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Article

Evaluation of Pollutant Removal Efficiency by Small-Scale Nature-Based Solutions Focusing on Bio-Retention Cells, Vegetative Swale and Porous Pavement

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Abstract: Rapid urbanization, aging infrastructure, and changes in rainfall patterns linked to climate change have brought considerable challenges to water managers around the world. Impacts from such drivers are likely to increase even further unless the appropriate actions are put in place. Floods, landslides, droughts and water pollution are just a few examples of such impacts and their corresponding consequences are in many cases devastating. At the same time, it has become a well-accepted fact that traditional (i.e., grey infrastructure) measures are no longer effective in responding to such challenges. Nature-based solutions (NBS) have emerged as a new response towards hydro-meteorological risk reduction and the results obtained to date are encouraging. However, their application has been mainly in the area of water quantity management with few studies that report on their efficiency to deal with water quality aspects. These solutions are based on replicating natural phenomena and processes to solve such problems. The present paper addresses the question of three NBS systems, namely, bio-retention cells, vegetative swales and porous pavements, for the removal of total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP) when applied in different configurations (single or networked). The results presented in this paper aim to advance the understanding of their performances during varying rainfall patterns and configurations and their potential application conditions.

Keywords: stormwater runoff; nature-based solutions; hydraulic model; SWMM; pollutant removal; stormwater management

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1. Introduction

Population growth and rapid urbanization is one of the reasons for an increase in impervious surfaces that are causing changes in hydrological patterns, runoff characteristics, peak discharges and pollution [1,2]. Furthermore, climate change is causing additional impacts (such as extreme variability in precipitations, droughts and flooding) on human well-being, the global economy and the environment [3]. These climate-related challenges have also altered the natural hydrological cycle in urban settings, thereby causing an increase in the interception of runoff water with effluents generated from urban settlements in the form of high organic and pathogenic substances, which, if left untreated, causes adverse effects on the environment and public health [4].

Such stormwater runoff is generally responsible for deteriorating water quality in water bodies by conveying nutrients and wastes. With an increase in pollutants in water sources, such as lakes, rivers, ponds and intrusion into groundwater aquifers, there has been an increased threat to water utilities on the potable and irrigational water use. Given the limitations of available land and financial resources, it has been a challenge for city authorities and urban managers to find economically feasible technologies that can manage stormwater runoff and reduce pollutants [5].

Different technologies have been introduced and adapted into urban settings over the decades in the USA with different names, such as Best Management Practices (BMPs) and Low-Impact Developments (LIDs) [1]. For example, bio-retention cells, vegetative swales, green roofs, wetlands, retention basins and permeable pavements [2] can be used for managing the water quality of the stormwater runoff generated from the urban areas. The key feature of these systems is the possibility of replicating certain working principles of the natural environment towards addressing the issues of flooding and pollution control, thereby improving human well-being, public health and various habitats. Many such solutions have been evaluated compared to traditional grey infrastructure for the economic-social benefits and water quality improvements, and such studies have been documented across several scientific publications [3,6]. In order to solve different societal and environmental challenges with natural process and ecosystems, nature-based solutions (NBS) have been considered as an "Umbrella concept" that adopts and covers different concepts and ecosystem-related approaches [6,7]. The terminology of NBS has evolved in the literature due to policy origins and in order to emphasis different natural functions. Figure 1 shows the evolution of the terminology related to NBS that is used in the scientific literatures, as mentioned by Ruangpan et al. [3].

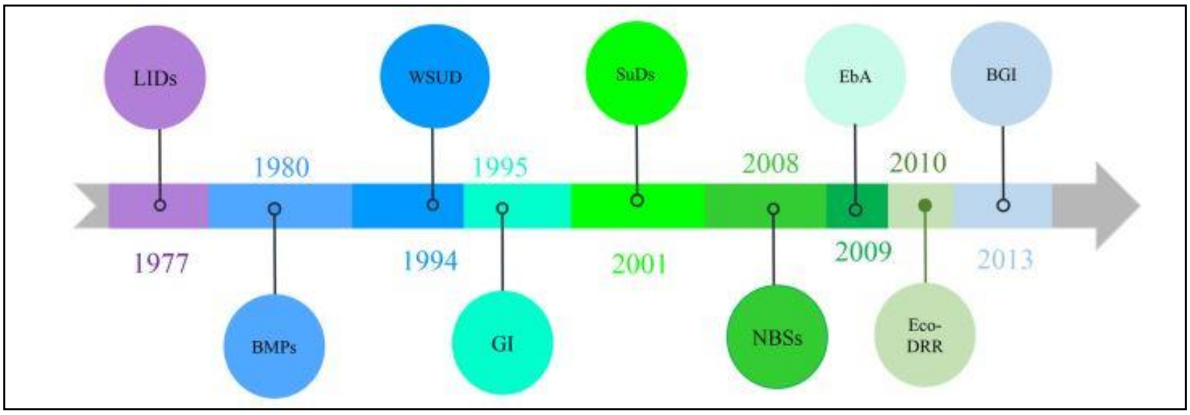


Figure 1. Development of terminologies of stormwater management technologies for hydro-meteorological risk reduction [3]. LIDS—low impact developments, BMP—Best Management Practices, WSUD—water sensitive urban design, GI—green infrastructure, SuDs—Sustainable urban drainage systems, NBS—Nature based-solutions, EbA—ecosystem-based adaptation, Eco-DRR—Ecosystem-based disaster risk reduction, BGI—Blue green Infrastructure.

For the specific purpose of controlling and eliminating water pollution from urban stormwater runoff, NBS is conceptualized as a treatment approach within the sanitary engineering fraternity to interlink features of an urban system of settlements with systems function within nature. This approach was already accepted and integrated within multilateral frameworks of institutions, such as the Convention on Biological Diversity (CBD), United Nations (UN), United Nation Framework Convention on Climatic Change (UNFCCC) and the Sendai Framework for Disaster Risk Reduction (SFDRR) [1].

The selection of NBS systems is made based on different benefits, such as social, economic and environmental. Understanding and assessing the implications of future changes on operation and maintenance, incurring additional costs and potential benefits and co-benefits of NBS systems, can provide a better outcome in terms of decision-making.

Modeling tools help to simulate a wide variety of flow conditions to understand the performance of NBS measures. Design engineers and decision-makers effectively make use of these models to understand the configuration of NBS as treatment units. Currently, most of NBS-related studies focused on managing water quantity, and there are not many studies that report their efficiency for water quality applications and urban runoff pollution control [1]. The present work involves modeling of NBS in the context of urban stormwater drainage and their performance concerning their pollutant removal efficiency is assessed. The paper focuses on small-scale NBS systems, such as bio-retention cells, vegetative swales and porous pavements, and evaluates their application in a case study area of Cul-de Sac, located in the island of Sint Maarten the Caribbean.

2. Materials and Methods

The methodology followed in the study, consists of number of steps starting with a review of academic publications, scientific articles and journals written in English. Different search engines were utilized to extract articles and journals, such as Google Scholar, ScienceDirect, ASCE | Library, PLoS ONE and Education Resources Information Center (ERIC). The search focused on the following thematic areas: nature-based solutions and pollutant removal from stormwater runoff. To shorten the search gap, essential keywords relevant to this study were applied during the search, such as stormwater runoff treatment, pollutant removal by nature-based solutions, stormwater management modeling and urban runoff management.

The concept of NBS and interlinking the urbanization with the environment also appear with different terminologies, as mentioned in Figure 1, which were also applied and extracted from the search engines mentioned above to be included for analysis in the matrix. Additionally, articles established on water quality improvement by different NBSs, such as bio-retention cells, vegetative swales, constructed wetlands, green roofs, rain barrels, porous pavements, detention basins, retention basins, bio-filters, infiltration trench and planted gravel filters, were used as keywords to find the necessary articles for analysis. Initially, all the articles extracted from the search engineers were evaluated based on their titles and the keywords used. In the second step, an in-depth review of the abstract was done to sort out the articles and keep a record of those relevant to the study's objectives. Articles covering topics such as flood control, health and hygiene and optimization of NBS, which are different from water quality studies, were omitted and not considered for this study. Finally, 100–110 papers were analyzed. This strategy narrows down the search option and the number of articles to be processed. The search engines mentioned above were mainly preferred for having open access to most published academic research papers.

The selected 100–110 papers were used to develop a matrix to identify and categorize the most common pollutants analyzed and reported in the academic literature as well as the nature-based solutions (technology) and modeling tool used. This systematic classification led to the development of a selection matrix table using Microsoft Excel [2–5,8–110]. An example of the developed selection matrix is included in Table A1. Table A1 in Appendix A shows different pollutants alongside the corresponding NBS technologies, such as Total Suspended Solids (TSS), Total Dissolved Solids (TDS), Total Kjeldahl Nitrogen (TKN), Total Nitrogen (TN), Organic Nitrogen (ON), Inorganic Nitrogen (IN), NO_3-N, NO_2, NH_4-N, Ortho- Phosphate (PO_4), Soluble Reactive Phosphorus (SRP), Total Phosphorus (TP), Potassium (K), Lead (Pb), Copper (Cu), Cadmium, Iron(Fe), Zinc (Zn), Total Organic Carbon (TOC), Biological Oxygen Demand (BOD) and fecal coliforms. Furthermore, the selection matrix also includes aspects or characteristic of the reported storm events, such as duration of the storm, location of the experiment conducted, the importance of analyzing the pollutant and the effects of the pollutants in the mentioned location. In the selection matrix, the modeling tools used for stormwater management were also added.

The modeling tools reported in the academic literature were listed, including their capabilities to model NBSs and the removal of pollutants. The advantages and disadvantages of the modeling tools reported were also listed in the matrix. In this way, it was possible to count the number of publications reporting each NBS technology, the type of pollutant and the modeling tools. The most reported ones were selected for testing and application. The framework shown in Figure 2 was used to develop the NBS models and the pollutant removal equations to be tested.

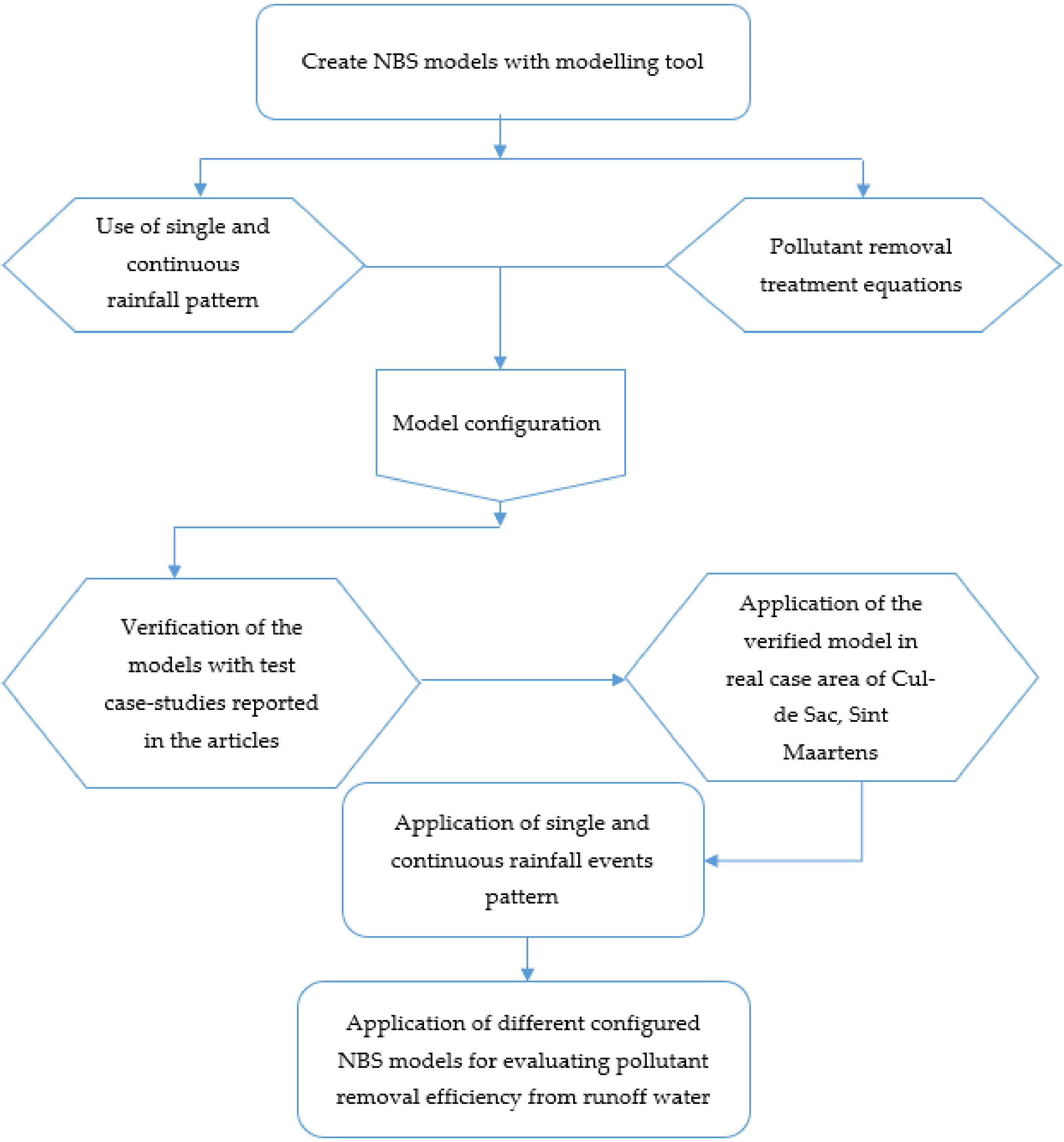


Figure 2. Schematics showing the modeling framework used to model NBSs for water quality analysis.

Each NBS technology was designed or sized for a two-year rainfall event return period. The total volume of each unit of each NBS was schematized in layers, where each tank represents each layer of NBS units. The pollutant generation were modeled by use of different land-use rate, wash-off rate, event mean concentration (EMC) or reported pollutant concentrations. Several treatment equations were analyzed and used to represent different pollutant removal processes in each layer as reported in [56,80,96,109]. All the tanks were designed to perform different treatment processes, such as sedimentation, filtration, nutrient uptake and the anaerobic processes for the removal of the pollutants. A hydraulic retention time of 8–10 h was considered inside the tank for effective treatment. To verify and compare the behavior of the pollutant removal equations, a similar system was described in [56], in which a bio-retention model that was developed and configured based on a development plan provided by Sarasota country in Florida was used. The aim of that study was to control the nitrogen in stormwater runoff.

A similar approach was used to analyze the performance of the NBSs in this study. The tanks were finally simulated with the rainfall events and the observed removal efficiency was plotted on a graph. The pollutant removal performance was compared with reported results from different studies in the literature [5,20,52,54–56,75]. Once verified, the model was applied to evaluate the small-scale NBS performance for pollutant removal in a real case study area.

As can be seen in Figure 2, after the verification of the NBSs setup and performances of the pollutant removal equations, a real case study was developed in the sub-catchment of Cul-de Sac in the Sint Maarten Island. The application of the approach in a real case study was used to assess the potential of several NBSs for stormwater runoff pollution control and the reduction of runoff peak flows. The performance of different NBSs was also tested with different rainfall event pattern including single events and continuous synthetic event for a period of 2 months. This was done to assess the performance of the NBS system during fluctuating inflow events.

3. Results

3.1. Formation of the Selection Matrix

A Selection Matrix was developed using Microsoft Excel after reviewing 100–110 academic publications. In this matrix, different categories/classes were recorded, such as NBS technologies, runoff pollutant and modeling tools if reported. Additionally, the duration of the reported storm events, the location of the NBS, the reason to analyze certain pollutants and the impacts of the pollutants in the mentioned location are recorded. The matrix was arranged based on the year of experiment and publications starting from old to new ones. This helped in sorting down the pollutants, NBS technologies and modeling tool used in this study. A sample of the selection matrix is mentioned in Table A1.

3.2. Selection Process of Pollutants and NBSs

The data assembled in the selection matrix were analyzed to select three pollutants and the NBSs considered in this study. The criteria adopted for the selection are as follows:

- The pollutants that were most reported in the articles reviewed.
- Reason for analyzing the pollutants in the mentioned location.
- Cause of generation of the pollutants in that location.
- Duration of the analysis.
- Effect of the pollutants in the mentioned location.

The compiled data in the selection matrix showed that out of 100–110 articles, 54 reported total suspended solids and total nitrogen as the main pollutant of concern, whereas 45 reported total phosphorus as the primary pollutant analyzed to be removed from stormwater runoff. Following the above-mentioned selection criteria, TSS, TN and TP were selected to be used in this study.

The selection matrix also categorized different NBSs and their pollutant removal efficiencies. The reported NBSs were green roofs with vegetation, a green roof without vegetation, vegetative swales, constructed wetlands, bio-retention cells, detention basins/ponds, retention basins/pond, permeable pavements, infiltration fields and bio-filters. Among all the NBS technologies analyzed, 16 publications reported vegetative swales, 13 reported bio-retention cells, and 14 reported permeable/porous pavements for the removal of TSS, TN and TP from stormwater runoff. Thus, these three NBS technologies were selected to be used in this study.

3.3. Modeling Tool Selection from the Matrix

Modeling tools have been used since the 1960s for simulating hydraulic behaviors [4]. They are capable of simulating stormwater runoff using different parameters. Thereby, most of the stormwater management modeling tools, as mentioned in Appendix A, Table A2, were analyzed based on their main functions, capabilities for modeling pollutants and simulating water quality. More than seventeen modeling tools that were reported in the articles were reviewed and their functions were analyzed. Among all the tools, Stormwater Management Modeling (SWMM) was reported to be most commonly used tool by researchers as a modeler for water quality analysis with NBSs. Therefore, SWMM was decided to be used for modeling and pollutant removal analysis in this study, as presented in Table 1.

Table 1. List of modeling tools used for stormwater management.

	Function	**Nature-Based Solutions**	**Main Functions**	**Pollutants**	**Reference**
EPA Stormwater Management Model (SWMM)	To plan, design and analysis of the performances of Green Infrastructures in runoff quality improvement and quantity reduction	Permeable pavement, rain gardens, green roofs, street planters, rain barrels, infiltration field and vegetative swales	Time series graphs, tables and statistical analysis of the simulation results, hydrological behavior and pollutant removal efficiencies	TSS, TN, TP, Lead, Zinc, BOD, COD, total coliform and settleable solids	[109]

The Stormwater Management Model (SWMM) tool can provide dynamic simulation of NBS systems, such as permeable pavements, rain gardens, green roofs, street planters, rain barrels, infiltration field and vegetative swales. Researchers use this modeling tool to evaluate the treatment of pollutants from stormwater runoff, such as total suspended solids, total nitrogen, total phosphorus, lead, zinc, biochemical oxygen demand and chemical oxygen demand. A dynamic rainfall-runoff simulation model, SWMM, is used for single or long-term continuous event simulations of the quality and quantity of runoff water from a particular catchment area.

The performance of the NBS systems is controlled by the filter media placed in the system, the surface area properties of every measure and the hydraulic capacity of the underdrain. In SWMM, the removal of pollutants can be modeled in two different ways: the first approach is to set a removal percentage for the selected NBS systems designed, and the second approach uses treatment equations for pollutant removal in the nodes or tanks in the model layout. In this study, the second approach was used for water quality modeling and analysis of pollutant removal efficiency.

3.4. SWMM Model Configuration

To test the NBS measures and the removal of the selected pollutants, a similar model setup approach as the one reported in [56,102] was followed. For the test run, 20 hectors of catchment area with 41.8% of imperviousness, 0.013 as manning's factor n for impervious portion (N-Imperviousness), 0.106 as manning's factor n for perviousness portion (N-Perviousness), 0.04 mm of Dstore-imperviousness (depth of depression storage on the impervious area) and 0.2 of Dstore-pervious (storage depression over the previous portion of the sub catchment) were considered, as reported in [56,101,102]. A rainfall event for a short period of time was used to generate runoff water from the designed catchment area. The rainfall event took place for 12 h with a peak precipitation rate up to 6.5 mm/h. Thus, the generated peak flow was used to calculate the hydrograph entering all the simulated NBSs. To include pollutants in the runoff, different land-uses, wash-off rates and real case-study inputs or event mean concentrations were used.

Each NBS was schematized in layers, where every layer corresponds to a different filter media configuration and was modeled as a tank as shown in Figures 3 and 4. Therefore, every NBS consisted of a series of connected tanks and was designed to provide a hydraulic retention time of 8–10 h with an orifice of different size to maintain the hydraulic level and flow in and out of every layer. The schematization of the NBS, presented in Figure 3, was used to conceptualize a series of tanks in SWMM as it is presented in Figure 4. A similar approach was used to model bio-retention cells and porous pavement.

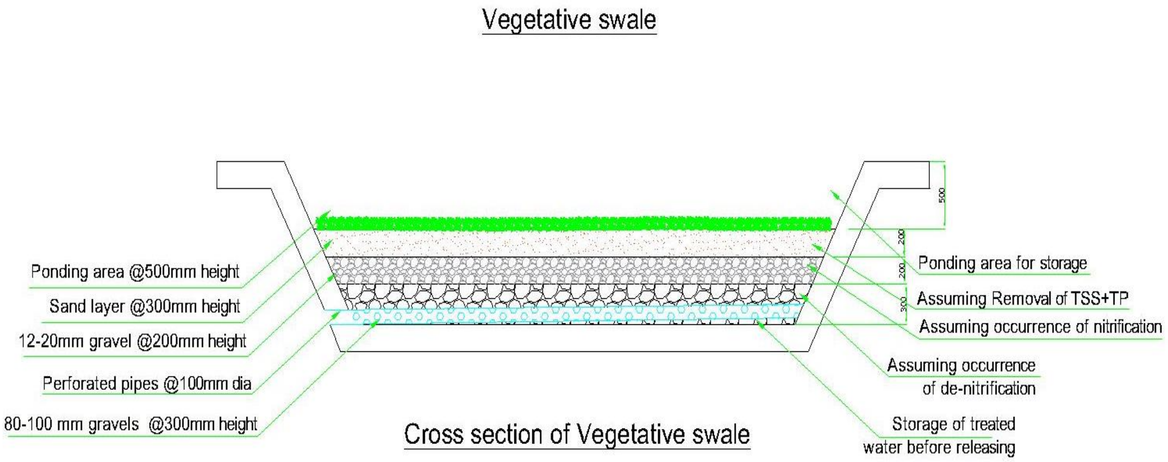


Figure 3. Schematic figure of vegetative swale.

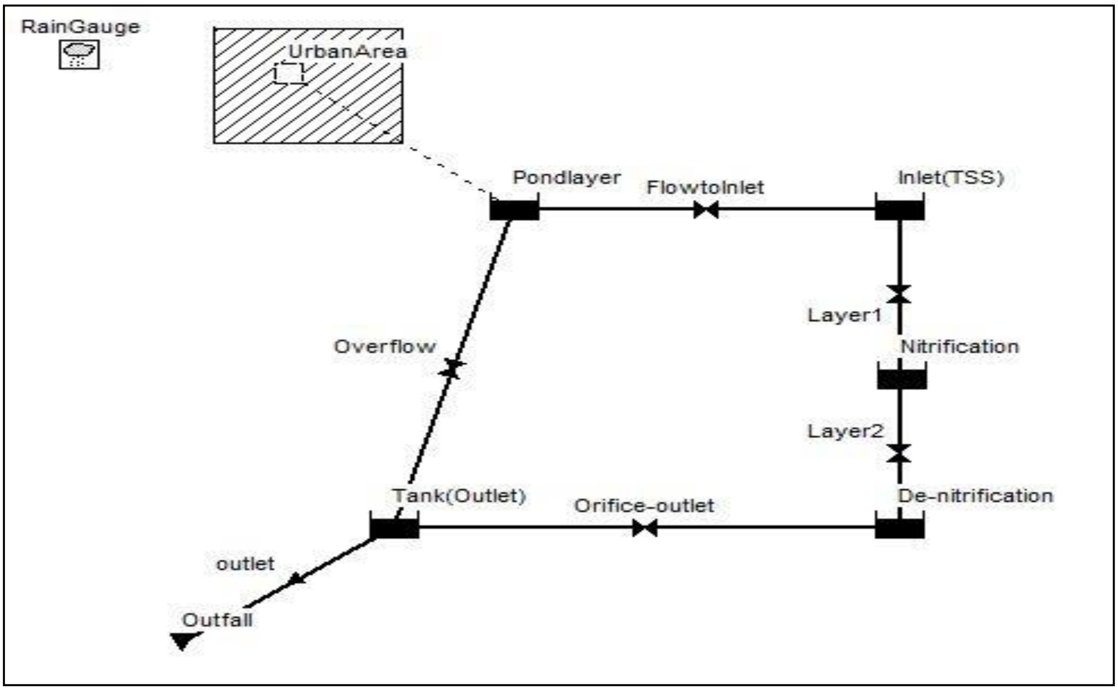


Figure 4. SWMM conceptual model representation of vegetative swale.

As shown in Figure 4, the vegetative swale model surface area was designed as 15% of the contributing impervious drainage area with a depth of 1.3 m. The tank representing the top layer (water storage) was designed with a depth of 0.5 m, the second layer (sand) of 0.3 m depth, the third layer (12–20 mm gravel) of 0.2 m depth and, finally, the last layer (80–100 mm gravel) of 0.3 m depth [20,39]. The system was designed to only treat a certain percentage of the runoff water entering until the system became saturated. Therefore, an overflow orifice was set up in the top layer (tank), to bypass the excess water entering the treatment unit to the downstream drainage node. The idea of the overflow orifice is to provide safety to the system during excess precipitation. Infiltration from or to the surrounding ground surface is not considered to/from the tanks.

The size of the orifices was finalized after several trial-and-error attempts, this was done to maintain the gradual flow between the tanks. Therefore, the top tank dewaters first, followed by the second and, finally, the last tank. This flow would ensure 8–10 h of hydraulic retention time for the pollutant removal treatment. Once the hydraulic behavior inside the system was controlled, the water quality simulation was set up. A similar approach was used to model the other two NBS systems (bio retention cell and porous pavement).

As vegetative swales and bio-retention cells are plant-based (use of vegetation) systems, it is essential to maintain a certain water level inside so that the vegetation can grow and be sustained. If the water levels are not maintained, the vegetation would need frequent replacement or would die soon after the storm event ends, which would increase the O&M (Operation and Maintenance) cost of the system, which will affect the performance for pollutant control and removal.

3.5. Removal of Pollutants in SWMM

From the selection matrix, three pollutants, i.e., TSS, TN and TP, were selected based on the selection criteria mentioned in Section 3.2. Mentioned below are the pollutant removal equations that were tested and applied in the models for analysis.

Total Suspended Solids (TSS): Particles larger than 2 microns found in the water column are considered as total suspended solids. Presence of TSS in aquatic bodies, such as lakes and rivers, stops the penetration of sunlight and creates oxygen depletion areas below the water surface, harming the flora and fauna of the water bodies. TSS contains both organic and inorganic matter, which is considered to be retained on the top layers of the system by sedimentation and filtration process. Hence, the removed TSS considered in this study was mainly by sedimentation/settlement and filtration process [99]. The following TSS removal equation used in this study was derived from [109]:

$$\mathrm{C} = 20 + (\mathrm{TSS} + 20) \times \ \mathrm{EXP}(-0.0011 \times (\mathrm{DT}/\mathrm{DEPTH})) \tag{1}$$

The minimal residual considered for TSS concentration is 20 mg/L. TSS in the expression is the identifier given to the TSS concentration C for this model, −0.0011 is the value for removal constant k, which is expressed in units of mm/sec, DEPTH is the reserved word that SWMM uses for the water depth D in mm and DT is the reserved word that SWMM uses for routing time step DT in seconds.

Total Phosphorous (TP): The phosphorus removal mechanism considered in this study was mainly ruled by the sedimentation and filtration process. PP, which is the dominant species in the stormwater runoff, is removed by filtration or sedimentation, whereas DP removal depends on chemical sorption and complex mechanism to immobilize P species [99]. They are also removed due to adsorption and precipitation. Amendment of soil with iron or aluminum helps in enhanced phosphorus removal. During stormwater, runoff phosphorus is deposited along with the sediments, adsorbed to the suspended solids, soil surface and vegetation. The following equation was derived from [79] for the removal of TP:

$$\mathrm{C} = 0.12 + (\mathrm{TP} - 0.12) \times \mathrm{STEP}(0.12 - \mathrm{TP}) + (0.880 \times \mathrm{TP} - 0.12) \times \mathrm{STEP}(0.880 \times \mathrm{TP} - 0.12) \tag{2}$$

where C = outlet concentration, TP = inlet concentration and STEP = binary function (0 for resultant ≤ 0; 1 for resultant >0).

The concentration of 0.12 mg/L in the above equation indicates an irreducible concentration and 12% reduction of pollutant concentrations higher in every time step than the threshold.

Total Nitrogen (TN): Nitrogen compound contains both organic as well as inorganic forms of nitrogen, such as ammonium (NH_4^+), nitrate (NO_3^-) and nitrite (NO_2^-). In stormwater, nitrogen is present as an organic nitrogen form and a dissolved form. Removal of nitrogen is a complex and slow process; hence, the removal process needs more time than other pollutants. The conversion of ammonium (NH_4^+) from organic N is termed as mineralization. On the other hand, the biological oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) and nitrate (NO_3^-) is known as nitrification. Removal of nitrogen from the NBS systems highly depends on a few factors, such as vegetation, hydraulics retention time provided, filter media and influent concentration in the stormwater runoff [42,43]. The following equations, derived from [56], were used for the nitrification and de-nitrification process in this study:

$$\mathrm{TKN_i} = (\mathrm{TKN_i}) \times \mathrm{EXP}\ (-0.81 \times \mathrm{HRT}) \tag{3}$$

$$\mathrm{NO_3} = \left(\mathrm{NO_{3i}} + \mathrm{R_{TKN_i}}\right) \times \mathrm{EXP}(-2.5 \times \mathrm{HRT}) \tag{4}$$

$$\mathrm{TN} = \mathrm{TKN_i} + \mathrm{NO_3} \tag{5}$$

In the above equations, $\mathrm{TKN_i}$, $\mathrm{NO_3}$ and TN represent first-order decay K-C *. R_$\mathrm{TKN_i}$ is the mass of the $\mathrm{TKN_i}$ reacted. For TN, the hydraulic residence time (HRT) was considered in the equation based on the study mentioned in [56,109]. For $\mathrm{TKN_i}$ and $\mathrm{NO_3}$, a decay constant of −0.81 and −2.5, respectively, was obtained from [56] for this study.

3.6. Verification of the Models

The schematized models for NBSs and water pollutant removal were tested before they were applied further in the case study. To analyze and understand the behavior of the model for water quality, the pollutant concentrations from five different academic publications [20,39,52,65,110] were used and their removal efficiency was compared with the model performance.

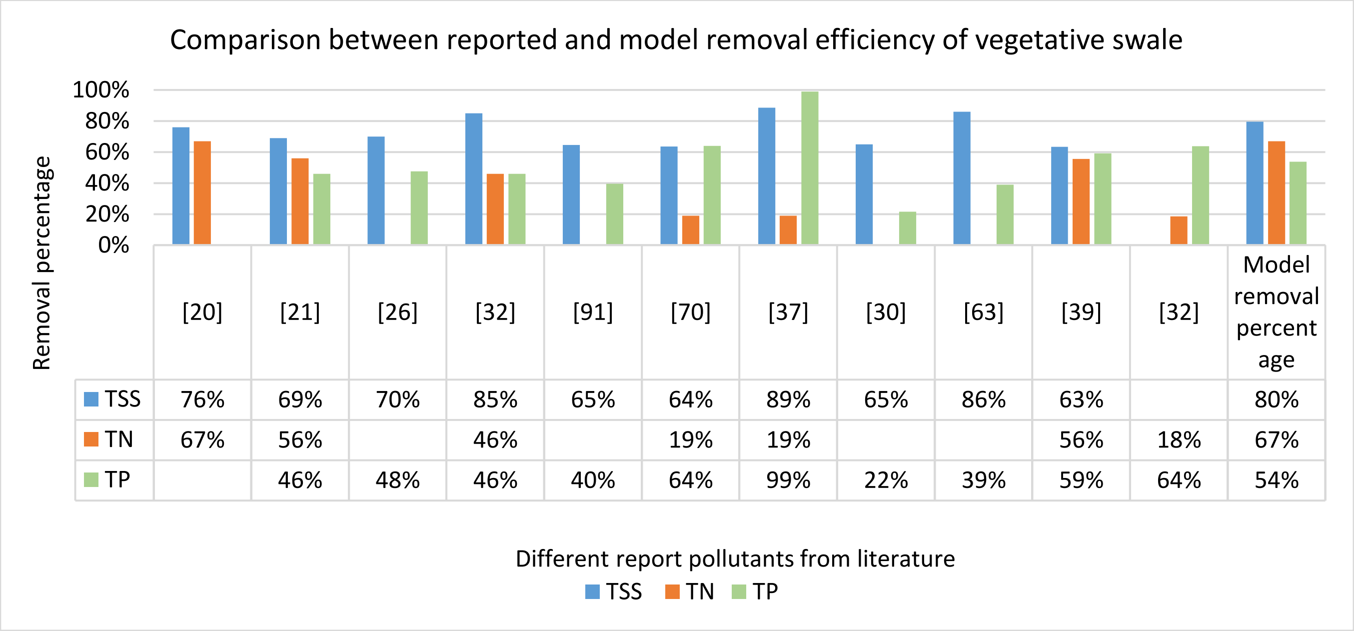
For bio-retention cells, a field experiment was conducted as reported in [52] on a street-side bio-retention cell in Seattle, Washington, United States. In that study, a composite sample was collected at the inlet and outlet of that treatment system. When the inlet pollutant concentrations mentioned in the report were used in the model, the model showed a pollutant removal treatment efficiency of 83% of TSS, 71% of TN and 69% of TP against the reported result, which showed a removal efficiency of 87–93% in TSS, 63–82% in TN and 67–83% in TP by the system.

The second test reference used for comparison was reported in [24], which was conducted with the bio-retention cells with synthetic stormwater runoff to evaluate the water quality. TKN and TP were the primary pollutants evaluated in that experiment. The results showed a removal of 55–65% of TKN and 70–85% of TP from the stormwater runoff, whereas the model result showed a removal of 83% of TSS, 71% of TN and 76% of TP from the system.

In the study [13], the water quality test on vegetative swales to treat highway runoff were reported. The performance of the swales was compared for over 4.5 years during 45 storm events. The report shows a reduction of 82% of TSS, 85.6% reduction of TN and 49.6–68.7% for TP. Similarly, to compare the efficiency of the vegetative model developed in this study, the pollutant details mentioned in [13] were used to validate the model and evaluate the pollutant removal performance. The model showed a removal efficiency of 75% of TSS, 76% of TN and 64% of TP from the system. As reported in [20], six vegetative swales were evaluated in the Los Angeles and San Diego area. The reported result showed a load reduction of 76% of TSS and 67% of TN, whereas the model showed a reduction of 80% of TSS, 67% of TN and 54% of TP.

To conduct a water quality test on permeable/porous pavements in Auckland's North Shore, 4–17 storm events were analyzed for removal of TSS and metals as reported in [65]. An area of 210 square meters (sqm) of permeable/porous pavement was considered for the water quality test. The report stated that the system efficiently removed 70% of TSS from the runoff water, whereas the developed model showed a removal efficiency of 83% for TSS and 71% for TP from the stormwater runoff. Following Table 2 shows the water quality parameters used for comparing the pollutant removal performance by the model against the reported results.

The test catchment area was subjected to short rainfall event as mentioned in Section 3.4. Different treatment equations of TSS, TN and TP removal were also used in each tanks schematizing different layers. The top tank was considered to remove TSS and TP by the sedimentation and filtration process, whereas the tanks in between were considered to remove TN by nitrification and de-nitrification process. Finally, the last tank was considered to store the water and release it to the drainage node. The equations were applied respectively. The tanks were finally simulated with the rainfall and the removal efficiency observed were plotted on graph. The calculated removal efficiency by the model was then compared against the reported result, as shown in Figure 5.



	[20]	[21]	[26]	[32]	[91]	[70]	[37]	[30]	[63]	[39]	[32]	Model removal percentage
TSS	76%	69%	70%	85%	65%	64%	89%	65%	86%	63%		80%
TN	67%	56%		46%		19%	19%			56%	18%	67%
TP		46%	48%	46%	40%	64%	99%	22%	39%	59%	64%	54%

Figure 5. Comparison of the vegetative swale model with the reported removal efficiencies from the literature.

All the NBS models developed showed overall similar or slightly higher pollutant removal efficiencies.

A final comparison graph of all the three NBSs is mentioned in Appendix A, Figure A1. The removal performance of TSS, TN and TP were analyzed in the models. As shown in Figure A1, the model showed a similar removal performance of TSS, between 78–90% reported in 14 publications [13,20,32,37,52,54,59,63,66,74,75,111], while 11 publications reported a TP removal performance between 54–69% [5,37,39,52,60,61,66,70,74,75,110]. Variations were seen in TN removal efficiency by the model where only seven showed a removal between 56–87% [5,20,21,39,52,56,75] and five showed removal less than 56% [32,37,55,70,110], whereas the treatment equation applied in the model showed a removal between 67–87% by the NBSs. The variations in TN removal are due to difference in designing and provided a hydraulic retention time for nitrification and denitrification processes in the reported case studies.

After testing and comparing the model outcome against the reported literature, it was considered that the schematization of the NBS models and overall pollutant removal methods were reproducing satisfactory results. The same setup was then used in a case study area of Cul-de Sac on Sint Maarten Island. The study work was conducted to analyze the performance of the small-scaled NBSs in urban catchment areas and assess their pollution control potential.

Table 2. Parameters used for pollutant removal performance comparison.

Study	**Reactor Volume (m^3)**	**NBS Used**	**TSS (mg/L)**				**TKN**				**NO_3**				**TN = (TKN + NO_3)**		**TP**			
			Cin	**Cout**	**% RRE**	**% MRE**	**Cin**	**Cout**	**% RRE**	**% MRE**	**Cin**	**Cout**	**% RRE**	**% MRE**	**% RRE**	**% MRE**	**Cin**	**Cout**	**% RRE**	**% MRE**
Minervini et al. [54]	300	BRC	120.38	20.01	87–93	83	1.15	0.07	NA	92	1.15	0.44	NA	62	62–82	71	0.42	0.13	67–83	69
Davis et al. [112]	300	BRC	120.38	20.38	NA	83	4.01	0.3300	55–65	91	0.58	0.29	NA	50	NA	71	0.49	0.12	70–85	76
Stagge et al. [41]	300	VS	98.31	24.6	82	75	3.39	0.39	85	89	2.38	0.85	85	64	85.6	76	0.55	0.2	49–68	64
Jiang et al. [22]	300	VS	94.75	19.42	76	80	3.44	1.06	NA	69	1.34	0.48	NA	64	67	67	0.26	0.12	NA	54
Fassman and Blackbourn [67]	300	PP	337.41	55.60	70	83	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.42	0.12	NA	71

Cin—Concentration at the inlet, Cout—Concentration at the outlet, % RRE—Reported removal percentage, % MRE —Model removal percentage, TSS = Total suspended solids, TN = Total Nitrogen, TKN = Total Kjedahl Nitrogen, NO_3—Nitrate, TP—Total phosphorus, BRC—Bio-retention cells, VS—Vegetative swales, and PP—Porous pavements.

4. Application of the Model in the Case Study Area

4.1. Case Study Area Description

The case study used in this work is located in the Cul-de Sac catchment area on the Island of Sint Maarten in the Caribbean. Sint Maarten has a population of approximately 42,710 inhabitants. The southern part of the island is part of the kingdom of the Netherlands, which is 40% of the island area, and the rest constitutes French territory. The island's economy is highly dependent on the tourism industry, which helps in the development and growth of the island. The Dutch side covers an area of 34 km^2. It has a hilly terrain with the highest peak at 383 m from sea level. Sint Maarten has a wet climatic season throughout the year, with the highest rainfall of 129 mm during September and the lowest rainfall of 43 mm during February and March. The temperature varies from 25 degrees Celsius to 31 degrees Celsius throughout the year. The catchment area used in this work is called Cul-de Sac, and its location is shown in Figure 6.

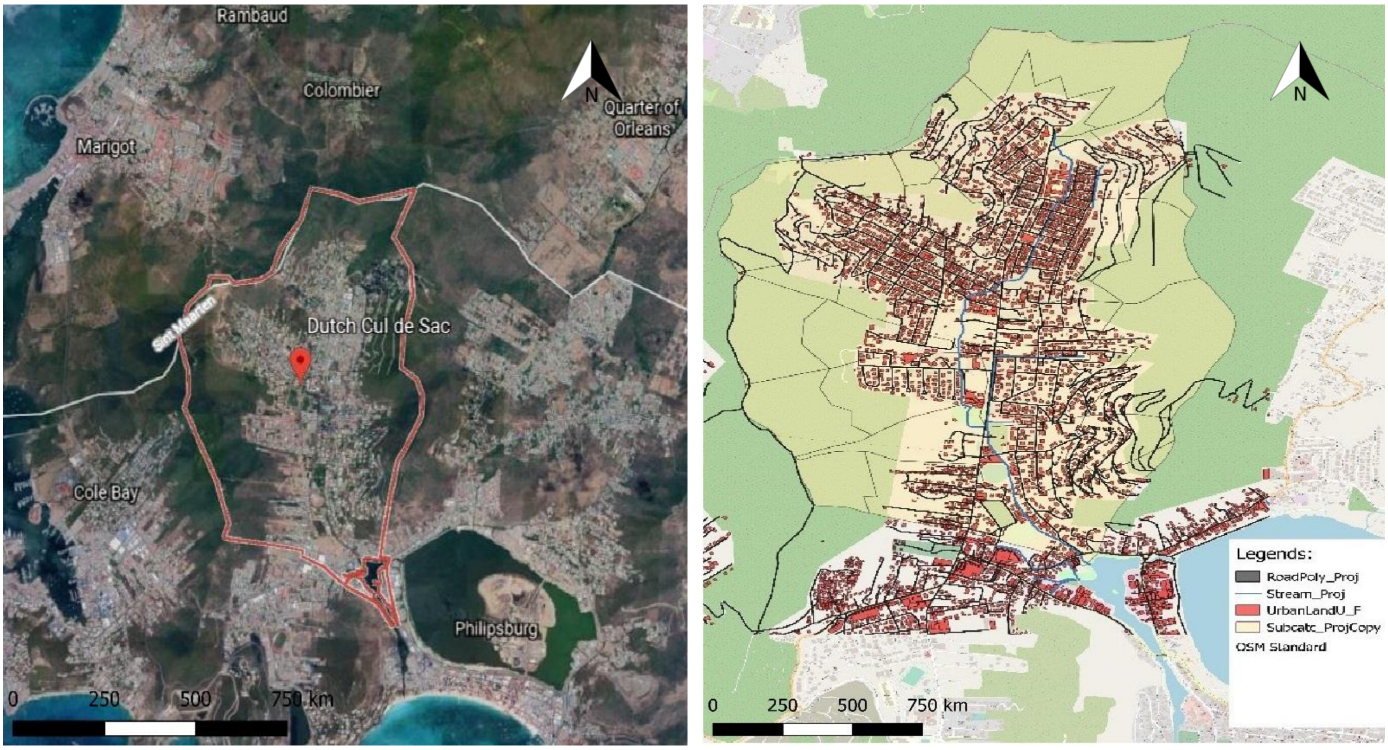


Figure 6. Cul-de Sac, Sint Maarten Catchment area.

Cul-de Sac is a densely populated area with a mix of residential and commercial buildings. The water quality of the Fresh Pond downstream of Cul-de Sac is being deteriorated by urban runoff from two open channels, mainly Bush road and Zarger's Gut. The capacity of the existing drainage system is not enough to transport stormwater for high intensity rainfall events causing flooding in the low-line area. Public space is not abandoned in the area and the implementation of a larger centralized system for stormwater management is challenging. Therefore, decentralized measures such as nature-based solutions can be a good approach to reduce stormwater runoff and at the same time reduce pollution.

The Cul-de Sac area has four land use categories, namely open space, residential, freeway and commercial. The forest, underdeveloped and green areas are considered open space, whereas the roads, public transportation lines and pathways are considered freeway. The residential building was subdivided into low-intensity residential (LIR) and high-intensity residential (HIR). High-intensity residential was assumed to have 80–100% of the urbanized area and less than 20% of vegetative or green area, and 30% to 80% urban area and 20% to 70% green area is considered from LIR. The upper catchment area of Cul-de

Sac is mainly covered with forest or an underdeveloped area with a steep slope. This soil in the upper catchment area is characterized by soil with significantly less infiltration capacity.

4.2. Nature-Based Solution Placements

The Cul-de Sac catchment area was modeled by dividing it into impervious and pervious areas. The entire catchment was sub-divided into twelve impervious and pervious sub-catchments. These twelve impervious sub-catchments were further divided into 60% and 40% areas. Due to a lack of open space observed in the catchment area, the placement of NBSs was done only in 40% of each impervious area. These impervious catchments were sub-divided into clusters according to the number of NBS units subjected to the contributing catchment area. Only the runoff from these areas was considered for treatment. The other parts of the generated runoff from 60% of the impervious area and the entire pervious area is connected to the existing drainage system downstream. Figure 7 shows the sub-divisions of each catchment and the placement of the NBSs in Cul-de sac.

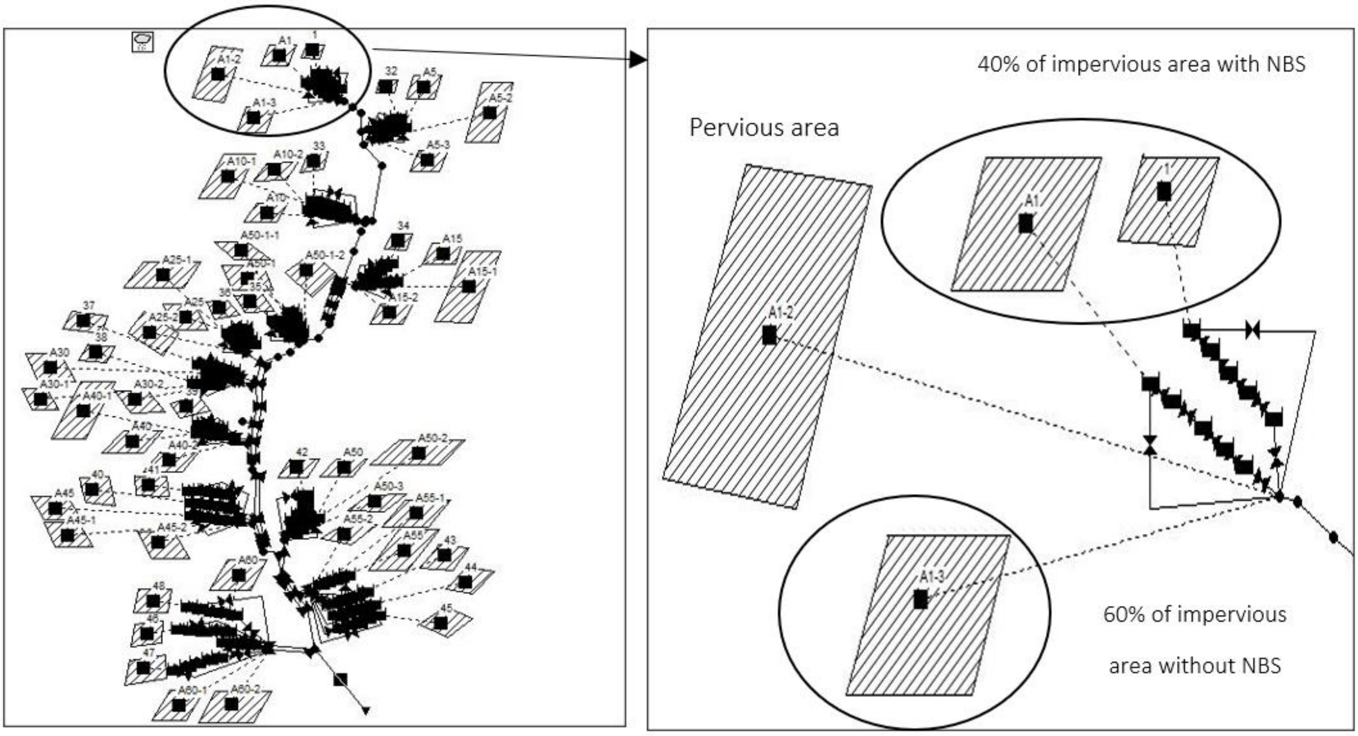


Figure 7. Catchment sub-divisions and placement of the NBSs in Cul-de Sac.

The drainage area of the sub-catchment areas are based on land-uses. Only runoff water from the streets of residential, commercial colonies and roof tops was considered. The area of bio-retention cells for every sub-catchment area was considered to be 20% of the contributing drainage area [112,113], with a length to width minimum ratio of 1:3 to maximize the distance between inlet and outlet and to allow better pollutant reduction by sedimentation and filtration processes. For vegetative swales, the area of the treatment systems was considered 15% of that of the contributing drainage area for every impervious sub-catchment [112], whereas permeable pavements are considered as alternatives to impervious areas, thereby replacing the urban streets, footpaths and parking lots, which increases the availability of covering more drainage area during runoff [112,113]. For this study, 20% of the contributing drainage area was considered to be covered with porous pavements.

The NBS systems were designed to act as a storage unit during various rainfall events to reduce the peak flow, provide sufficient retention time for treatment and gradually dewater into the drainage system. The hydraulics levels of the schematized layers were designed for sequential dewatering layer-wise, starting from emptying of the top layer followed by second, third and finally the last tank into the existing drainage system.

5. Model Set-Up for Cul-De Sac

5.1. Precipitation Setup

After defining the pollutants generated and land use for the catchment, the models were simulated for different rainfall patterns as follows:

- Firstly for rainfall events, which correspond to a two- and five-year return period, where the peak precipitation rate reaches up to 36 mm/h and 52 mm/h, respectively. The peak precipitation rates were designed to analyze the performance of the NBSs due to flow fluctuation entering the system and the pollutant removal efficiency by the generation of peak stormwater runoff within a short period of time.
- Secondly, a synthetic rainfall with continuous storm events was designed for the simulation. For designing a continuous synthetic rainfall, the data presented on the meteorological website of Sint Maarten were analyzed. Figure 8, presents the continuous rainfall event used for the continuous simulations; 20-day periods were simulated. In selecting the events, data collected from a meteorological database (http://www.meteosxm.com/publications, accessed on 30 July 2020), reflecting the variation in rainfall throughout the year in Sint Maarten, were used. The annual rainfall varied from a minimum of 495.4 mm (2015) to a maximum of 1180 mm (2014). The meteorological report also states that the year's wettest month in Sint Maarten lies between July–December of every year, where the peak rainfall is recorded. For the rest of the year, a decent amount of precipitation was recorded on the island. Usually, as reported in the metrological reports of Sint Maarten, the island receives a decent amount of rainfall throughout the year, with very few dry periods in between, which varies from five days to twenty days in a month. Data from the meteorological website of Sint Maarten showed that due to variation in climatic conditions, the average peak flow during the wettest month has experienced an enormous amount of variation in the last decade.

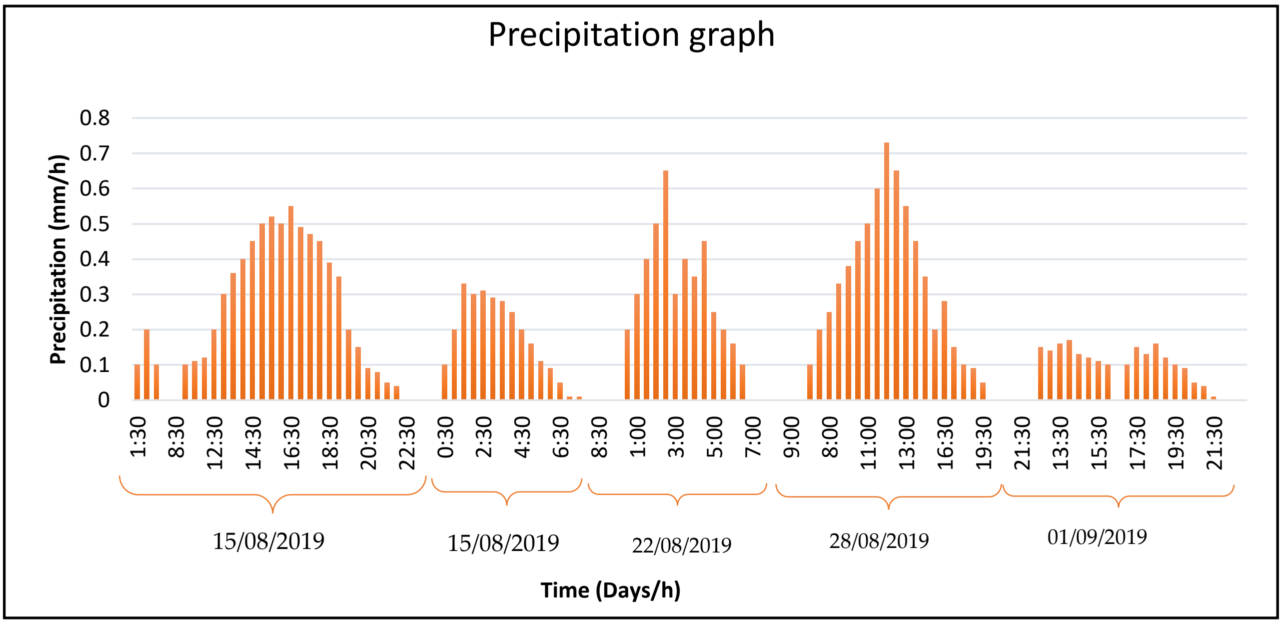


Figure 8. Designed continuous synthetic rainfall trends used for analysis.

Performance of the NBSs could be affected by high flow fluctuations, thereby affecting, especially, pollution control abilities. Pollutants needs sufficient retention time for degradation and reduction in concentration, e.g., total nitrogen (TN). With a lack of sufficient retention time, the pollutants drain out of the system without proper treatment. Therefore, in this study, the storm events used were designed to analyze the dynamic behavior of the system and pollutant removal during varying rainfall events. This analysis can give a clear understanding of NBS designing as well as operation and maintenance requirements. Additionally, this analysis can clarify if any retrofitting is required to increase the efficiency of the system to be able to handle both the removal of the pollutants and the flow fluctuation during variations in incoming stormwater runoffs.

5.2. Hydraulics inside the NBSs

Each bio-retention units was designed with 20% of the surface area with a depth of 1.3 m compared to the drainage area covered for every catchment. The tank representing the top layer (water storage) was designed with a depth of 0.3 m, the second layer (sand) of 0.3 m depth, the third layer (5–7 mm gravel) of 0.2 m depth, the fourth layer of (12–20 mm gravels) with 0.2 m and, finally, the last layer (80–100 mm gravel) of 0.3 m depth [109,114,115].

Vegetative swales—Similar to bio-retention cells, vegetative swale was designed with 15% surface area with 1.3 m depth of the drainage area covered. Vegetative swale was designed with four tanks where the top tank was designed with a depth of 0.5 m for free water storage, second layer (sand layer) with 0.3 m depth, third layer (12–20 mm gravels) 0 with 0.2 m, and last layer (80–100 mm gravels) with 0.3 m depth [20,39,109].

Permeable/porous pavements were designed with 20% surface area of the contributing drainage area. The systems were also designed with 0.6 m depth, composed of only three layers. The model consists of a top layer of 0.2 m of paver blocks, a second layer of 0.1 m of sand and a last layer of 0.3 m of 20–40 mm gravels.

Figure 9 shows the hydraulic volume inside the tank and dewatering pattern from the tanks.

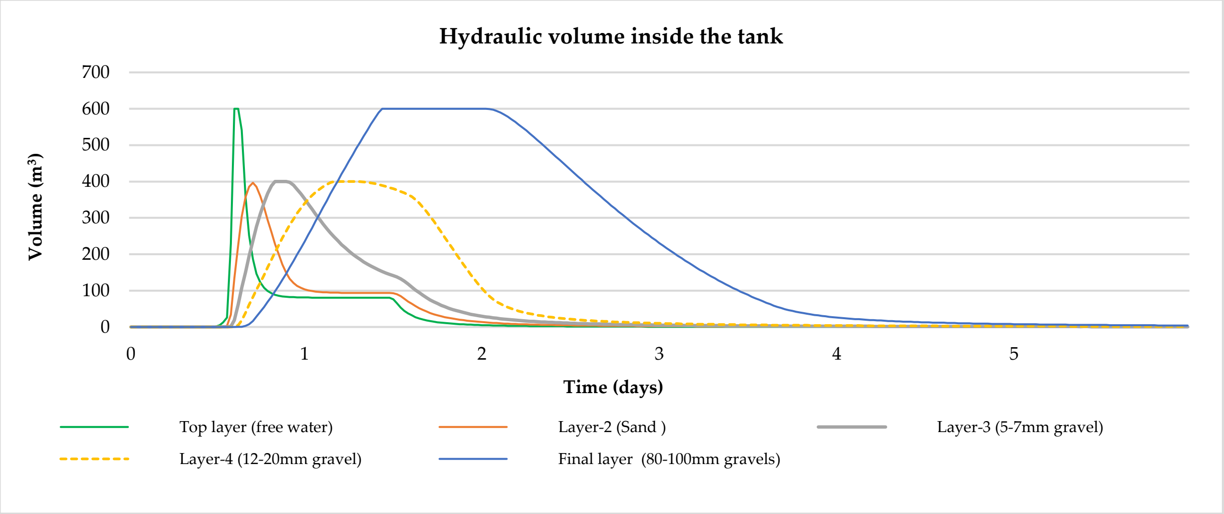


Figure 9. Volume and dewatering pattern inside the tanks for bio-retention cells.

A similar approach was used for both vegetative swales and porous pavements.

Orifices were sized and provided in the tanks to maintain a gradual flow between the tanks. Therefore, as shown in Figure 9, the top tank dewaters were followed by the second, third, fourth and, finally, the last tank. Similar approach was conducted for the tank setup for vegetative swale and porous pavement. An overflow orifice was set up in the top layer (tank) to bypass the excess water entering the system to the downstream drainage node to provide safety to the system during excess precipitation. After maintaining the hydraulic behavior inside the system, the pollutant generation in Cul-de Sac, was set up for the pollutant removal performance analysis.

5.3. Pollutant Generation

Different land-use types were defined in the catchment area, such as residential, commercial and open non-urban lands. Due to a lack of local data on pollutants, the wash off Event Mean Concentration (EMC), which considers each pollutant to have a constant runoff concentration throughout the simulation [103,109]. Table 3 shows the EMC used for simulation in the Cul-de Sac catchment to generate runoff pollutants.

Table 3. Event mean concentration used for urban land use.

Sr. No.			Residential	Commercial	Open/Non-Urban Areas
1	Pollutants	Units	Median	Median	Median
2	Total Suspended Solids (TSS)	mg/L	101	69	70
3	Total Kjeldahl Nitrogen (TKN)	mg/L	1.900	1.179	0.965
4	Nitrate (NO_3)	mg/L	0.736	0.572	0.543
5	Total Phosphorus (TP)	mg/L	0.383	0.201	0.121

TSS, being one of the major pollutants, plays an important role in water quality assessment. As observed in Table 3 above, there is a significant difference between the concentration of TSS compared to TP, TKN and NO_3 (the sum of TKN and NO_3 is considered as TN). Good reduction in TSS also helps in reducing nutrients such as TP and TN, which gets reduced as they remain attached with the solids, which are being retained back by filter materials; hence, a portion of the nutrients gets retained along with TSS. Nutrients also get removed due to uptake by the vegetation planted in the NBSs. In certain cases, the concentration of TP and TN is small, which, in most places, even comes under the nutrient regulatory permits allowed in water discharge. Hence, with the implementation of the NBS systems, these pollutants can be reduced before getting discharged into the downstream water bodies.

6. NBS Performance Analysis

6.1. Bio-Retention Cell Model Water Quality Analysis

During the initial model run for the Cul-de Sac catchment, NBSs were placed as single units. At first, the bio-retention cells were placed in contributing impervious sub-catchments. Each unit with a size of 20% of the contributing drainage area was placed in series with a length-to-width ratio of 1:3 for increasing the distance and travel time of the runoff water for sufficient treatment of the pollutants.

When a rainfall pattern with a two-year return period was applied, the configuration showed an overall removal efficiency of 41% of TSS, 43% of TN and 41% of TP from the catchment. It also showed a reduction of 51% of peak flow from the sub-catchments during the storm event. The overall removal rate for the pollutants is affected because only 40% of the impervious areas were being treated; hence, the rest of the area directly discharged the runoff water into the existing drainage system. Figure 10 shows the TSS removal performance at the outlet of the catchment area when the treatment equation 1 was applied for simulation.

As shown in Figure 10, the time series with no treatment units (i.e., no NBSs) with a two-year return period shows a peak flow of 2 h, and then a minor flow is maintained until it entirely disappears at about two days. Once the treatment units were incorporated, a reduction of the TSS concentration was observed almost immediately. The TSS concentration is maintained for a more extended period, as the NBS units are fully occupied (total volume), and water gets slowly released from the tanks. Additionally, a certain amount of water is being stored and managed inside the system to help the vegetation or plants in the system to survive. If the water level is not maintained, the vegetation would require frequent replacement, increasing the operation and maintenance of the system. Thereby, the simulation period was extended to 10 days to observe the amount of time it takes to fully dewater the units. A minimal amount of fluctuation in the TSS concentration can also be observed, as only a portion of the catchment is subjected to treatment; hence, when the rest of the untreated runoff water is released in the existing drainage line, it mixes with the treated runoff water and causes a fluctuation in the concentration.

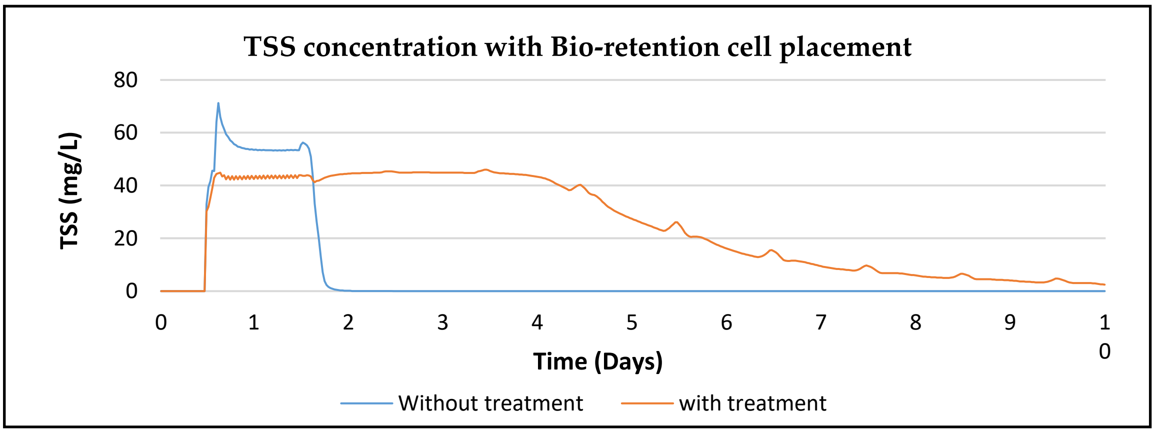


Figure 10. TSS concentration reduction with bio-retention cell placement with a two-year return period rainfall pattern.

A similar analysis was done with a five-year return period. In this case, the system showed a reduction of 24% of peak flow and volume of the stormwater. There was a gradual decrease in the pollutant slowly after the peak load reduces. The system showed 14% removal of TSS, 17.70% removal of TN and 23% of TP removal from the system. It was also observed that there was a lower removal of TSS for the first two days of the storm event due to a continuous higher flow of runoff into the system. An increase in flow velocity and less settlement time limited the settlement of the pollutants. Thus, with the reduction in inflow rate into the system, the model showed a good amount of TSS removal in the later stage. To summarize, the bio-retention cells designed showed an efficiency of 14–41% of TSS, 17–43% of TN and 23–41% of TP removal from the catchment area for the five-year return period.

6.2. Vegetative Swale Water Quality Analysis

Similarly to the bio-retention model, a vegetative swale with an area of 15% of the contributing drainage area was placed for every twelve catchments. The dynamic analysis was conducted by observing the changes in volume and hydraulic heads during the two storm events. When a rainfall pattern with a two-year return period was applied, the configuration showed an overall reduction of 46% in the peak flow from the contributing sub-catchment area, including a removal efficiency of 43% of TSS, 56% of TN and 62% of TP. Figure 11 shows the simulation results with and without treatment units. The time series is analyzed at the outlet of the system.

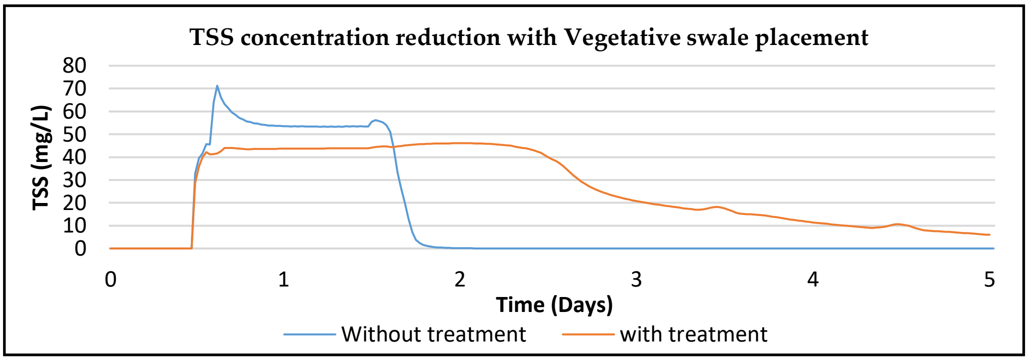


Figure 11. TSS reduction with vegetative swale placement with a two-year return period rainfall pattern.

When the model was simulated with a rainfall event with a five-year return period, there was a reduction of 23% for the peak flow and volume. The system also showed a removal efficiency of 40% of TSS, 45% of TN and 41% of TP in the catchment area.

6.3. Porous Pavement Water Quality Analysis

A similar approach was also applied for the porous pavement model. The model showed a removal efficiency of 43% of TSS and 48% of TP from the final outlet point with a two-year return period rainfall pattern. The TN pollutant was not considered in this model, as the storage layers for porous pavement does not provide enough HRT for nitrification and denitrification processes to reduce nitrogen. Henceforth, the removal of only TSS and TP pollutants was considered in this model. The model was also analyzed with a five-year return period rainfall pattern. The performance showed a reduction in the removal efficiency compared to the two-year return period; it showed a TSS removal efficiency of 38% and 40% of TP, respectively. Figure 12 illustrates the dynamic behavior of TSS for a two-year return period event.

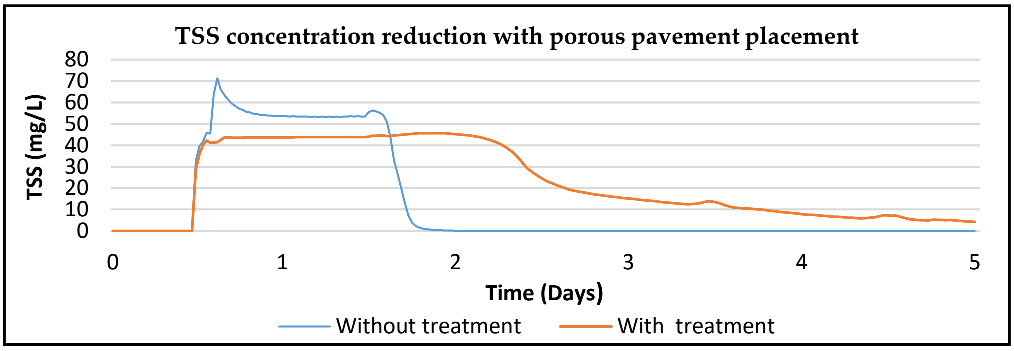


Figure 12. TSS concentration reduction with porous pavement placement with a two-year return period rainfall pattern.

6.4. Application of Combined or Networked NBSs for Water Quality Analysis

Three networked configurations of NBS models were applied to the Cul-de Sac catchment area for a detailed analysis of the models for water quality. A combination of vegetative swale and porous pavement, bio-retention cells and porous pavement and a combination of all the three models were applied to the catchment area for water quality analysis.

In the first setup, eight of the impervious areas were subjected to the porous pavement and vegetative swale-networked NBS system, whereas the other four sub-catchments were subjected to vegetative swales only. The runoff water from the impervious areas enters the porous pavement first, followed by vegetative swales. It was also observed that there was a constant removal of 33% of TSS, 42% of TN and 38% of TP from the catchment area with a two-year return period and 36.7% of TSS, 38% of TN and 38.10% of TP with a five-year return period. The efficiency was expected to be more if more catchment areas were subjected to the networked treatment system. However, the model results show that the efficiencies in pollutant removal are similar to if they operate separately.

In the second setup, a combination of bio-retention cells and porous pavement was applied to the same catchment area. Eight of the sub-catchments were subjected to the networked model, and the remaining four sub-catchments were subjected to a single bio-retention cell model. Different rainfall trends were simulated with a two- and five-year return period and applied to the model. It was observed that the model showed a removal efficiency of 36% of TSS, 39% of TN and 38% of TP with a two-year return period rainfall pattern, whereas a removal efficiency of 38% of TSS, 38% of TN and 38% of TP was observed with a five-year return period rainfall pattern. Again, as was the case in the first tested configuration, the model results indicate no significant differences in efficiency when the measures are connected.

In the third and final setup, another combination of vegetative swales, bio-retention cells and porous pavement was applied to the same catchment area. Alternate combinations were applied to all the 12 impervious sub-catchment areas, with six sub-catchment areas subjected to networked NBSs of bio-retention cells and porous pavement, and the other six sub-catchments subjected to vegetative swales and porous pavements. The catchment was simulated with a two-year and five-year rainfall return period to analyze the performance of the combined system. The system showed a removal efficiency of 37% TSS, 40% TN and 38% of TP from the systems with a two-year return period, whereas removal of 39% of TSS, 39% of TN and 38% of TP was also observed. Similar to the previous model setup runs, the system did not show much variation in pollutant removal efficiency. The model setup indicates that NBS measures work better individually than networked or combined, but this also depends on the return period being analyzed. The results appear to be better for the five-year return period once they were connected; this can be explained that the volume of the units working together is higher than when they work individually.

6.5. Water Quality Performance during Continuous Synthetic Rainfall Events

We analyzed the system's performance with a dataset of a continuous rainfall pattern for 20 days. All models with single and combined configuration developed in this study were simulated with the designed continuous synthetic rainfall presented in Figure 8. Different model setups were used to analyze the effect of flow variations inside the system and their treatment performance. This synthetic rainfall pattern was designed to have five storm events with different peaks and duration within 20 days, as mentioned in Figure 9.

Table 4 shows the pollutant removal performance of the systems with a continuous rainfall pattern of 20 days.

Table 4. Removal efficiency of the models with continuous synthetic rainfall events.

Sr. No.	Name of NBS Model	Setup	Removal Efficiency		
			TSS	TN	TP
1	Bio-retention cells	Single	22%	19%	20%
2	Vegetative swale	Single	23%	19%	22%
3	Porous pavement	Single	21%	NA	21%
4	Vegetative swale and porous pavement	Networked	38%	28%	31%
5	Bio-retention cells and porous pavement	Networked	27%	15%	56%
6	Vegetative swale, bio-retention cells and porous pavements	Networked	40%	54%	56%

The above table shows the variations in pollutant removal performances of different single and networked NBSs when applied to the same catchment area with continuous rainfall storm events.

7. Discussion

NBS are well-known for managing stormwater runoff and improving water quality as well as maintaining a sustainable environment [3]. To identify the need for evaluating different types of NBSs and understanding the performance regarding water quality improvement, a set of model-run experiments were developed in this study. The NBS system provides various co-benefits, such as social, economic and environmental [40]. Thereby, it is crucial to understand the process occurring in the NBS and opt for an appropriate solution to manage the stormwater runoff for selected site location.

NBS can reduce the peak flows and the volume of the stormwater runoff, and in addition, they also help as measures for pollution control [1]. Modeling analysis provides a tool for modelers and designers to test and analyze the effectiveness of the NBSs with existing and predicted scenarios towards the improvement of water quality and environmental benefits [24,25]. The model analysis conducted in this study provides guidance and understanding of the hydraulic behavior occurring inside the systems, where every layer plays a vital role in controlling the peak flow, volume and removal of pollutants. When three NBSs, namely bio-retention cells, vegetative swales and porous pavements, were placed individually in the Cul-de Sac catchment area to analyze the pollutant removal efficiency, it allowed us to understand which system performs better as a standalone system in improving the runoff water quality.

Analyzing the behavior of the NBSs with different rainfall trends in a larger catchment with complex drainage network and various land-use options enhances the analysis of the measures for modelers, designers, stakeholders and decision-makers to make the rightful decision on implementation of a rightful treatment system which is economical and sustainable.

In this study, different types of small-scale NBSs were analyzed to understand their behavior with different rainfall patterns. It was observed that these small-scale nature-based solutions are practical and efficient during small rainfall events. It can efficiently reduce the peak flow and the pollutants from the runoff stormwater. These measures can provide benefits in terms of improving water quality during rainfall events, as shown in Table 4.

It was also observed that these small scale NBS systems' performance reduces during more such storm events. As they were designed for small events, during large storms, due to higher flow and limited storage capacity of the treatment systems, it becomes less effective in reducing the peak flows and removing pollutants; this can be observed in Figures 13 and 14. However, for all the simulations, the NBSs could reduce the concentration of the pollutants before finally being discharged back to the existing drainage system and into the receiving water body.

The combination of three networked NBS system in series was also applied in the catchment to analyze the difference in pollutant removal. The controlled flow through the networked systems also showed a reduction in peak flow from the catchment and reduced pollutant concentration. The results suggest that the networked NBSs worked better for higher return periods than individually.

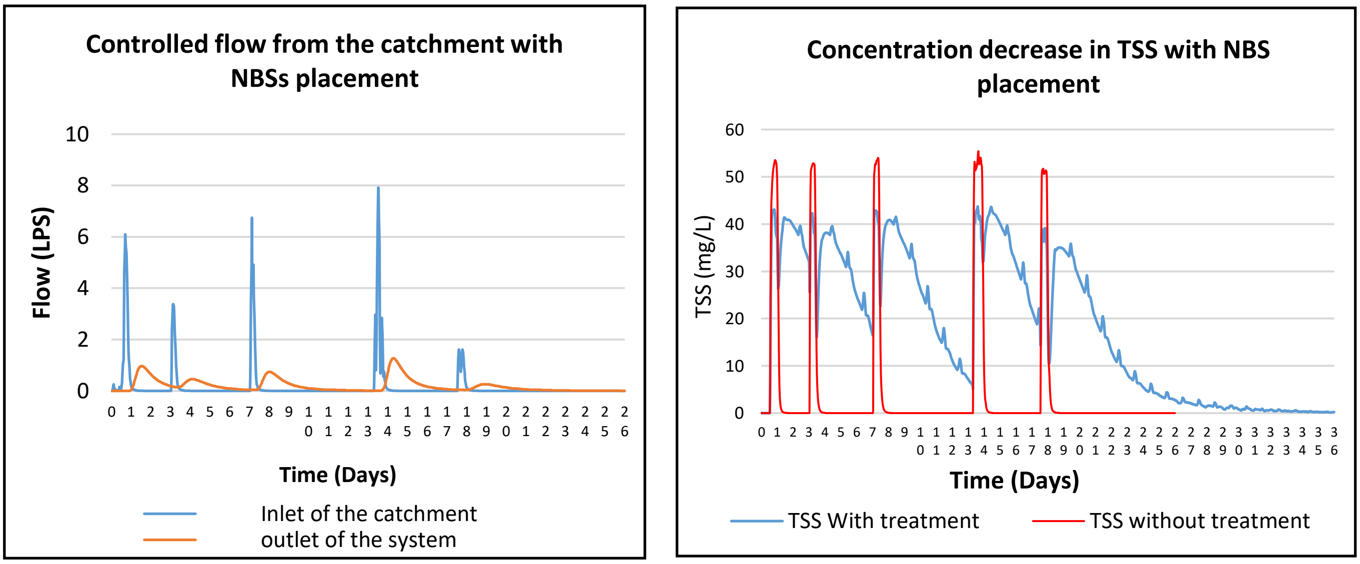


Figure 13. Controlled flow after NBS placement (**left**) and decrease in concentration of pollutants with NBS (**right**) with the designed synthetic continuous rainfall events.

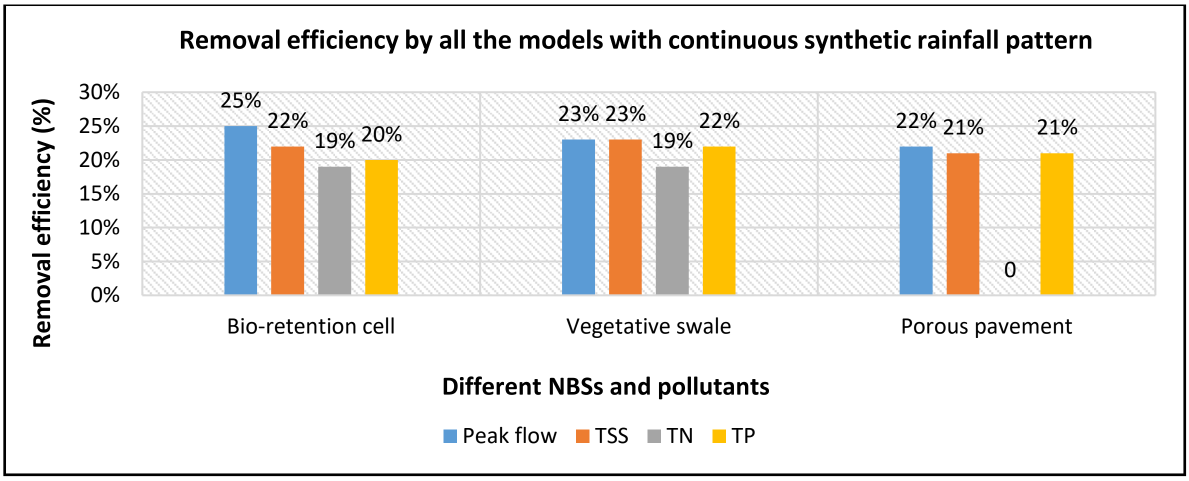


Figure 14. Removal efficiency of single configuration models with continuous synthetic rainfall pattern.

When the designed continuous synthetic rainfall was applied to the models, variations in efficiency were prominently observed between the combinations where the third setup was more suitable and efficient in all rainfall trends than the first two setups shown in Table 4.

Flow variations cause flush out of nutrients through the filter media's and out for the system without getting settled and treated. As mentioned before in this study, the main treatment processes considered for removing TSS and TP are sedimentation and filtration [21], whereas, for TN removal, nitrification and denitrification process [22] will depend on the hydraulic retention time inside the system. To increase the efficiency during these events, a large system needs to be installed, which would impact cost and area of implementation.

Additionally, to replicate the natural phenomenon and add aesthetics to the area, most of the NBS systems use vegetation that helps in absorbing and utilizing the nutrient from the runoff water for their growth but also helps in improving the water quality getting out of the system [24]. To guarantee the proper operation and full utilization of the system, the hydraulic analysis and maintenance of these systems are of utmost importance. Most variations in the hydraulic level inside the system are observed during varying rainfall and the dry period between the events, making the pipes' designing a critical factor for analysis and verification. This analysis would help the designers, stakeholders and decision-makers to provide and select an appropriate system with proper O&M guidelines and provide an understanding of the impact of the investment on the systems required for a particular location.

The result of the networked NBS configurations does not provide too many variations in the net outcome, which makes it difficult for providing the best solutions. Minor differences in treatment efficiencies were observed from the model results. The approach used for the treatment in this paper was by setting treatment equations to every tank specified to remove the pollutants. SWMM is sensitive to such kind of equations [25]. It is suggested to experiment with different equations, and several model trials should be made to come out with more realistic results.

8. Conclusions

Different externalities can cause variations in the performance of NBS. The present paper evaluates the treatment performance of urban stormwater runoff by small-scale NBSs, such as bio-retention cells, vegetative swales and porous pavements, with different configurations (single and networked) and varying rainfall patterns. The effectiveness of these three small-scale NBS systems was assessed concerning runoff peak reduction and pollutant removal.

The work was carried out at the Cul-de Sac catchment (which served as a demonstration site) in Sint Maarten. The NBS was evaluated in the following different configurations:

- Single configuration—catchment was subjected to single unit of bio-retention cells, vegetative swales and porous pavements.
- Networked configuration—catchment was subjected to the different combinations of NBS units, such as bio-retention cells with vegetative swales, vegetative swales with porous pavements and finally bio-retention cells with porous pavements.

The model results show that the small-scale NBSs perform better in improving the water quality of the stormwater for events with a smaller magnitude (rainfall with a two-year return period) compared to more significant rainfall events (five-year return period). In addition to the water quality improvements, these NBS systems appear to also be effective in reducing the peak flow, thus avoiding flooding and increasing the aesthetic value of the surroundings. In terms of the single configuration of vegetative swales, it was found that such systems are more efficient when compared to the other two NBSs (bio retention cells and pervious pavement). In contrast, in a networked combined configuration of all three NBS together, it was found to be the most effective configuration for pollutant removal with varying rainfall patterns.

The analysis also aimed to provide design engineers and decision-makers with some additional knowledge about the performance of small-scale NBS. For example, the simulations conducted with a continuous rainfall pattern of 20 days provided insights into the filling and emptying cycles of the NBS units after consecutive rainfall events. The analysis is essential to define operation and maintenance activities and help maintain vegetation inside the NBS. However, the present work would further benefit from laboratory analysis and accurate world monitoring of water quality data that can support and enhance the designing of these NBC. Altogether, the modeling work and the laboratory/monitoring information will further advance the direction of formulating design standards and guidelines for the implementation and operation of NBS systems.

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Conflicts of Interest: The authors declare that they have no conflict of interest.

Appendix A

Table A1. Sample of the Selection matrix developed for selection of NBS and pollutants used for this study.

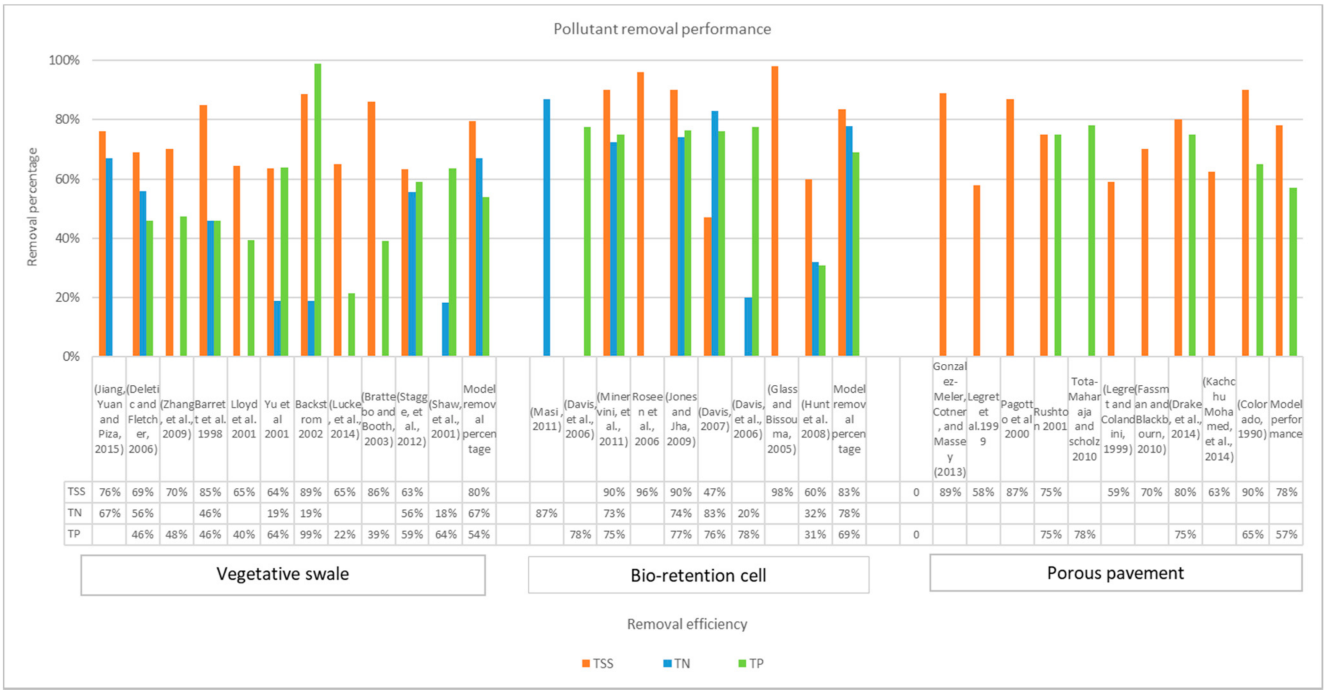
Sr. No.	**NBS**	**Pollutants Effectiveness**							**Location**	**Reference**
		TSS	**TKN**	**TN**	**NO_3-N**	**NH_4-N**	**TP**	**Organic Matter**		
1	Vegetative swales	76%	67%	67%	65%					[22]
2		69%		56%			46%			[23]
3		50–90%				10–35%	25–70%	30–55%	Shenzhen, China	[28]
4		85%		31–61%			31–61%		Texas, USA	[34]
5		55–74%					24–55%		Melbourne, Australia	[93]
6		30–97%		14–24%			29–99%		Virginia, USA and Taipei, Taiwan	[72]
7		79–98%		14–24%			99%		Sweden	[39]
8				99.05%	98.98%	99.08%		99.53%	Davis, California	[29]
9		50–80%					20–23%			[32]
10		41–84%								[33]
11		80–99%								[33]
12		85–87%					34–44%			[65]
13		79–98%								[40]
14		44.1–82.7%		25.6–85.6%			49.6–68.7%			[41]
15				13.8–23.1%			28.8–98.6%			[72]
16		46–86%		56%			46%		Aberdeen and Brisbane, Australia	[23]

Table A2. Selection Matrix developed for modeling tools.

	Function	**Nature-Based Solutions**	**Main Functions**	**Pollutants**	**Reference**
EPA National Storm calculator	Hydrology analysis, cost module and climatic scenarios	Rooftop, rainwater harvesting, green roof, rain garden, street planter, infiltration basin, porous pavement	To estimate reduction in peak flow		
WERD BMP SELECT model	To examine the effectiveness of alternative scenarios for controlling stormwater pollution	Extended Detention, bio retention wetlands, swales, permeable pavements		TSS, TN, TP and total zinc	[96]
(P8 Urban Catchment Model)	To predict the generation and transport of pollutants in urban runoff and design GI to achieve reduction in total suspended solids.	Retention ponds, infiltration basins, swales, buffer strips	Water mass balance, removal efficiencies, comparison of flow, loads and concentration across devices.	Total suspended solids	[97]

Table A2. *Cont.*

	Function	Nature-Based Solutions	Main Functions	Pollutants	Reference
EPA Stormwater Management Model (SWMM)	To plan, design and analysis of the performances of Green Infrastructures in runoff quality improvement and quantity reduction	Permeable pavement, rain gardens, green roofs, street planters, rain barrels, infiltration field, vegetative swales	Time series graphs, tables, and statistical analysis of the simulation results, hydrological behavior and pollutant removal efficiencies.	TSS, TN, TP, Lead, Zinc, BOD, COD, total coliform, settleable solids,	[111]
UVQ	To analyze the water and contaminated flow through urban areas and provide incorrectness of water supply, stormwater and wastewater systems	The system provides information on impacts on the water cycle and provides information of the contaminant loads on the system and at each and every receiving point	Impact assessment of water cycle, stormwater and wastewater in urban water supply systems		[110]
Virginia Runoff Reduction Method (VRRM)	To incorporate built-in incentives for environmental site design, such as forest preservation and the reduction of soil disturbance and impervious surfaces	Green roofs, downspout disconnection, permeable pavements, grass channels, dry swales, bio retention infiltration, extended detention ponds, wet swales constructed wetlands, wet ponds		Total phosphorus, total nitrogen	[99]
Aquacycle	To simulate the urban water cycle as an integrated system and investigate the use of locally generated stormwater and wastewater	N/A	N/A	N/A	[100]
City Water Balance	To assess the water demand, water quality, energy consumption and life-cycle cost of the systems	Green roofs, rainwater harvesting, wastewater recycling, septic tanks, bore-hole abstraction, porous pavement, porous asphalt, swales, filter strips, retention ponds, detention basins	To assess the impact of different future scenarios and future urban water management strategies on water quality, cost and energy for a city scale.		[108]
Model for Urban Stormwater Improvement Conceptualization (MUSIC)	To evaluate GI practices in order to achieve stormwater quantity reduction, quality improvement and cost effectiveness	Bio retention systems, infiltration systems, media filtration systems, gross pollutants traps, buffer strips, vegetated swales, and pond and sedimentation basins. Rainwater tanks, wetlands, detention basin, generic treatment nodes			



	(Jiang, Yuan and Piza, 2015)	(Deletic and Fletcher, 2006)	(Zhang, et al., 2009)	Barrett et al. 1998	Lloyd et al. 2001	Yu et al 2001	Backstrom 2002	(Lucke, et al., 2014)	(Brattebo and Booth, 2003)	(Stagge, et al., 2012)	(Shaw, et al., 2001)	Model removal percentage
TSS	76%	69%	70%	85%	65%	64%	89%	65%	86%	63%		80%
TN	67%	56%		46%		19%	19%			56%	18%	67%
TP		46%	48%	46%	40%	64%	99%	22%	39%	59%	64%	54%

		(Masi, 2011)	(Davis, et al., 2006)	(Minervini, et al., 2011)	Roseen et al., 2006	(Jones and Jha, 2009)	(Davis, 2007)	(Davis, et al., 2006)	(Glass and Bissouma, 2005)	(Hunt et al. 2008)	Model removal percentage
TSS				90%	96%	90%	47%		98%	60%	83%
TN		87%		73%		74%	83%	20%		32%	78%
TP			78%	75%		77%	76%	78%		31%	69%

			Gonzalez-Meler, Cotner, and Massey (2013)	Legret et al.1999	Pagotto et al 2000	Rushton 2001	Tota-Maharaja and scholz 2010	(Legret and Colandini, 1999)	(Fassman and Blackbourn, 2010)	(Drake, et al., 2014)	(Kachchu Mohamed, et al., 2014)	(Colorado, 1990)	Model performance
TSS		0	89%	58%	87%	75%		59%	70%	80%	63%	90%	78%
TN													
TP		0				75%	78%			75%		65%	57%

Figure A1. Removal efficiency graph for bio-retention cell, vegetative swales and porous pavements.

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