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THE QUALITY OF STORMWATER IN SANA'A CITY FROM THE PERSPECTIVE OF INTEGRATED WATER RESOURCES MANAGEMENT

A thesis submitted in partial fulfilment of the requirements for the

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بكالوريوس في الهندسة المدنية

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Abstract

The impact of urbanization on water quality has drawn much attention worldwide because of its environmental impacts. Urbanization exerts a significant influence on the quality of urban water bodies, which are seen as alternative resources. In this study, the focus was on the impact of urban areas in Sana'a city on stormwater quality. Sana'a city is situated in the southern part of the Sana'a Basin. Many basins streams flow through the city, which exposes to many pollutants. Moreover, rainwater is the only renewable water resource in the city and in the level of the Sana'a basin. Therefore, there must be a strategy to benefit from this stormwater runoff to cover the demand for water escalates due to growing urbanization and agriculture. This master thesis assesses the stormwater quality in Sana' a city as a contribution to applying the concept of integrated water resources management (IWRM) to help make an appropriate decision to protect and benefit from using stormwater runoff.

This thesis research used qualitative approaches to achieve the main objective of studying the stormwater quality in Sana'a city from the IWRM approach. So, this research tested stormwater runoff from selected sites four along the Al-Saylah channel and one on the building rooftop of the faculty of engineering at Sana'a University that was selected as a reference site. In addition, focus group discussion was conducted to collect qualitative data of socio-economic for using stormwater runoff in Sana'a city for irrigation. Finally, All the data and information from the testing stormwater quality, focus group discussion, and site observation were analyzed.

The findings of the research showed that the maximum concentrations of twelve parameters were (pH = 6.9 moles/l, TSS = 3720 mg/l, COD = 1389 mg/l, FC = 2990 mg/l, NO_3 = 12.34 mg/l, NO_2 = 1.66 mg/l, PO_4^{3-} = 5.5 mg/l, Zn = 8.22 mg/l, Cu = 4.71 mg/l, Pb = 1.62 mg/l, Ni

= 0.23 mg/l, Cr = 0.91 mg/l). Six of these parameters (pH, COD, FC, Zn, Cu, Cr) did not meet with Yemeni and FAO standards for reuse wastewater for water irrigation exception the NO_2, NO_3, PO_4^{3-}, Pb, and Ni due to the nonpoint source pollution spread within the city. Most likely, the reason is the spread of pollution sources within the city, vehicle traffic, building construction and commercial activities, surface erosion, waste disposal, flooding in the sewage system, and stray animal waste are potential sources of pollutants in the city.

The farmers depend on stormwater retention ponds during the rainy seasons to irrigate their farms, and they save about 70% of diesel quantities when they use these ponds, according to their statements, and this measure also contributes to reducing groundwater depletion.

In general, Yemeni law addresses the dangers of various pollutants, regardless of their source. However, the Ministry of Water and Environment lacks the implementation of some proposed programs to mitigate and control nonpoint source pollutants in urban areas, and the reason for this is the scarcity of material resources as a result of the current war in most parts of the country. It was deduced that the coordination mechanism between government institutions that are related to stormwater runoff management is weak.

Finally, one of the most important recommendations of this study is the need to solve water problems based on the IWRM perspective. IWRM allows all the water institutions to work under one umbrella to protect water resources and maximize the benefit from stormwater runoff that is the only renewable water source in Sana'a Basin. In addition to the integration of water resources in the basin level.

الملخص

جذب تأثير التوسع الحضري على جودة المياه الكثير من الاهتمام في جميع أنحاء العالم بسبب آثاره البيئية. حيث يؤثر التحضر بشكل كبير على جودة المسطحات المائية الحضرية التي يُنظر إليها على أنها موارد بديله. وفي هذه الدراسة تم التركيز على تأثير المناطق الحضرية في مدينة صنعاء على جودة مياه السيول، حيث تقع مدينة صنعاء في الجزء الجنوبي من حوض صنعاء و تتدفق العديد من مجاري الوديان عبر المدينة مما يعرضها للعديد من الملوثات. علاوة على ذلك ، فإن مياه الأمطار هي المورد الوحيد للمياه المتجدد في المدينة وعلى مستوى حوض صنعاء ايضا. لذلك ، يجب أن تكون هناك استراتيجية للاستفادة من مياه السيول لتغطية الطلب المتزايد على المياه بسبب أتساع المناطق الحضرية والانشطة الزراعية. تقيم أطروحة الماجستير هذه جودة مياه السيول في مدينة صنعاء كمساهمة في تطبيق مفهوم الإدارة المتكاملة للموارد المائية والمساعدة في اتخاذ القرار المناسب للحماية والاستفادة من مياه السيول.

أستخدم في هذا البحث أساليب البحث النوعي لتحقيق الهدف الرئيسي و الاهداف الفرعية لدراسة جودة مياه السيول في مدينة صنعاء من منظور الإدارة المتكاملة للموارد المائية. لذلك ، اختبر هذا البحث جودة مياه االسيول من أربعة مواقع مختارة على طول قناة السائلة ، وتم اختيار موقع مرجعي واحد على سطح مبنى كلية الهندسة بجامعة صنعاء. تم إجراء مجموعة النقاش المركزة مع المزراعين لجمع البيانات في الجانب الاجتماعي و الاقتصادي لاستخدام مياه السيول في الجانب الزراعي داخل مدينة صنعاء. أخيرًا ، تم تحليل جميع البيانات والمعلومات المجمعة عن جودة مياه السيول و بيانات مجموعة النقاش المركزة والزيارات الموقعية.

أظهرت نتائج البحث أن أقصى تركيز لكل من الاثني عشر متغيرًا كانت (pH = 6.9 مول / لتر ، TSS = 3720 مجم/لتر ، COD = 1389 مجم/لتر ، FC = 2990 مجم/لتر ، NO_3 = 12.34 مجم/لتر. ، NO_2 = 1.66 مجم/لتر، PO_4^{3-} = 5.5 مجم/لتر، Zn = 8.22 مجم/لتر، Cu = 4.71 مجم/لتر، Pb = 1.62 مجم/لتر، Ni = 0.23 مجم/لتر، Cr =0.91 مجم/لتر). سته من هذه القيم (pH و COD و FC و Zn و Cu و Cr) القصوى لم تتوافق مع المعايير اليمنية ومنظمة الأغذية والزراعة لإعادة استخدام مياه الصرف الصحي في الزراعة بأستثناء اربع قيم قصوى لتلك المتغيرات هي Pb و NO_2 و NO_3 و PO_4^{3-} ، والسبب في ذلك، على الأرجح، هوانتشار مصادر التلوث داخل المدينة، وتعتبر حركة مرور المركبات ، وتشييد المباني والأنشطة التجارية ، وتآكل الأسطح ، والتخلص من النفايات ، والفيضان في نظام الصرف الصحي ، ومخلفات الحيوانات الضالة مصادر محتملة للملوثات في المدينة.

يعتمد المزارعون على المياه من حفر حصاد مياه السيول في مواسم الأمطار، لري مزارعهم ، وبالتالي يوفرون حوالي 70٪ من كميات الديزل عند استخدام هذه المياه، وفقا لتصريحاتهم ، وهذا الاجراء أيضًا يساهم في الحد من استنزاف المياه الجوفية.

بشكل عام يتصدى القانون اليمني لمخاطرالملوثات المختلفة أيا كان مصدرها. ولكن ينقص وزارة المياه و البيئة تنفيذ بعض البرامج المقترحة للتخفيف والسيطرة على الملوثات غير محددة المصدر في المناطق الحضرية، والسبب في ذلك

هو شحة الامكانات المادية كنتيجة للحرب الدائرة حاليا في معظم ارجاء الوطن، كما يتضح بأن آلية التنسيق بين المؤسسات الحكومية ذات الصلة بإدارة مياه السيول ضعيفة.

أخيراً، فان من أهم التوصيات التي خرجت بها هذه الدراسة هي ضرورة حل المشاكل بناءً على منظور الادراة المتكاملة للموارد المائية الذي يسمح لجميع مؤسسات المياه بالعمل تحت مظلة واحدة لحماية الموارد المائية وتعظيم الاستفادة من مياه السيول الذي يعد المصدر الوحيد للمياه المتجدد في حوض صنعاء بشكل عام. بالإضافة إلى تكامل الموارد المائية على مستوى الحوض.

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List of abbreviation

BMPs: Best Management Practices

COD: Chemical Oxygen Demand

DB: Detention Basin

GWP: Global Water Partnership

FAO: Food and Agriculture Organization

FC: Fecal Coliforms

FGD: Focus Group Discussion

FTW: Floating Treatment Wetland

GIS: Geographic Information Systems

IWRM: Integrated Water Resources Management

MAI: Ministry of Agriculture and Irrigation

MPN: Most Probable Number

MWE: Ministry of Water and Environment

NO_3-N: Nitrate-Nitrogen

NGO: Non-government Organization

GO: Government Organization

pH: Potential of Hydrogen

PO_4-P: Orthophosphate-Phosphorus

TP: Total Phosphorus

TSS: Total Suspended Solids

UWM: Urban Water Management

US EPA: United States Environmental Protection Agency

WEC: Water and Environment Center

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Chapter 1: Introduction

Urban stormwater is seen as a water resource that needs to be captured, stored, and utilized for meeting current and future water supply demands, and is one of the renewable sources of water that has to benefit from it in areas that suffer from scarce water resources. Further, the growing urbanization is a common phenomenon worldwide, resulting in the conversion of previously vegetated areas into impervious surfaces.

On the other hand, the increase in impervious surfaces due to the expansion of urbanization has led to an increase in deposited (built-up) pollutants in urbanization. Then these pollutants are transported by stormwater runoff to the receiving water bodies. The anthropogenic activities in urban regions deposit a range of physical, chemical, and microbial pollutants on these impervious surfaces. These include gross pollutants, sediments, nutrients, metals, hydrocarbons, and microbial contaminants that come from nonpoint source pollutants.

All these pollutants are under physical and chemical transformations after deposition continuously, which will result in changes to their mobility, toxicity, and bioavailability. United States Environmental Protection Agency (US EPA) defines the terms of nonpoint as the "any source of water pollution that does not meet the legal definition of a point source in section 502(14) of the Clean Water Act" (US EPA 2018).

The quantity and quality impacts on stormwater due to urbanization are influenced by a range of factors, including urban from, land-use activities, traffic characteristics, and climate characteristics (Goonetilleke and Lampard 2019). The Integrated Water Resource Management (IWRM) provides solutions for the specific challenges related to the management of water resources (Parkinson and Mark 2005), as happened in Bangladesh that has successful experience with IWRM (Rouillarda, Bensonb and Gainc 2014).

The Global Water Partnership defines IWRM as " a process that promotes the coordinated development and management of water, land and related resources to maximize resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems." (GWP 2000). The principles of IWRM entails environmental sustainability, economic efficiency, participation approaches, and women's participation. The management of stormwater runoff is a vital issue for municipalities whose citizenry demand clean drinking water, flood prevention, water drainage, and sanitation (Steinman, Isely and Thompson 2015) and should therefore have a stake in IWRM.

Yemen faces a terrible water availability crisis, with groundwater being extracted at a rate exceeding the rate of natural recharge. Sana'a city is at risk of running out of water (Weiss 2015), and the water shortage security situation in the Sana'a basin is alarming. IWRM was applied in Sana'a Basin since 2003 to develop and manage water resources and deliver water services for different levels of the society (Taher, et al. 2013). The volume of runoff in the Sana'a basin was estimated at about 40.9 MCM/year (NWRA 2007) which can be utilized as a new water supply resource for Sana'a city (Kruseman 1966).

The storm water runoff flows from the south to the north of Sana'a city and flows through Al-Saylah channel that is the most important drainage channel in Sana'a city. The Saylah is located in the central part of Sana'a plain and has a drainage area of 950 km^2 and a length of 19.25 km. Al-Saylah channel divides the city into eastern and western parts. This channel is designed to drain rainwater and ultimately functions as road for vehicles to mitigate the city's traffic congestion.

The water crisis in Sana'a city has two dimensions; the quantity and quality of water resources because of urban development. The first dimension is referred to urbanization in Sana'a city, which led to an increase in runoff volume because of changes in existing land use to impervious surfaces. The second dimension, the quality of stormwater runoff that can represent a significant source of pollutants to receiving water bodies. Most farmers have used the stormwater runoff as an alternative to meet the increasing water demand in Sana'a city and on the level of the basin.

This research studied some characteristics of the quality of stormwater runoff in Sana'a city as the first research of this kind in Yemeni cities. Water institutions will benefit from this research to develop their strategies that will maximize the benefit of using the stormwater runoff in the Sana'a basin. The research aims at shedding light on the quality of stormwater runoff in Sana'a city from the IWRM approach. This approach mainly depends on the broad understanding of IWRM principles and actions that support the decision-makers to make appropriate decisions in line with the IWRM objectives.

1.1 Objectives of the research

1.1.1 Main objective

To study the quality of stormwater runoff in Sana'a city from the IWRM approach, which can cope with complex issues of urban stormwater management and encourages a coordinating approach for managing water resources in a way that balances social and economic demands with care for the environment, and water scarcity.

1.1.2 Sub-objectives

In order to achieve the main objective of this thesis, the following sub-objectives were identified.

- To evaluate the quality of stormwater runoff in Sana'a city according to the Yemeni and Food and Agriculture Organization (FAO) standards for water irrigation.
- To determine the pollution sources for helping researchers to develop management strategies to mitigate and control stormwater pollution at the catchment level.

- To define possible solutions from the perspective of IWRM approach to treat and mitigate stormwater runoff pollution.

1.2 Problem statement

Groundwater aquifers in the Sana’a basin have been severely overexploited, as demonstrated by the continued decline of the water levels (Alderwish 2010). Rainwater is the only renewable water resource in the Sana'a Basin, where the urbanization affects the quality of stormwater runoff by creating many pollutants that are observed in some of the stormwater harvesting ponds in Sana’a city. Vehicular traffic, building construction and commercial activities, corrosion of surfaces, waste disposal, overflow of the sewage system, and stray animals wastes are potential sources of pollutants in the city. The estimated number of vehicles in Sana’a city is 450,000 vehicles, according to the Sana’a Traffic Department 2019. Furthermore, several thousand dogs are straying and digging in the garbage of the city.

The National Water Resources Authority, Sana’a Branch has tested the quality of the stormwater retention pond in the south of Sana’a city, and came up with zinc and manganese levels of 2.55 and 0.327 mg/L which were exceeded the acceptable range of wastewater reuse in agriculture according to Yemeni and FAO standards. Stormwater harvesting may help to achieve self-sufficiency in the rainy seasons for agriculture when its quality complies with water national and international standards to protect the human health, environment, and natural resources.

Accordingly, the Yemeni government has to make a strategy to use the stormwater runoff to cover the water demand that escalates due to growing urbanization, industrialization, agriculture. Therefore, this research investigated some characteristics of the quality of stormwater runoff in Sana’a city.

This research comes out with workable solutions from the perspective of IWRM to protect and mitigate stormwater runoff from contamination and protect the water sources at the catchment levels.

Chapter 2: Literature Review

The quality of stormwater runoff is a subject that has been studied by several researchers worldwide as a matter of its impact on human health, environment, and the economic aspect. This literature review will give an insight into the effects withdrawn at different local, regional, and global levels.

2.1 Previous studies on urban stormwater quality at global

In the United States:

Yang and Toor (2017) conducted a study named “Sources and mechanisms of nitrate and orthophosphate transport in urban stormwater runoff from residential catchments”. This study found that the main source of NO_3-N in street runoff was atmospheric deposition (range: 35-64 %), followed by chemical N fertilizers (range: 1-39 %), soil and organic N (range: 7-33 %), whereas PO_4-P in the street runoff likely originated from erosion of soil particles and mineralization from organic materials such as leaves, grass and clippings.

Appel and Hudak (2014) studied the “Automated Sampling of Stormwater Runoff in An Urban Watershed, North-Central Texas”. This study has tested the quality of stormwater runoff in Pecan Creek, Denton, Texas. Stormwater runoff from four storm events was sampled from four stations. The concentrations atrazine, Diazinon, cadmium, and arsenic detected were 7.19 mg/l, 0.9 mg/l, and 0.008 ug/l, 0.039 ug/l respectively that exceeded maximum contaminant levels for drinking water, but were within ranges typical for urban runoff. Also, calcium and phosphorous concentrations were slightly elevated compared to typical ranges for urban runoff, which was attributed to soils, building materials, and fertilizer applications in the study area.

Amina and Kumud (2014) conducted a study named the “Detention basins as best management practices for water quality control in an arid region”. Detention Basins (DBs) can be used as BMPs not only to control stormwater runoff quantity (by holding peak discharge) but also to improve quality by allowing suspended particles that carry contaminants such as phosphorus to settle out. DBs work especially well for water quality control when undeveloped areas surround them since DBs easily trap sediments that can be removed from the basins. It is benefited from this study on stormwater runoff treatment methods.

Engstrom (2004) conducted a study entitled “Characterizing Water Quality of Urban Stormwater Runoff: Interactions of Heavy Metals and Solids in Seattle Residential Catchments”. This research has indicated that high concentrations of total suspended solids (TSS), dissolved metals, nutrients, total petroleum hydrocarbons, pesticides, herbicides, and E. coli and fecal coliform bacteria are present in the stormwater runoff in urbanized catchments in the Pipers Creek watershed in North Seattle.

Kaplowitz and Lupi (2012) conducted a study named “Stakeholder preferences for best management practices for non-point source pollution and stormwater control”. A choice experiment survey was designed and implemented by this study to know about public preferences for alternative BMP for stormwater management to be supported by local stakeholders, and to grow public participation in watershed management decision making.

In Canada: Makepeace, Smith, and Stanley (2014) conducted research named “Urban stormwater quality: Summary of contaminant Data”. He reviewed 140 research studies related to stormwater quality. Whereas he has found that the concentrations of TSS = 1.00 to 36200 mg/l, COD = 1 to 2200 mg/l, Zn = 0.0007 to 22 mg/l, Cu = 0.00006 to 1.41 mg/l, Pb = 0.00057 to 26 mg/l, Ni = 0.001 to 49 mg/l, Cr = 0.001 to 2.3 mg/l, and FC = 0.2 to 1.9E6 MPN/100.

In Italy: Gnecco, et al. (2005) conducted the study named “the storm water pollution in the urban environment of Genoa, Italy”. This research has found the most significant pollutant constituents in road runoff are TSS, COD and among heavy metals in dissolved from Cu, Pb, and Zn. Also. TSS and COD event mean concentrations exceed European water quality standards in 70% of the monitored rainfall events.

In France: Guido Petrucci (2014) studied “Nonpoint source pollution of urban stormwater runoff: a methodology for source analysis” as the characterization and control of runoff pollution from nonpoint sources in urban areas are a significant issue for the protection of aquatic environments. The specific results of this study are that human activities are the primary sources for Cu is a brake pad wear, and the sources of Polycyclic Aromatic Hydrocarbons (PAH) is tire wear, while land cover materials are responsible for most of Pb such as roof point elements, the source of Zn is roof cover and linear elements.

In China: Du, et al. (2018) conducted a study titled “The influence of traffic density on heavy metals distribution in urban road runoff in Beijing, China”. It studied the concentrations, distributions, and possible risk of heavy metals in urban road runoff from different traffic density that were determined and compared in Beijing, China. It found that the concentrations of heavy metals in road runoff were strongly influenced by traffic density, and the resulting in total concentrations of Zn, Cu, Fe, Mn, and Pb in the runoff from the highway were higher than those from the road nearby campus (The buildings of the university and the land around them). The traffic density did not influence the distributions of heavy metals. The possible ecological risk of heavy metals in the runoff from the highway was higher than those from the road nearby campus.

2.1 Previous studies that are related to urban stormwater quality regionally

In Jordan: Omar Ali Al-Khashman (2013) conducted a study titled "Assessment of heavy metals contamination in deposited street dusts in different urbanized areas in the city of Ma'an, Jordan". 190 street dust samples from 9 different locations including, residential streets, school gardens, hospital, health centers, high traffic, moderate traffic, light traffic industrial sites, parks and background sites of Ma'an area (Areas were not affected by traffic emissions and any source of contamination) were tested for Fe, Zn, Ni, Pb, Mn, Cu, and Cd.

The study found that there are notable levels of metals in urban and industrial sites compared to the values obtained from the background sites. The variation in concentration of the heavy metals that were determined from different locations was in the decreasing order as industrial site > high traffic > park sites > moderate traffic > hospital and health centers > school's gardens > light traffic > background sites. The research indicated the main sources of heavy metals are fossil fuel combustion, wear of brake lining materials, traffic emissions, and several industrial processes.

In Egypt: Abdel-Latif and Saleh (2012) conducted a study named "Heavy Metals Contamination in Roadside Dust along Major Roads and Correlation with Urbanization Activities in Cairo, Egypt". This study analyzed the heavy metals' concentrations (Pb, Zn, Cd, Ni, Co, Cr, As, Ag, and V) in roadside dust in 46 sites in Cairo districts. This study found the concentrations of heavy metals were higher in traffic roads and industrial areas. Also, the lead and zinc were the most widespread heavy metals in both dust fractions from all areas.

In Saudi Arabia: Odat and Alshammari (2011) conducted a study named "Seasonal Variations of Soil Heavy Metal Contaminants along Urban Roads: A Case Study from the City of Hail, Saudi Arabia". This research evaluated seasonal variations in the mean concentrations of heavy metals for Pb, Cd, Zn, Ni, Cr, Cu, Co, V, and Hg in seasonal variations (summer and winter), and the concentrations of heavy metals were 88-89, 5-8, 197-203, 33-37, 96-126, 95-104, 49-53, 82-90, and 3-4 ppm in summer season and 88-94, 6-8, 201-207, 38-42, 98-120, 98-106, 50-55, 83-93, and 3-4 ppm in the winter season, respectively. The concentrations of heavy metals in the soils are generally higher than the usual values, emphasizing the adverse impacts of the vehicle exhausts and the relatively heavy traffic on the highways.

In Iran: Taebi and Droste (2004) conducted a study named the "First flush pollution load of urban stormwater runoff". This research was conducted in a semi-arid region of a mixed residential and commercial urban catchment in Iran. This study has tested the stormwater runoff for TS, TSS, COD, TN, Zn, and Pb. It was found that the TSS and COD were 467 mg/L and 2542 mg/L that are above the standards for wastewater effluent quality discharged to surface water in Iran, which are 40, and 30 mg/L respectively.

In Bahrain: M. Salim Akhter & Ismail M. Madany (1993) contucted a study named "Heavy Metals in Street and House Dust in Bahrain". One hundred six dust samples were collected from street and household dust throughout Bahrain and analyzed for Pb, Zn, Cd, Ni, and Cr. The dust samples were collected from seven sites, including the control site. The results indicated that the dust samples contained significant levels of heavy metals. The results of six sites compared with the control values. The mean concentration of heavy metals streets for Pb, Zn, Cd, Ni, and Cr were 697.2, 151.8, 72.0, 125.6, and 144.4 µg/g, respectively, whereas for household dust they were 360.0, 64.4, 37.0, 110.2 and 144.7 µg/g. This study indicated that motor vehicles are a major source of these metals in dust samples. Concerning Ni, elevated concentration could be attributed to smoke from the burning of Kuwait oil fields.

2.3 Previous studies that are related to urban stormwater quality locally

In Yemen:

April 20, 2019, the Water Resources Authority in Sana'a Branch has tested the quality of the stormwater retention pond at Al-Sabeen district, Sana’a city, which harvests the urban stormwater runoff. Zinc and manganese (2.55 and 0.327 mg/L) were higher than water standards for agriculture, according to FAO.

Al-Samawi, Al Hadrami, and Ramadan (2015) conducted a study named “Applying IWRM in Al-Sabeen Pond.” This study found that the percentage of oil and grease in the stormwater retention pond at the Al-Sabeen region reached 45.2 mg/l, which was more than the typical runoff from residential and commercial areas, which is 9 mg/l, and threat the shallow groundwater aquifer.

Chapter 3: Methodology

In this chapter the researcher used a qualitative research approach for collecting data to evaluate the quality of stormwater runoff in Sana'a city from the IWRM perspective. Johnson and Christensen (2017) define qualitative research as "Qualitative research that relies primarily on the collection of qualitative data". According to Kothari (2004) "Qualitative research is concerned with a qualitative phenomenon, i.e., phenomena relating to or involving quality or kind.". The following sections will explain in detail how the researcher has planned for the study and how the research was implemented and the data were analyzed.

3.1 Conceptual framework

The conceptual framework of this thesis was based on the application of the IWRM concept. IWRM aims to overcome water-related problems that arise in the community as a result of the uncoordinated, inefficient use, and misuse of water resources. The quality of urban stormwater runoff in this study was linked to IWRM from the water resources, the socio-economic, and the institutional aspects. The relationship between these aspects is illustrated in figure (3.1).

This research studied the relationship between Institution and Socio-Economic by discussing the measures taken by the governmental institutions in Sana'a city in the role of harvesting stormwater to cover the growing demand for water resources. The link between institutional aspects and water resources were discussed in the context of the legal framework related to stormwater quality management. The water resources were linked to the socio-economic context by assessing the stormwater runoff quality in Sana'a city and conforming these results to the Yemeni and FAO wastewater reuse standards for irrigation.

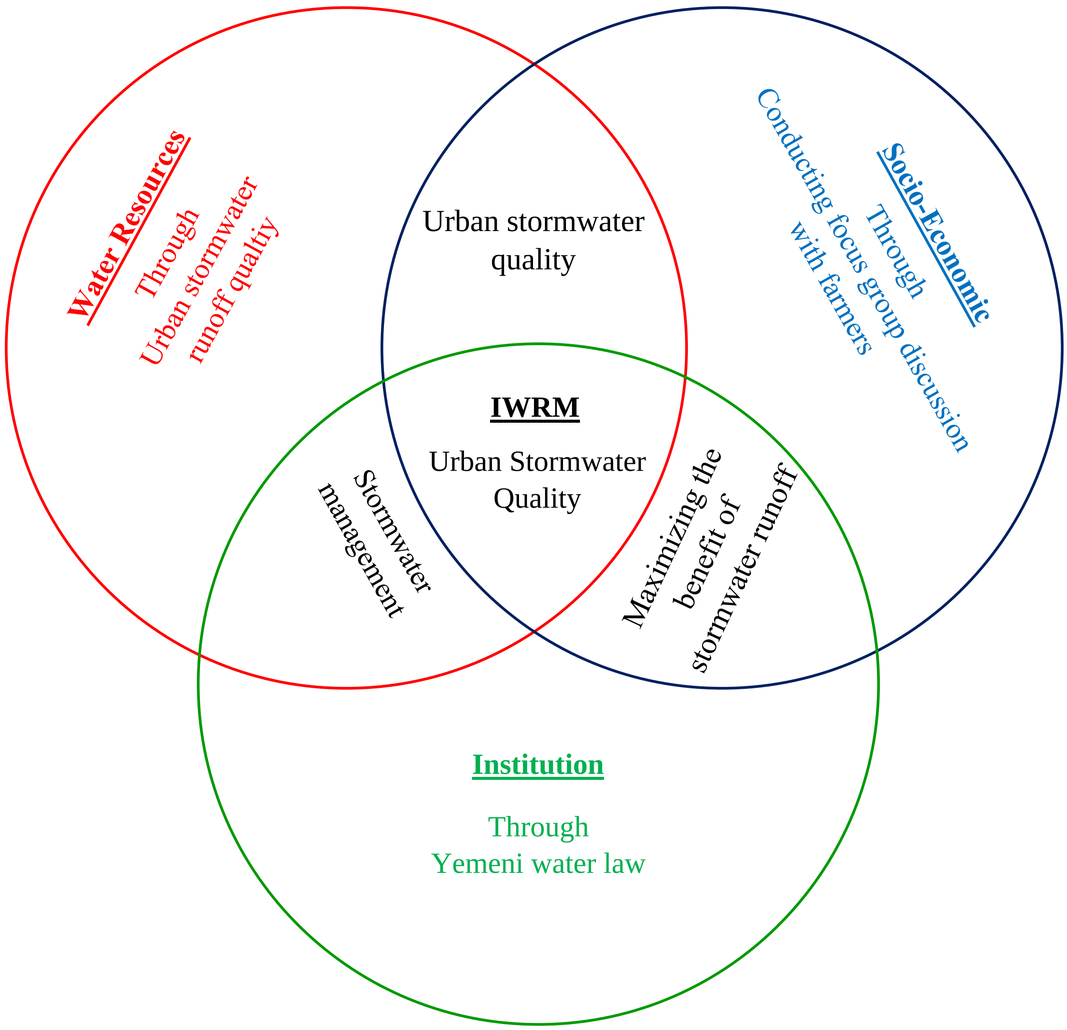

Figure (3.1): Research framework

3.2 Study area

Sana'a, the capital of the Republic of Yemen is situated in the southern part of the Sana'a Basin, see figure (3.2). It is the biggest city in the country, with approximately 3,937,500 inhabitants (European Commission 2019) and an urban average annual growth rate of 4.05% (Al-shalabi, et al. 2012).

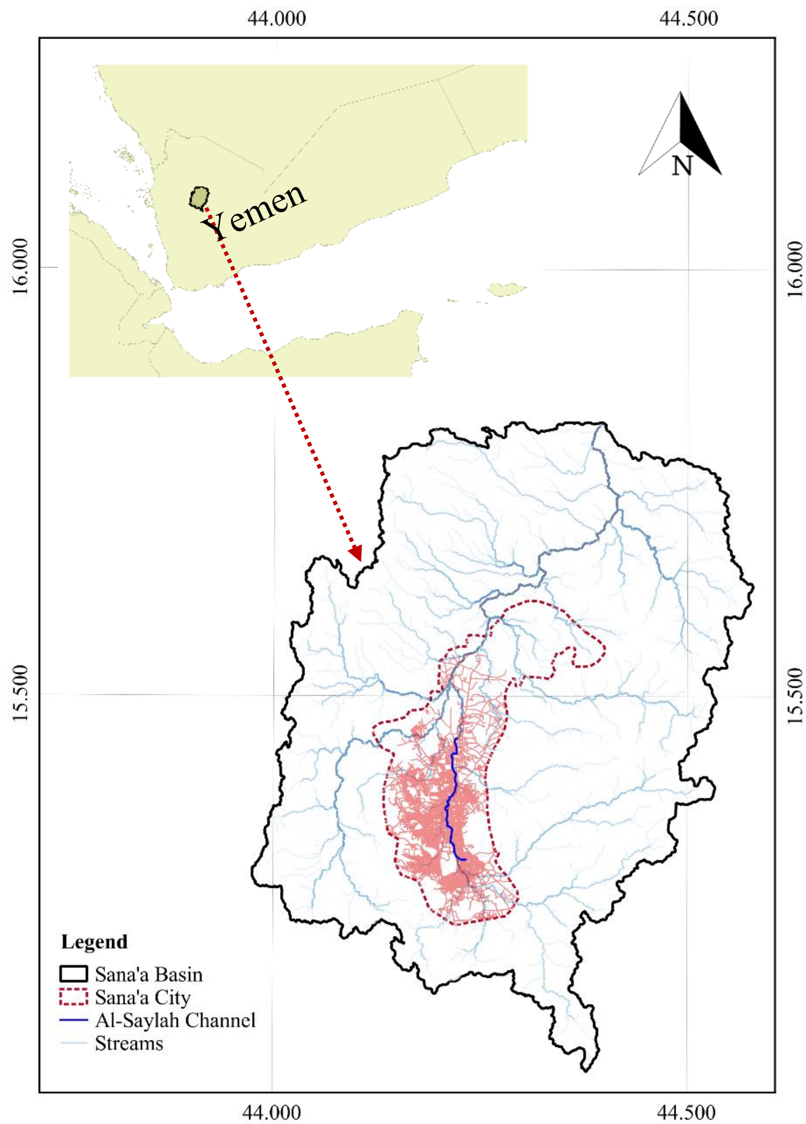

Figure (3.2): Study area

Sana'a city has for many centuries been the main economic center of the Yemen, as well as the broad commercial activity in the city. It is located within the latitudes 15° 10' 00" and 15° 30' 00" North and longitudes 44° 05' 00" and 44° 20' 00" East. Sana'a city lies at an elevation of 2,300 m above sea level.

The mountain regions in the southeast and southwest areas of the basin receive more rainfall than the plains in the central area (Root, et al. 2010). The climate of Sana'a is semi-arid with two rainy seasons during the spring (April-May) and summer (July-August). The annual rainfall ranges from 117.6 mm in the northern part of the Sana'a city to 281.8 mm in the southern part (WEC 2007).

3.2.1 Catchment area

The catchment area of sampling sites 4 at the Al-Saylah channel were calculated by using Geographic Information Systems (GIS) with ArcMap 10.2 program, and the catchment area is 945 km^2. About 25% of this catchment lies in urban Sana'a with commercial, industrial, residential and transportation activities, while 75% of this catchment of rural nature. There are Wadi Ghayman, Wadi Shahik, Wadi Akhwar, Wadi Hizayaz, Wadi Miliki, and Wadi Sa'wan and these sub-basins flow in to the Sana'a city, as shown in figure (3.3).

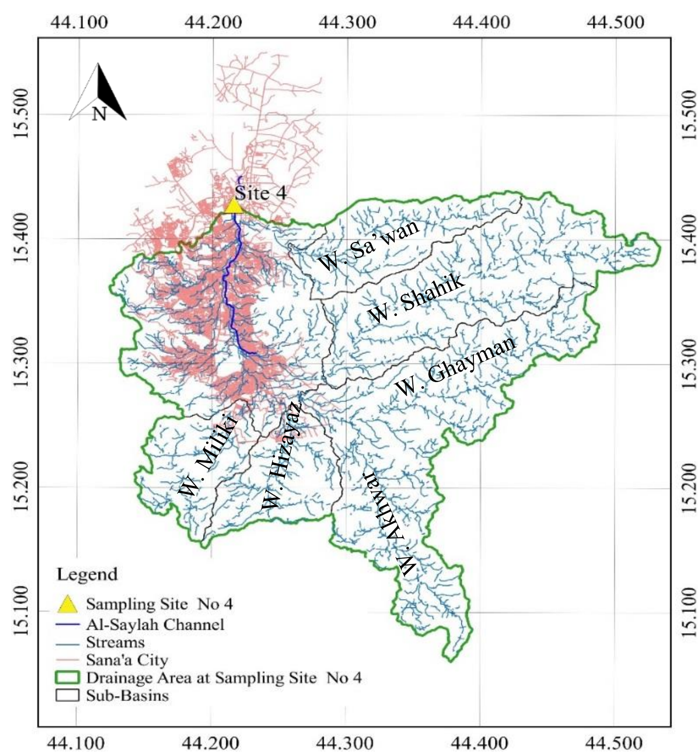

Figure (3.3): Drainage area of sampling site No 4 at Al-Saylah channel

3.3 Date collection

3.3.1 Secondary data

National, regional, and international peer-reviewed studies and reports on the quality of stormwater runoff and the best solutions to mitigate stormwater runoff pollution were collected via scholarly browsers, local governmental institutions, and the Water and Environment Center (WEC) at Sana'a University. The Water Resources Authority in Sana'a Branch provided rainfall data for Sana'a city, the results of tests for the water quality in Al-Sabeen storm water retention pond, and the Yemeni Water Law. The Sana'a Traffic Department provided the number of vehicles in Sana'a city to get a vague notion about the dimension of stormwater pollution with heavy metals that are deposited on roads due to exhausts and corrosion of vehicles bodies.

3.3.2 Primary data

3.3.2.1 Testing of stormwater runoff quality

Stormwater quality parameters

The Clean Water Action defines stormwater pollution as the polluted runoff gathered from rain, roads, parking lots, and other impervious surfaces (Clean Water Action 2020). Twelve parameters (pH, TSS, COD, FC, NO_2, NO_3, PO_4^{3-}, Z, Cu, Pb, Ni, and Cr) were measured to study the quality of stormwater runoff in Sana'a city. These were selected based on the studies of Du, et al. (2018), Gnecco, et al. (2005), Engstrom (2004) and the Environment Protection Authority Victoria in Australia (EPA Victoria 2019).

Sampling sites

Four sites along Al-Saylah channel were chosen for stormwater sampling; one at the upper-stream of Al-Saylah channel, two sites in the middle-stream, and one site down-stream, see figure (3.4). The rooftop of the Faculty of Engineering at Sana'a University was taken as the reference site (see figure 3.5). The rooftop of a building is considered protected from pollution and can therefore be taken as a reference (Sipes 2000).

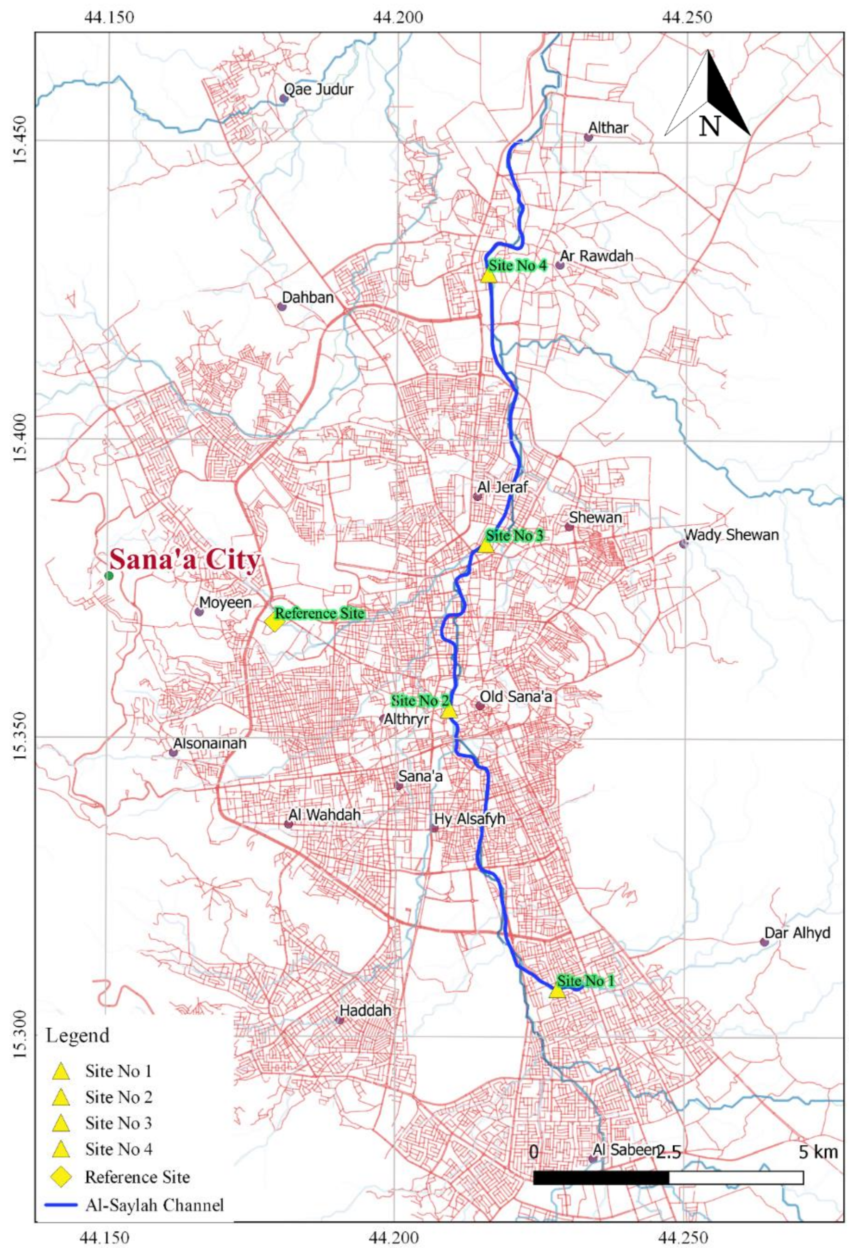

Figure (3.4): Sampling sites location of stormwater runoff

Figure (3.5): The rooftop of the Faculty of Engineering at Sana'a University-Reference site (Google Earth)

The GPS device (Garmin GPS-MAP 64s) was used to determine the locations of these sites and locate them on the Sana'a city map. Table (3.1) lists the location of sampling sites, including the nearest geographic reference.

Table (3.1): the location of sampling sites

Site No	Latitude	Longitude	Geographic Reference
Site 1	15.308005°	44.228073°	Soqatra St
Site 2	15.354924°	44.209239°	Bab-Alsabah
Site 3	15.382623°	44.215458°	Amjad Private Schools
Site 4	15.427928°	44.215779°	The intersection of TV Street with the Asayilah channel
Reference site	15.369472°	44.179017°	The faculty of engineering at Sana'a University

When selecting sampling site locations, the following measures were considered. First, it is accessible to reach these sites without risk and safety for the volunteer who will collect the sample, such as there is a stair in Al-Saylah Channel to inter and take a stormwater runoff samples. Second, the availability of assistants trainees volunteers because the stormwater samples must be taken at the same time (see figure 3.6 and 3.7).

Figure (3.6): Collection of storm water runoff samples from site 1

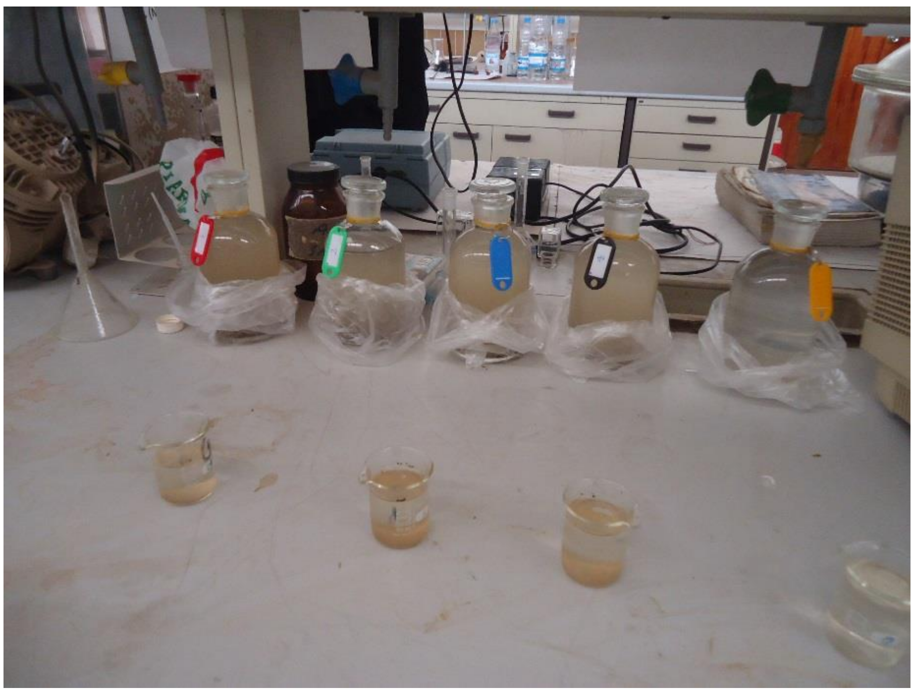

Figure (3.7): Labeling of glass bottles

Sample collection

In 2019, the stormwater runoff began in Al-Saylah channel on March the 16th (see annex 1). Samples were collected during three rainfall events during March and April (see table 3.2) to measure the pollutant concentrations in the stormwater runoff. Five male trainees volunteers were chosen to assist in storm water runoff collection simultaneously within the first 45 minutes of rainfall, according to the Washington State Department of Ecology 2015 and trained by the researcher on safe and proper collection techniques according to the HACH 2012.

Table (3.2): Sampling dates per rainfall event

No	Rainfall event test	Date of rainfall event
1	First samples collection	March 16, 2019
2	Second samples collection	April 11, 2019
3	Third samples collection	April 18, 2019

Three samples per site were collected in three separate glass bottles (500 ml) on each rainfall event for pH, TSS, COD, NO_2, NO_3, FC, Z, Cu, Pb, Ni, and Cr analysis. All samples were transported and stored in a cooler box at 4°C (figure 3.8) according to the HACH 2012 method.

Figure (3.8): The storm water runoff samples stored in a cooler box.

3.3.2.2 Focus group discussion

A focus group discussion (FGD) was used to collect qualitative socio-economic data for using storm water runoff in Sana'a city for irrigation. Johnson and Christensen (2017) defined a focus group as "a type of group interview in which a researcher leads a discussion with a small group of individuals to examine, in detail, how the group members think and feel about open-ended questions". The main characteristic of using a focus group is the interaction between the researcher and the group, as well as the interaction between group members.

In the 2nd of March, 2020 at PM time, the researcher conducted one FGD with five male farmers during the Yemenis rest time (Chewing Qat[1]) at the seat of the Water Users Association (WUA) of Al-Sabeen District. Eight farmers were originally invited to attend the session but three farmers apologized for personal reasons.

The focus group discussion of about two hours with farmers provided the opportunity to get more in-depth feedback through open-ended questions, see annex (4). According to Dawson (2010), one and a half hours is an ideal length for FGDs, although sometimes a focus group may take more than that. Scripts were distributed to farmers, which explained the purpose of the meeting, reviewed the focus group rules (see annex 4), and reinforced this discussion's confidentiality. At the beginning of the meeting, the reason for this meeting was introduced to the farmers by the researcher, and each farmer introduced himself to others.

[1] Al-Motarreb, Baker, and Broadley (2002) indicate in their research that Yemeni Qat sessions represent a momentous social occasion to meet other people and exchange ideas and information. It allows free talks conducted in a friendly atmosphere. This situation also strengthens social relationships, leads to the flow of information among society, and allows the solving of social problems.

3.3.2.3 Site observation

Another method for data collection is site observation, according to Kothari (2004). Before sites selection and during the sampling periods, the researcher spent the time between February and April 2019 to visit the Al-Saylah channel, stormwater retention ponds, and acquire the data related to stormwater runoff quality in Sana' a city (see annex 6). The observation was done by taking pictures of the Al-Saylah channel, stormwater retention ponds, and overflow of the sewage system that is currently used with a smartphone camera, as shown in figure (3.9), (3.10), (3.11), and (3.12). Extensive notes were written during picture-taking to help the researcher remembering important information while analyzing the data.

Figure (3.9): Stormwater runoff washing away solid waste

Figure (3.10): Sewage system overflow because rainwater has mixed with wastewater, this picture was taken in Tahrir Square during a rainfall event

Figure (3.11): The stormwater retention pond in Al-Sabeen region at Sana'a city

Figure (3.12): Water pumping from the retention pond at Al-Sabeen district into nearby farms

3.4 Data Analysis Methods

3.4.1 Analysis of stormwater runoff

WTW Multiline P4, is the brand name of the device that was used to measure the pH. A Hach (DR/2010) spectrometer was used to measure the concentration of the Chemical Oxygen Demand (COD), Nitrite (NO_2), Nitrate (NO_3), Orthophosphate (PO_4^{-3}), Zinc (Zn), Copper (Cu), Lead (Pb), Nickel (Ni), and Chromium (Cr). Before analyzing the samples, all devices were calibrated. To calibrate the Hach spectrometer a 2.0 mg/L PO_4^{3-} standard solution was prepared by pipetting 4.0 mL of a Phosphate Standard Solution (50 mg/L as PO_4^{-3}) into a volumetric flask and diluted to 100 mL with deionized water, stoppered and mixed.

The EPA method 160.2 was used to calculate the Total Suspended Solid (TSS). The samples collection of stormwater runoff for pH and Fecal coliforms (FC) were analyzed on the first day, where the stormwater runoff samples for FC must be analyzed within six hours of taking the sample, and measurements of pH for stormwater samples were taken at the sites while taking the samples.

The samples collection of TSS, COD, PO_4^{3-}, NO_2, NO_3, Zn, Cu, Pb, Ni, Cr were analyzed in second day. All the collected samples were analyzed in the Water and Sanitation Laboratory at the Faculty of Engineering, Sana'a University. The data analyzed were compared to Yemeni and FAO irrigation standards and not for drinking purposes because of stormwater's potential use for irrigation purposes instead of stormwater runoff drains to the desert and not be benefited from it.

3.4.2 Analysis of focus group discussion

The findings of the FGD were analyzed by using the thematic analysis approach. Thematic analysis is a qualitative research method that can be widely used across a range of research questions. It is an approach for identifying, analyzing, organizing, describing, and reporting themes found within a data set according to Nowell, et al. (2017).

3.4.3 Analysis of documentary data

Documentary data were analyzed by document analysis. Bowen (2009) indicated that "Document analysis is a from of qualitative research in which documents are interpreted by the researcher to give voice and meaning for these data". The reason for choosing the document analysis approach, that document analysis is an efficient and effective method of gathering data because documents are manageable and practical resources.

Also, obtaining and analyzing documents is often far more cost-efficient and time-efficient than conducting new research or experiments. Besides, documentary data are stable (non-reactive) data sources, meaning that they can be reading and reviewing multiple times and remained unchanging by the researcher's influence or research process, according to Bowen (2009).

3-5 Limitation of study

The limited number of analyzed water samples is mainly due to insufficient financial resources. The samples analysis was expensive and were to be paid from own resources of the researcher. Therefore, the researcher did just three tests for each parameter in the four sites with the reference site during three rainfall between March and April in 2019.

The researcher could not conduct FGDs with women because Yemen's customs and traditions do not allow for a man (researcher) to meet women during Qat chewing sessions which are separate from sessions for men.

Chapter 4: Results and Discussion

This chapter provides research findings and its explanation and interpretation from IWRM perspectives.

4.1 The evaluation of the quality of stormwater runoff and pollution sources

As mentioned earlier in the methodology, stormwater runoff samples were collected on three stormwater events, on March 16, April 11 and 18, 2019 (see annex 2). The mean values of analyzed parameters for the stormwater runoff quality in Sana'a city are presented in table (4.1), then presented in graphical shapes, individually. The mean values of parameters have been compared with Yemeni and FAO standards for water irrigation (see annex 3). Also, the four sites' mean value results have been compared with the reference site's mean values.

Table (4.1): The mean values of parameters for four sampling sites and reference site

No	Parameter	Unit	Site 1	Site 2	Site 3	Site 4	Reference site	Standard for Reuse Wastewater	
								Yemeni	FAO
1	pH	moles per liter	6.40	6.37	6.40	6.20	6.43	6.5-8.5	6.5-8.5
2	TSS	mg/liter	3826.50	1991.00	2646.67	2993.00	405.67	-	-
3	COD	mg/liter	898.00	797.00	811.67	949.00	61.00	500	-
4	NO_2	mg/liter	0.63	0.53	0.83	0.80	0.02	30	-
5	NO_3	mg/liter	5.83	4.82	7.49	7.57	0.24	30	10
6	Po4-3	mg/liter	4.50	3.50	2.30	4.21	0.84	30	5
7	Zn	mg/liter	5.44	4.98	5.59	4.62	0.03	2	2
8	Cu	mg/liter	2.56	3.51	3.00	3.46	0.00	0.2	0.2
9	Pb	mg/liter	1.41	1.27	1.16	1.33	0.00	5	5
10	Ni	mg/liter	0.19	0.11	0.15	0.19	0.00	0.5	0.2
11	Cr	mg/liter	0.23	0.44	0.40	0.37	0.00	0.1	0.1
12	FC	MPN/100 ml	2295.00	2223.33	2453.33	1840.00	13.73	1000[2]	≤1000[3]

[2] Irrigation of crops likely to be eaten uncooked, sports fields, public parks

[3] Irrigation of crops likely to be eaten uncooked, sports fields, public parks

4.1.1 Potential of Hydrogen (pH)

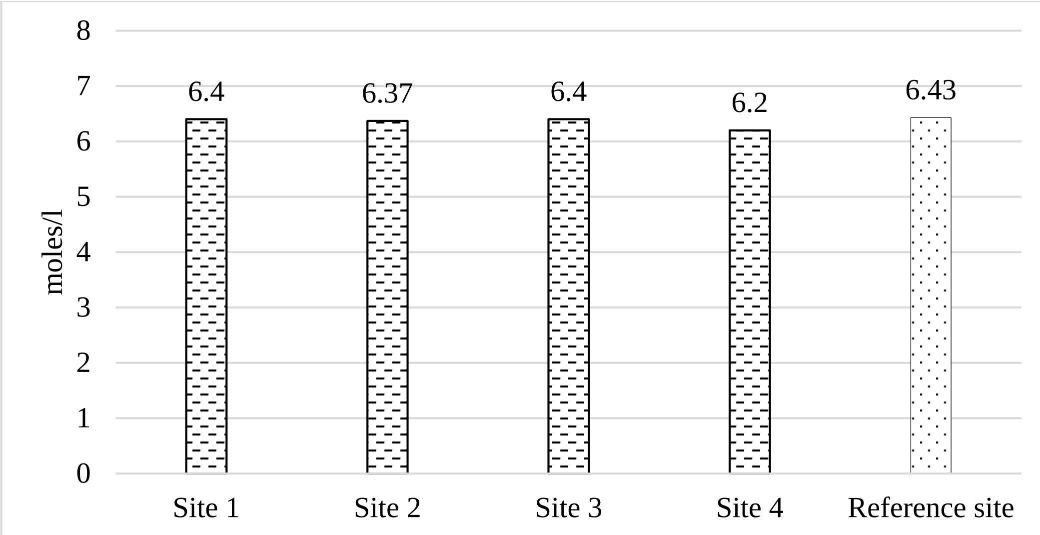

Figure (4.1): The mean values of stormwater pH in four sites and reference site

From the figure (4.1), all results of pH were acidic (pH < 7). The mean values of pH in the four sites were less than the Yemeni and FAO standards for irrigation reuse wastewater (6.5 - 8.4 mole/l). The common range of pH values for stormwater is between 4.5 – 8.7 moles/l (Makepeace, Smith and Stanley 2014). Nonpoint sources pollutions that affect stormwater runoff samples' pH values are atmospheric deposition, illegal discharge, organic matter decay, and erosion of roofing material (EPA Victoria 2019), which are deposited and scattered on impervious surface in the city.

4.1.2 Total Suspended Solid (TSS)

The impact of suspended solids on water quality can be categorized into physical and chemical impacts. The physical influences include the reduction in water transparency and the consequent inhibition of photosynthesis. Besides, heavy loads of solids can also suffocate bottom-dwelling fauna and flora and changes to the substrate. The chemical impact of solids is the adsorption of other pollutants and their transport into the receiving waters

(Gunawardena, et al. 2018). Due to their crucial role in transporting other pollutants, suspended solids are considered the most significant pollutant species in storm water quality.

The total suspended solid (TSS) loading is generally believed to be directly related to the degree of urbanization. The concentration range of TSS was found between 405.67 - 3826.5 mg/l as shown in figure (4.2).

The impact of nonpoint source pollutants from the urban and rural areas on the quality of stormwater runoff in Sana'a city was apparent through the comparison of the analysis result of TSS between the four sites and reference site, where the maximum mean value of TSS in site 1 equal 9.4 times higher than the reference site's concentration mean value.

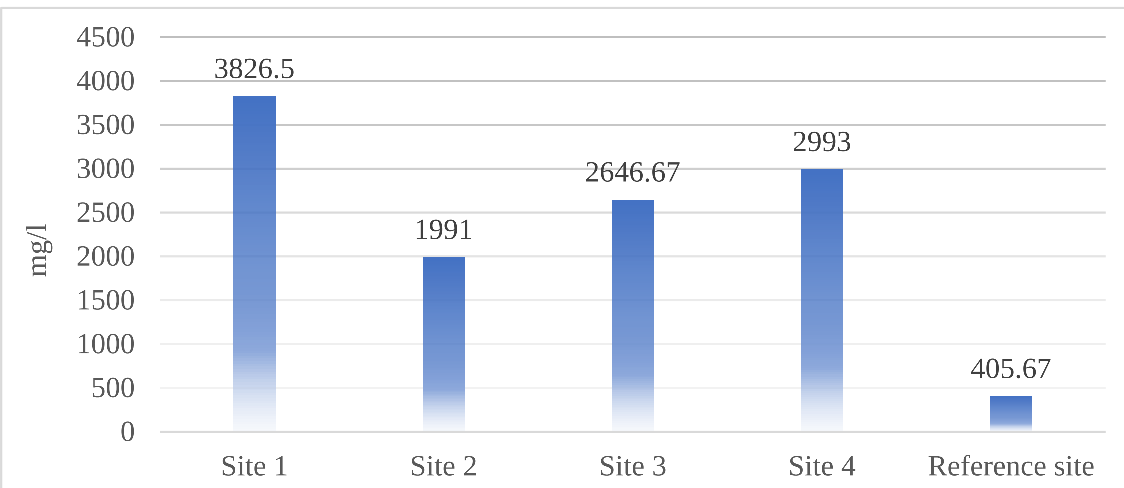

Figure (4.2): The mean TSS values of the sample and reference sites

This can be explained by nonpoint sources built up in Sana'a due to atmospheric deposition and urbanization activities like construction works and unpaved areas. According to the volumetric basis, suspended solids are the largest non-point source pollutant in urban receiving waters (Claudio 2007). Keener, Faucette and Klingman (2007) indicated in their research that soil loss rate from construction sites could be 1000 times higher than the average of natural soil erosion rates and 20 times more than erosion in agriculture lands.

In this study, the TSS could be referred to sediment spilled with stormwater runoff from the sub-basins into Sana'a city because of soil erosion, which affects the quality of stormwater runoff. It is to be mentioned that Sana'a city was exposed to a mass of air laden with dust from the Arabian Peninsula during the period of stormwater samplings on March 16, 2019, according to daily reports of the Civil Aviation & Meteorology Authority. So, it is worth noting that it is difficult to compare the parameters analysis results between the four sampling sites because the drainage areas overlap with each other, as shown in Figure (4.3-1) and (4.3-2).

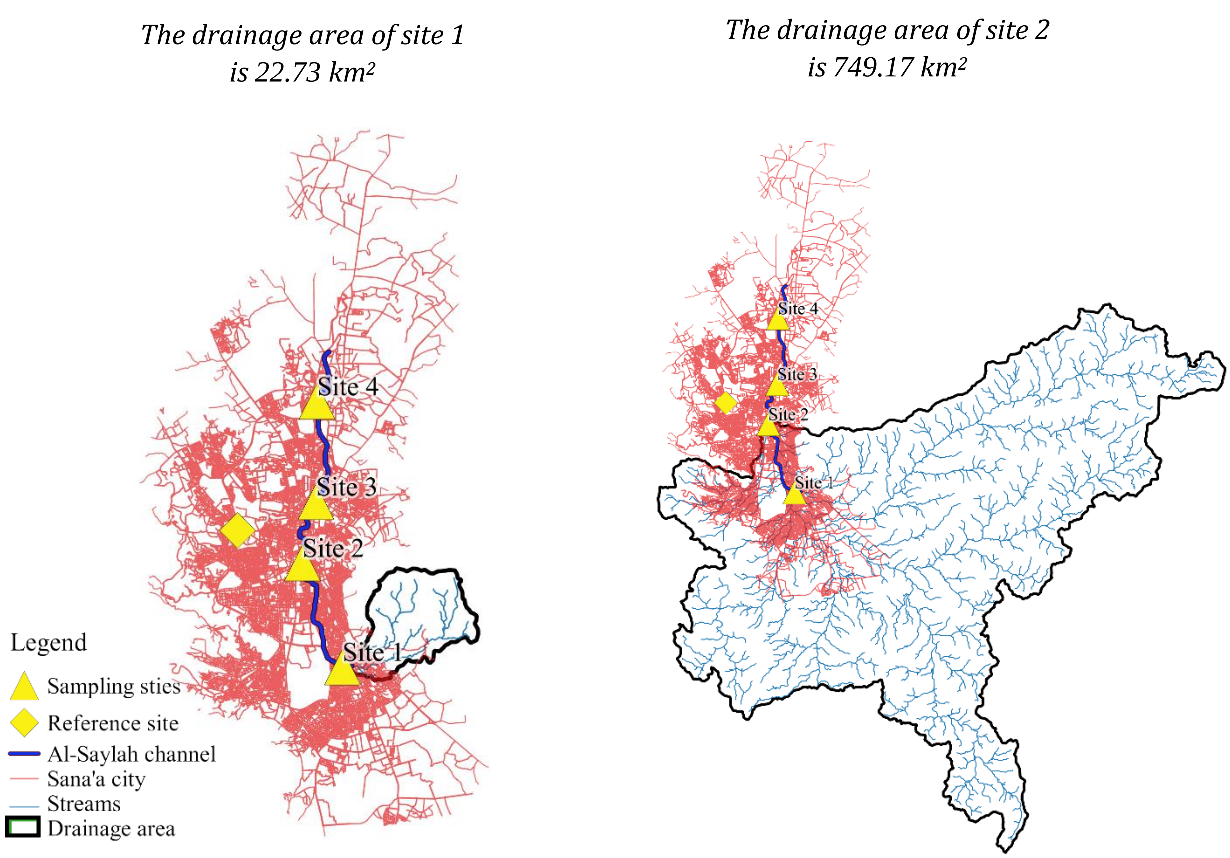

Figure (4.3-1): The drainage areas of four sampling sites

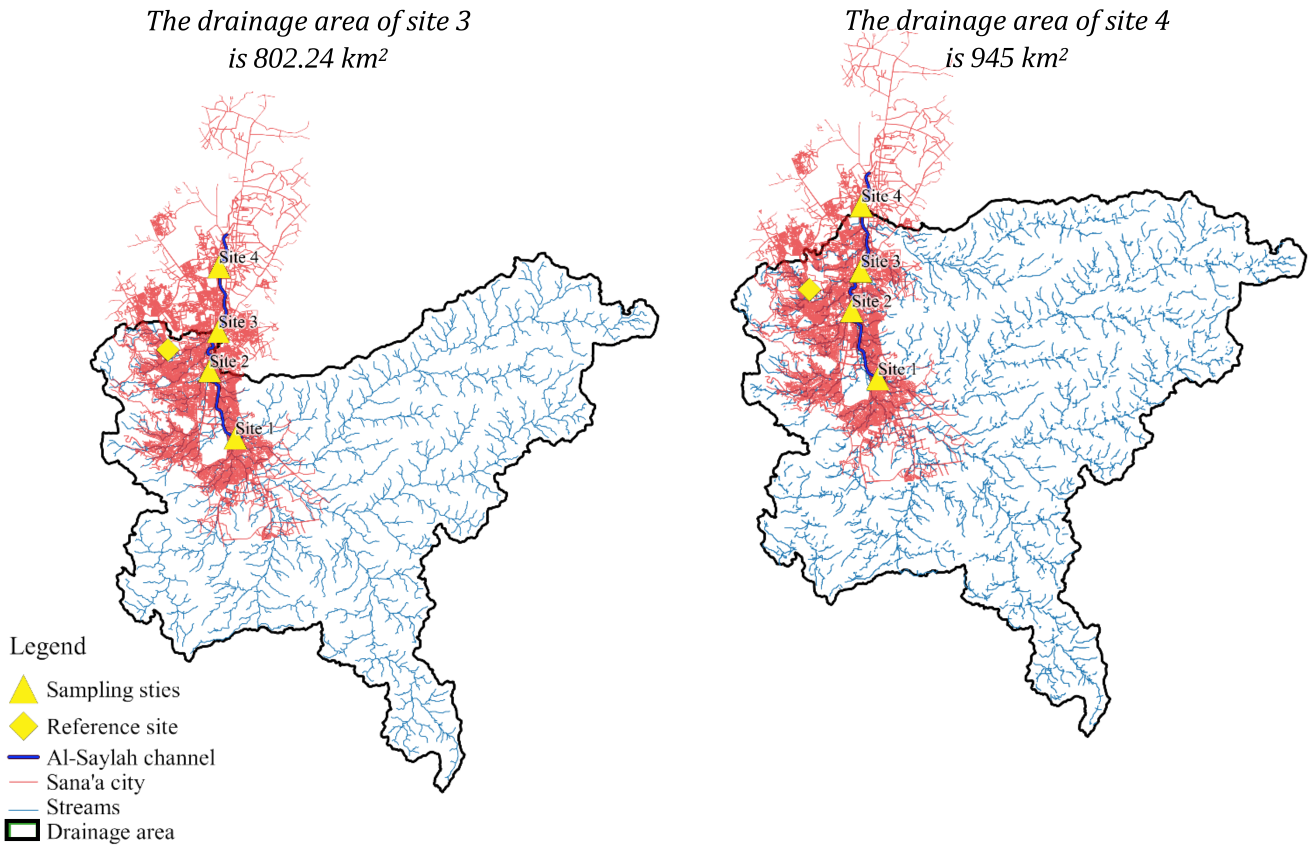

Figure (4.3-2): The drainage areas of four sampling sites

4.1.3 Chemical Oxygen Demand (COD)

The mean concentrations of COD in the four sites exceeded the maximum recommended value of the Yemeni Wastewater Reuse Standard for irrigation (500 mg/l), as shown in figure (4.4).

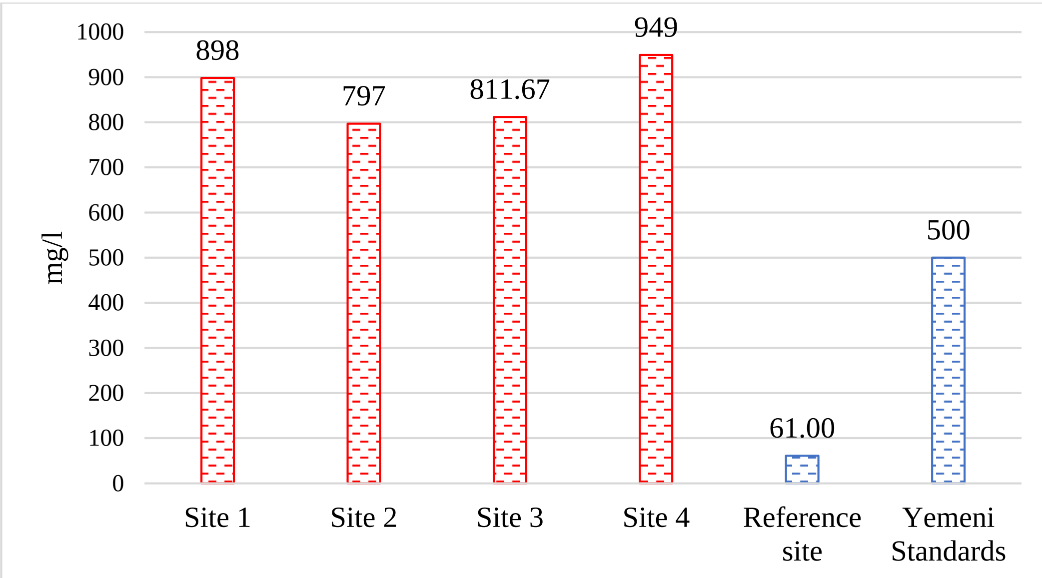

Figure (4.4): The mean values of COD in four sites and reference site

The mean values of COD in the four sites were higher than the reference site due to the nonpoint source pollutants that are scattered in the city, such as animal waste (dogs, cats, etc.), sewers overflows, and solid waste. Approximately seventy thousand stray dogs live in the city, according to the statement of a general director of spraying and fighting stray dogs in Sana'a capital municipality to the Al-Hawyah Channel[4] on April 2, 2019. They defecate on the streets, and their excrements are spilled away during the rainfalls. The municipality of Sana’a city was unable to fight the increasing number of stray dogs due to the lack of financial resources, particularly during the ongoing war in Yemen.

[4] Yemeni non-governmental satellite TV channel

Moreover, raw wastewater from sewer overflow can mix with stormwater runoff. During the research period, the researcher observed overflows in some sewage networks during the rainfalls, as shown in figures (4.5), (4.6) and (4.7).

Figure (4.5): The overflow of the sewage system in the Ma'ain District in Sana'a city

Figure (4.6): The overflow of the sewage system in the Al-Saylah channel close to the old Sana'a city

Figure (4.7): Overflow of the sewage system and mix up with runoff in Shuob region (Social Media Platform 2019)

Nonpoint source pollutions of COD most probably originate from sewers directed into stormwater drainage system as happened in Al-Sonainah zone in the west of Sanaa city. It is evident that residents have connected the sanitation outlets of their homes illegally to the stormwater drainage system due to the absence of sewage serves in this region. It is worth to mention, that the percent coverage of sewerage networks across Sana'a city lies at about 48% (Merghem, et al. 2016).

It is estimated that the percentage of organic matter in municipal solid wastes in Yemen is 65% (GIZ 2014). The solid waste management in Yemen is a major concern due to the lack of financial resources on the war crisis, where it is estimated that urban and rural municipal waste generated less than 0.6 kg/person/day (Kaza, et al. 2018). As the presence of this solid waste in the streets and drainage channels of rainwater that will affect the quality of stormwater runoff with the nutrient pollution.

It is observed that there are places in the drainage channels of rainwater became a garbage dump, and also filled with sediments due to the absence of maintenance, as shown in figures (4.8) and (4.9). The higher COD levels indicate a greater amount of oxidizable organic material in stormwater runoff, which will decrease dissolved oxygen (DO) levels. A decline in DO can lead to anaerobic conditions, which is deleterious to aquatic life forms (Gunawardena, et al. 2018).

Figure (4.8): Wastes and sediments in Al-Saylah channel in Al-Sabeen district

Figure (4.9): Wastes and sediments in rainwater channel in Ma'ain district

4.1.4 Nitrite, Nitrate, and Orthophosphate (NO_2, NO_3, and PO_4^{3-})

Phosphorus and Nitrogen compounds are the most important nutrients and are relatively abundant in urban stormwater runoff (Khwanboonbumpen 2006). The analysis demonstrates that all mean values of NO_2, NO_3, and PO_4^{3-} concentrations did not exceed Yemeni and FAO standards for wastewater reuse for irrigation, as shown in figure (4.10).

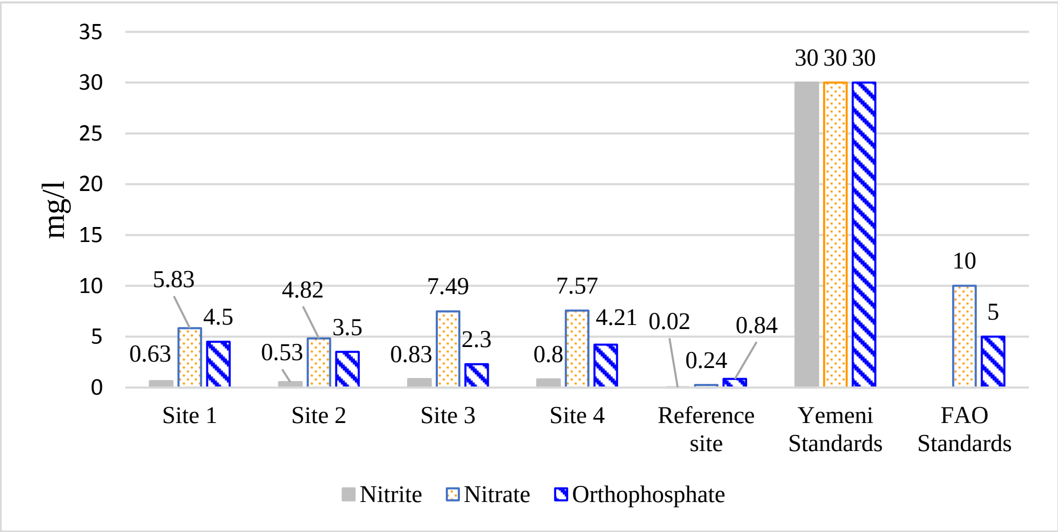

Figure (4.10): The mean values of NO_2, NO_3, PO_4^{3-} in the four sites and reference site

From table (4.1) shows that all concentrations of PO_4^{3-} exceeded the permissible limit of 0.005 mg/l to prevent eutrophication in water bodies (Huo, et al. 2013). When theses stormwater runoffs are harvested in the retention ponds in the city, these ponds will be exposed to excess the nutrients pollution that lead to abundant plant growth in these ponds, which in turn can decrease dissolved oxygen due to microbial degradation on death and decay of the plants.

The phenomenon resulting from nutrient enrichment is referred to as eutrophication. The sources of PO_4^{3-}, NO_2, and NO_3 in stormwater runoff samples may come from fertilizers by stormwater runoff that were used in agriculture lands at sub-basins. Also, many nonpoint source pollutants for nutrients are spared at impervious surfaces at the city such as solid wastes, sewer overflows, and atmospheric deposition.

Merghem et al. (2016) stated that the mean influent of NO_3 and PO_4 in raw wastewater of the Wastewater Treatment Plant (WWTP) in Sana'a city are 281 and 87 mg/l, respectively. Also, during field visits to stormwater retention ponds in the city of Sana'a on June 13, 2019, eutrophication was observed in some of these ponds, as shown in figures (4.11) and (4.12).

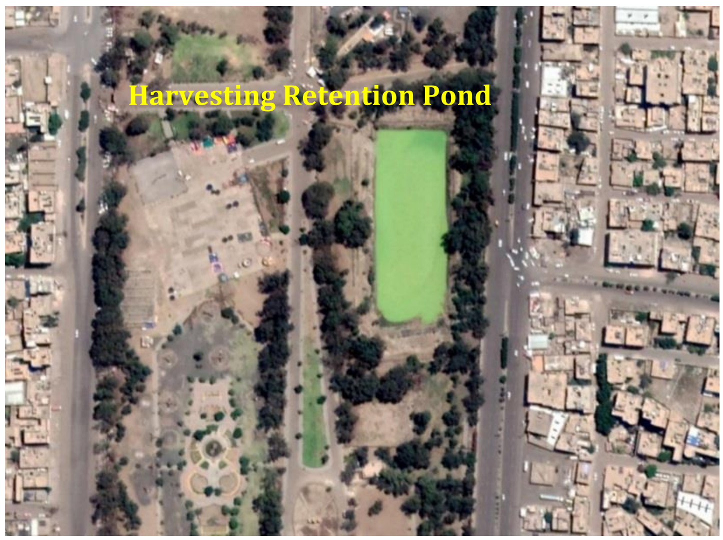

Figure (4.11): Eutrophication in the stormwater retention pond inter Revolution Park, Sana’a city (Google Earth)

Figure (4.12): Eutrophication in the stormwater retention pond in the Al-Rawdah region, Sana’a city (Google Earth)

4.1.5 Heavy Metals (Zn, Cu, Pb, Ni, and Cr)

The mean values of Zn, Cu, Cr exceeded the Yemeni and FAO wastewater reuse standard for irrigation, while the Pb and Ni did not, see figures (4.13) and (4.14).

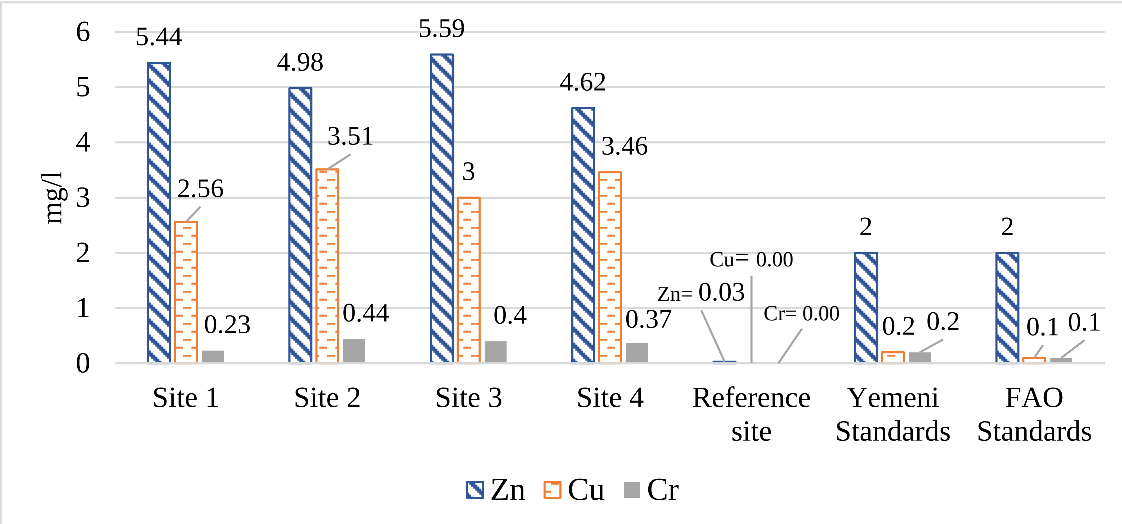

Figure (4.13): The mean values of Zn, Cu, and Cr in four sites and reference site

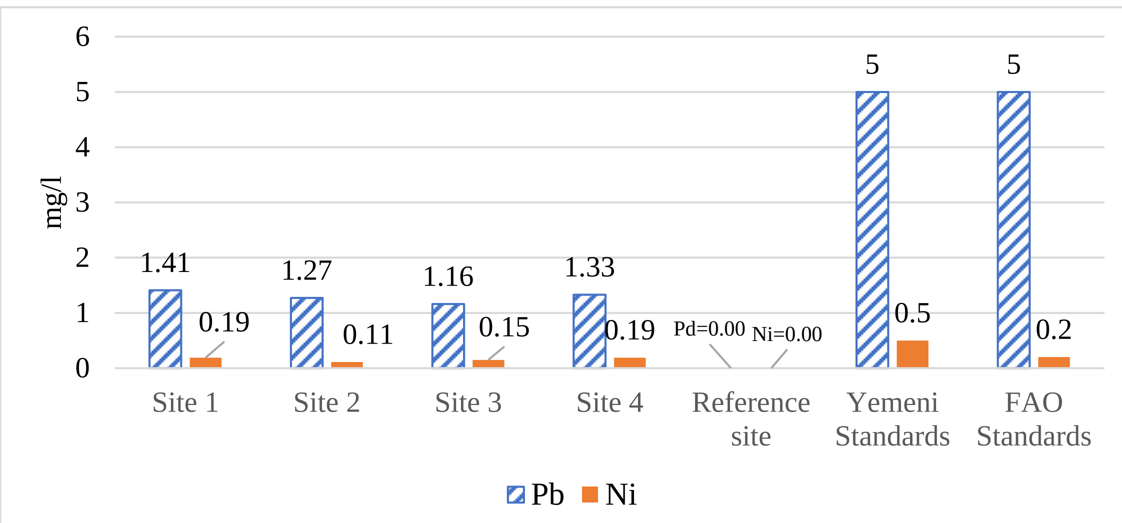

Figure (4.14): The mean values of Pb and Ni in four sites samples and reference site

When comparing the results of heavy metals between the four sites with the reference site it is unquestionable that the urban environment is adversily affected by a variety of anthropogenic activities that introduce numerous pollutants to the water environment.

Potential sources of heavy metals in stormwater runoff in Sana'a city are atmospheric deposition, intensity traffic, sewer overflows, and weathering of structures. Gupta (2019) stated that the EPA in United Stated indicated that potential sources of heavy metals in urban stormwater such as Pb, Cu, Cr, Ni, and Zn could mainly be from road traffic such as fuel exhaust, brake pad wear, tire wear, engine wear, and engine oil.

Furthermore, the numbers of vehicles in Sana’a city are estimated at 450,000, according to the Sana’a Traffic Department 2019. These vehicles can create heavy metal pollution and deposit on the road surfaces in Sana'a city by the exhaust of diesel and petrol, corrosion of metallic parts, engine wear, tire, and brake pad wear due to vehicular movement.

Table (4.2) indicates the common sources of heavy metals in stormwater runoff due to traffic activities and their effects on human health (Bakr, Fu and Hedeen 2020).

Table (4.2): The sources of heavy metals in stormwater runoff and their effects on human health (Bakr, Fu and Hedeen 2020)

Pollutant	**Source**	**Effect on human health**
Chromium	Metal plating, moving engine parts, break lining wear	Acute toxicity at high concentrations or continuous exposure
Lead	Bearing and tire wear, lubricating oil and grease	Acute toxicity
Copper	Metal plating, bearing and bushing wear, moving engine parts, break lining wear, and maintenance operations	Acute toxicity at high concentrations or continuous exposure
Zinc	Tire wear, motor oil	Acute toxicity at high concentrations or continuous exposure
Nickel	Diesel fuel and gasoline exhaust, lubricating oil, metal plating, bushing wear, break lining wear and asphalt paving.	Cancer and pulmonary diseases

As reported by Drozdova, et al. (2018), the population growth and the associated human activities, such as industry and household activities, lead to an increase in the content of hazardous elements in wastewater. Therefore, urbanized areas are an important pathway for metals to the environment. The sanitary sewer overflow in Sana'a city is one of the potential sources of heavy metals in stormwater runoff. Merghem, et al (2016) proved that the mean influent of Zn, Cu, Pb, Ni, and Cr of the WWTP in Sana'a city is less than 1 mg/l, pinpointing to that the origin of most heavy metals found in raw sewage from the city is particularly industrial oils uses, hydrocarbons, pesticides, photo labs, etc.

Moreover, according to Drozdova, et al. (2018), the main source of Cr and Ni from household is stainless steel and the process of cleaning metal cookware, and the corrosion, plumbing-galvanized materials, UV absorbent agents and health supplements are also important sources of Zn. Also, Drozdova stated the main sources of Zn in domestic wastewater are food, tap water, laundry detergents, and personal care products like toothpaste, shampoo, and deodorants.

4.1.6 Fecal coliform (FC)

The fallow figure (4.15) shows the mean values of FC in the four sites and reference sites.

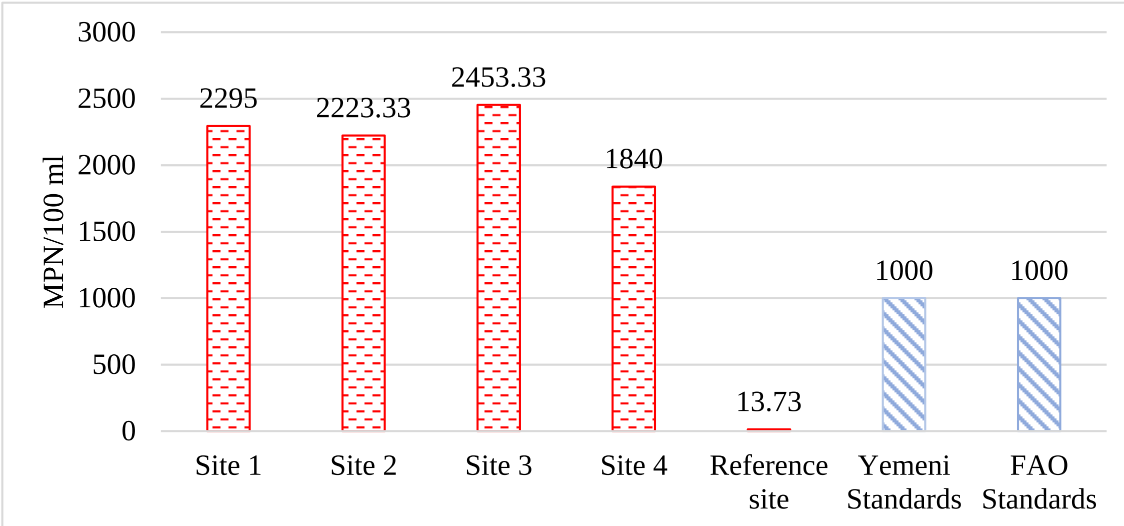

Figure (4.15): The mean values of FC in four sites and reference site

The stormwater runoff samples contained fecal coliforms. Their presence in stormwater runoff was serious because they cause diseases to humans and indicated that stormwater runoff had been polluted by sewage or animal wastes containing other diseases-causing microorganisms. Besides, fecal Coliforms generally indicate the presence of other disease-causing bacteria, such as those that cause typhoid, dysentery, hepatitis A, and cholera.

Figure (4.15) shows the mean values of fecal coliform densities in the four sites that were exceeded the Yemeni and FAO wastewater reuse standards for irrigation. Comparing the analysis results of fecal coliform in the four sites to the references site shows that urbanization influences the quality of stormwater runoff in Sana’a city.

The Potential sources of fecal coliform that affected the quality of stormwater runoff in Sana'a city are animal faeces (dogs, cats, etc.). Also, the sanitary sewer overflow in Sana'a city is one of the potential sources of fecal coliform. Al-Nozaily, Radhwan and Salah (2006) indicated that FC in raw wastewater in WWTP in Sana’a city exceeded 2400 MPN/100ml.

4.2 The role of governmental institutions to mitigate stormwater runoff pollutions

Government institutions in Sana’a city have to concern about the importance of managing stormwater pollution in order to protect the critical environmental values of receiving waters and benefit from stormwater runoff as an alternative source that can cover the growing need for water, especially by farmers.

The analysis results of stormwater samples showed that the concentrations of COD, Zn, Cu, Cr, and FC exceeded the Yemeni wastewater reuse standard for irrigation. Also, the analysis results for COD, Zn, Cu, Cr, and FC exceeded the FAO standards for irrigation wastewater reuse standard. The governmental institutions of Sana'a dealt with the stormwater runoff from the perspective of its quantity through the construction of Al-Saylah channel to protect the city from flood disasters. Also, four stormwater retention ponds were constructed beside the Al-Saylah channel (figure 4.16) for the same reason.

These ponds are used by farmers who are surrounding these ponds. The types of all harvesting ponds in Sana’a city are retention ponds used to promote infiltration, recharge the shallow aquifer, and decrease flooding during storm events.

On the other hand, NWRA Sana’a branch has tested the quality of the retention pond water at Al-Sabeen district, Sana’a city. Concentrations of Zn and Mn were at 2.55 and 0.327 mg/l, which exceeded the Yemeni and FAO standards of irrigation wastewater reuse. It is not straightforward to evaluate these ponds' water quality to find solutions to treat and mitigate the stormwater pollutants because there is insufficient data on their water quality for at least one year.

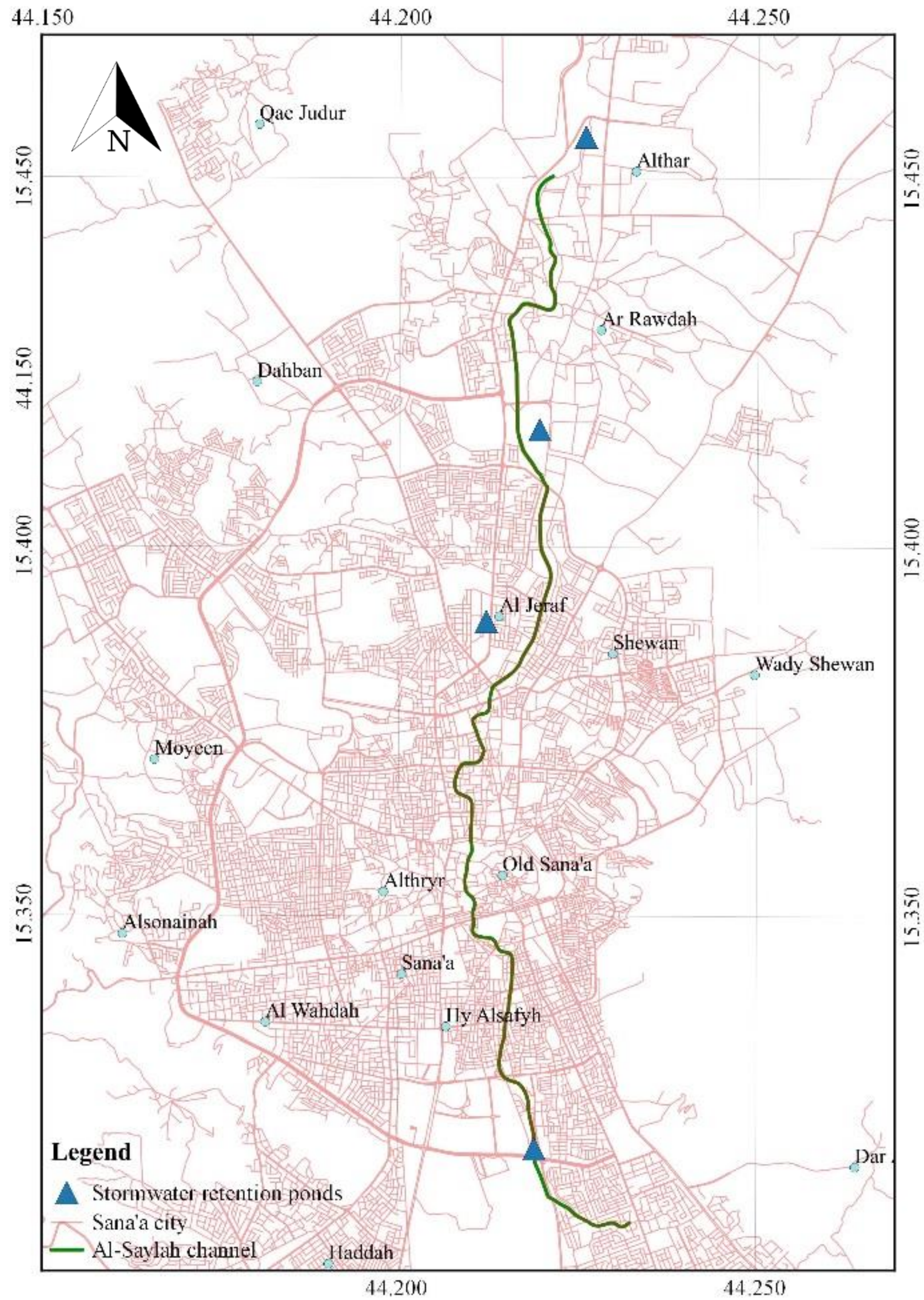

Figure (4.16): Locations of stormwater retention ponds in Sana'a city

Actually, the responsibility to protect water resources from all forms of pollution rests with the Ministry of Water and Environment. Moreover, stakeholders should be involved when choosing the best management practices (BMPs) to mitigate pollution sources and manage stormwater runoff to obtain the best results as confirmed by Steinman, Isely and Thompson (2015) and Kaplowitz and Lupi (2012). There are different kinds of stormwater pollution, and there are different techniques and technologies to treat stormwater pollution.

The storm water treatment is the action of capturing pollutants and contaminants from surface water runoff before reaching a water body, and the treatment measures are considered non-structural and structural measures. The non-structural measures do not involve fixed permanent facilities but entail regulations and economic instruments for changing stakeholder behavior about pollutant generation. The structural measures are permanent facilities to capture or divert pollutants that are transported by stormwater.

The measures of storm water treatment promote pollutant removal or mitigation through physical, chemical, and biological processes. Use of non-structural and structural measures in stormwater treatment is contextualized by using a range of terms across the world. For instance, in the USA, Best Management Practices (BMPs) is the term commonly used to refer to strategy to protect the urban water environment (Lee, et al. 2012).

Rainwater is the only renewable source in the Sana'a basin; Water resources in this basin are scarce; the treatment cost increases for a stormwater runoff with the increasing of pollutants degree according to the user (Erickson, Weiss and Gulliver 2013).

Therefore, it is possible to follow the steps below to harvest stormwater runoff with the lowest possible degree of pollution by taking the necessary measures to treat stormwater runoff from pollutants according to who will benefit from this water.

4.2.1 Harvesting stormwater runoff in sub-basins

Several studies have stated that cities' urbanization is a threat source for water resources due to anthropogenic activities (Hwang, et al. 2016, Yang and Toor 2017, Gupta 2019). There are sub-basins in the southern part of the Sana'a basin (Figure 3.3), and agricultural lands are spread in these basins. Whereas, the end of the streams of these sub-basins flows to Sana'a city. It is logical to harvest stormwater runoff of these sub-basins within the sub-basins' catchment areas to prevent polluted stormwater runoff entering Sana'a city and accumulating there, causing severe harm to the entire ecosystem.

4.2.2 Harvesting stormwater runoff in Sana’a city

Rainfall in Sana’a city and stormwater runoff from the sub-basins are exposed to a greater amount of pollutants due to human activities. As previously mentioned, four stormwater retention ponds were constructed in the city. Their water quality has not been studied in depth. However, through an examination on April 20, 2019 (one test) by NWRA, Sana'a Branch, the retention pond in Al-Sabeen district proved to be contaminated with heavy metals. Urgent action needs to be taken by the Yemeni water sectors for proper treatment according to who will benefit from this water.

4.2.3 Rooftop rain water harvesting

Testing the rainwater taken from the reference site (rooftop of the Faculty of Engineering at Sana’a University) demonstrated a good quality. The amount of rainwater that can be harvested annually from rooftops of building in Sana’a city is estimated at 11.3 Mm^3 (Salleh and Taher 2012). Thus, harvesting rainwater from the roofs of buildings is way to benefit from rainfall in Sana’a city and at the Sana'a basin level. Therefore, governmental and non-governmental agencies must support and encourage citizens to harvest rainwater.

4.2.4 Stormwater runoff treatment steps

Stormwater runoff in Sana'a city areas must be treated before storage in harvesting facilities. The stormwater treatment stages can pass to three steps based on the degree of contamination by pollutants as mentioned in table (4.3).

Table (4.3): Stages of the treatment of stormwater pollution (Melbourne Water 2019, Erickson, Weiss and Gulliver 2013)

Treatment	Processes	Pollutants
Primary treatment	▪ Physical screening ▪ Rapid sedimentation	▪ Gross pollutants ▪ Coarse sediment
Secondary treatment	▪ Fine particle sedimentation ▪ Filtration techniques	▪ Fine sediment ▪ Attached pollutants
Tertiary treatment	▪ Enhanced sedimentation and filtration ▪ Biological uptake ▪ Absorption onto sediments	▪ Nutrients ▪ Dissolved metals

The following steps can be used to treat and mitigate stormwater pollution in retention ponds in Sana'a city and other places in the Sana'a Basin:

4.2.4.1 Gross Pollutants Traps (Primary treatment)

Gross Pollutant Trap (GPT) is a method for removing solids conveyed by runoff that are typically greater than 5 millimeters, and debris that is larger than 5 mm defines as gross pollutants as mentioned by the Government of South Australia (2018). Several different types of GPTs are used for stormwater treatment, where every GPT has different design specifications with specific performance ability in trapping gross pollutants. So, the primary treatment is necessary for solid waste spilled into the ponds. In Sana'a city, all stormwater retention ponds are missing this type of treatment.

4.2.4.2 Retention ponds (Secondary treatment)

Retention ponds retain and not release water into a waterway. Retention ponds allow the infiltration of stormwater and recharge the shallow aquifer. Consequently, this pond provides downstream protection and flood control by attenuating peak flow and reducing runoff volume. The primary mechanism of pollutant removal in retention ponds is by the physical settling of suspended solids, including particle-bound pollutants (Amina and Kumud, 2014).

All stormwater retention ponds in Sana'a city lack this treatment for the uncontrolled stormwater runoffs during the sedimentation period. Sufficient time for sedimentation is not given between consecutive rainfall events, as shown in figure (4.17), (4.18), and (4.19).

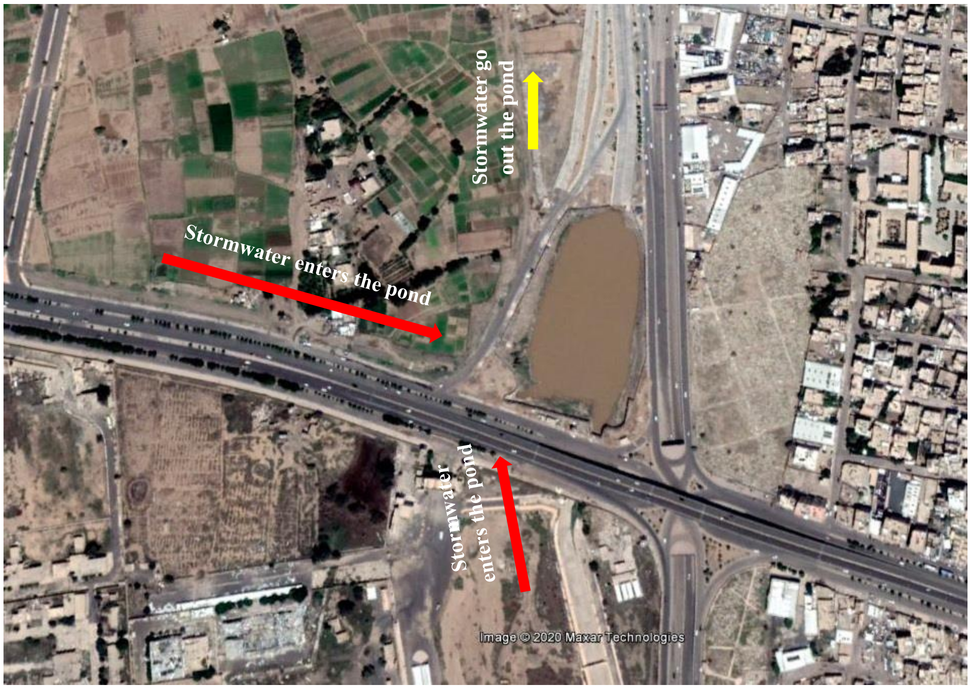

Figure (4.17): Retention pond in Al-Sabeen district (Google Earth)

Figure (4.18): The retention pond of Al-Sabeen district filled with stormwater runoff

Figure (4.19): Concrete channels to drain rainwater pour into the stormwater retention pond in Al- Sabeen district

4.2.4.3 Floating treatment wetlands (Tertiary treatment)

Borne, et al. (2015) defines the Floating Treatment Wetland (FTW) as an innovative device that can be installed on the surface of a stormwater retention pond to improve pollutant removal efficiency. FTW is composed of a porous floating mat planted with emergent macrophytes. Plant roots grow through the mat and are suspended in the water column underneath, as shown in figure (4.20). FTWs are suitable for new construction or retrofit installation in existing stormwater ponds. These systems can enhance the removal of pollutants from the water column such as nutrients and heavy metals.

Schück (2019) identified two types of plants called Carex pseudocyperus and Carex riparian that can reduce the concentration of heavy metals by FTWs. Moreover, Plant of Iris pseudacorus can reduce nutrient removal by FTWs (Keizer-Vlek, et al. 2014). This treatment technology is eventually suitable for treating and mitigating stormwater pollution in retention ponds in Sana'a city.

Figure (4.20): Floating Treatment Wetlands **Invalid source specified.**

4.3 The legal and institutional aspects of stormwater management

With the aggravating urbanization effects on the quantity and quality of stormwater runoff, many countries became imperative to produce legislation to conserve water sources and the ecosystem. For instance, in 1987, the U.S Congress released Section 402 of the Clean Water Act (CWA), bringing stormwater control into the National Pollutant Discharge Elimination System (NPDES) program.

In Yemen, the Water Law is the legislative and institutional back-up for the country's water resource management. Article 7 of the Water Law indicates that "Water resources shall be developed and regulated by the provisions of this Law and its executive procedures and in light of a water strategy proposed by the MWE based on the presentation by NWRA, which shall be issued by a decree of the Cabinet, and in accordance with the sectoral policies, plans and programs emanating from this strategy".

The Yemeni Parliament approved the Yemeni Water Law Article No. 33 in 2002, which was amended in 2006. It gave large power to water users associations in regulating the water use within their geographical areas and also entails specific operational regulations for the functioning of Basin Committees. The law is laid out in eight chapters, some with sub-sections.

The Yemeni Water Law No. 41 for the year 2006 expresses the principles of integrated water resources management. Article 41 of the law stipulates that it refers to harvest rainwater runoff to benefit from it and develop water resources. Article 54 of the law stipulates that MWE has the power to protect water resources against pollution and maintain water quality. Article 54-2 of the law stipulates that it is forbidden to throw the wastes into the stormwater streams that will affect water resource quality. Article 61 of the law indicates to manage flood to protect watersheds and properties.

In Yemen, no specific regulations for urban stormwater runoff quality discharged to water bodies. Therefore, the analysis results of stormwater runoff samples were compared to the permitted limit for irrigation wastewater reuse by Yemeni and FAO standards (Taebi and Droste 2004).

The Yemeni Water Law encourages harvesting rainwater and protecting these water sources from pollutants through what was mentioned above. Moreover, the Yemeni water law addresses pollutants in general, but not nonpoint sources pollutants in specific. Thus, the MWE should have programs to mitigate and control the nonpoint sources' pollution in urban settings.

4.4 Stormwater and agriculture

To better understand how stormwater quality is considered as an important factor in agriculture, a FGD was conducted with farmers who used stormwater retention ponds (see annex 5). The farmers showed their satisfaction with irrigating their fields using harvested stormwater runoff from the retention pond near to their farms in Al-Sabeen district during the rainy season.

The farmers also indicated that the Sana'a City Municipality irrigate streets' trees from these stormwater retention ponds. The farmers also shared their experience on the economic benefits of using harvesting stormwater ponds as one of the water sources that are available to irrigate their agricultural lands during the rainy season. Most farmers indicated that irrigation of their agricultural lands from the harvesting pond is more economical than irrigation by the artesian wells. “When I water my farm from the pond, I only need 120 liters of petrol to pump the water. On the other hand, if I water my farm from the artesian well, I need two and a half barrels (500 liters) of diesel.” A farmer said.

The claims of farmers during FGDs proved the high contamination of retention ponds with solid waste. Where a farmer said, "we want from the government of Sana'a city to solve the problem of throwing garbage bags into the rainwater drainage channels.". They signalized that the best way to take advantage of stormwater runoff is through harvesting stormwater in ponds. The farmers indicated that they had given up ownership of the land on which the stormwater retention pond was constructed in Al- Sabeen District. So, the farmers mentioned that the government in Sana'a city has to clean rainwater drainage channels from solid waste and prevent people from throwing waste into them.

Chapter 5: Conclusions and Recommendations

5.1 Conclusions

This research studied the quality of stormwater runoff in Sana’a city from the perspective of IWRM. The conclusions drawn from the study can be summarized as follows:

- The quality of stormwater is not a standalone matter but is closely connected to environmental, socio-economic, and institutional aspects.
- The maximum concentrations of pH, TSS, COD, FC, NO_3, NO_2, PO_4^{3-}, Z, Cu, Pb, Ni, and Cr were 6.9 moles per liter, 3720 mg/l, 1389 mg/l, 2990 mg/l, 12.34 mg/l, 1.66 mg/l, 5.5 mg/l, 8.22 mg/l, 4.71 mg/l, 1.62 mg/l, 0.23 mg/l, and 0.91 mg/l, respectively.
- The order of the maximum concentration of the heavy metals that were appeared in stormwater runoff samples were Zn > Cu > Pb > Cr > Ni.
- The stormwater samples’ analysis results for TSS, COD, FC, Zn, Cu, and Cr did not comply with Yemeni and FAO standards for irrigation water.
- The results of stormwater samples' tests showed the exposure of stormwater runoff to nonpoint source pollution inside the city due to the effects of urbanization and human activities.
- There are no specific regulations for urban stormwater runoff quality discharged to water bodies, and the Yemeni water law did not address nonpoint sources pollutants.
- The study's findings show that the farmers use the water of stormwater retention ponds to irrigate their farmers during the rainy seasons, and they save about 70 % of diesel quantities.
- In the design of stormwater retention ponds did not consider the treatments and mitigation of stormwater pollution.

- There was a gap in the coordination mechanism between government institutions that are related to stormwater management in Sana'a city. Whereas, stormwater management includes controlling flooding, reducing erosion, and improving water quality.
- There are many ways to treat and mitigate stormwater pollution in urban and rural areas, such as gross pollutant traps, retention ponds, and floating treatment wetlands
- The findings of the study show that it is possible to solve the problems that are related to stormwater management based on the IWRM perspective that allows water institution sectors to work under one umbrella to protect water resources and maximize the benefit from rainwater that is the only renewable source of water in Sana’a Basin.

5.2 Recommendations

In order to benefit from stormwater runoff as an alternative source that can cover the growing water demand in Sana’a city. the researcher extracted recommendations that can be implemented to protect the water environment and surface water bodies in Sana’a city, and this can be achieved by the following:

- Harvesting stormwater runoff in the sub-basins before these waters enter Sana'a city and being exposed to pollution.
- Harvesting rainwater from the rooftop of buildings in Sana’a city to maximize the benefit from rainwater.
- The MWE, the Sana’a Water and Sanitation Local Corporation, and the Sana'a City Municipality have to take immediate measures to clean and maintain the rain water drainage network from pollutant sources, especially before the rainy season to prevent any clogging.
- In the design of stormwater retention ponds must consider the treatment measures of stormwater pollution, by MWE and the Sana'a City Municipality.
- Sewers connected to stormwater drainage networks must be disconnected. Appropriate solutions should be sought to discharge sewage, by the Sana’a Water and Sanitation Local Corporation
- Drainage networks of stormwater runoff should be constructed in the areas that do not have these drainage systems, by MWE and the Sana'a City Municipality.
- Implementing the sewerage networks in the areas that do not have these sewerage networks because the rate of sewerage networks, by the Sana’a Water and Sanitation Local Corporation

- NWRA have to test water of stormwater retention ponds and Al-Saylah channel periodically in Sana’a to ensure that water conforms to the Yemeni and FAO standards and to build a database that can be used by researchers to design and choose the methods of mitigation and treatment of stormwater runoff pollutants.
- NWRA should intensify awareness programs to the public that aim to substantially change human behavior to preserve the environment from nonpoint source pollutants in urban and rural areas.
- Formulate a complete intensive package of training programs towards IWRM components for water institution sectors, by WEC in Sana'a university.
- Governmental and non-governmental water institutions and research centers have to extend urban and rural stormwater studies and apply more studies to get enough data to define the best management practices for minimizing stormwater runoff pollutants and maximizing the benefit from stormwater runoff. Also, examining the parameters that are related to stormwater quality and are not tested in this the study.
- Install stations to measure the discharge of stormwater runoff in sub-basins and Al-Saylah channel, which will be useful for researchers in stormwater management fields in urban and rural areas, by NWRA.
- Water problems that are related to the management of urban stormwater runoff and the nonpoint source pollution have to be solved based on the IWRM perspective that allows all the water institutions to work under one umbrella to protect water resources and maximize the benefits of rainwater that is the only renewable source of water.

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Annexes

1-Rainfall data in Sana'a city during the tests of stormwater runoff quality

Table (A1-1): data of rainfalls[5]

Date of Rainfall	Rainfall Stations mm/ day		
	Al-Msbahi	Al-Sonainah	Sana'a Branch of NWRA
3/16/19	**12.95**	**12.70**	**11.6**
3/17/19	0.00	0.00	0.2
3/18/19	0.00	0.00	0
3/19/19	0.00	0.00	0
3/20/19	4.32	0.00	0
3/21/19	0.25	0.00	0
3/22/19	0.00	0.00	0
3/23/19	0.00	0.00	0
3/24/19	0.00	0.00	0
3/25/19	0.00	0.00	0
3/26/19	0.00	0.00	0
3/27/19	6.86	0.00	0.6
3/28/19	0.25	0.00	0
3/29/19	0.00	0.00	0
3/30/19	0.00	8.89	0.2
3/31/19	0.00	0.00	0
4/1/19	0.00	0.00	0
4/2/19	0.51	0.00	0
4/3/19	0.00	0.00	0
4/4/19	4.57	0.76	0.2
4/5/19	0.00	4.57	1.6
4/6/19	9.91	0.00	0
4/7/19	0.00	0.25	0
4/8/19	0.00	0.00	0
4/9/19	0.25	0.00	0
4/10/19	0.00	1.27	0
4/11/19	**1.02**	**20.07**	**2.6**
4/12/19	0.00	0.00	0
4/13/19	0.00	0.00	0
4/14/19	0.00	0.00	0
4/15/19	0.00	0.00	2.6
4/16/19	4.83	0.00	0.2
4/17/19	0.00	0.51	4.4
4/18/19	**20.32**	**61.98**	**13.4**

[5] These data were obtained from NWRA - Sana'a Branch

2- The analysis results (physicochemical and microbiological) of stormwater runoff samples for three events in Sana'a city

Table (A2-1): Stormwater runoff quality parameters, site 1
(X = 44.228073, Y= 15.308005)

No	Parameter	Unit	March 16, 2019	April 11, 2019[6]	April 18, 2019	Mean
1	pH	moles per liter	5.90	-	6.90	6.40
2	TSS	mg/liter	3520.00	-	4133.00	3826.50
3	COD	mg/liter	1161.00	-	635.00	898.00
4	NO_2	mg/liter	0.87	-	0.39	0.63
5	NO_3	mg/liter	6.26	-	5.39	5.83
6	Po_4^{-3}	mg/liter	3.50	-	5.50	4.50
7	Zn	mg/liter	8.22	-	2.66	5.44
8	Cu	mg/liter	3.01	-	2.11	2.56
9	Pb	mg/liter	1.51	-	1.31	1.41
10	Ni	mg/liter	0.23	-	0.14	0.19
11	Cr	mg/liter	0.14	-	0.31	0.23
12	FC	MPN/100 ml	1600.00	-	2990.00	2295.00

Table (A2-2): Tests' results of stormwater runoff quality on site 2
(X = 44.209239, Y = 15.354924)

No	Parameter	Unit	March 16, 2019	April 11, 2019	April 18, 2019	Mean
1	pH	moles per liter	5.6	6.7	6.8	6.37
2	TSS	mg/liter	3440	1000	1533	1991.00
3	COD	mg/liter	913	582	896	797.00
4	NO_2	mg/liter	0.59	0.48	0.53	0.53
5	NO_3	mg/liter	4.19	4.26	6	4.82
6	Po_4^{-3}	mg/liter	5.02	1.37	4.1	3.50
7	Zn	mg/liter	7.92	4.11	2.91	4.98
8	Cu	mg/liter	4.41	3.11	3	3.51
9	Pb	mg/liter	1.62	1.23	0.95	1.27
10	Ni	mg/liter	0.17	0.08	0.08	0.11
11	Cr	mg/liter	0.18	0.91	0.22	0.44
12	FC	MPN/100 ml	2070	1610	2990	2223.33

[6] Because the intensity of rainfall is very low on the areas around the sampling site 1 Sana'a city, there was no stormwater runoff in Al-Saylah Channel at this site.

Table (A2-3): Tests' results of stormwater runoff quality on site 3
(X = 44.215458, Y = 15.382623)

No	Parameter	Unit	March 16, 2019	April 11, 2019	April 18, 2019	Mean
1	pH	moles per liter	5.6	6.9	6.7	6.40
2	TSS	mg/liter	3440	1100	3400	2646.67
3	COD	mg/liter	1389	374	672	811.67
4	NO_2	mg/liter	1.66	0.33	0.5	0.83
5	NO_3	mg/liter	12.34	4.84	5.3	7.49
6	Po_4^{-3}	mg/liter	2.92	1.62	2.35	2.30
7	Zn	mg/liter	8.7	4.95	3.11	5.59
8	Cu	mg/liter	3.93	2.62	2.45	3.00
9	Pb	mg/liter	1.46	1.01	1.01	1.16
10	Ni	mg/liter	0.22	0.06	0.16	0.15
11	Cr	mg/liter	0.33	0.72	0.16	0.40
12	FC	MPN/100 ml	2760	2415	2185	2453.33

Table (A2-4): Tests' results of stormwater runoff quality on site 4
(X = 44.215779, Y = 15.427928)

No	Parameter	Unit	March 16, 2019	April 11, 2019[7]	April 18, 2019	Mean
1	pH	moles per liter	5.9	-	6.5	6.20
2	TSS	mg/liter	3720	-	2266	2993.00
3	COD	mg/liter	1038	-	860	949.00
4	NO_2	mg/liter	1.21	-	0.39	0.80
5	NO_3	mg/liter	9.28	-	5.85	7.57
6	Po_4^{-3}	mg/liter	5.46	-	2.95	4.21
7	Zn	mg/liter	5.61	-	3.62	4.62
8	Cu	mg/liter	4.71	-	2.21	3.46
9	Pb	mg/liter	1.32	-	1.34	1.33
10	Ni	mg/liter	0.18	-	0.2	0.19
11	Cr	mg/liter	0.22	-	0.52	0.37
12	FC	MPN/100 ml	2300	-	1380	1840.00

[7] Because the intensity of rainfall is very low on the areas around the sampling site 2 Sana'a city, there was no stormwater runoff in Al-Saylah Channel at this site.

Table (A2-5): Tests' results of rainwater on the building rooftop of the faculty of engineering at Sana'a University as reference site
(X = 44.179017, Y = 15.369472)

No	Parameter	Unit	March 16, 2019	April 11, 2019	April 18, 2019	Mean
1	pH	moles per liter	6.2	6.8	6.3	6.43
2	TSS	mg/liter	780	337	100	405.67
3	COD	mg/liter	76	62	45	61.00
4	NO_2	mg/liter	0.05	0.01	0	0.02
5	NO_3	mg/liter	0.55	0.15	0.02	0.24
6	Po_4^{-3}	mg/liter	0.81	0.79	0.92	0.84
7	Zn	mg/liter	0.1	0	0	0.03
8	Cu	mg/liter	0.01	0	0	0.00
9	Pb	mg/liter	0	0	0	0.00
10	Ni	mg/liter	0	0	0	0.00
11	Cr	mg/liter	0.01	0	0	0.00
12	FC	MPN/100 ml	16	16	9.2	13.73

Table (A2-4): The mean values of tests' results for four sampling sites and reference site

No	Parameter	Unit	Site 1	Site 2	Site 3	Site 4	Reference site
1	pH	moles per liter	6.40	6.37	6.40	6.20	6.43
2	TSS	mg/liter	3826.50	1991.00	2646.67	2993.00	405.67
3	COD	mg/liter	898.00	797.00	811.67	949.00	61.00
4	No_2	mg/liter	0.63	0.53	0.83	0.80	0.02
5	NO_3	mg/liter	5.83	4.82	7.49	7.57	0.24
6	Po4-3	mg/liter	4.50	3.50	2.30	4.21	0.84
7	Zn	mg/liter	5.44	4.98	5.59	4.62	0.03
8	Cu	mg/liter	2.56	3.51	3.00	3.46	0.00
9	Pb	mg/liter	1.41	1.27	1.16	1.33	0.00
10	Ni	mg/liter	0.19	0.11	0.15	0.19	0.00
11	Cr	mg/liter	0.23	0.44	0.40	0.37	0.00
12	FC	MPN/100 ml	2295.00	2223.33	2453.33	1840.00	13.73

3- Yemeni and FAO standards for reuse wastewater for agricultural use

Table (A3-1): Yemeni standards for reuse wastewater for agricultural use

NO	Parameter	Unit	Yemeni standards (1999)
1	Potential of Hydrogen (pH)	moles per liter	6.5-8.5
2	Total Suspended Solid (TSS)	mg/liter	-
3	chemical oxygen demand (COD)	mg/liter	500
4	Nitrite (NO_2)	mg/liter	30
5	Nitrate (NO_3)	mg/liter	30
6	Orthophosphate (Po_4^{-3})	mg/liter	30
7	Zinc (Zn)	mg/liter	2
8	Copper (Cu)	mg/liter	0.2
9	Lead (Pb)	mg/liter	5
10	Nickel (Ni)	mg/liter	0.5
11	Chromium (Cr)	mg/liter	0.1
12	Fecal coliforms (FC)	MPN/100 ml	1000

Table (A3-2): FAO standards for reuse wastewater for agricultural use

NO	Parameter	Unit	FAO standards
1	Potential of Hydrogen (pH)	moles per liter	6.5-8.5
2	Total Suspended Solid (TSS)	mg/liter	-
3	chemical oxygen demand (COD)	mg/liter	-
4	Nitrite (NO_2)	mg/liter	.
5	Nitrate (NO_3)	mg/liter	10
6	Orthophosphate (Po_4^{-3})	mg/liter	5
7	Zinc (Zn)	mg/liter	2
8	Copper (Cu)	mg/liter	0.2
9	Lead (Pb)	mg/liter	5
10	Nickel (Ni)	mg/liter	0.2
11	Chromium (Cr)	mg/liter	0.1
12	Fecal coliforms (FC)	MPN/100 ml	$\leq$1000

4- Leading questions of focus group discussion

Topic: The Quality of Stormwater Runoff in Sana'a city from the Perspective of Integrated Water Resource Management

FGD rules

- No right or wrong answers, only differing points of opinion.
- We are recording, one person speaking at a time.
- You do not need to agree with others, but you must listen respectfully as others share their opinions.
- The role of researcher will be to guide the discussion

Leading questions

1) How have farmers benefited from integrated water resources management since this approach was applied in Sana'a Basin?
2) Do you know and how using stormwater runoff in general and in agricultural activities in specific in Sana'a city?
3) Are you economically benefiting from the use of stormwater runoff in agricultural activities? Explain, whether yes or no.
4) Have you noticed sometimes that stormwater harvested in the pond is polluted? If Yes, what did you see?
5) Do you know that stormwater runoff runs to the desert? How can we utilize this water source in the best way? And how to protect this from pollutants?

5- Farmers’ Answers on Questions of Focus Group Discussion

Table (A5-1): Question 1 of Focus Group Discussion

NO	Names of Farmers	Farmers’ Answers
1	Farmer No 1	The farmers have greatly benefited from the Sana’a Basin Project. The increase in the water supply has led to an increase in the agricultural crops, and it decreased the amount of diesel consumed which was very profitable for the farmers especially in these last few years since the diesel prices has been unstable and it’s limited availability from time to time due to the country’s condition. Moreover, we are grateful for the Sana’a Basin Project for directing us to irrigate crops through networks, fertilize crops through modern irrigation, and use greenhouses. About 80% of farmers in Al-Sabeen area are using modern irrigation networks except some potato farms because they need larger quantities of water in order to produce good crops that can be sold in the market.
2	Farmer No 2	We benefited a lot from the Sana’a Basin Project and similar projects because of their great role in guiding us to use modern irrigation methods. Because of the recent events in Yemen, had I not had an irrigation network, as well as the rain season helping fill the retention pond, it would have been hard keeping the crops irrigated.
3	Farmer No 3	My brother Abdullah, times change and science is developing, especially here in Yemen. We in a crisis after a crisis, and the merchants are following the needs of the people in every field. Modern irrigation networks and agriculture fertilizers are available, even though they can be expensive especially since our currency is collapsing. Experts are available from universities to provide their services to the farmers.
4	Farmer No 4	Farmers in the Sabeen area have no choice but to research, care and develop agriculture especially since it is their source of livelihood. Furthermore, the property prices in this area have drastically increased in the past few years; however, we cannot benefit from selling our properties because we have been forbidding since the previous president’s era up until this day because this area is a security zone. We have been allowed none other than to use our lands for agriculture and to build homes for ourselves.
5	Farmer No 5	Previously, organizations had benefited the farmers who are using the Sana’a basin in donating modern irrigation networks with 70% decrease in prices to encourage farmers to use

		modern irrigation networks in agriculture because of its benefit in preserving water and maintaining the land. Support for organizations is currently limited to training and capacity building only. All they have been doing is offering courses on how to irrigate and fertilize through modern irrigation networks, even though these courses have been available on the internet which makes their courses useless. Our products have more demand in the market since the crops that come from north Sana'a is irrigated using sewage water.

Table (A5-2): Question 2 of Focus Group Discussion

NO	Names of Farmers	Farmers' Answers
1	Farmer No 1	Previously, the pond was excavated to absorb the excess quantities of flood that caused problems in the area and to recharge the nearby wells. At the time, we did not care for the pond since the diesel prices were appropriate. However, after the beginning of the crises in Yemen since the Arab Spring, the diesel was limited and its price increased which forced us to buy diesel from the black market. In addition, during the rainy season which continues through the summer and autumn, we were able to make use of the water in the pond.
2	Farmer No 2	As Abdullah indicated, after the rise in diesel prices and diesel is available on the black markets, our farms were affected by the inability to pump sufficient water to irrigate crops. The farmers tend to irrigate their farms from the retention pond.
3	Farmer No 3	During the past year, the Sanaa city municipality prevented farmers from using pond water and protested that the water was owned by the government. Whereas the water trucks owned by the Agriculture Office use the pond water to irrigate ornamental trees in city. We did not remain silent on these procedures, and we contacted the Sanaa city municipality and protested these unacceptable actions from the government of city. Moreover, we told them that we waived the pond land for the sake for the establishment of this project where the ban lasted for about fifteen days, and then they allowed us up until this day to use the pond water for agriculture.
4	Farmer No 4	Commenting on the words of Mohammed Al-Mada'i, I want to say that Agriculture Office wants to reduce the amount of diesel that used to run their water trucks for transporting water from the harvesting pond in Rowdah region. The prevention was on the basis that the water would not be sufficient for both them and the farms in the Al-Sabeen region.
5	Farmer No 5	During the period of disagreement with Agriculture Office, they came out with the excuse that the water is not suitable for irrigation during the same days that the cholera disease was spread in Yemen and Sana'a. The Sana's governorate Water Authority was commissioned to examine the water, and they told us that there are no cholera bacteria in the water of the pond and that there are some elements found in higher amounts that what is allowed for the water to be used in agriculture. Furthermore, I know that this is the first and only time that the water quality of the pond has been tested, knowing that there

		are two artesian wells that are regularly tested during 2019 to make sure that the water is suitable to be sold for water trucks.

Table (A5-3): Question 3 of Focus Group Discussion

NO	Names of Farmers	Farmers' Answers
1	Farmer No 1	Definitely, all farmers benefit economically from the use of the pond water during the rainy season. When I water my farm from the pond, I only need 120 liters of petrol to pump the water. On the other hand, if I water my farm from the artesian well, I need 2 and a half barrels of diesel. There is a large difference between the two. Every farmer in the Sabeen area prefers to water from the pond when the stormwater runoff is available. In the past, stormwater runoff passed through our farms from the west, but after implementing the project that collects stormwater runoff from the areas of Biet Alafif, Sana, and haddah directly into the pond, we lost these stormwater runoffs that were directly watering our farms. But now, thank god, we do not lose the stormwater runoff because they accumulate in the pond and we now pump the water from the pond of irrigate our farms.
2	Farmer No 2	Yes, farmers benefit from the pond during rainy season. You know that we grow crops throughout the year, and we need a large amount of water. After the diesel prices increased, if we hadn't had the pond and solar power, we would have quitted farming. Even though solar power is expensive, a farmer can manage paying its cost.
3	Farmer No 3	The depth of our artesian wells reaches more than 600 meters, and the temperature of the water coming out of the well is hot, and it is necessary to cool this water because it will affect agricultural products. But the temperature of harvesting pond's water is normal. And you can irrigate during the night and day and run more than one pump, meaning that you are watering the land while you are satisfied and a short time.
4	Farmer No 4	Of course, there is a benefit from the pond; however, I think it needs to be expanded in order to feed the wells and suffice throughout the year. I asked the last organization that put up the fence to expand the pond.
5	Farmer No 5	Definitely, there is a benefit from the pond water. Water is necessary for agriculture, and the pond needs government capabilities to preserve it.

Table (A5-4): Question 4 of Focus Group Discussion

NO	Names of Farmers	Farmers' Answers
1	Farmer No 1	At the beginning of the rainy season, stormwater runoff entered into retention pond (Al-Sabeen region) is dirty, and garbage was transported by stormwater runoff from the upper areas (Qadisiyyah region) directly to the retention pond. Also, the rainwater drainage channel is filled with garbage bags, and there are no maintenance and cleaning works for this channel.
2	Farmer No 2	There is no disagreement that stormwater runoff in Sana'a city is cleaner than wastewater that comes out from the treatment plant in the north of Sana'a city, which is used to irrigate crops. And the quality of stormwater runoff is different from one stormwater runoff to another, and it is difficult to know when, and we want from the government of Sana'a city to solve the problem of throwing garbage bags into the rainwater drainage channels.
3	Farmer No 3	The agricultural areas surrounding the retention pond in the Al-Sbeen area are prohibited from buying and selling these lands by the government because it is adjacent to the area belonging to the Republic's presidency, and the investment in these lands is limited to agriculture activities. Therefore, the authorities in Sanaa's city must clean rainwater drainage channels from wastes, which reach a retention pond.
4	Farmer No 4	Sometimes stormwater runoff is clean, but sometimes we notice algae's appearance in the water because of food waste in the garbage bags that enter the retention pond with stormwater runoff, and it is known that no problem prevents irrigation with this water quality.
5	Farmer No 5	When the cholera problem arose, some organizations sprayed chemical material at these retention ponds for preventing the spread of malaria. And then a stormwater runoff is renewed during the rainy period. I see that there is no problem with the stormwater runoff cleaning. In rare cases, people living near the retention pond complain about the retention pond's smells during the night; this is due to the breakdown of garbage bags in the retention pond.

Table (A5-5): Question 5 of Focus Group Discussion

NO	Names of Farmers	Farmers' Answers
1	Farmer No 1	I think it reaches the desert when the amount of rainfall is heavy in Sanaa and its surroundings, but now farmers along the Sana'a Basin have used this water to irrigate agricultural lands. It must be to benefit from stormwater runoff by increasing the numbers of harvesting facilities in the Sana'a basin. The government in the Sana'a basin must compensate for owners of lands that are suitable sites for carrying out stormwater runoff harvesting facilities to irrigate agricultural areas, especially now, and Yemen is in a state of war and siege. We must preserve the rest of the farming lands in the city of Sana'a from converting them into an urban area (impervious surface), as the green areas in Al-Sabeen region. We have to protect water sources by applying the law to violators.
2	Farmer No 2	A person in the rainy season watches the amount of rainstorm water in the Al-Saylah channel, especially when it is raining heavily, and the level of stormwater runoff in the channel was at the top of the facility and along the length of the channel. You can imagine the amount of this water. The Sanaa City Municipality must submit its duty to clean the rainwater drainage channels continuously, especially before the rainy season, and to punish those who throw garbage bags in channels. Between January and April (a season in which rain does not fall in the city of Sana'a usually), it is assumed that the organizations working in cleaning the streets of Sanaa should clean the rainwater drainage channels, which will have a benefit in the cleanliness of rainstorm water inside the city.
3	Farmer No 3	When the land is saturated by rainwater, stormwater runoff reaches the desert. We are considered successful if we maintain these existing retention ponds and find ways to protect these ponds from pollution problems. The strange thing is that garbage dumpers are passing through streets to collect the municipals waste from specific locations, and the residents who live next to the rainwater drainage channels throw waste garbage in these channels instate the places of waste garbage. These people have no sense of responsibility.
4	Farmer No 4	The urbanization in Sana'a city is increasing from year to year. People moved to Sanaa due to the war in their area. Planning how to conserve and take advantage of stormwater runoff will solve many water problems in the future. Maintaining stormwater runoff from pollution is among the duties of the Municipality of Sana'a city to activate these laws.
5	Farmer No 5	From year to year, the water crisis in the city is increasing, the water pressure in a network was sufficient to reach the water to

		the upper floors of the buildings, and there is no need for a water tank in the yard of the house, but now the water pressure has become low and does not even reach the ground floor, where you must purchase a tank. Water was previously available in the network daily. After that, it became once every two weeks. Then it became monthly. The problem of providing water service was exacerbated in the city of Sanaa. The Ministry of Water should take advantage of stormwater runoff to recharge the underground basins. The city's municipality should also improve the city's cleanliness and direct the competent authorities to tackle the problem of throwing garbage in the streets and rainwater drainage channels and punishing violators.

6- Research's Pictures

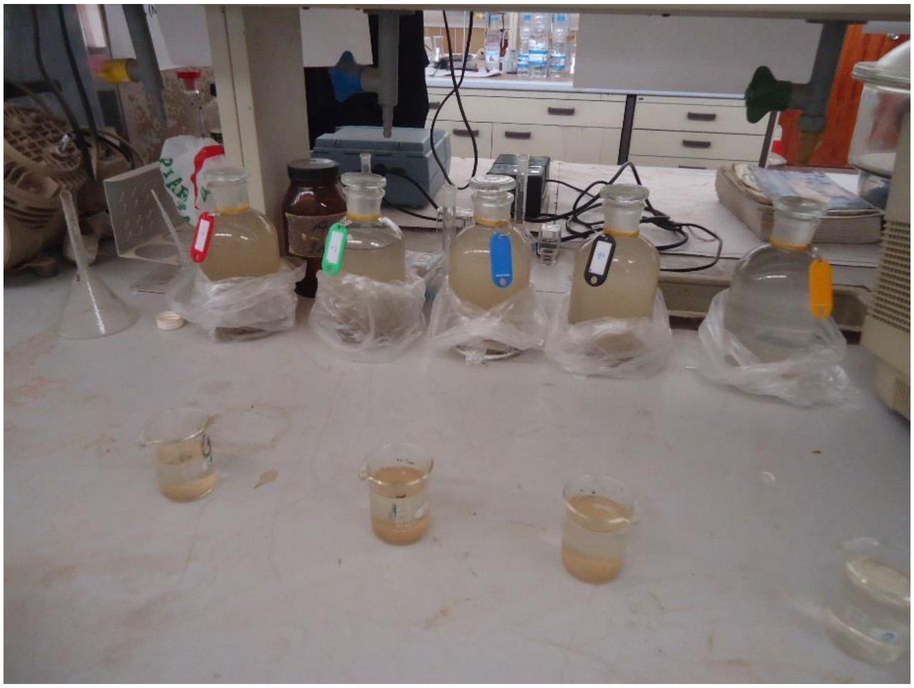

Figure (A6-1): The samples collected in glass bottles (500 ml)

Figure (A6-2): Collection of stormwater runoff samples

Figure (A6-3): volunteer took the stormwater runoff samples

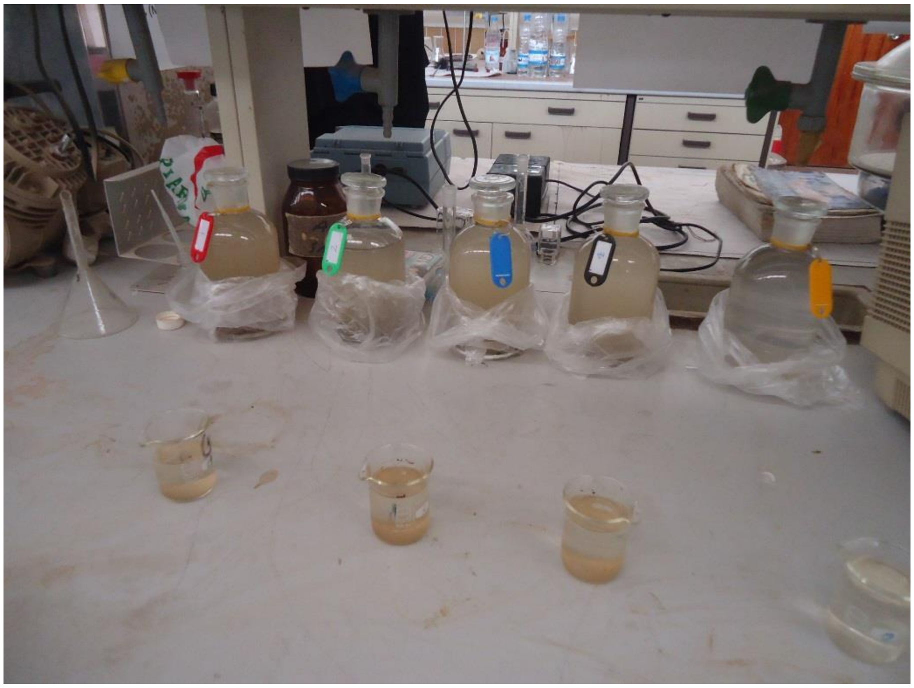

Figure (A6-4): Labeling of glass bottles

Figure (A6-5); Stormwater runoff washing away solid waste

Figure (A6-6): Sewage system overflow Because rainwater has mixed with wastewater, this picture was taken in Tahrir Square during a rainfall event

Figure (A6-7): The stormwater retention pond in Al-Sabeen region at Sana'a city

Figure (A6-8): Water pumping from the retention pond at Al-Sabeen district into nearby farms

Figure (A6-9): The overflow of the sewage system in the Hayel region in Sana’a city

Figure (A6-10): The overflow of the sewage system in the Al-Saylah channel close to the old Sana’a city

Figure (A6-11): Wastes and sediments in Al-Saylah Channel in Al-Sabeen district

Figure (A6-12): Garbage dumps in main channel. This picture was taken by researcher in Al-Sabeen district

Figure (A6.13): Wastes and sediments in rainwater channel in Ma’ain district.