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Water Quality Improvement and Pollutant Removal by Two Regional Detention Facilities with Constructed Wetlands in South Texas

Javier Guerrero [1,*], Ahmed Mahmoud [2], Taufiqul Alam [3], Muhammed A. Chowdhury [3], Adeniyi Adetayo [3], Andrew Ernest [2] and Kim D. Jones [3]

1 Research, Applied, Technology, Education and Service, Inc., Rio Grande Valley, Edinburg, TX 78540, USA
2 Department of Civil Engineering, University of Texas Rio Grande Valley, Edinburg, TX 78539, USA; ahmed.mahmoud@utrgv.edu (A.M.); andrew.ernest@utrgv.edu (A.E.)
3 Department of Environmental Engineering, Texas A&M University-Kingsville, Kingsville, TX 78363, USA; taufiqulce113@gmail.com (T.A.); chowdhury_wasa@yahoo.com (M.A.C.); Adetayoadeniyi1@gmail.com (A.A.); kjones@tamuk.edu (K.D.J.)
* Correspondence: jguerrero@ratesresearch.org

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Abstract: Stormwater runoff introduces several pollutants to the receiving water bodies that may cause degradation of the water quality. Stormwater management systems such as detention facilities and wetland can improve the water quality by removing various pollutants associated with the runoff. The objective of this research project is to determine the performance and efficiency of two major regional detention facilities (RDFs) with different designs and structures in reducing pollutants based on various storm events in McAllen, Texas. The two sites are the McAuliffe RDF and the Morris RDF; each site was incorporated with a constructed wetland with a different design and structure to enhance the pollutant removal process. The McAuliffe RDF reduced the concentration and load of many stormwater constituents in comparison to the Morris RDF. The observed concentrations and pollutant loads of suspended solids were much lower in the runoff of the inlet compared to the outlet for both sites. The McAuliffe RDF showed better concentration and load reduction for nutrients, such as nitrogen and phosphorus, of different species. However, both sites did not show a significant improvement of organic material. In addition, the indicator bacteria concentration represented a fluctuation between the inlet and outlet at each site.

Keywords: stormwater management; urban runoff; load reduction; green infrastructure; wetland; indicator bacteria; nutrients; semi-arid

1. Introduction

Urban stormwater runoff contains substantial loads of numerous chemical and physical constituents that may adversely affect the water quality of rivers, channels, and lakes. These constituent loads are caused by rainfall wash-off. They carry various pollutants that cause a decline in aquatic biota and degradation of the water quality, and they are often discharged into untreated surface water [1,2]. Recently, the rapid urbanization in the Lower Rio Grande Valley (LRGV) has increased the stormwater runoff and pollutant loading into the receiving water bodies through the region. One of the affected waterbodies is the Arroyo Colorado Watershed, which flows through the LRGV [1]. The transformation of the watershed from its natural state has contributed to a water-quality problem. The watershed has been exposed to non-point source pollution from the extensive agricultural development that is interspersed with areas of rapid urban development [3]. Henceforth, an overload of nutrients and oxygen-demanding materials was transported across the river stream water; both components of this overload were associated with agricultural and stormwater runoff. Local entities through the LRGV region started the adoption and implementation of Green Infrastructure (GI) as an effective management strategy to address the water-quality issues. GI not only reduces runoff volume; it also increases water quality through structures such as detention basins, bioretention ponds, and wetlands [4,5]. Several studies have also shown the water-quality benefits of GI through the effective reduction of nutrients, biodegradable organic material, and bacteria from urban stormwater runoff [6,7].

Detention basins are stormwater management structures that temporarily collect runoff and then release a reduced flow gradually to decrease the risk of flooding [8]. Detention systems provide effective low-cost, low-maintenance treatment of stormwater runoff from highways and other urban or industrial areas [9]. Their implementation is considered one of the most widely used management practices to reduce runoff volume. Detention basins are stormwater management strategies that may also be used to improve water quality by maximizing sedimentation through chemical and biologic processes. Detention ponds with relatively simple design criteria can be used to provide excellent water-quality benefits over a wide range of storm conditions [10]. Extended detention basins are constructed to hold stormwater for at least 24 h to allow solids to settle and to reduce local and downstream flooding. The basins are designed to detain smaller storms for a sufficient period of time to remove pollutants from the runoff. The water-quality improvement is optimized by maximizing the detention time of stormwater in a detention pond. The primary pollutant removal mechanism in detention basins is sedimentation through settling up the solid particles at the bottom of the basin. Some studies have shown that detention basins are effective at removing solids from urban runoff. In addition, nutrients and heavy metals may also be removed through flowing urban runoff in the detention systems [11,12]. Nutrients associated with solids, such as nitrogen and phosphorus, are also removed through sedimentation. The two main components that affect the system performance are the retention time and influent concentration [13]. A significant water-quality improvement through settling is achievable by increasing the retention time of the water, removing suspended solids with associated pollutants [14–16]. Pretreatment can be a fundamental design component of a detention pond to reduce the potential for clogging. A properly designed detention basin is effective in reducing pollutant loads and may be used to meet the stormwater management standards. If it is maintained as shallow wetland, the lower stage of the detention basin incorporates natural biological removal processes to enhance the removal potential of soluble pollutants [17].

Stormwater wetlands are engineered systems consisting of shallow ponds that have been planted with aquatic plants; they rely on the utilization of the natural functions of vegetation, soil, and microbes associated with assembled processes to treat the wastewater [18]. Stormwater wetlands use physical, chemical, and biological processes to treat urban runoff. Previous studies have demonstrated that wetlands have efficiently removed sediment, nutrients, and heavy metals associated with runoff through sedimentation, attachment of porous media, chemical and biological processes, and plant uptake [19,20]. Wetlands are classified into two types: either natural or constructed. Natural wetlands act as ecosystem filters by improving the water quality passing through the system. However, constructed wetlands are engineered systems designed to remove pollutants from contaminated water by using natural processes. Constructed wetlands have higher removal efficiency than a natural one due to the longer water circuits in the constructed system, which allows more retention time [21]. Organic compounds are removed by the wetland through microbial degradation under anaerobic conditions in the filtration bed where oxygen levels are very limited [22]. Several studies have shown that wetland is effective in reducing the suspended solids from stormwater runoff [23–25]. Wetlands are highly effective in removing suspended solids from runoff through the settling and filtration provided by dense vegetation [26]. However, an upstream sedimentation process unit is suggested to enhance their performance by avoiding the premature clogging of the wetland by total suspended solids (TSS) [27]. Moreover, stormwater wetlands provide flood control benefits by decreasing the flow velocity, reducing the peak discharge, and slowly releasing the stored water over a period of time [28].

Similar to detention basins and other GI systems, wetlands are installed to reduce the delivery of pollutants to surface waters, and their performance is commonly reported as being variable due to the site-specific nature of influential factors [29,30].

The removal of nitrogen and phosphorus through wetlands is variable and depends on several factors, such as the load variation, inflow concentration, hydraulic retention time, temperature, hydraulic efficiency, and type of wetland [31]. Nitrogen can be removed through different independent processes, such as denitrification, volatilization, sedimentation, and plant uptake. However, denitrification is considered the major removal mechanism of nitrogen in the wetland. Studies have shown that wetlands typically perform well for nitrate removal because the anaerobic conditions and organic material in wetland sediment create an ideal environment for denitrification. At the same time, due to a lack of oxygen in the wetland filtration bed, the removal of ammonia is limited [32]. Significant nitrate reduction is commonly observed in stormwater wetlands, but total nitrogen reduction depends on the species and concentration of incoming nitrogen [32,33]. Several studies have demonstrated that wetland can effectively remove the total nitrogen (TN) with a median removal efficiency of 37%, and that this reduction significantly correlates with the hydrological loading rate and temperature [31].

Similar to nitrogen removal mechanisms, phosphorus can be removed by sedimentation and plant uptake. In addition, phosphorus can be removed also by sorption or ligand exchange reactions; phosphate replaces hydroxyl or the water group from the surface of iron and aluminum hydrous oxide [32]. A study compared the total phosphorus (TP) removal of 146 studies from wetlands. Results showed that the median removal efficiency of all studies of TP is 49%, and it was significantly correlated with the TP concentration, hydrologic loading rate, and wetland area [31]. Similar to metals, phosphorus can desorb from sediments in a wetland under anaerobic conditions [24]. Humphrey et al., 2014 studied the stormwater water-quality improvement in a constructed wetland in North Carolina. Results showed that high pollutant reduction efficiency is due to the relatively large size of the wetland area and below-average rainfall that likely contributed to improving the water-quality performance [30].

Further investigations are needed to evaluate the sustainable removal performance of constructed wetland and detention basins, which will contribute greater insights into the nutrient treatment process [11,34]. Numerous studies have been conducted on detention basins in a wet climate, but their functionality in removing pollutants in arid/semi-arid regions has not been widely investigated during a rain event for certain land-use types [35]. The best prospects for successful wetland treatment and pollutant removal should be in warmer regions of the world [18], which indicates that the LRGV can be an ideal region for studying wetland performance and its effects on various pollutants. Previous studies have shown the effectiveness of wetland and detention ponds for improving stormwater quality separately under variable rainfall events. However, it is important to evaluate the performance of a regional detention facility (RDF) incorporated with a combination of a constructed wetland and a detention pond to improve the quality of stormwater runoff during different rainfall events. The overarching goal of this study is to quantify the effectiveness of regional detention facilities in improving the quality of stormwater runoff. The main objectives of this study are to compare the performance of two regional detention facilities with a constructed wetland—one with a detention pond and another without a detention pond—to achieve a feasible pollutant load reduction. The second objective is to evaluate the RDFs' performance for pollutant load reduction and to identify the factors influencing their effectiveness at each site.

2. Methodology

2.1. Site Description

The Morris RDF is located behind Morris Middle School at 1400 Trenton Ave, McAllen, Texas, spanning an area of 121,406 m^2. The RDF is elliptical in shape, and the slope within the RDF is ~1%. The RDF was intended to serve as a recreational facility during dry weather. The design includes a channel on the periphery that serves to drain some runoff from within the basin (Figure 1A). No microscreen was installed at the upstream of this facility. However, the Morris RDF has one wetland in the middle of the channel connecting the inflow and outflow monitoring points. A constructed wetland was created near the midpoint of this channel (Figure 1B). This wetland was planted with a mixture of vegetation, including California bulrush (*Schoenoplectus californicus*) and Olney bulrush (*Schoenoplectus americanus*). The constructed wetland is elliptical in shape with a width of 22 m and average depth of 0.30 m. The side slope of this wetland is less than 1%. The average width of the incoming and outgoing channel is 4.87 m with a depth of 0.76 m (Figure 1C,D). The total drainage area of the Morris RDF is over 20.6 km^2, which is comprised of more than 93% urbanized landscape. According to the National Land Cover Database (NLCD), the dominant percentage of land cover drainage area in the Morris RDF urbanized areas is developed between high to low intensity, such as in parking lots and on pavements; the remaining 7% is either cultivated crops or developed open space (Figure 2A). The Morris RDF drainage area has more urbanized area and less cultivated crops in comparison to the McAuliffe RDF. The dominant percentage for the Morris RDF drainage area lies with hydrologic soil group B soil (97%). The dominant soil type in this watershed is type B soil (97%).

Figure 1. The Morris Regional Detention Facility (RDF) site: (**A**) aerial view for the site location, (**B**) vegetation on the wetland, (**C**) wetland structure, and (**D**) cross section showing the depth and dimensions of Morris wetland.

Spanning 113,312 m^2, the McAuliffe Regional Detention Facility (RDF) is located behind McAuliffe Elementary School (Figure 3A). This RDF serves a drainage area of approximately 5 km^2. It is a dual-purpose facility, providing recreational opportunities during dry periods and stormwater detention during wet weather. The RDF site boundaries are Nolana Avenue on the north and US 83 Business Expressway. On the south boundary, Ware Road is on the west side, and an eastern boundary extends to N 23rd Street. Runoff generated in the watershed is delivered to the RDF by a man-made drainage channel located upstream of the RDF. The watershed is comprised mainly of urbanized landscapes (83%). The NCLD land cover database showed that the majority of the urbanized area is either medium to low intensity (Figure 2B). Cultivated crops and developed open space cover about 0.75 km^2 of the total drainage area. The flow to the RDF mainly consists of stormwater runoff along with some groundwater seepage. The dominant hydrologic soil group B (92%) has moderately low runoff potential when thoroughly wet [36]. The soil in the watershed is mainly comprised of type B

(92%) with type D (6%) and type C (2%) forming the rest. The detention basin at McAuliffe Elementary School has gradually sloping banks. A larger amount of urban runoff with sediment and nutrients during wet weather discharges to the man-made drainage channel located upstream of the RDF. There are two wet detention ponds that are considered permanent pools. They provide more residence time for the runoff, as they are aided by sedimentation and infiltration. The first wet pond starting from the upstream has an estimated area of 3400 m^2, and the second pool has an estimated area of 5139 m^2. To maintain flow balance in between these two pools, a connection via a concrete pipe has been established. The water from the second pool drains out to the wetland area at the end of the basin through another concrete pipe.

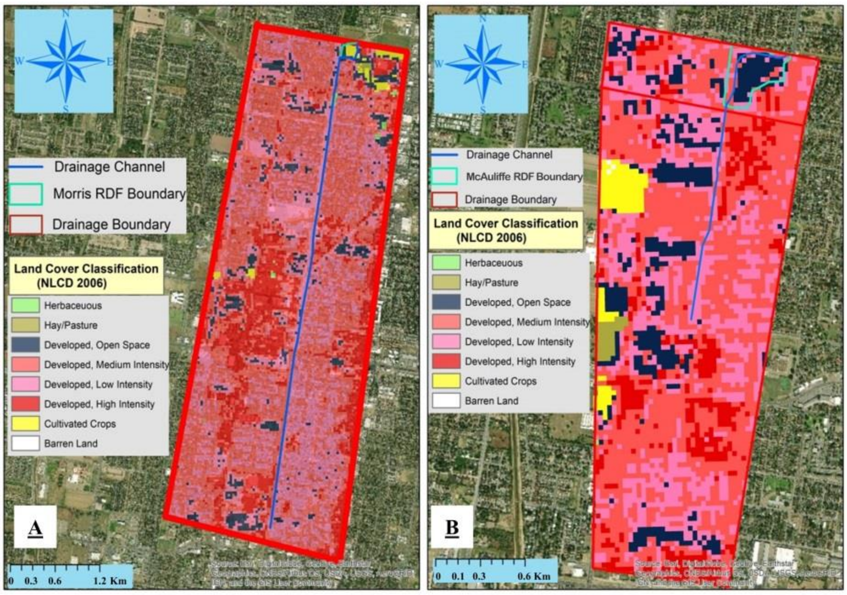

Figure 2. Land cover distribution for the watershed area at each site: (**A**) Morris and (**B**) McAuliffe.

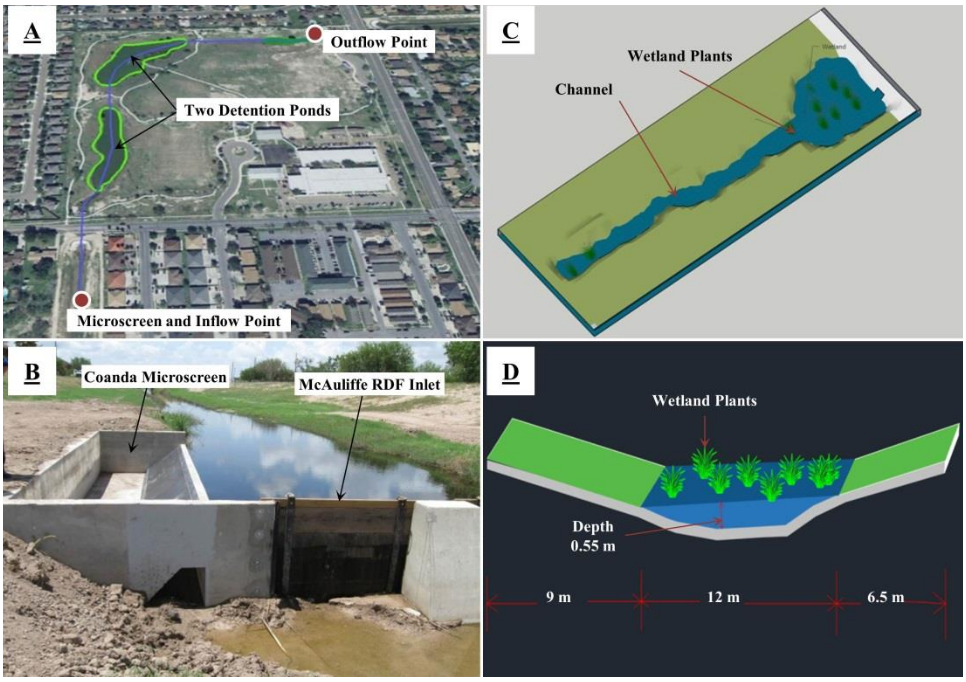

Figure 3. The McAuliffe Regional Detention Facility (RDF) site: (**A**) site location showing the two wet detention and wetland locations, (**B**) microscreen installed at the inlet, (**C**) wetland structure, and (**D**) cross section showing the depth and dimensions of the McAuliffe wetland.

The McAuliffe RDF was designed with a small channel wetland near the outflow monitoring point and the microscreen close to the inflow monitoring point on the upstream. A Coanda screen was installed in a concrete structure built parallel to the McAuliffe inlet (Figure 3B). There is an increasing need to screen water in surface water collection systems to remove floating debris and small aquatic organisms to protect the receiving water bodies [37]. Previous studies found that a microscreen can remove solids by 3.5 times regardless of mesh size, but it is not effective in lessening the amount of dissolved substances [38]. The main purpose of using a microscreen in this study was to make the water free from debris or other larger particles, such as floatables, which may have clogged the channel by depositing on the channel bed. This screen is a self-cleaning apparatus, which performs without any power requirement. The microscreen used at the McAuliffe inlet RDF site operates based on the Coanda screen principle. The Coanda effect is a hydraulic feedback circuit that produces a fluidic oscillator for which the frequency is linear with the volumetric flow rate of fluid [39]. This screen is a self-cleaning apparatus that does not require any power. The Coanda screen is installed perpendicular to the two concrete chambers for storing and diverting the overflow. The dimensions of this microscreen are 7.6 m long and 0.76 m wide; it can handle a maximum flow of 2 cm/s. If the flow exceeds this maximum capacity, there will be an overflow, resulting in some debris being carried downstream. During normal operation, the incoming water flows over the screen, passes through the openings in the screen, and falls into the outlet underneath, which is approximately 0.46 m deep. A headwall perpendicular to the channel is provided in order to increase the head by 0.37 m. The flow from upstream of the Coanda screen flows through the screen aperture and the debris or other particles larger than the screen openings are trapped upstream. The debris collection chambers assist to hold the debris for a certain time before periodic maintenance is carried out.

A small wetland was constructed just before the McAuliffe RDF outlet; this wetland consists of a channel wetland of primarily Olney bulrush (*Schoenoplectus americanus*) plants (Figure 3C,D). The *Schoenoplectus* species complex includes interesting and dynamic wetland species of ecological importance, and the growth of the stem largely depends on the combined nitrogen and phosphorus concentration present in the water [39]. This plant provides some biological treatment by nutrient uptake, infiltration, and reduction in the flow of stormwater from the McAuliffe RDF basin. The wetted area of the wetland is 170.94 m^2 with side slopes of 5:1 horizontal to vertical (H:V) on the left side and 4.5:1 H:V on the right side. The maximum width of the main wetted portion of the wetland is 11.89 m with an average depth of 0.55 m from the water level. The wetland water flows from a concrete outlet with dimensions of 3.3 m × 1.7 m.

2.2. Sampling, Monitoring, and Analysis

The area velocity flow module (2150 Teledyne ISCO) was used to measure the stream velocity and the stream level. These two parameters can be used, along with the cross-sectional area of the stream, to calculate the flow rate. The velocity sensors installed in each of the stormwater monitoring sites work based on the Doppler effect. The level of the stream was detected based on the difference in atmospheric and hydrostatic pressures acting on an internal transducer. The velocity and level measurements were recorded by the sensor on a second-by-second basis. However, the data were saved once every 15 s to 24 h, depending on the requirement. The flow modules at the two RDFs were programmed to store data every 5 min. The velocity and level data were retrieved by a computer running the FLOWLINK program to calculate the flow using the velocity and level readings from the velocity sensor. The data recorded by the field instruments were retrieved and viewed on the FLOWLINK software. The retrieved flow data were imported into Excel software to draw the inflow and outflow hydrographs for each rainfall-runoff event and calculate the flow volume. The RDFs' residence time for each event was estimated based on the time between the inflow and outflow peak.

The water-quality sampling protocol adopted in the initial Texas Commission on Environmental Quality (TCEQ) approved the Quality Assurance Project Plan (QAPP) for collecting composite samples for every 41 m^3 of flow [40]. Automated composite samplers (Teledyne ISCO 6712 Portable) were set up at the inlet and outlet of the McAuliffe and Morris RDFs, which collected composite samples based on a user-programmed frequency in a 15 L bottle. The sampling interval was based on flow pacing (sampling process triggered by the flow) and was the same for both sites initially. A peristaltic pump was mounted on the control console that was housed in a protective acrylonitrile butadiene styrene (ABS) plastic casing. The pump was programmed to retry sampling up to a maximum of 3 times. The pump also purged the suction line before and after collecting the sample to ensure that the suction line was not plugged. The autosampler was connected to 2150 via cable, and the 2150 acted as the primary controller for the 6712. All samplers were programmed to enable themselves when certain level-rise conditions were satisfied. Before May 2012, the samplers were initially programmed to draw a fixed aliquot (100 mL) for every 41 m^3 of flow once the event started; this decision was based on a preliminary evaluation of historical rainfall data and drainage areas and estimated runoff coefficients. From the 2011–2012 data, a new sampling protocol was developed based on an event of 17,000 m^3 of design inlet flow to fill up a 3 L volume or one 100 mL aliquot for each 567 m^3 of flow. Additionally, as the sample bottle has a much larger capacity of 15 L, this protocol could representatively sample an event up to 5 times as large (85,000 m^3). This range of sampling would encompass over 90% of the 24-h storm events for this area based on the historical data. For the McAuliffe RDF, water-quality samples at the inlet and outlet point were collected over 22 months, from June 2011 through April 2013, and they were analyzed (approximately 8 events). During the same monitoring period, approximately 12 samples were collected from the Morris RDF. After collecting, composite samples were transferred to a National Environmental Laboratory Accreditation Program (NELAP) certified lab contractor (Ana-Lab Corp facility), and concentration data were obtained after the analysis.

In our study, composite samples analyzed nutrients, suspended solids, and the bacterial concentration, which were used to calculate the pollutant load reduction on an event-by-event basis. The inflow and outflow volume for each event was obtained from FLOWLINK software. All samples were analyzed for five nutrient components: Nitrate-Nitrite Nitrogen (NO_x), Total Kjeldahl Nitrogen (TKN), Total Nitrogen (TN) and Total Phosphorus (TP), total suspended solids (TSS), *Escherichia coli* (*E. coli*), and Biochemical Oxygen Demand (BOD_5). All the water-quality parameters were analyzed within the recommended holding time using standard methods for NOx (EPA 300.0), TKN (EPA 351.2), TP (SM 365.3), TSS (SM 2540 D), *E. coli* (SM 9223-B), and 5-day BOD_5 (SM 5210 B) [40]. The percentage load reduction of pollutants achieved by the RDF for each monitored rainfall event was calculated using the following a mass balance equation:

$$\text{removal efficiency}: \ RE_i = 1 - \frac{C_{i-Outlet}}{C_{i-Inlet}} \tag{1}$$

$$\text{total pollutant mass}: \ M = \sum_{i=1}^{n} V_i \times C_i \tag{2}$$

$$\text{summation of pollutant loads}: \ SOL = 1 - \frac{\sum_{i=1}^{n} M_{Outlet}}{\sum_{i=1}^{n} M_{Inlet}} \tag{3}$$

where, C_{outlet} = concentration at the outlet for event $i = 1, 2, 3 \ldots n$; C_{inlet} = concentration at the inlet for event $i = 1, 2, 3 \ldots n$; and V = event volume

In terms of water quality, the dataset of each pollutant was assessed using the Kolmogorov–Smirnov test to ensure the concentration values followed the normal distribution. Based on the characteristics of the data, the significance in the difference between the influent and effluent concentration would be hypothetically justified either by using a paired *t*-test (parametric) or the Wilcoxon signed-rank test (non-parametric). The correlation between different hydrologic and water-quality parameters was determined by Pearson Multiple Correlation Coefficient (PMCC) analysis. The significance of the correlations was also validated by the regression hypothesis test. In terms of the pollutant load, the significant difference in the amount between the inlet and outlet would be hypothetically tested by using either the *t*-test (parametric) or Mann–Whitney U test (non-parametric) based on the distribution of the calculated data.

3. Results and Discussion

3.1. Water-Quality Sampling and Analysis

Figures 4 and 5 represent the comparison of the influent and effluent concentrations at the Morris and McAuliffe RDF sites for different rainfall magnitudes, which were recorded during the monitoring timeframe. Results from the Kolmogorov-Smirnov test suggest that our concentration data do not differ significantly ($p > 0.1$) from that which is normally distributed. The pollutant concentrations for both RDFs were compared to those reported by the US Environmental Protection Agency (USEPA) National Urban Runoff Program (NURP) for mixed land-use settings.

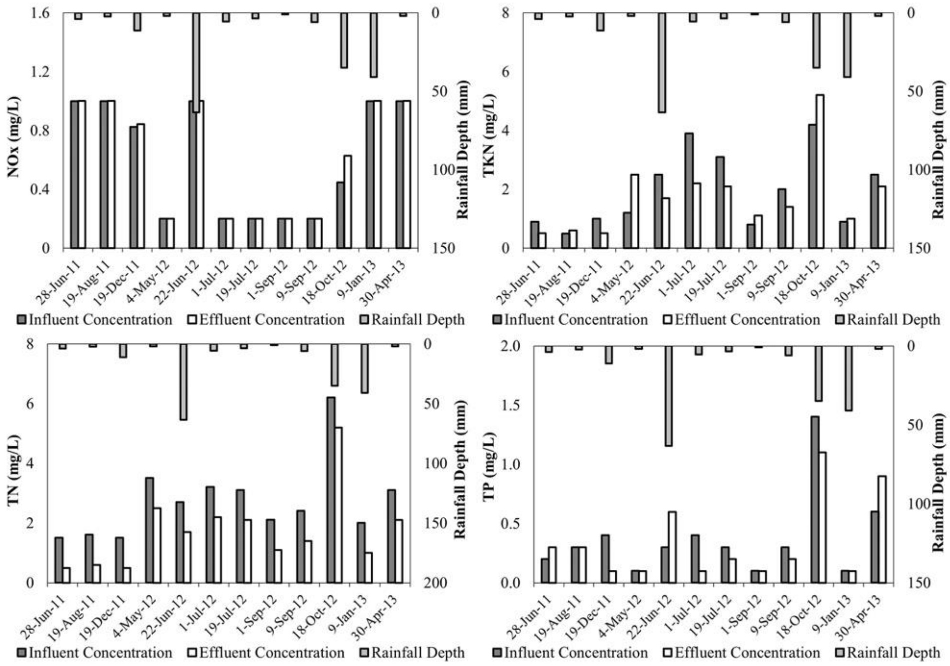

Figure 4. Bar chart representing influent and effluent concentrations for different nutrient components (Nitrate-Nitrite Nitrogen (NO_x), Total Kjeldahl Nitrogen (TKN), Total Nitrogen (TN), and Total Phosphorus (TP)) collected at the outlet of the Morris RDF for the different magnitude of rainfall events within the monitoring timeframe of 28 June 2011–30 April 2013.

Figures 4 and 5 demonstrate the concentration of pollutants and the corresponding rainfall depth from the Morris RDF. Samples were collected from 12 rainfall events throughout the monitoring period. The concentration of all pollutants was relatively higher from May 2012 to October 2012. The number of BOD_5 and *E. coli* samples was less than for the other parameters due to the holding-time limitation after the sample collection. The holding for BOD_5 and *E. coli* was 48 and 24 h, respectively. Some of the samples passed the test standards holding time and were not analyzed for either BOD_5 or *E. coli*. Therefore, reliable BOD_5 and bacterial data were cumbersome to collect due to their shorter holding time. The median influent concentration of NO_x, TKN, TP, TSS, and BOD_5 was observed much closer to the NURP standard, which was approximately 1.1 to 1.6 times higher than the standard values. However, the mean influent *E. coli* concentration (15,079 MPN/100 mL) was below the NURP average (25,000 MPN/100 mL), approximated from the typical range of 400–50,000 MPN/100 mL [41]. Our paired *t*-test results indicate that the observed influent and effluent concentrations from the Morris RDF is not significantly ($p > 0.05$) different for the parameters analyzed. The NO_x intake concentration was around 0.99 or 0.197 mg/L for most of the events; thus, those values were approximated to 1.0 & 0.2 mg/L. The maximum influent concentration of NO_x (1.0 mg/L), TKN (4.20 mg/L), TN (5.20 mg/L), TP (1.4 mg/L), *E. coli* (61,310 MPN/100 mL), and TSS (2270 mg/L) was reported on 18 October 2012, induced from 35 mm of rainfall depth, which was depleted to 5.20, 6.20, 1.1, 853, and 12 mg/L prior to reaching the outlet, respectively. Surprisingly, the *E. coli* concentration was also observed higher at the outlet (57,940 MPN/100 mL) for the same event. The maximum BOD_5 intake (57 mg/L) was observed from 4 mm rainfall depth (occurred on 1 July 2012), which was depleted to 29 mg/L at the outlet. An increase in the effluent concentration was observed for TP, TSS, and *E. coli* for about 25% of the total sampling events. Although there was no significant change observed in NO_x concentration, less than 60% of the total rainfall events were reported with lower TKN, TN, and BOD_5 concentrations at the outlet.

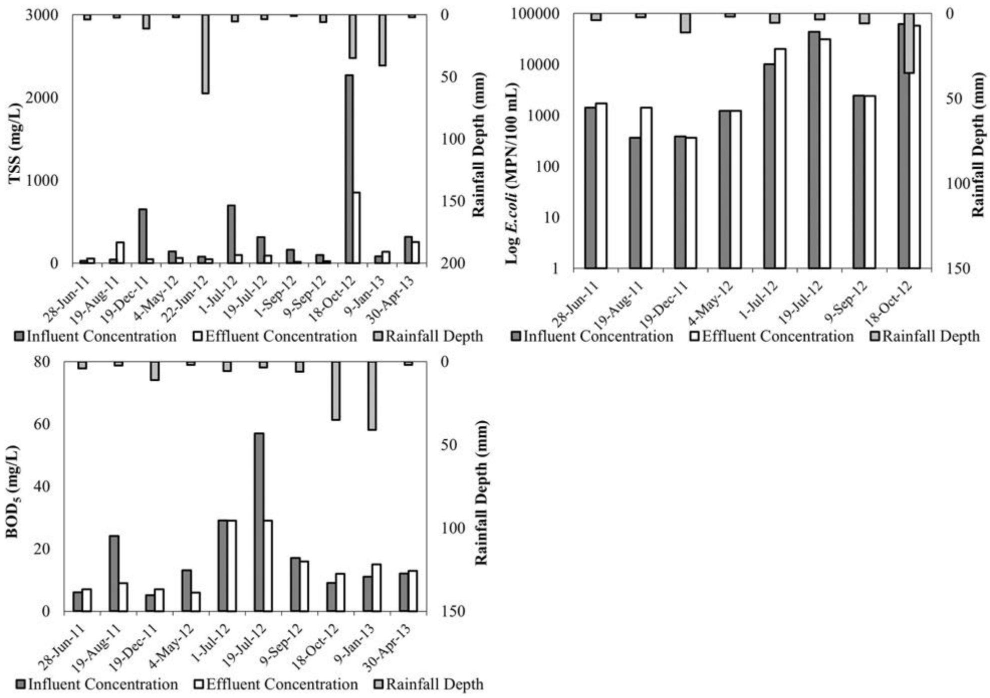

Figure 5. Bar chart representing influent and effluent concentrations of total suspended solids (TSS), *E. coli*, and Biochemical Oxygen Demand (BOD_5), collected at the outlet of the Morris RDF for the different magnitude of rainfall events within the monitoring timeframe of 28 June 2011–30 April 2013.

Table 1 demonstrates the water-quality results summary for the Morris RDF for all parameters of analysis. Almost all the pollutants showed an elevated median concentration at the outlet of the Morris RDF. Although there was some depletion observed for TKN (11%), TN (7%), TP (9%), and BOD_5 (22%) on average, the median TKN, TSS, and BOD_5 concentration at the outlet slightly exceeded NURP typical values by 1.2, 1.1, and 1.6 times, respectively. Despite the relatively higher median than the NURP standard, the median TSS depletion efficiency was achieved by 49%, which was the maximum among all the pollutants analyzed. However, the expected TSS removal efficiency from a conventional detention facility is 75% [41,42].

Table 1. Summary of detailed statistics of observed water-quality results for different pollutants (NO_x, TKN, TN, TP, TSS, *E. coli*, and BOD_5) at the outlet of the Morris RDF based on the total number of monitoring events and their comparison to US Environmental Protection Agency (USEPA) National Urban Runoff Program (NURP) standard.

Parameters		NO_x		TKN		TN		TP		TSS		*E. coli*		BOD_5	
		In [1]	**Out** [2]	**In** [1]	**Out** [2]	**In** [1]	**Out** [2]	**In** [1]	**Out** [2]	**In** [1]	**Out** [2]	**In** [1]	**Out** [2]	**In** [1]	**Out** [2]
Concentration (mg/L) [3]	Mean	0.6	0.6	2.0	1.7	3.0	2.7	0.4	0.3	406	161	15,079	14,511	18.3	14.3
	S.D. [4]	0.4	0.4	1.3	1.3	1.3	1.3	0.4	0.3	629	232	23,735	20,860	15.6	8.5
	Min	0.2	0.2	0.5	0.5	1.5	1.5	0.1	0.1	25	15	361	365	5.0	6.0
	25% [5]	0.2	0.2	0.9	0.7	1.9	1.7	0.1	0.1	79	46	595	1269	8.3	7.0
	Median	0.6	0.7	1.6	1.6	2.6	2.6	0.3	0.2	150	76	1917	2076	12.5	12.5
	75% [6]	1.0	1.0	3.0	2.2	4.0	3.2	0.4	0.5	565	222	35,140	28,250	25.3	19.3
	Max.	1.0	1.0	4.2	5.2	5.2	6.2	1.4	1.1	2270	853	61,310	57,940	57.0	29.0
% RE [7]	Mean	−3		11		7		9		60		4		22	
	Median	−16		3		2		33		49		−8		0	
N Samples [8]		12		12		12		12		12		8		10	
NURP Median		0.56		1.29		N/A [9]		0.26		67		400–50,000 [10]		7.8	

[1] Inflow Volume, [2] Outflow Volume, [3] Concentration for *E. coli* = MPN (Most Probable Number)/100 mL, [4] Standard Deviation, [5] 25 Percentile, [6] 75 Percentile, [7] Removal Efficiency, [8] Number of Samples, [9] N/A = Not available, [10] Mean concentration.

Figures 6 and 7 demonstrate the results of the water-quality analysis of composite samples collected at the inlet and outlet points of the McAuliffe RDF. A total of eight rainfall events were considered for the analysis. The last two samples (for events that fell on 9 January 2013, and 30 April 2013) were taken after the installation of the Coanda microscreen. The depletion of nutrient constituents was found inconsistent for the samples analyzed from unprotected inlet conditions. The results from the paired *t*-test suggested that there was no significant ($p > 0.1$) difference between the inlet and outlet concentration of pollutants analyzed from the McAuliffe RDF. It appears that the effluent concentration of nutrients and organic solids (TKN, TN, TP, and BOD_5) was reported higher in less than 50% of the total sampling events before installing the microscreen. The maximum NO_x inlet concentration (2.55 mg/L) appeared on 19 August 2011, which was depleted to 1.0 mg/L at the outlet. The maximum inlet concentration of TKN (8.09 mg/L), TN (8.29 mg/L), TP (1.47 mg/L), BOD_5 (135 mg/L), and *E. coli* (86,640 MPN/100 mL) appeared on 4 May 2012, which was depleted to 2.40, 2.6, 0.25, 78 mg/L, and 2180 MPN/100 mL, respectively, prior to reaching the outlet.

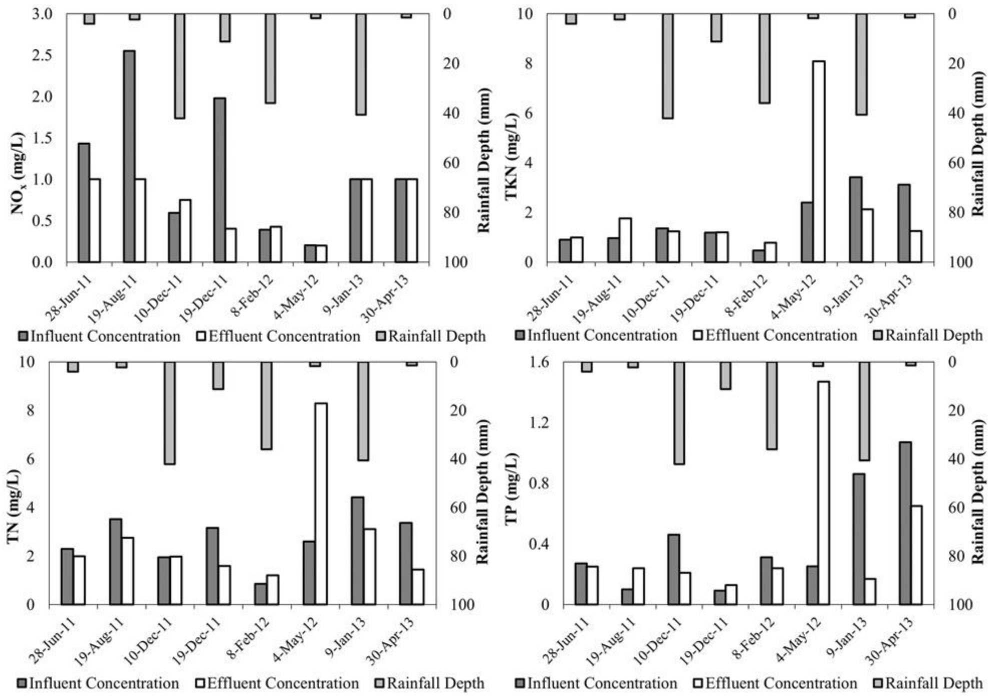

Figure 6. Bar chart representing influent and effluent concentrations for different nutrient components (NO_x, TKN, TN, and TP) collected at the outlet of the McAuliffe RDF for the different magnitude of rainfall events within the monitoring timeframe of 28 June 2011–30 April 2013.

Table 2 demonstrates the results summary of the influent and effluent concentrations for all the water-quality parameters of analysis for the McAuliffe RDF. Nutrient and BOD_5 showed somewhat contradictory concentration results at the outlet. Among all nutrient constitutes, NO_x depletion was relatively better with a 37% mean and 13% median reduction. However, a noticeable depletion of TSS concentration was observed in 83% of the first six samples collected during the monitoring period. Before installing the microscreen, the overall depletion efficiency of TSS concentration was moderate (50%), and the median concentration (41 mg/L) in the effluent remained below NURP guidelines (67 mg/L). A substantial improvement in the TSS mean depletion (up to 98%) was noticed just after the installment of the Coanda microscreen (last two sampling events). The maximum TSS concentration (836 mg/L) was observed on 9 January 2013, which was substantially depleted to 13 mg/L. Also, the nutrient constituents (TKN, TN, TP) and BOD_5 were moderately depleted (30–80%) by the Coanda microscreen and well below the NURP standard. However, a further assessment would be important to ensure the long-term performance of the microscreen. The mean *E. coli* concentration (18,118 MPN/100 mL) at the McAuliffe outlet was within the NURP typical average (400–500 MPN/100 mL). Alike, at the Morris outlet, the maximum *E. coli* concentration was observed to be exceedingly higher (86,640 MPN/100 mL) than at the McAuliffe outlet; it was spiked with one very large accumulation on 5 April 2012. Overall, *E. coli* reduction was poor for about 40% of the total time monitoring events with an intense accumulation near the outlet.

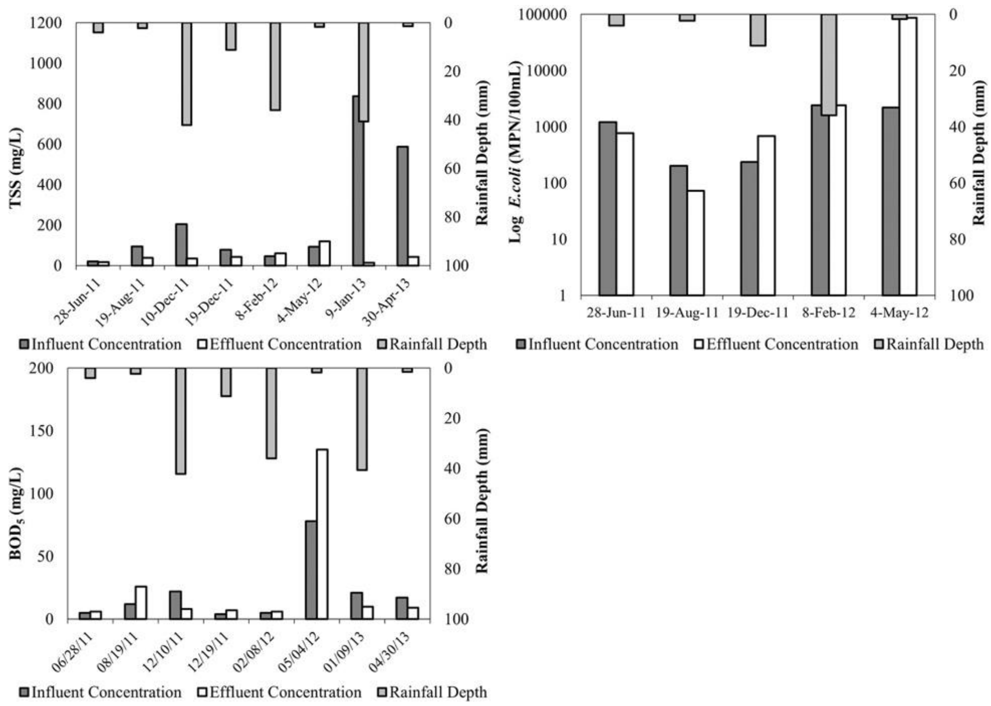

Figure 7. Bar chart representing influent and effluent concentrations of TSS, *E. coli*, and BOD_5, collected at the outlet of the McAuliffe RDF for the different magnitude of rainfall events within the monitoring timeframe of 28 June 2011–30 April 2013.

Overall, both of the RDFs showed a relatively better removal of TSS than the other pollutants analyzed. In our study, the mean depletion efficiency of TSS concentration (81%) by the McAuliffe RDF was achieved 21% higher than that from the Morris RDF. This result was closer to the desired removal efficiency (80%) achieved by GI controls [42]. The depletion of TSS concentration was more consistent in the McAuliffe RDF for most of the sampling events. However, the median TSS influent concentration in the Morris RDF (150 mg/L) was substantially higher than the McAuliffe RDF (93 mg/L) as it serves a relatively bigger basin (4 times higher than the McAuliffe RDF) with a higher percentage of high-density impervious cover (17.1%). For the rainfall that occurred on 9 January 2013, the lowest TSS effluent concentration achieved from the Morris and McAuliffe RDFs was 15 and 13 mg/L, respectively, which were considerably below the normally expected discharge concentration from a conventional facility (30 mg/L) [10,43]. It is important to note that the inlet modification with the installation significantly enhanced the depletion of TSS concentration.

Table 2. Summary of detailed statistics of the observed water-quality results for different pollutants (NO_x, TKN, TN, TP, TSS, *E. coli*, and BOD_5) at the outlet of the McAuliffe RDF based on the total number of monitoring events and their comparison to the USEPA National Urban Runoff Program (NURP) standard.

Parameters		**NO_x**		**TKN**		**TN**		**TP**		**TSS**		***E. coli***		**BOD_5**	
		In [1]	**Out [2]**	**In [1]**	**Out [2]**	**In [1]**	**Out [2]**	**In [1]**	**Out [2]**	**In [1]**	**Out [2]**	**In [1]**	**Out [2]**	**In [1]**	**Out [2]**
Concentration (mg/L) [3]	Mean	1.1	0.7	1.7	2.2	2.8	2.8	0.4	0.4	245	46	1248	18,118	20.5	14.3
	S.D. [4]	0.8	0.3	1.1	2.4	1.1	2.3	0.4	0.5	301	33	1044	38,315	24.3	8.5
	Min	0.2	0.2	0.5	0.8	0.9	1.2	0.1	0.1	20	13	201	73	4.0	6.0
	25% [5]	0.4	0.4	0.9	1.0	2.0	1.5	0.1	0.2	54	21	219	380	5.0	7.0
	Median	1.0	0.9	1.3	1.2	2.9	2.0	0.3	0.2	93	41	1203	770	14.5	12.5
	75% [6]	1.8	1.0	2.9	2.0	3.5	3.0	0.8	0.6	491	56	2300	44,530	21.8	19.3
	Max.	2.6	1.0	3.4	8.1	4.4	8.3	1.1	1.5	836	120	2419	86,640	78.0	29.0
% RE [7]	Mean	37		−27		−1		1		81		−1352		−26	
	Median	13		2		31		17		56		36		41	
N Samples [8]		8		8		8		8		8		5		8	
NURP Median		0.56		1.29		N/A [9]		0.26		67		400–50,000 [10]		7.8	

[1] Inflow Volume, [2] Outflow Volume, [3] Concentration for *E. coli* = MPN/100 mL, [4] Standard Deviation, [5] 25 Percentile, [6] 75 Percentile, [7] Removal Efficiency, [8] Number of Samples, [9] N/A = Not available, [10] Mean concentration.

In conventional detention facilities, the primary mechanism of pollutant removal is sedimentation resulting from gravitational settling [43]. Several factors can influence the variability in the quality of effluents achieved in RDFs through the sedimentation process. Among them, three important hydrologic variables can have a possible impact on a RDF's settling mechanism: the residence time, the volume of feed, and the temperature [11]. Both RDFs are hydrologically connected to a vegetated wetland to improvise the overall retention and settling process. The water holding depth and aerial footprint of the McAuliffe RDF are much higher than that of the Morris RDF, including the drainage channels, two sequential wet ponds, and a wetland. These act like wet ponds and they offer more residence time for the runoff, thus aiding sedimentation. For the same rainfall event that occurred on 9 January 2013, the residence time of the McAuliffe RDF (4 h) was estimated at almost 8 times higher than that for the Morris RDF (0.5 h). This event could account for the McAuliffe RDF being 98% in terms of TSS concentration removal while the Morris RDF was 70%. In addition, the greater depth of the McAuliffe RDF's downstream wetland might have improved the storage volume for larger storm events and increased the overall residence time in the McAuliffe RDF. Temperature also affects the viscosity of the sediment particles in contact with water and, thereby, improves the settling process [11]. During our monitoring period, the local temperature varied in a range between 24 and 31 °C, which might have enhanced dynamic viscosity and the particle settling velocity. Apart from the hydrologic benefits, the inlet modification by the installation of the Coanda microscreen resulted in an enhanced TSS concentration (81% on average), which slightly exceeded the acceptable removal efficiency (80%) from other GI controls [42]. It is possible that a polluted stream entering the McAuliffe RDF, generated from the watershed, passed through a rigorous prescreening of large suspended solid particles and later received direct rainfall volume (cleaner than the stormwater runoff), which contributed to the significant depletion of concentrations in some cases. Thus, it can be said that the Coanda screen could be used in the RDF when comparable performance is required.

In terms of nutrients, the mean effluent concentration of TKN, TN, and TP was similar or slightly lower than the influent concentration for both RDFs. A smaller portion of nutrients was removed from both RDFs. For the Morris RDF, a slight depletion of nutrient concentration was observed for most of the rainfall events. The side-slope drainage area surrounding the RDF is the mostly vegetative or agricultural land cover and may have been a potential source of the organic and nutrient load generation through the erosion of the topsoil. During heavy rainfall events, these excess nutrients could be carried out by the agricultural runoff (i.e., fertilizers). This condition might induce a potential nutrient recharge near the RDF. Comparatively, the McAuliffe site covers a higher percentage of cultivated croplands (3.2%), which could lead to a significant amount of nutrient generation in the facility. Besides the negative value of the percentage, the BOD_5 mean and median reduction in the McAuliffe RDF indicates that there is a chance of organic solid accumulation in the wetland bed.

Maintaining low organic levels and adequate plant support are important to maintain the aerobic condition in the water for the effective oxidization of NH_4^+ or other organic nitrogen to produce more mineral NO_3 form, which is later consumed by the roots of most plants [44]. The mean depletion of TKN (11%), TN (7%), TP (9%), and BOD_5 (22%) was relatively better in the Morris RDF. For most nutrient constituents, the percentage average depletion was negative in the McAuliffe RDF, which indicated an elevated concentration before reaching the RDF outlet. Several studies have found that higher BOD_5 and TN (predominantly present as NH_4^+) removal is possible when a wetland bed is vegetated with plants of the bulrush genus (*Schoenoplectus*) because of their deeper root penetration (30–60 cm), which results in aeration and microbial nitrification [45]. From our visual inspection of the site, the density of bulrush plants was observed to be comparatively higher in the Morris RDF, which might have led to a relatively better depletion of all organic nitrogen sources (TKN, TN, and BOD_5) near the outlet. However, the mean depletion efficiency of NO_x (37%) was much better in the McAuliffe RDF. The *E. coli* result exemplifies a large variability in both RDF results for different sizes of rainfall events. Considerably higher bacterial accumulation appeared near the outlet of the RDFs. Surprisingly, the number of *E. coli* per 100 mL of the effluent was highly spiked in the McAuliffe on 4 May 2012. The maximum *E. coli* depletion efficiency was observed at 64% and 29% by the McAuliffe and Morris RDFs, respectively. Nonetheless, the interaction between different water-quality parameters might have affected the performance of each other, which is explained by determining Pearson Multiple Correlation Coefficient (PMCC) values between different variables among all the parameters analyzed and tabulated in Table 3. The significance of the correlations was validated by the regression hypothesis test.

Table 3. Correlation coefficients for outflow water-quality results in both sites.

		Inflow [1]	Outflow [2]	NO_x	TKN	TN	TP	TSS	BOD_5	*E. coli*	Temperature	Rainfall
McAuliffe RDF	Inflow [1]	1.00										
	Outflow [2]	0.63	1.00									
	NO_x	0.01	−0.37	1.00								
	TKN	−0.48	−0.23	−0.55	1.00							
	TN	−0.54	−0.27	−0.47	0.99	1.00						
	TP	−0.41	−0.32	−0.48	0.91	0.86	1.00					
	TSS	−0.32	−0.09	−0.80	0.84	0.80	0.87	1.00				
	BOD_5	−0.54	−0.25	−0.58	0.99	0.97	0.92	0.88	1.00			
	E. coli	−0.40	−0.18	−0.62	0.99	0.98	1.00	0.93	0.99	1.00		
	Temperature	−0.64	−0.45	0.07	0.49	0.51	0.51	0.39	0.55	0.40	1.00	
	Rainfall	0.61	0.46	−0.01	−0.32	−0.29	−0.47	−0.32	−0.38	−0.34	−0.77	1.00
Morris RDF	Inflow [1]	1.00										
	Outflow [2]	0.99	1.00									
	NO_x	0.19	0.11	1.00								
	TKN	0.70	0.70	−0.28	1.00							
	TN	0.70	0.70	−0.28	1.00	1.00						
	TP	0.48	0.40	0.39	0.67	0.67	1.00					
	TSS	0.63	0.61	0.18	0.80	0.80	0.80	1.00				
	BOD_5	−0.80	−0.78	−0.55	0.19	0.19	−0.15	−0.11	1.00			
	E. coli	0.26	0.24	−0.20	0.88	0.88	0.80	0.82	0.41	1.00		
	Temperature	−0.01	0.05	−0.50	0.34	0.34	0.15	0.16	0.25	0.34	1.00	
	Rainfall	0.19	0.22	0.43	0.24	0.24	0.36	0.25	−0.04	0.79	−0.18	1.00

[1] Inflow Volume, [2] Outflow Volume.

The positive correlations between the pollutants and inflow volume in the Morris RDF suggest that much of the nutrient and TSS generation was triggered beyond the RDF inlet, perhaps because the basin area serves a highly intense impervious land cover (17%). Conversely, the negative correlations between the McAuliffe inflow volume and outlet pollutant concentration suggested that much of the pollutant generation was not triggered by the total feed volume; rather their concentration underwent potential changes through the subsequent retention and sedimentation process throughout the RDF length, improvised by two sequential wet ponds. The same explanation could be appropriate for the negative correlation ($R = -0.8$) between the inflow volume and outlet BOD_5 concentration in the Morris RDF.

Possibly, the progression of nutrients throughout the RDFs was associated with sediment transportation, perhaps because of the ability of sediment particles to adhere to nitrate and phosphate on its surface. In the McAuliffe RDF, this hypothesis is strongly supported by the positive correlation ($R \geq 0.80$, $p < 0.05$) between nutrient constituents (TKN, TN, and TP) and TSS concentration. For the McAuliffe RDF, strong positive correlations ($R > 0.85$, $p < 0.05$) were observed between BOD_5 and the rest of the probable organic sources (TKN, TN, TP, and TSS), perhaps because a large number of organics were carried by the solids. Adversely, high sediment concentration can interrupt NO_x generation because it raises the issues of dissolved oxygen depletion and nitrification [46]; the hypothesis can be supported by the strong negative correlation ($R = -0.80$) between the TSS and NO_x concentrations in the McAuliffe RDF. In general, high organic compounds are highly associated with an escalated bacterial population. Bacteria consume organic compounds for their growth and reproduction and deplete oxygen from the water [47]. This hypothesis can be supported by the strong correlation ($R > 0.8$) between *E. coli* and all probable organic sources (TKN, TN, TP, TSS, and BOD_5). However, the bacteria-nutrient interaction was more dominant ($R > 0.95$) in the McAuliffe RDF compared to the Morris RDF ($R > 0.8$). There was a close association ($R = 0.91$) between TKN and TP in the McAuliffe RDF.

However, the analysis of the variation of event-specific concentrations does not explain the differences observed in the pollutant load reduction. The following section of the paper discusses the results in terms of load reduction estimates for all pollutants analyzed from both RDFs.

3.2. Pollutant Mass Load Reduction

Water-quality data were collected for concentration along with the flow data at the inlet and outlet from each site to calculate the pollutant load reduction. Overall, during the monitoring period, the McAuliffe RDF exhibited better load reduction in comparison to the Morris RDF. A summary of load reduction at the inlet and outlet for each site for the different pollutants is presented. Figure 8 shows the box and whisker plots of the total load for all the collected samples of each pollutant at the outlet monitoring station on each site.

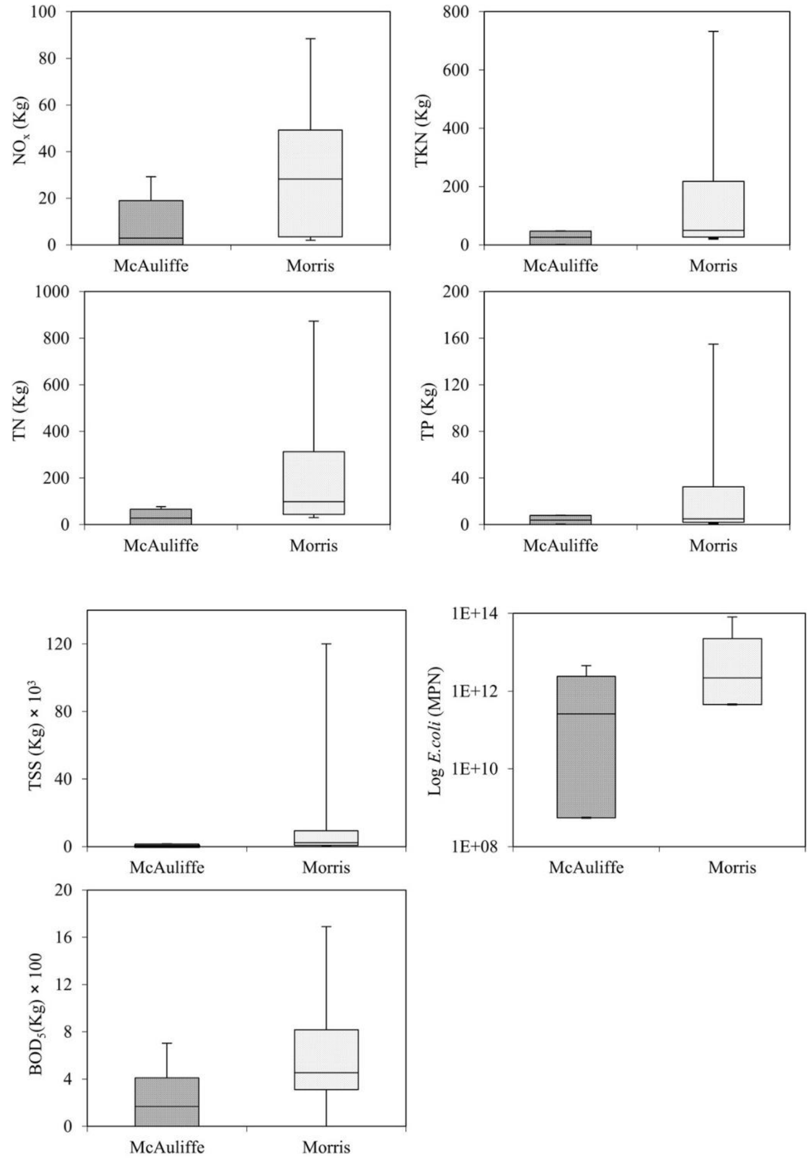

Figure 8. Box and whisker plots representing a comparative summary of calculated loads for different pollutants (NO_x, TKN, TN, TP, TSS, *E. coli*, and BOD_5) at the outlet of the McAuliffe and Morris RDFs, based on the total number of monitoring events. The large box represents the 25th percentile, median, and 75th percentile; the whiskers represent the 5th and 95th percentiles.

For the Morris RDF site, only TSS loads were significantly ($p < 0.05$) different between the inlet and outlet. While the loads for TN, TSS, TP, BOD_5, TKN, and *E. coli* were not significantly less at the outlet than the inlet. On the other hand, for the McAuliffe site, NO_x compounds the load, which includes nitrate and nitrites. They were significantly ($p < 0.05$) different between the inlet and outlet. However, the load for the TN, TSS, and TP were significantly less at the outlet than the inlet. However, there was a significant difference ($p < 0.05$) between the loads of BOD_5, TKN, and *E. coli* between the two monitoring stations at the McAuliffe RDF.

Statistically significant reductions in loads of TSS were observed from both of the RDFs. For the Morris RDF, the median value of the inflow and outflow for the TSS load was 4309 ± 97,388 and 2316 ± 38,130 kg, respectively, for eight collected samples. The average and median load reductions were 53% and 60%, respectively. Only one stormwater event showed a negative reduction with a value of −64%, while in the McAuliffe RDF, the median value of the inflow and outflow for the TSS load was 1173 ± 3581 and 637 ± 681 kg, respectively, for eight collected samples. The average and median load reductions were 48% and 75%, respectively. The median average indicated a higher removal as only one event occurred on 4 May 2012; the TSS load at the outlet was higher than the inlet. For this event, TSS load reduction was negative due to both the TSS concentrations, and the outflow flow volume was higher at the outlet. Results from both sites indicate that TSS can be removed from the detention basin in the semi-arid coastal region under certain conditions, such as with certain concentrations, rainfall depth, and flow reduction. TSS is removed in detention facilities through sedimentation of the solid particles at the bottom of the basin. The removal mechanisms are achieved by reducing the water velocity and, hence, allowing the solids to settle before reaching the outlet.

For nutrients such as nitrogen and phosphorus, the Morris RDF did not show any significant difference for the NO_x species. However, in the McAuliffe RDF, the NO_x total load at the outlet was significantly ($p > 0.05$) less than at the inlet. Generally, there are two ways for NO_x depletion to occur; it is either absorbed by plants as a form of nitrate, or it is biologically converted to nitrogen gas through the denitrification process. However, the detention time between the inlet and outlet was short and may not be enough to trigger the denitrification process. It is possible that NO_x reduction was achieved through plant assimilation in the wetland section. This process can be supported by the difference in the wetland area between both sites. The wetland area in the McAuliffe RDF was 258 m^2, and the average load reduction was 47%; the wetland in the Morris RDF was 9.3 m^2 with an average reduction of 6%. The McAuliffe RDF's large wetland area could enhance the NO_x uptake from the urban stormwater runoff. Due to the relatively small area of the Morris RDF wetland, minimum NO_x removal was observed. Both sites did not show any significant difference in TKN load reduction between the inlet and outlet at each monitoring station. However, the McAuliffe RDF showed better performance due to the runoff reduction volume. From eight storm events, the TKN load at the outlet was lower than at the inlet in seven events; the average pollutant load was 24 and 25 kg, respectively. In the Morris RDF, the TKN load was higher at the outlet in four storm events. The average load at the outlet and inlet was 156 and 137 kg, respectively. TN and TP loads showed significant reductions in the McAuliffe RDF only. As the McAuliffe RDF showed better performance in NO_x and TKN removal than the Morris RDF, the TN total load at the McAuliffe outlet was expected to be lower than the at the inlet and the Morris RDF because the TN comprises all the nitrogen species, including NO_x and TKN. Several studies have shown that a detention basin can reduce the TP in stormwater runoff [11,12]. Detention basins improve runoff water quality through the settling out of suspended particles that may carry contaminants such as phosphorus [35]. Both the McAuliffe and Morris RDFs showed reductions in TP load in comparison to the inflow load at each site. However, the McAuliffe RDF has an extended retention time compared to the Morris RDF due to the larger wetland volume and the presence of two wet basins. Therefore, the McAuliffe RDF showed an enhanced removal of solids and phosphorus.

Similar to the TKN load reduction, both sites did not show any significant difference between the BOD_5 and *E. coli* outlet and inlet loads for each site. The average BOD_5 load reduction for the McAuliffe and Morris RDFs was 22 and 19, respectively. Some events showed a negative reduction for BOD_5.

The main constituents for TKN and BOD_5 are organic compounds that require a microbial activity for their degradation. However, the major mechanism for water-quality improvement is sedimentation. However, the microbial activity may not achieve the desired results due to the short distance between the inlet and outlet monitoring stations. This distance might not be enough to enhance the microbial activity to breakdown the organic compounds. Five samples were collected for the bacterial reduction in the RDFs from each site. The *E. coli* load showed fluctuation between the outlet and the inlet. Both sites showed a negative removal of bacteria. Several factors control bacterial concentration, such as temperature and the presence of organic matter. *E. coli* can be removed in green infrastructure either by adsorption or filtration [5,48] as none of the previous mechanisms were introduced in the detention basin or the wetland. *E. coli* showed the lowest removal values among the other pollutants.

4. Summary and Conclusions

The analyses used in evaluating the performance and efficiency of the two RDFs in McAllen, Texas were able to give some insight into pollutant reduction in the constructed facilities. Both the McAuliffe and the Morris RDFs were incorporated with constructed wetlands to enhance the urban runoff water quality by reducing some pollutants. Both sites showed a significant ($p > 0.05$) reduction of suspended solids at different storm events. On the other hand, the McAuliffe RDF showed a better reduction in the pollutant concentration and load between the inlet and outlet in comparison to the Morris RDF. The outlet pollutant load for NO_x, TN, and TP were significantly ($p > 0.05$) lower than the inlet monitoring site at the McAuliffe RDF. This result could be attributed to the different design and structural enhancement incorporated with the McAuliffe RDF, which effectively contributed to the improvement of the water quality. The McAuliffe RDF had a larger constructed wetland that could utilize more nutrients through plant uptake and sedimentation. Additionally, the site was constructed with two wet detention ponds that probably worked in augmenting the sedimentation process at the McAuliffe site. On the other hand, neither of the sites showed a significant contribution to lowering either the organic compounds or the bacteria. In particular, *E. coli*, as an indicator bacteria, demonstrated an obvious fluctuation in concentration at the various rainfall events.

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