** 2YR24HR (Max 788.7); 5YR24HY (Max 790.1); 10YR24HR (Max 791.3).

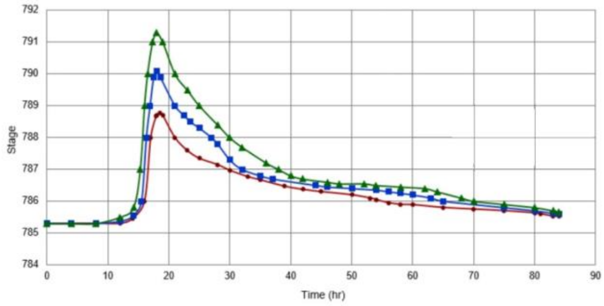
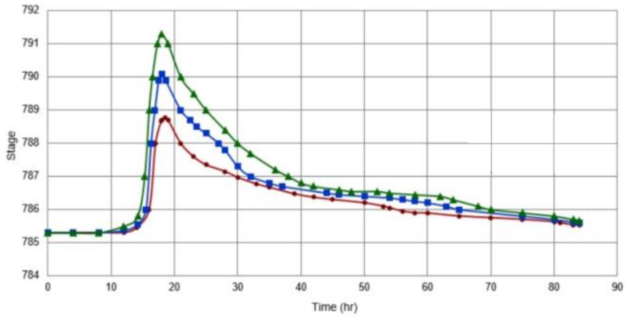


Figure 5. Simulated hydraulic performance of wet-bottom basin. **Note:** 2YR24HR (Max 798.7); 5YR24HR (Max 790.3); 10YR24HY (Max 791.1).



Baseline monitoring

Following each of eight storm events with rainfall intensity of half to one-inch over a 24 hour period, water quality monitoring of the dry-bottom detention basin were conducted at the two inlets and the outlet of the basin. The monitoring parameters included collecting dissolved oxygen, pH, flow rates, total suspended solids, nitrate and total nitrogen, total and dissolved phosphorus, specific conductivity, e coli coliform, and macroinvertebrate distribution data. A YSI Pro DSS multi meter digital water quality meter equipped with four probes (for measuring pH/temperature, conductivity, dissolved oxygen, and nitrate) and a Global Positioning System (GPS), were used to collect the field data.

For the benthic macroinvertebrates monitoring, we used the D-Net sampling method procedure [15-17]. This benthic macroinvertebrate monitoring was conducted near the two inlets and the outlet of the dry-bottom basin. The Membrane Filtration Procedure was used to test for E. coli bacteria [18].

In addition, discrete grab water samples were collected and analyzed in the laboratory for total suspended solids, total nitrogen, and dissolved and total phosphorus. We used the EPA Method 160.2 gravimetric to determine the total suspended solids concentrations, the persulfate digestion method to determine the total nitrogen concentrations, the PhosVer 3 Method to determine the dissolved phosphorus concentrations, and the PhosVer 3 with acid persulfate digestion method for determining the total phosphorus concentrations.

Naturalized basin monitoring

The naturalized, wet-bottom, basin was monitored for flora and fauna development and for the same physical, chemical and biological water quality parameters that were monitored in the baseline study of the dry-detention basin. We used the same instruments, methods, and protocols to collect the water quality data and samples at the two inlets to the naturalized basin (Inlet 1 and Inlet 2), at the outlet, and from the basin sediments. Eight rounds of physical and chemical monitoring events were conducted. We used the D-Net sampling protocol for benthic macroinvertebrate sampling and the PTI score to rate the biological water quality of the basin [15,16].

RESULTS

For each stormwater runoff pollutant, we calculated the pollutant concentration removal efficiencies of the runoff from each of the two inlets for each sampling event and average overall removal efficiency over the eight sampling events. For the dry-bottom detention basin with concrete channels (base-line monitoring), the concentration-based removal efficiency of total suspended solids varied between 25% to 87% with an overall average of 62%; nitrate nitrogen removal varied between -33% to 72% with an average overall removal efficiency of 40.3%; total nitrogen removal varied between 2.5% to 39.7% with an overall removal efficiency of 25.9%; dissolved phosphorus removal varied between -11.8% to 33.3% with an overall removal efficiency of 12.8%; total phosphorus removal varied between 13.8% and 42.2% with an overall average removal efficiency of 27.6%. A summary of these results is presented in Table 1. The pH of the water at the inlets to the basin varied between 7.5 and 8.7 with an average of 7.9 while the pH of the outlet water varied between 7.65 and 8.95 with an average pH of 8.4. The conductivity measured in units of milliSiemens per centimeter (mS/cm) of the inlets water varied between 0.2 mS/cm and 1.8 mS/cm with an average of 1.15 mS/cm, while the outlet water conductivity varied between 0.3 mS/cm and 0.8 mS/cm with an average of 0.6 mS/cm. E. coli bacteria counts in the inlets water varied between approximately 50 colony-forming-units (cfu) per 100 mL and 2950 cfu/100 ml with an average of 850 cfu/100 ml while the count varied between approximately 50 cfu to 2050 cfu/100 ml with an average of 750 cfu/100 ml in the basin effluent.

For the naturalized detention basin, the concentration-based removal efficiency of total suspended solids varied between 75% to 95% with an overall average of 88.6%; nitrate nitrogen removal varied between 43.8% to 62.5% with an average overall removal efficiency of 51.0%; total nitrogen removal varied between 53.3% to 62.2% with an overall removal efficiency of 57.3%; dissolved phosphorus removal varied between 7.1% to 68.0% with an overall removal efficiency of 41.5%; total phosphorus removal varied between 22.2% and 77.8% with an overall average removal efficiency of 55.4%. A summary of these results is presented in Table 1.

Table 1. Summary of mean removal efficiencies.

	Mean removal efficiencies (%)				
Basin/Material	**TSS**	**Nitrate-N**	**TN**	**DP**	**TP**
Dry-bottom	62	40.3	25.9	12.8	27.6
Wet-bottom	88.6	51	57.3	41.5	55.4

The pH of the water at the inlets to the basin varied between 5.9 and 7.9 with an average of 7.01 while the pH of the outlet water varied between 6.64 and 7.15 with an average pH of 6.98. The conductivity of the inlets water varied between 0.95 mS/cm and 2.99 mS/cm with an average of 1.55 mS/cm, while the outlet water conductivity varied between 0.93 mS/cm and 2.4 mS/cm with an average of 1.31 mS/cm. E. coli bacteria counts in the inlets water varied between approximately 150 and 2050/100 ml with an average of 920/100 ml while the count varied between approximately 150 to 2000/100 ml with an average of 1136/100 ml in the basin effluent.

The flora and fauna of the naturalized basin included American pondweed (*Potamogeton nodosus*), small pondweed (*Potamogeton foliosis*), duckweed (*Lemna minor*) and Coontail (*Ceratophyllum demersum*). Native riparian vegetation noted consisted of Bulrush (*Scirpus validus*), Arrowhead (*Sagittaria latifolia*), Goldenrod (*Solidago altissma*), Tall Boneset (*Eupatorium altissimum*) and Sawtooth Sunflower (*Helianthus grosseserratus*). The fauna consisted of Common Carp (*Cyprinus carpio*) and Mallard ducks (*Anas platyrhynchos*). Although not technically an invasive/exotic species, Duckweed reproduces rapidly and has the potential to cover the entire surface of a waterbody. Further, Duckweed can cause oxygen depletion in a waterbody by blocking out beneficial sunlight to the pond which will cause all other plants to die and decompose.

Analysis

The dry-bottom detention basin north inlet is the main contributor of suspended solids, nutrients (nitrate, total nitrogen, dissolved phosphorus, and total phosphorus), and E. coli bacteria. The base-line water quality monitoring results show that the dry-bottom detention basin resulted in an increase of the effluent water pH (from an average of 7.9 to 8.4), increase in dissolved oxygen concentration from an average of 7.0 mg/L to 9.0 mg/L, decrease of E. coli bacteria count in the effluent by an overall average of approximately 12%, decrease in effluent water conductivity (from an average of 1.15 mS/cm to 0.6 mS/cm), 62% decrease in total suspended solids , 40% reduction in nitrate, 26% reduction in total nitrogen, 13% reduction in dissolved phosphorus, and 28% reduction in total phosphorus. Benthic macroinvertebrates communities were severely impaired (PTI<2) throughout and along the inlets and outlet of the basin. Similar to the dry-bottom detention basin, the north inlet to the naturalized basin is the main contributor of suspended solids, nutrients, and E. coli bacteria. However, the naturalized basin significantly improved the stormwater runoff quality by reducing the influent pollutants concentrations by an overall average of 88.6% of total suspended solids, 51% of nitrate, 57.3% of total nitrogen, 41.5% of dissolved phosphorus, and 55.4% of total phosphorus. While the benthic macroinvertebrates rated poorly near inlet number 1 both before (PTI=1.6) and after (PTI=3) the naturalization, it was rated excellent (PTI=29) near inlet number 2 and at the outlet (PTI=27) after the naturalization. A summary of the macroinvertebrates analysis results is presented in Table 2.

Table 2. Summary of macroinvertebrate pollution tolerance rating.

Basin/Location	Inlet 1	Inlet 2	Outlet
Dry-bottom	Poor	Poor	Poor
Wet-bottom/Naturalized	Poor	Excellent	Excellent

DISCUSSION

It is well known that dry-bottom detention ponds remove stormwater-laden pollutants primarily through the settling of suspended solids. There is typically a limited amount of biological and chemical activity taking place in these basins since they are mostly dry for several days between storm events. Limited amounts of particulate phosphorus and nitrogen may be removed due to the settling process. This explains the low removal efficiency of nutrients (dissolved phosphorus, total phosphorus, nitrate nitrogen, and total nitrogen) and total suspended solids compared to the removal efficiencies in the naturalized basin. While we observed that the Dissolved Oxygen (DO) concentration in the dry detention pond increased at the outlet of the basin, it decreased across the naturalized basin from the inlet to the outlet. We contribute the increase in DO concentration to reaeration of the water due to its relatively fast flow in the concrete channel across the dry detention pond and the decrease in DO concentration to the decomposition of oxygen-demanding organic materials, aquatic life, and other biological activities. The naturalized basin appears to slightly dampen the pH variation between the inlets and the outlet. The measured pH values at the inlets varied between 5 and 9.5, while it varied between 6 and 9 units at the outlet. We observed the water temperature of the naturalized basin inlets and outlet was relatively constant during the cold seasons while it was significantly lower by about 50% by the late spring season.

We also observed significant dampening of water conductivity during the winter months. The water conductivity measurements at the inlets were as high as 16.0 mS/cm in February while the outlet conductivity measurements did not exceed 2.5 mS/cm during any monitoring event. Otherwise, it was slightly higher at the outlet during the rest of the year. This can be attributed to the use of road salt brine spraying during the winter months. While the naturalized basin significantly improved the fauna biodiversity, we did not observe a significant difference of E. coli counts between the inlets and the outlet.

CONCLUSION

The naturalized basin significantly improved stormwater runoff water quality by removing a significant amount of nutrients and suspended solids, dampening the pH, conductivity, and temperature variations, and significantly improved the richness of the basin biological environment. Therefore, this project is proven to be a worthy City of Valparaiso investment in improving stormwater runoff quality. However, such investment would have been more cost-effective and had a higher positive environmental impact on Salt Creek and Lake Michigan if the dry-bottom detention basin had been originally designed as a naturalized, wet-bottom, basin. Ultimately, this project supports environmental sustainability beyond local community benefits.

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DECLARATIONS

All data and materials are available from the corresponding author.

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COMPETING INTEREST

The authors have no competing interest to declare that are relevant to the content of this article.

AUTHORS CONTRIBUTIONS

Zuhdi Aljobeh directed the field work, wrote the main manuscript text, and prepared draft figures and tables. Rick Gillman performed the formatting and editing on the manuscript and organized the references. Cruz Ibarra Jr. prepared the final versions of the figures. All authors reviewed the completed manuscript.

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