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Sustainable Coastal Landscaping Using Reclaimed Irrigation Water in Dubai

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Abstract

Dubai became a truism and business hub of the Middle East. Dubai Municipality (DM) treats municipal wastewater and has implemented reclaimed water (RW) distribution systems for the irrigation of greeneries in the city. Reusing water has been a sustainable solution to reduce the consumption of potable water, which is produced through the expensive processes of desalination. Using RW raises concerns regarding the accumulation of RW's nutrients in soil and consequently stormwater pollution especially in coastal areas. The quality of RW, the accumulation of RW's nutrients in soil and interaction between stormwater and soil should be assessed to estimate the environmental impacts of using cost-effective RW. The objective of this research is to form a practical assessment methodology for estimating the extent of stormwater pollution when rainwater is exposed to soils irrigated with RW. The research attempts to determine the impact of RW's nutrients concentrations and the land characteristics including foliage and land slopes on stormwater pollution and potential environmental catastrophes in seashores. The results of pollution estimation were considered to moderate the pollution of runoff generated from lands in coastlines.

Keywords

Stormwater, Eutrophication, LEED Rating System, Seawater Contamination, Palm Jumeirah Island

1. Introduction

Dubai Climate: The United Arab Emirates including the city of Dubai, as its most populated city, is known as arid and mainly desertic area. According to Population Bulletin Emirate of Dubai (2019), the city accommodates about 3.4 million, including 1.1 million workforces living outside of this emirate, with an estimated potable water demand of 1.72 million cubic meters per day (Dubai Statistic Center, 2017). The city is dealing with shortage of freshwater resources that can cause noticeable hindrance for natural plant growth and wildlife.

As reported by Dubai International Airport, the average monthly maximum day temperature of the city is greater than 30˚C for 8 months of a year and its monthly rainfall is from zero up to the maximum value of 25 mm in February. Average annual rainfall has been 94 mm and the average daily sunshine hours are about 9.8 hours (Climate Report by Dubai Airport). Dubai topsoil is mainly categorized as sandy soil with minimal organic content. The soil has high permeability of 0.0005 to 0.00065 cm/second depending on the area (Kfoury et al., 2015). Such permeability is a key reason for typical topsoil's low moisture content in dry days. According to existing climate records, Food and Agriculture Organization (FAO) categorizes Emirate of Dubai as a hyper-arid zone (Food and Agriculture Organization of the United Nations, 1989).

Water Demand in Dubai: Dubai Electricity and Water Authority (DEWA) report indicates that current Dubai's water supply capacity is 2.14 million cubic meters per day. The report shows that freshwater from Dubai's shallow aquifer potentially contributes only 6.8 percent of current water supply capacity and is mainly held as reserved supply (DEWA Annual Statistics Report, 2019). The minimal reliance on groundwater is mainly due to observed rapid intrusion of seawater or deep saline aquifers into shallow freshwater aquifers after a period of over-pumping in the past (Alsharhan et al., 2001).

Seawater desalination has been practiced as the only effective way to cope with growing demand for potable water in Dubai. There have been substantial financial and intellectual investments on making desalination processes more feasible globally. Employing new materials and more energy efficient technologies have reduced the cost and embodied energy of desalinated water in half and to the range of 0.45 to 1.00 US$/$m^3$ and about 290 kJ/m^3. Recent technological improvement reduced both capital and operational costs (Zhang & Babovic, 2012); Yet, desalination expenses depends on variable unit energy price as it forms more than 50% of the total desalination cost (Technology Brief I12, 2012). Regardless of such evident improvements, desalination processes have not met the goals of cost-effectiveness and environmental friendliness. To manage such financial burden and excessive greenhouse gas emission associated with the construction, operation and maintenance of desalination facilities, Dubai government has conducted all measures to reduce the potable water consumption including outdoor water demand for landscaping.

Irrigation of Greeneries: The Dubai Municipality (DM) is planning to put a cap on the irrigation water demand for private landscaping projects and residential gardens using additional soil conditioners that help Dubai soil hold water for longer time. This water conservation technique might assist developers and owners reduce water wastage from landscape and save in their bills. Director of the Drainage and Irrigation Department has stated "We are looking at limiting it to five liters per square meter of greeneries per day". UAE government has provided comprehensive guidelines and quantitative irrigation efficiency measures for reasonable saving of irrigation water (Dubai Government, 2014).

Previous studies of potential effects of greeneries and developments on temperature variations in Dubai revealed that the greeneries could reduce the temperature of the area substantially (Taleb & Abu-Hijleh, 2013). In addition, existing green building rating systems such as Leadership in Energy and Environment Design (LEED) and the regional peer rating system called Estidama recommend proper integration of pervious lands and greeneries in landscaping. Greeneries including shade trees of houses could successfully reduce seasonal cooling costs between 26% and 47% (Akbari et al., 1997). The use of grass ground cover and shade trees in outdoor landscape has made a 9% reduction in the electrical energy use and greenhouse gas emissions in UAE (Al-Sallal, 2012). Dubai has conducted several urban greeneries with the total value of 1.6 billion dollars and total area of 12,000 hectares according to the official announcement by DM at the fourth edition of the Middle East Smart Landscape Summit-2016 (Emirates 24/7, 2016).

Irrigation and Economy: Dubai's hospitality sector directly contributed about 5.1% of its total GDP in 2019. As reported by the Department of Tourism and Commerce Marketing, the sector includes 521 hotels and 196 hotel apartments with 93,304 rooms and 25,249 apartments with average occupancy of 83 percent (Dubai Statistic Center-Tourism, 2019). Tourism industry in the broader sense is a much bigger driver of economic growth of Dubai to the extent of 20% to 30% of Dubai's GDP. Studies show that man-made greenery plays a significant role in attracting tourists towards a city (Chaudhry & Tewari, 2010). There has not been any research conducted to quantify the role of greenery in Dubai's tourist attraction. However, DM is careful about maintaining and expanding greeneries for the discussed benefits. As reported by Gulf News, DM has developed greeneries from about 19.7 to 25 square meters per capita from 2005 to 2012. DM has planned to expand greeneries from 3.63% in 2005 to 8% in near future (Gulf News, 2016). In such a tourism-oriented pathway, landscaping with drought-tolerant and slow-growing plants requiring minimal irrigation and trimmings should be thoroughly implemented as it is recommended by LEED and Estidama Green Building Rating Systems. In addition, employing underground irrigation technologies combined with soil moisture probes and proper programmable irrigation controllers might conserves irrigation water effectively (Choi & Suárez-Rey, 2004).

Reclaimed Water for Irrigation: To supply cost-effective irrigation water, a reclaimed water (RW) transmission and distribution system from wastewater treatment plants to landscapes and developments can potentially address the demand for scarce irrigation freshwater. In such situations, tertiary treatment of wastewater to remove remaining nutrients may not seem rational since the dissolved nutrient in RW enhances the soil fertility. However, the potentially accumulated nutrients in the topsoil may contaminate runoff in such landscapes then cause eutrophication in seawater especially at seashores (Pote et al., 1995).

The quality of RW, the extent of landscape irrigation, the side effects of nutrient supply for soil fertility, the potential of stormwater contamination then the risk of seawater contamination should be discussed, examined and assessed to identify a balance among reusing suitable water resources and protecting the environment.

Objectives of the Investigation: The objective of this research is to develop and practice a relatively simple experimental and theoretical assessment to identify *how* and *to what extent* nutrients in reclaimed water may be carried by runoff toward the seawater and what parameters affect this process. A coastal development in the city of Dubai is selected to implement this investigation and observe how informative such assessment can be for the engineers interested in this aspect of sustainable landscaping. The information might assist the developers to allocate proper types of landscapes, and to manage the nutrients' concentrations in the runoff generated from a development. Various nutrients in RW may be differently accumulated in continually irrigated topsoil then be released in runoff in distinct rates. The effects of soils' conditions such as types of foliage and slope of the land on the rate of nutrient release will be investigated in this case study to identify the importance of soil condition on such potential contaminants transportation and seawater pollution. Simple mass balance equations should be developed to estimate the ultimate concentration of nutrients in runoff collected from different type of land surfaces such as roofs, pavements, hardscapes and landscapes with different foliage and slopes. Such assessment might be informative for developers to estimate the quality of runoff and investigate if land applications can properly address the concern of severe seawater contamination. Such effort might provide fundamental information about how to balance needs for developing coastal landscapes, satisfy demand for RW irrigation as an effective water conservation solution and respond to concerns associated with rainwater nutrient enrichment causing seawater eutrophication. The specific objectives of this research are:

- To identify the main chemicals or nutrients that are released from landscapes in stormwater.
- To determine the effect of parameter such as foliage, land slope and distance from irrigation points on nutrient release.
- To estimate the concentrations of nutrients in the runoff at different slopes for both dry and saturated soil.
- To conduct a simple simulation for examining the hydrologic responses of Dubai's sandy-soil when exposed to a typical local rainfall.
- To incorporate the results of the experimental assessment in an objective plan to reduce the risk of seawater eutrophication caused by polluted runoff from a development.

2. Literature Review

Wastewater Treatment and Considerations: To supply cost-effective irrigation water, DM has developed an advanced and large reclaimed water (RW) transmission and distribution system from Dubai's main wastewater treatment plants to majority of landscapes and developments. Local real estate developers such as Nakheel constructed similar systems for their own developments. According to Dubai Statistics, the quantity of water used for irrigation is about 230 million cubic meters per year which is about 84% of total generated potable water (Dubai Statistic Center, 2017). In wastewater treatment plant, typical removal of solids including oxygen demanding materials in wastewater has been achieved through the primary and secondary treatment processes. The tertiary treatment for removing remaining nutrients is not applied since the nutrient content of wastewater is considered as an asset for irrigation water. The nutrients are partially consumed by foliage, accumulated in the topsoil or infiltrated to the depth of soil. The mass of accumulated nutrients in the topsoil and the release rate of the nutrients from the soil are crucial parameters when studying the contamination of runoff in the landscapes irrigated by reclaimed water. The runoff from this watershed may contain excessive nutrients causing eutrophication in seawater especially at seashores (Pote et al., 1995).

Applying extended (tertiary) treatment on RW to remove nutrients from irrigation water may seem an effective solution without knowing Dubai's soil quality. Applying tertiary treatment to remove nutrients requires additional investment on extended RW treatment and involves further typical challenges in tertiary sludge handling and disposal. If irrigation water does not contain required nutrients, property owners must add supplementary nutrients to the barely fertile Dubai topsoil nearly in an uncontrolled and mostly intensive way. The poor sandy soil requires continual complementary nutrient supply using typical commercial fertilizers or using nutrient rich RW. Hence, the removal of naturally existing nutrients in RW prior to irrigation then adding imported costly supplementary solid nutrients to soil does not seems feasible.

Seawater and Stormwater Quality Regulation: Environment Protection Agency (EPA) has recommended surface water quality criteria for the protection of aquatic life and human health; and also, criteria for the quality of disposed runoff to avoid eutrophication occurrence in water resources (Environmental Protection Agency, 2009; Environmental Protection Agency, 2006). **Table 1** reports the summary of the maximum allowable concentrations in water bodies to protect aquatic lives and similar standard for runoff focuses on limiting the impurities in the stormwater mainly to protect receiving water bodies.

Risk of Seawater Contamination: The point source nutrient enrichment of seawater due to unauthorized wastewater discharges is not a main concern in Dubai shoreline since strict municipal rules and constant monitoring of the shorelines are implemented. The main concern regarding the nutrient enrichment of seashores is the transportation of nutrients potentially deposited in soil irrigated with RW known as a nonpoint source pollution. It should be noted that DM and DEWA made remarkable effort to monitor seawater quality in Dubai's

Table 1. Maximum allowable concentrations of nutrient in water resources by (Environmental Protection Agency, 2009; Environmental Protection Agency, 2006).

Nutrients	Max. Allowable, for Aquatic Life	Runoff Standard
Total Nitrogen	0.1 - 1.27 mg/L	0.4 - 20 mg/L
Total Phosphate	8 - 33 μg/L	0.02 - 4.3 mg/L
Ammonia	163 - 331 μg/L	-
Arsenic	36 - 69 μg/L	-
Total Chlorine	7.5 - 13 μg/L	-
Copper	3.1 - 4.8 μg/L	0.01 - 0.4 mg/L
Cyanide	1 μg/L	-
Lead	8.1 - 210 μg/L	-
Zinc	81 - 90 μg/L	0.01 - 2.90 mg/L

seashore. Such attention is due to both the tourism's sensitivity to seawater quality at the shorelines and the fact that seawater in Dubai's coasts is the water resource for Dubai's potable water desalination plants. Dealing with such reasonable sensitivities, DEWA frequently tests seawater quality around the desalination treatment plants according to a comprehensive procedure. The UAE government satellite remote sensing is monitoring this supply system to sense potential eutrophication scenarios and track any sort of algal bloom in the UAE shorelines (Al Shehhi et al., 2012). The release of pollutions including nutrients along stormwater discharge in the Dubai coast should be inspected and evaluated to ensure that it does not cause any concerns such as atypical bacterial or algal growth. The study of seawater in the Gulf of California revealed that nitrogen-rich runoff exerts a substantial and steady influence on biological activities and in 80% of times caused blooms within days (Beman et al., 2005). Local studies have considered current widespread coastal development in the whole region as an important stressor caused by human (Sale et al., 2011).

The collection and transmission of stormwater to occasional treatment facilities or existing main treatment plants located in suburbs has not been regarded as a cost-effective and practical solution. In such scenario, an additional extended stormwater collection with either transmission infrastructures to main treatment plants or a nearby occasional treatment plant in such highly dense and expensive coastal areas are required. Due to construction complexity and expenses, both options should be considered as last reserves if the stress on seawater exceeds its tolerance.

Required Investigation: To estimate the extent of landscape irrigation's environmental impacts on the quality of stormwater in coastal areas, several steps should be taken. First, existing standards or recommendations for quality of stormwater should be identified; then the quality of RW in Dubai should be evaluated and compared with the standards. Further assessment including sampling, chemical analysis, and exposure tests of lands in the coastal area might be conducted to assess the fate of nutrient carried by RW in soil. Assessing soils with different foliage might reveal the influence of soil properties and types of foliage on the absorption and release of nutrient by the soil. Furthermore, the release of absorbed nutrient in soil to stormwater can be evaluated using lab scale short-term and long-term soil-water exposure experiments. As the slope of landscape affect soil-water contact time, it might cause soil disturbance leading to more intensive soil-water exposure. Hence, examining different soil slopes either in small-scale laboratory testing or using in situ experiments might provide essential data for the estimation of nutrients' concentration in stormwater from a land. Comparing the estimated concentrations of nutrient in stormwater and maximum allowable concentrations may reveal critical nutrients in the area and support thorough recommendations for their control and removal.

3. Materials and Methods

This research focuses on identifying critical nutrients in irrigation water, assessing the release of nutrient from soil, the potential of seawater nutrient enrichment, and eventually attempting to propose practical techniques to decrease such environmental impacts. To set the research plan, a land was selected to study the potential nutrient accumulation in soil, the rate of nutrient release in stormwater and estimate ultimate concentration of nutrient in the stormwater from the land when the land is completely developed. In this section the methods, materials, applicable regulations, and records that were utilized for conducting the investigation are explained.

***Lands Used for Case Study*:**

As shown in **Figure 1**, a developing residential plot in the Dubai's Palm Jumeirah Island (PJI) was selected to assess its soil properties, estimate nutrient accumulation in its soil, and predict the risk of stormwater contamination and seawater eutrophication. The main project was already assigned to a team to design the whole components of the project including structures, road and transportation facilities, water distribution, sewer system and landscapes of the land. The project entailed the complete design of a residential complex composed of three high-rise buildings with 4 parking levels and 36 floors. The integrated design allowed the team to incorporate concerns and goals of each aspect of the project in the whole design. As the plot is underdevelopment, the team had the opportunity to apply different potentially influential parameters such as soil slope and rain collection piping and study the results.

The second plot was selected in The Garden area at the vicinity of the first plot. The second plot was selected to provide soils samples with the same initial sandy-soil properties but long-term exposure to the same RW. The collected samples from the Garden were used to estimate the fate of nutrients in the main plot. The landscape in the Garden consists of different foliage with various distances from RW dripping irrigation systems.

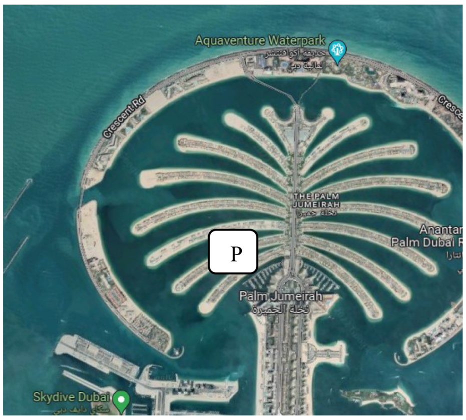

Figure 1. Project area, shown with letter "P".

Investigation of Reclaimed Water Quality:

The quality of RW provided for the area has been reported by the technical office of Jebel Ali Wastewater Treatment Plant (JAWWTP) and shown in **Table 2**. The information reveals that substantial removal of solids including oxygen demanding materials in wastewater has been achieved through the primary and secondary treatment processes. As expected, the tertiary treatment for removing remaining nutrients is not applied since the nutrient content is considered as an asset for irrigation water. The nutrient is partially consumed by foliage, accumulated in the topsoil, or transported by infiltrated water to the depth of soil. The mass of accumulated nutrients in the topsoil and the release rate of the nutrients from the soil are crucial parameters when studying the contamination of runoff in the landscapes irrigated with RW.

Paved Areas versus Irrigated Areas:

The investigations in this research are mainly devoted to the estimation of stormwater quality rather than consequent changes in seawater quality. According to EPA Guidelines, the pH of the runoff must also be monitored and should be within the range of 6.5 - 8.5. The project area generally includes paved areas (not irrigated), irrigated areas (irrigated greenery) and the area of the building. The runoff from both paved area and buildings is assumed to be uncontaminated in terms of nutrient content. The runoff from these two areas is beneficial to dilute the nutrients in stormwater from the irrigated area. The area of buildings is a fixed value while paved areas and irrigated areas could be altered to meet the recommended criteria mentioned in **Table 1**. Hence, the ratio of paved area to greeneries area can be determined to ensure that these standards are met.

It should be noted that green building rating systems such as LEED typically promote more and wider pervious pavements (LEED Rating System V4.1, 2019; Kibert, 2022). This is suggested to avoid excessive stormwater generations in a certain land and to reduce heat island effect. As mentioned earlier, paved areas reject rainwater with minimal contamination. To manage pollutions in stormwater appropriately, improve well-being of the landscapes and contribute to reduction of heat island effect, the area of greeneries and other pervious areas

Table 2. Analysis of effluent water at JAWWTP.

Parameter	Unit	Outflow	Remarks
Total Suspended Solids	Mg/l	10	96% Removal
Biochemical Oxygen Demand (BOD_5)	Mg/l	10	97% Removal
Chemical Oxygen Demand	Mg/l	75	88% Removal
Ammonia (NH_3-NH_4)	Mg/l	2	95% Removal
Phosphate	Mg/l	25	59% Removal
Total Coli forms	MPN/100ml	<20	30 days
E. Coli	MPN/100ml	<10	30 days

(including non-irrigated and unpaved areas) in the project were determined. Such efforts might also be beneficial to reduce the heat island effects in the city noticeably if it is applied vigorously in new developments.

***Quantifying Different Soil's Nutrient Content*:**

There have been substantial characterization studies of residential stormwater in the literature (Carpenter et al., 2014; Orta de Velásquez et al., 2013). However, there has not been a specific standard methodology to characterize the quality of runoff from residential area. To identify potential pollutants in stormwater, the quality of RW should be examined. Therefore, a rigorous literature review was conducted, and the most relevant measurable chemicals were selected (Karbassi et al., 2005; Manas et al., 2009; Brewer & Dyrssen, 2010; Mohammad & Mazahreh, 2011) to shortlist chemicals of interest in this research. The reported quality of RW (shown in **Table 2**) was beneficial to shortlist the potentially violating chemical in the stormwater. The concentration of chemicals including total phosphate, ammonia-ammonium, nitrite, nitrate, total nitrogen, chlorine, copper, and zinc, as well as hydrogen ion (as pH) were measured. The concentrations of ammonia, ammonium, nitrite, and nitrate were summed to determine total nitrogen assuming the concentration of organic nitrogen in RW is negligible. All measurements were conducted according to manuals introduced by YSI (ysi.com) as reflected in **Table 3**. Some samples of RW were collected at the beginning of the experiment and then during the final stage of the experiment to characterize the nutrient content of the water and the consistency of the water quality.

The exposure of soil to existing impurities (including nutrients) in RW might lead to the adsorption of the impurities then the accumulation of excessive chemicals in the irrigated soil. Misra (2009) reported that the extension of this accumulation might eventually cause clogging in the topsoil. The typical method suggested by Pote et al. (1995) was used to analyze the quality of the project's soil with substantial exposure to the reclaimed water. Several soil samples, irrigated with the same RW, were taken from The Garden Development to estimate the fate of chemicals in the project's clean soil. The taken samples are like project's sandy soil. As shown in **Figure 2**, four sets of samples were taken from

Figure 2. Samples taken from Discovery Garden. 1: underneath the IP, no foliage; 2: 50 cm away from the IP, no foliage; 3: underneath the IP and a tree; 4: underneath the IP and grass.

Table 3. Experimental methods.

Chemical	Method	Measurable Range	Reference
Ammonia/Ammonium	YSI, PHOT.4.AUTO, Indophenol Method	0 - 1.0 mg/L N	YSI 9300 and 9500 Photometers User Manual
Nitrite	YSI, PHOT.24.AUTO (Nitricol)	0 - 0.5 mg/L N	
Nitrate	YSI, PHOT.23.AUTO (Nitratest)	0 - 23 mg/L N	
Zinc	YSI, PHOT.35.AUTO	0 - 4.0 mg/L	
Phosphate	YSI, Phosphate HR, PHOT.29.AUTO Vanadomolybdate Method	0 - 100 mg/L	
Copper	YSI, Coppercol test, PHOT.10.AUTO	0 - 5.0 mg/L	
Total Chlorine	YSI, PHOT.7. AUTO, DPD Method (free chlorine plus combined chlorine including mono chloramine, di chloramine)	0 - 5.0 mg/L	

The Garden to study nutrient content of soils with different types of foliage and different distances from the Irrigation Point (IP). In addition, a sample from the project site was taken for comparison purposes (Sample #5). The samples were taken from the 30 cm topmost soil layer to ensure that the soil samples would emulate the interaction between soil and runoff from overland flow. The results of nutrient contents testing at different positions are considered as the actual soil's future nutrient content. In addition, the results were utilized to estimate the concentrations of nutrients in the stormwater generated from the project area.

As considered before, the type of foliage and the distance between soil and IPs might be important factors. In addition, the duration of the contact between runoff and soil, the slope of the land and the stage of irrigation right before precipitation (i.e. from dry to fully drenched soil) might affect the stormwater contamination level. The contamination of stormwater which is in contact with dry soil would be a function of soil's contamination level as well as soil's tendency to release the nutrients. On water-saturated soil, stormwater might not infiltrate considerably. Hence, the interaction between the soil and stormwater occurs mainly at the top surface where stormwater may mix with excessive RW on the area's surface. The investigation of the impact of wide ranges of vegetation might suggest some solutions for the project but this evaluation is beyond the scopes of this research.

The objectives of the first set of experiments were both to assess the amount of nutrients released from the soil samples and to estimate their release rates. Similar experiments have been conducted in the literature to study the chemical content of soil samples (Ponnamperuma, 1972; Kirk, 2004). The importance of the foliage and the distance of the soil from irrigation points could be inferred as the results of soils with different foliage and distances from irrigation points are compared. In this experiment, 100 g of soil was added into 1 liter of distilled water for different periods of time, followed by decanting the water, filtering and testing the decanted samples for their nutrients' concentration. The experiment was preformed 5 times for each sample for 5 different durations of contact, 10 seconds, 1 minute, 10 minutes, 1 hour and 24 hours. The concentrations of nutrients were measured twice. The project's typical inlet time of catchment areas was determined to estimate applicable contact time between the soil and rainwater then to determine the amounts of nutrients release. Comparison between the results for sample 1 and sample 2 (reflected in **Table 4**) would help to assess the importance of the distance from the IPs. To evaluate the effects of foliage, samples 1, 3 and 4 should be compared as they are all taken from underneath of the IPs but with different types of foliage.

***Quantifying Nutrients Released in Stormwater*:**

The slope of the land and consequently rainwater velocity might affect the contact time of the runoff with the soil; higher slopes result in greater velocities, which in turn lead to shorter contact times between runoff and the soil. In addition, soil erosion could occur due to the greater slopes and the sediment in the runoff would give much larger contact times for nutrient release. Therefore, some fundamental experiments are needed first to encompass the entirety of the required study and then additional experiments should be conducted to generate information required for a sustainable design.

The second set of experiments aimed to estimate the concentrations of nutrients in the runoff at different slopes for both dry and saturated soil. Since DM Dubai Municipality (2010) has recommended the pipe slopes to be 0.5% - 10%, same slope range was considered for the slope of irrigated areas to minimize excavation costs and have practical design for a project dealing with relatively

Table 4. Concentration of nutrients and pH for the first set of experiments.

Nutrients mg/l	Sample 1, underneath the IP, no foliage					Sample 2 50 cm away from the IP				
	10 Sec.	1 Min.	10 Min.	1 Hr.	24 Hr	10 Sec.	1 Min.	10 Min.	1 Hr.	24 Hr
Cu	0	0	0	0.05	-	0	0	0	0	0
Zn	0	0	0	1.27	-	0	0	0	-	0
NH_3/NH_4	0.05	0.12	0.14	0.26	0.11	0.02	0.04	0.07	0.12	0.09
Comb. Cl	0	0	0	0	0	0	0	0	0	0
PO_4^{3-}	0.22	0.50	2.3	3.3	1.3	0.14	0.23	1.14	2.09	1.3
Total N	5.19	8.3	18.7	42.9	24.4	5.09	8.07	12.0	19.5	16.5
pH	8.6	7.65	7.42	8.02	7.72	7.12	7.23	7.16	7.87	7.63
	Sample 3 underneath the IP and a tree					Sample 4 underneath the IP and grass				
Cu	0	0	0	0	0	0	0	0	0	0
Zn	0	0.13	0.18	0.32	0.29	0	0.01	0.04	0.07	0.05
NH_3/NH_4	0.04	0.08	0.10	0.2	0.16	0.18	0.36	0.6	0.53	0.07
Comb. Cl	0	0	0	0	0	0	0	0	0	0
PO_4^{3-}	0.08	0.13	0.30	0.71	0.42	0.15	0.25	0.44	0.65	0.55
Total N	5.16	8.19	12.12	19.72	8.55	14.0	20.8	34.0	38.2	30.1
pH	7.21	7.24	7.14	7.59	7.4	7.14	7.14	7.30	7.58	7.71
	Sample 5 Soil from the undeveloped site									
Cu	0	0	0	0	0					
Zn	0	0	0	0	0					
NH_3/NH_4	0.01	0.01	0.02	0.05	0.02					
Comb. Cl	0	0	0	0	0					
PO_4^{3-}	0.39	0.43	0.57	1.1	0.88					
Total N	5.82	7.19	8.44	11.2	9.68					
pH	7.39	7.16	7.22	7.5	7.87					

loose sandy soil. Therefore, both maximum and minimum allowable slopes of 0.5% and 10% were included in this experiment set.

To simulate the behavior of soils under different stages of irrigation with RW, soil samples were placed in RW bath (RW was added to the soil in the bath to have a minimum of 5 cm of RW on the top of the soil surface) for 4 hours to prepare a fully water-saturated soil. Preliminary experiments revealed that submerging soil for extended periods does not affect the soil moisture content.

These samples were used later to examine the behavior of soil when sprinklers have just stopped and the rain falls. In addition, soil samples were left in the lab to become dry for 1 week and were used to examine the behavior of dry or non-water-saturated sample. The period of one week was chosen as the longest dry phase that soil may face is one week in winter season as per interview with property operators.

A rainfall simulation apparatus was built according to literature (Dimoyiannisi et al., 2001; Moussouni et al., 2012) and local rain precipitation parameters (Mohsen et al., 2009). The simulation was conducted to examine the hydrologic responses of Dubai's sandy soil when exposed to a typical local rainfall. To prepare the soil surface with a known constant slope in the lab, a 600 by 300 mm wooden plate was wrapped with sterilized sheet plastic and soil samples were placed on the 300 by 300 mm top half of the surface. The slope was set by some stand feet under the wooden plate. To collect the generated runoff, the whole apparatus was contained in a new and clean 600 mm width by 1200 mm length by 400 mm height plastic container. The rain was simulated using a spray nozzle connected to an elevated 5 liter distilled water container by plastic tubing. According to a study conducted about the intensity and duration of rains in UAE (Mohsen et al., 2009), the rain intensity of 50 mm/hr for the duration of 15 minutes were chosen and replicated. This rain intensity represents a typical 5 years frequency rain (Mohsen et al., 2009) that is considered to estimate reasonably intensive rain in Dubai. This is a typical rain intensity considered when designing stormwater management infrastructure for typical developments (Sr. Hammer & Hammer Jr., 2011). This means that for a surface area of 0.09 m^2, 4.5 liter of distilled water is required to simulate the rain. During this simulation, the spray nozzle was held 30 cm away from the top of the surface. The generated runoff flows to the bottom of the slops and collected in the container to be used for water quality test. The whole apparatus was cleaned, washed and dried to be used for next experiments. The collected runoff samples were filtered using 1.5 µm nominal size glass fiber filters (47 mm diameter Whatman 934-AH) to remove any suspended solids (recommended by Method 160.2, USEPA, 1999) and to prepare samples for nutrient analysis. As explained above, some modifications such as changing the spray distance from the soil surface was applied as compared to methods in the literature (Dimoyiannisi et al., 2001; Moussouni et al., 2012) to control unnecessary soil displacement. Such soil erosion was avoided as it might cause unrealistic soil-water interaction. It should be noted that the impact of seasonal temperature change was not particularly investigated in this experiment. The rainwater was simulated in the lab with the temperature of 21˚C.

4. Results

4.1. Laboratory Results

The first set of experiments was conducted to determine both the total amounts of nutrients that can be released from the soil samples and the rates of nutrients' release. In addition, the effects of different foliage and the distance of the soil from the IPs could be studied. The results of total amounts of released nutrients from the soil samples have been shown in Table 4. The values are average concentrations. As it can be seen in Table 4, the concentration of total chlorine and copper are zero and do not vary by time. This indicates that there have been elements that are not accumulated in the soil. Since no measurable release is observed during 24 hours of contact, these elements might not be released during a short water-runoff contact time.

The results indicated that the concentrations of NH_3/NH_4^+, total N and phosphate increased by time. This shows that the accumulated nutrients in soil tend to be released gradually. The rates of nutrients release at each period have been calculated and the results are shown in Figure 3 and Figure 4. It should be noted that N and P profiles in Figure 3 and Figure 4 provide insight into the rates of impurity release rather than the exact impurities concentration in the runoff. These results reveal that the rates of nitrogen release and phosphate released were high at the first minutes and decreased substantially afterward. It can be concluded that the nutrients that are dominantly stored through adsorption

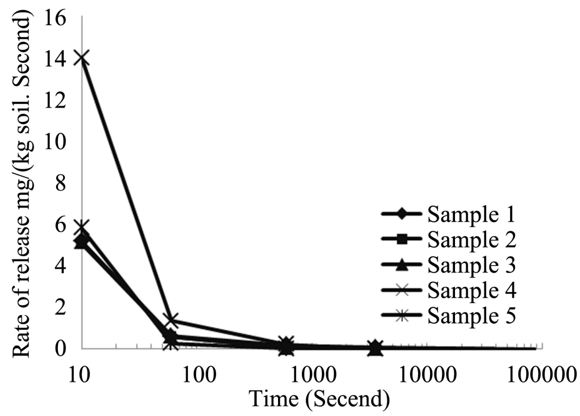

Figure 3. Rate of total N release vs contact time in experiment 1.

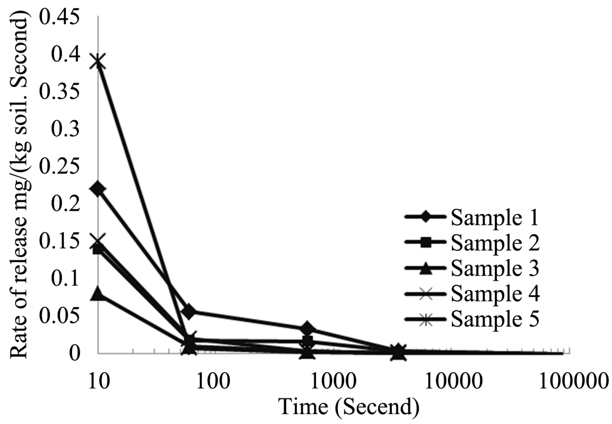

Figure 4. Rate of phosphate release vs contact time in experiment 1.

are mainly released at the first minutes of the contact between runoff and soil. Hence, considerable release of nitrogen and phosphate in stormwater is expected at the first minutes of soil-runoff contact. The pH of samples fluctuates from 7.12 to 8.6 depending on the sample and contact time. This variation might be due to different rates of chemical release in water.

As shown in **Figure 5**, the results of total nitrogen for the second experiment reveal the effects of slope and the stage of irrigation of the soil. The results show that the concentration of nitrogen in the stormwater would be substantially above 0.4 mg/l, which is the lower range of allowable nitrogen concentration for stormwater introduced in **Table 1**.

A t-test with a confidence interval of 85% was performed on all the results to investigate the significance of differences between the N concentrations for different samples. The results reveal that soil surfaces saturated with RW release significantly higher amount of nitrogen in the stormwater compared to not saturated soils. In addition, slopes have significant impacts on the release rate of nitrogen when soil is saturated. The results suggest discontinuing irrigation when a rainfall is expected in future hours. Furthermore, the impact of slope on level of stormwater contamination might be due to non-laminar flow of stormwater on the surface then higher disturbance of the soil. Such condition might cause greater contact areas among water and soil particles and consequently higher stormwater contamination.

As it can be seen from **Figure 6**, the concentrations of phosphate are above allowable concentration of phosphate in stormwater generated from irrigated landscapes. The impact of saturation condition and the surface slope on phosphate release are consistent with the impacts on nitrogen.

The results show that eutrophication could indeed be a valid concern where using wastewater to irrigate the land. As shown here, it is very evident that total nitrogen and phosphate are the prevailing nutrients for achieving compliance with standards for stormwater quality. For the case of landscape design, total nitrogen was taken into consideration as a critical nutrient according to our test

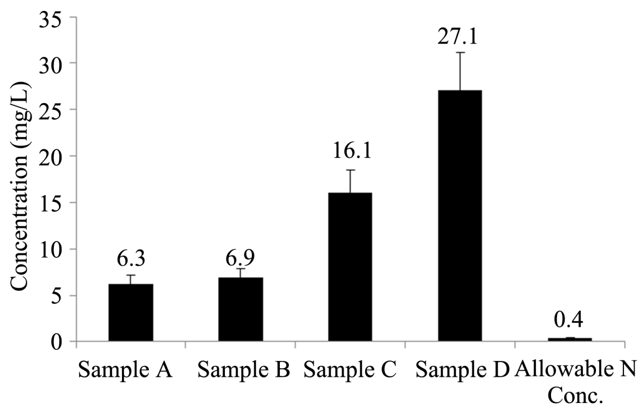

Figure 5. Total nitrogen in stormwater from soil: Sample A: Not saturated—0.5% slope, Sample B: Not saturated—10% slope, Sample C: Saturated—0.5% slope, Sample D: Saturated—10% slope.

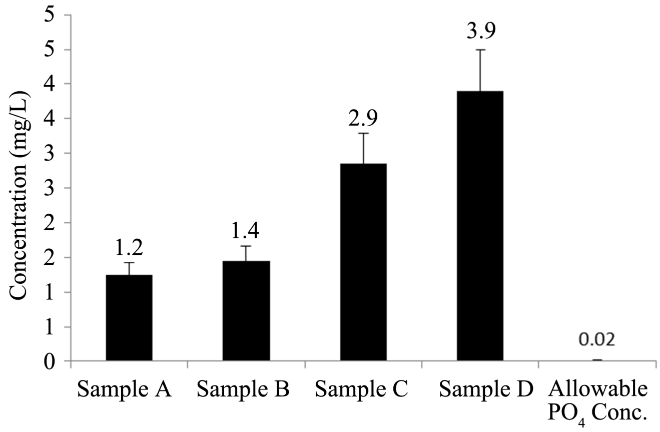

Figure 6. Total phosphate in Stormwater from soil: Sample A: Not saturated—0.5% slope, Sample B: Not saturated—10% slope, Sample C: Saturated—0.5% slope, Sample D: Saturated—10% slope.

results reflected in **Table 4** and **Figure 4**. After a preliminary design, the release of phosphate was estimated to assure the compliance with the regulations. As shown in **Table 4**, there is an increase in concentration of nitrogen with soil-runoff contact time. Hence, a shorter contact time is suggested to reduce the intensity of stormwater contamination with nitrogen. Therefore, a particular distribution of inlet points or manholes is designed to limit the contact time to the typical inlet time of 5 minutes for the drainage system (Sr. Hammer & Hammer Jr., 2011). Attaining 5 minutes inlet time and translating this value to the maximum contact time directed the research to the estimation of nutrient release from different samples through 5 minutes of soil-runoff contact time. The estimations through the second experiments revealed the release of nitrogen are 13.5, 12, 10.2 and 27.4 mg/l for samples 1 to 4 respectively. The results show that excessive N concentrations released from all samples.

The highest concentration of total nitrogen was found in sample 4 in soil with grass plantation. The soil under tree (sample 3) released the least amount of total nitrogen. This shows that the type of foliage plays a major role in the nutrients release scenario. Comparison between the results for sample 1 and 2 showed that the soil contamination reduces by distance from the irrigation point.

Based on samples 1 and 2 a linear relationship can be drawn between the nutrients release and the distance from the release point. Therefore, the concentration of nutrient in stormwater collected from 1 m^2 of area can be calculated.

4.2. Stormwater Collection System

To design the stormwater drainage system, the reported return periods of rain for several durations and intensities in UAE were utilized (Ward & Trimble, 2003). The Hazen method (Sr. Hammer & Hammer Jr., 2011) used to derive a relationship between the duration, return period and intensity of rain for a 25-year period as the most reasonably conservative data. The stormwater collection system was simulated based on Rational Method using StormCAD V8i software through multiple iterations considering different applicable rain durations and return periods. The most critical return period and rain duration that causing maximum contamination was determined to be 25 years and 15 minutes, respectively. The critical duration of rain (15 minutes) was expected since the plot is relatively small and a concentration time at this range was expected. Hence, the stormwater drainage system designed to handle all expected rains that occur typically.

Using the above-mentioned intensity, the project plot with the area of 81,643 m^2 was split up into 24 catchment areas and drainage points for roofs, roadway (paved areas) as well as irrigated landscape. The area of individual catchment areas varied between 1440 m^2 and 7450 m^2. Special attention was paid to design catchment areas with semi-concave shaped facilitating receiving runoff as quick as possible (as reflected in 5 minutes inlet time earlier) with minimum number of drainage manholes and the least construction costs. A scaled drawing based on the natural topography of the land with project elevations updates were introduced to StormCAD V8i software to design required pipes. Additional analysis and design iterations were conducted to minimize pipe materials required. The velocities and slopes for these pipelines were compared with Dubai Municipality (2010) to make sure they are in the allowable range (maximum slope and velocity of 0.005 - 0.1 m/m and 0.6 - 2.5 m/s). The indicator of total pipe material mass was the summation of pipe length times pipe diameter since the thickness of pipes are expected to be almost constant. The catchment areas, pipe and outfall (OF) point have been shown in **Figure 7**. The total pipe length is 2261 m. PVC pipe was chosen since it is recyclable, durable, local product and the most environmentally friendly material recommended in local guidelines (Dubai Municipality, 2010). It should be noted that PVC pipes are local products that are recommended as sustainable materials (LEED Rating System V4.1, 2019). Through the design of stormwater collection system, it was evident that the hydrology of the project and hydraulics of the design plays a major role in ultimate pollution level in stormwater. The integrated design of the whole system

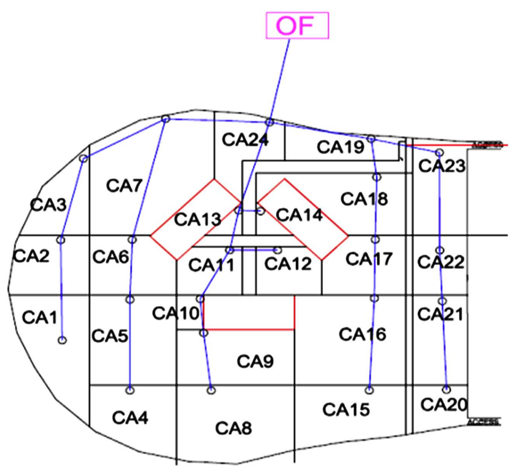

Figure 7. Pipe layout (blue lines) and catchment areas (CAs).

was observed to be an essential approach to have a resource efficient or sustainable design.

Based on simulation with StormCAD V8i software, the slope for the landscape was optimized based on minimizing the land surface slope in the direction of the pipes to the extent that it does not require considerable increase in the diameter of the pipes. At minimum pipe slopes (0.5%) which was expected to result in the minimum stormwater contamination, nearly every pipe in the pipeline needed to be 1 meter or larger in diameter. Obviously, this is uneconomical and not acceptable. Therefore, the reasonable landscape slope and pipe slopes were chosen to make sure that the depths of pipe trenches are not exceeding 2 meters and evidently pipes with reasonable diameter are able to transmit stormwater without any overflow in the land. The branch pipes and main pipes with sizes of 300 and 500 mm were found the most optimum design.

A comprehensive trial-error assessment was conducted to maximize the area of greeneries while the concentrations of pollutants meet the stormwater quality standard. The highest allowable concentrations for total nitrogen and total phosphate were set to be 2.5 g/l and 0.1 g/l, respectively. It should be noted that choosing a target concentration may require further simulation about the rate of the dispersion and dilution of nutrients in seawater to compare ultimate concentrations of nutrients in seawater.

The total area outside of building's roofs and roads was divided into areas of all season grasses with all season irrigation, area devoted to trees with consistent irrigation, area with mainly summer vegetation irrigated during dry days and areas without irrigation. The recent non-irrigation areas are designed to be amenities covered by light color and pervious materials like gravels as recommended by LEED rating system (LEED Rating System V4.1, 2019; Kibert, 2022). These materials reduce heat island effects as well as the size of stormwater collection system in the project (Kibert, 2022). The maximum nutrients concentrations were estimated using interpolating the results of both sets of experiments. The estimated results for different samples at the applicable range of slope and contact time between the soil and stormwater are reflected in **Table 5**.

Table 5. Estimated maximum nutrient concentrations in mg/L to be used in design process.

Nutrients (Mg/l)	Sample number					
	1	**2**	**3**	**4** (wet soil)	**4** (dry soil)	**5**
Copper	0.0	0.0	0.0	0.0	0.0	0.0
Zinc	0.0	0.0	0.2	0.0	0.0	0.0
Total Chlorine	0.0	0.0	0.0	0.0	0.0	0.0
Phosphate	1.4	1.1	0.2	0.5	0.3	0.5
Total Nitrogen	13.5	12.0	10.2	27.4	20.2	7.8

Sample 1: underneath the IP, no foliage; Sample 2: 50 cm away from the IP, no foliage. Sample 3: underneath the IP and a tree; Sample 4: underneath the IP and grass.

The values of total nitrogen and phosphate concentration within runoff were estimated by integrating the results of Table 5 for various types of areas and the number of irrigation points in a unit area. The results are indicated in Table 6. Average concentrations were used assuming that there is 1 irrigation point for every 1 m^2 of area. The catchment areas were selected according to other constraints imposed by construction engineers and road and transportation engineers. The summation of weighted N and phosphate concentrations were set to be below 2.5 mg/l and 0.1 mg/l, respectively. These targeted maximum concentrations are within the ranges reported in Table 1. As addressed earlier, the rain duration of 15 minutes was considered, and quantities of runoff were estimated using rational method. The coefficients of runoff were chosen for different components of the development. Several rounds of iterations were conducted to determine right application of areas generating stormwater with nutrient concentrations just below the targeted concentrations.

The weighted total nitrogen and phosphate for each catchment category was calculated by multiplying weighted area by coefficient of runoff and estimated total nutrient concentration of water. This parameter indicates the contribution of each land category in polluting the whole collected runoff from the development. The summation of these parameters indicates the concentration of the nitrogen in the whole collected runoff, which was found to be 2.43 mg/l, which is targeted value of 2.5 mg/l in this design. As shown in Table 6, the estimated concentration of weighted phosphate in whole collected runoff is 0.08 mg/l, which is below the maximum targeted phosphate concentration.

It should be noted that smaller areas of irrigated land can be selected to meet any other smaller target concentration or stricter standards. Implementing the tertiary treatment of wastewater can be another solution to meet such smaller targets. This scenario was avoided due to potential complexity and excessive cost associated with developing an extended treatment facility in the island. Using plants and vegetation with less water demand and capable of consuming higher

Table 6. Estimation of final N concentration.

Catchment Type	Area (m^2)	Weighted Area (%)	Average Coefficient of Runoff	Estimated Total N (mg/L)	Weighted Total N (mg/L)	Estimated Total Phosphate (mg/L)	Weighted Total Phosphate (mg/L)
Buildings	5600	6.8	0.95	0	0	0	0
Roads	3900	4.8	0.85	0	0	0	0
Grass	8164	20	0.25	27.4	1.37	0.5	0.02
Trees	9471	17.2	0.20	11.6	0.40	0.9	0.03
Seasonally Irrigated Soil	21,851	21.2	0.10	20.2	0.43	0.3	0.01
Not irrigated Soil (other amenities)	32,657	30	0.10	7.8	0.23	0.5	0.015
Total	81,643	100%	-	-	**2.43**	-	**0.08**

amounts of nitrogen and phosphate would be beneficial to reduce the concentration of accumulated nutrients in the soil and could be a potential complementary solution in this context. This requires a comprehensive soil-vegetation interaction assessment. Such investigation might introduce more sustainable greeneries for such projects.

The results of this case study revealed that the type of foliage, the position of RW irrigation dripping points, and the slope of lands affect the level of nutrients release after a certain precipitation and runoff. The major concern associated with pollution of seawater at shorelines and in extreme cases eutrophication due to abundance of phosphorous and nitrogenous nutrients can be addressed as the landscape designers are given opportunities to determine the percentage of hardscaping and greeneries that are irrigated with RW. In such approach suitable percentage of hardscapes, along with roofs and paved areas will be selected to assure generation of sufficient flows of clean runoff, which adequately dilute polluted runoff from greeneries. This case study attempted to showcase all steps of runoff pollution estimation in a development irrigated with RW, identify most critical pollutants and their levels and rates of release, and the extent of pollution in whole collected runoff from a typical land on coastal areas. While properties of soil, the soil-runoff interactions, land slopes, rain intensities, RW characteristics, and foliage are project-specific, the methodology yet can be employed to alleviate the risk of seashore pollution in similar coastal cities.

Its noteworthy that the research team has not noticed any eutrophication case around the project area, the Palm Jumeirah, during the research period. The conducted research has just assessed the potential of such occurrence in case considerable number of the development's properties utilizes reclaimed water, substantial fractions of landscapes are devoted to irrigated greeneries, and the generated runoff is allowed to enter seawater. Hence, considering the current land arrangements there, the result does not forecast any vulnerability to eutrophication there in near future.

5. Conclusion

The objective of this research is to form a practical assessment methodology for estimating the extent of stormwater pollution when rainwater is exposed to soils irrigated with RW. The research attempts to determine the impact of RW's nutrients concentrations and the land characteristics such foliage and land slopes on stormwater quality in seashores.

The local RW of this study consists of high concentrations of nutrients as tertiary treatment of wastewater for extended removal of nutrients is not applied to hold nutrients as an asset for the growth of plants. While some fractions of nutrients are partially consumed by foliage, the rest were accumulated in the topsoil, which were readily released in occasionally occurring stormwater. The concentrations of phosphate and nitrogenous nutrients in stormwater generated from irrigated landscapes were above allowable concentration. These results also revealed that the release rates of these nutrients were high at the first minutes of soil-runoff contact and decreased substantially afterward. This suggests that even short showers with considerable runoff may impose seawater pollution beyond EPA maximum allowable concentrations. It was evident that total nitrogen and phosphate are the prevailing nutrients when assuring compliance with standards for stormwater quality.

The results of rainfall simulation in laboratory also indicated that the concentrations of phosphate and total nitrogen in stormwater generated from the greeneries were above allowable concentrations. Statistical assessments indicated that the slope of land had significant impact on nutrients rate of release in stormwater. This might be due to non-laminar flow of stormwater on the surface, then higher disturbance of the soil. Such condition might cause greater contact areas among water and soil particles and consequently higher stormwater contamination. In addition, it can be observed that soil surfaces saturated with RW release higher amount of nutrients in the stormwater compared to relatively dry soils. This suggests discontinuing irrigation when a rainfall is expected in future hours.

The attained results of pollution estimation were considered to moderate the pollution of runoff generated from a land in Dubai Palm Jumeirah. In this case study, the research showed major steps of runoff pollution estimation in a development irrigated with RW using attained project-specific laboratory results. In such approach, proper fraction of land area was devoted to greeneries known as main contributor of stormwater pollution. The rest of land, including hardscaped land, and somewhat fixed roof areas and paved areas were considered as lands with runoff that could adequately dilute polluted runoff from existing greeneries. Dividing project's non-roof and unpaved areas to hardscapes and greeneries provided a great opportunity to meet stormwater pollution standards recommended by EPA. Regardless of the project-specific data such as properties of soil, the soil-runoff interactions, land slopes, rain intensities, RW characteristics, and foliage, the methodology yet can be utilized to reduce the risk of seashore pollution in similar coastal developments and cities.

The results of this research are project-specific and depend on the properties of soil, the soil-runoff interactions, land slopes, rain intensities, RW characteristics, and foliage; However, the methodology yet can be employed to study the potential of seawater pollution by runoff and alleviate the risk of seashore pollution in similar coastal cities. Future researches may focus of shorelines with other categories of soil and foliage, regions with different rain precipitation records and irrigation reclaimed water with more or less extent of wastewater treatment.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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