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The Quality of Stormwater in Sana'a City from the Perspective of Integrated Water Resources Management

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ABSTRACT

Urbanization has attracted the attention of researchers worldwide towards studying the quality of urban water runoff as an alternative water resource. With an estimated population of 3.52 million inhabitants, the water scarce capital city of Yemen, Sana'a, receives seasonally huge amounts of the Sana'a Basin stormwater runoff which could be utilized effectively, provided it is free of pollutants. This research thus investigates the effect of urbanization on stormwater quality in Sana'a city. Based on a qualitative approach and the Integrated Water Resources Management (IWRM) concept, the researcher discusses the complex interrelated nature of runoff water quality along the Saylah channel to socio-economic and environmental aspects with recommendations to policy makers on a potential water resource for the city's rapidly growing population. Results show increased pH, COD, FC, Zn, Cu, and Cr parameters that refer to non-point source pollution taken at selected sites along Al-Saylah from the South to the North. A focus group discussion with male farmers indicates a saving of about 70% of diesel consumption for water pumping from stormwater retention ponds rather than wells. Yet, using this water for irrigation creates a big risk to the accumulation of heavy metals in crops and consequently to the health of crop consumers, human beings and animals alike. Finally, this research recommends to protect urban stormwater runoff from pollution and to apply best practices to maximize its use.

Keywords:
Urbanization; Stormwater; Sana'a city;
IWRM; Retention ponds; Al-Saylah
channel

1. Introduction

The growing urbanization is a common phenomenon worldwide, resulting in the conversion of previously vegetated areas into impervious surfaces. This further leads to an increase in deposited (built-up) pollutants that are transported by stormwater runoff to the receiving retention pond. Non-point source pollution including gross pollutants, sediments, nutrients, metals, hydrocarbons, and microbial contaminants can be of natural and anthropogenic origin which are difficult to quantify. The impact of stormwater quality thus affects the surrounding urban environment but also embraces public health, socio-economic, institutional and legal dimensions[1]. Addressing stormwater quality from a broader and a more holistic IWRM concept can thus lead to best management practices and to promote sustainable development. IWRM is considered an interdisciplinary tool to discourse water management[2]. It provides solutions for the specific challenges related to social equity,

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economic efficiency, environmental sustainability, and the management of water resources[3]. This approach will be utilized in this case of stormwater management in Sana'a.

Yemen faces a terrible water availability crisis, with groundwater being extracted at a rate exceeding the rate of natural recharge. In view of the rapidly growing population (urban average annual growth rate of 4.05% [4] and near to 3,52 million inhabitants[5]), the capital city Sana'a is at risk of running out of water[6]. The alarming water shortage security in the Sana'a Basin as a whole, it barely can keep up with meeting high water demands. An estimated 40.9 MCM/year[7] runoff in the Sana'a basin can however be utilized as an alternative water source[8] if managed wisely. IWRM was introduced to and applied in Sana'a Basin since 2003 to develop and manage water resources and deliver water services for different levels of the society[9]. This research is the first of this kind that addresses the quality of stormwater runoff in Yemen, with a focus on Sana'a city, from an IWRM approach. Acquiring knowledge of stormwater pollutants can be helpful for relevant water institutions in advanced rainwater management[10] to develop strategies that will maximize the benefit of using the stormwater runoff in the Sana'a basin and will encourage 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 Study Area

The capital city Sana'a, also called Amanat Al-Asemah, is the largest city of Yemen and situated in the southern part of the Sana'a Basin and in mid of Sana'a governorate but considered a separate administrative part (Figure 1).

The stormwater runoff enters from the sub-urbans of Sana'a basin from the South, then meanders through natural waterbed towards the North and drains into Al-Saylah channel, along 19.25 km. The Saylah channel divides Sana'a city into eastern and western parts, Figure 2. It is its most important drainage channel and ultimately functions as a road for vehicles to mitigate the city's traffic congestion in dry seasons. During wet seasons in spring and summer, the stormwater enters Sana'a city carrying lots of gravel, dust and pollutants. Four stormwater retention ponds were implemented along Al-Saylah channel to mitigate the risk of floods and store stormwater. This water is used to irrigate nearby farmland as an alternative to groundwater.

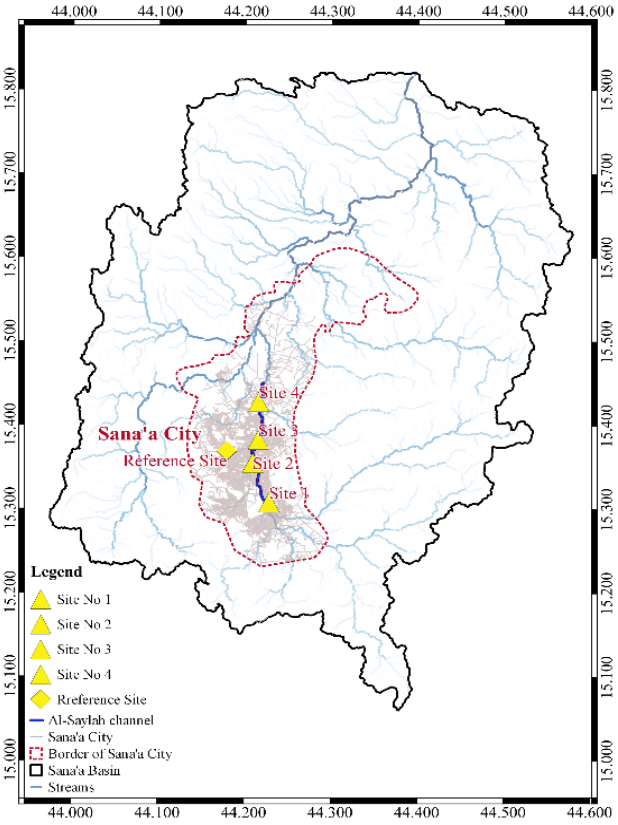

Fig. 1. The location of Sana'a city

2. Methodology

This research is based on a qualitative approach to address the quality of stormwater runoff in Sana'a city from an IWRM perspective. The document analysis method was used to grab informative data from water quality studies and related reports issued by the Yemeni water sector and some local and international organizations and the Yemeni Water Law.

Bowen and Glenn indicated that "Document analysis is a form of qualitative research in which documents are interpreted by the researcher to give voice and meaning for these data"[11]. The reason for choosing this approach lies in the fact that it is an efficient and effective method of gathering data because documents are manageable and practical resources. Also, obtaining and analysing 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[11].

The 945 km^2 catchment area of sampling sites at the Saylah channel were calculated by using ArcMap 10.2 Geographic Information Systems (GIS) program. About 25% of this catchment lies in urban Sana'a with commercial, industrial, residential and transportation activities, while 75% is of rural nature. Four sites along Al-Saylah channel were chosen for stormwater sampling and collection simultaneously within the first 45 minutes of rainfall according to the Washington State Department of Ecology[12]; one at the upper-stream of Al-Saylah channel, two sites in the middle-stream of Al-Saylah channel, and one site down-stream of Al-Saylah channel, Figure 2. 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 volunteers who were trained by the researcher because the stormwater samples must be taken at the same time. Five male 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[12] and trained by the researcher on safe and proper collection techniques according to the HACH[13].

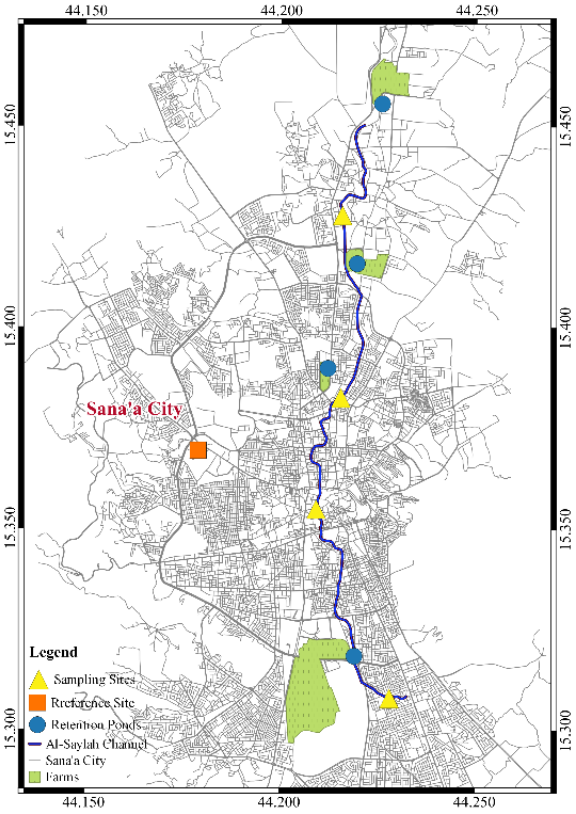

Fig. 2. Sampling sites location for stormwater runoff

The rooftop of the Faculty of Engineering at Sana'a University was taken as the reference site considering rooftops of building are considered protected from pollution [14]. Twelve parameters (pH, TSS, COD, FC, NO_2, NO_3, PO_4^{3-}, Z, Cu, Pb, Ni, and Cr) were analyzed based on the studies of DU[15], Gnecco[16], and Engstrom[17]. WTW Multiline P4 is the brand name of the device that was used to measure the pH. A Hach 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). 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. Results were compared with Yemeni and FAO wastewater reuse standards for irrigation. No Yemeni guidelines or regulations in the Yemeni Water Law are available for urban stormwater quality discharged into retention ponds.

A Focus Group Discussion (FGD) with seven available male farmers whose ages between 25 and 60 years old in the southern Al-Sabeen District of the city aimed to collect qualitative socio-economic data for using stormwater runoff of retention ponds for irrigation. Discussion questions were centred on the use of stormwater runoff by farmers, its quality, as well as related economic dimensions. Female farmers were not accessible for cultural and traditional restrictions. The findings of the focus group discussion (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, analysing, organizing, describing, and reporting themes found within a data set according to Nowell, et al[18].

Another method for data collection that is used in the research is site observation, according to Kothari[19]. Before sites selection and during the sampling periods in the rainy season, 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. 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. Extensive notes were written during picture-taking to help the researcher remembering important information while analysing the data.

3. Results and Discussions

3.1 The Quality of Stormwater Runoff

Rainwater is commonly not considerably polluted, yet urban runoff can show severe alteration in quality depending on the type, size and location of industrial activities, traffic and rainfall events[10].

The total suspended solid (TSS) loading is generally believed to be directly related to the degree of urbanization. The TSS range in all four sites showed values between 1991 and 3826.5 mg/l, as shown in figure 3 which can be explained by nonpoint pollution built in Sana'a city due to atmospheric deposition and urbanization activities like construction works and unpaved areas. 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. Admittedly, the concentration of TSS in stormwater impedes the use of modern irrigation networks such as drip irrigation due to a clogging, which will lower the efficiency or damage the modern irrigation systems[20].

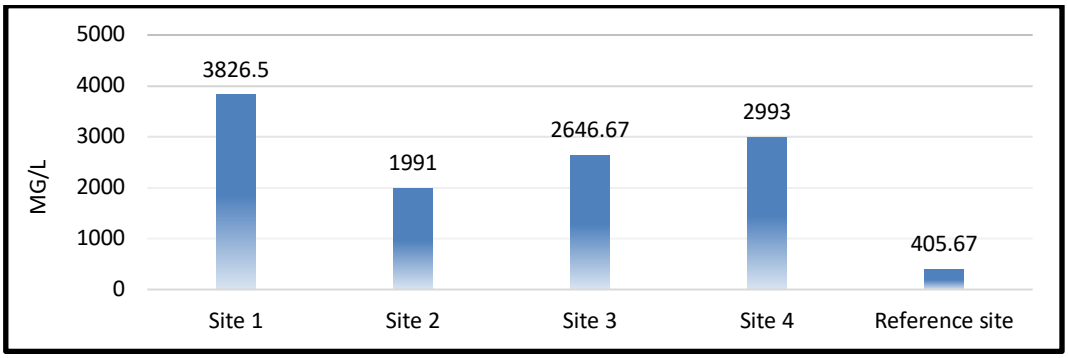

Fig. 3. The mean TSS values of the sample and reference sites

The high COD values between about 800 and 950 mg/l, as shown from figure 4, may most likely originate from nonpoint source pollutants that are scattered in the city, such as animal waste from stray dogs and cats, as well as human debris, sewers overflows, and solid waste. According to Al-Mahdi[21], the percentage of organic matter in municipal solid wastes in Yemen was estimated at 65% whereas the urban and rural municipal waste generated counts for less than 0.6 kg/person/day[22]. On one hand, the amount of organic matter might have been decreased during

the past few years of war since people are no longer able to purchase fresh vegetables and fruits, on the other hand greengrocers may dispose their unsold rotten crops more frequently. The solid waste management in Yemen is a major concern due to the lack of financial resources, particularly during the ongoing war.

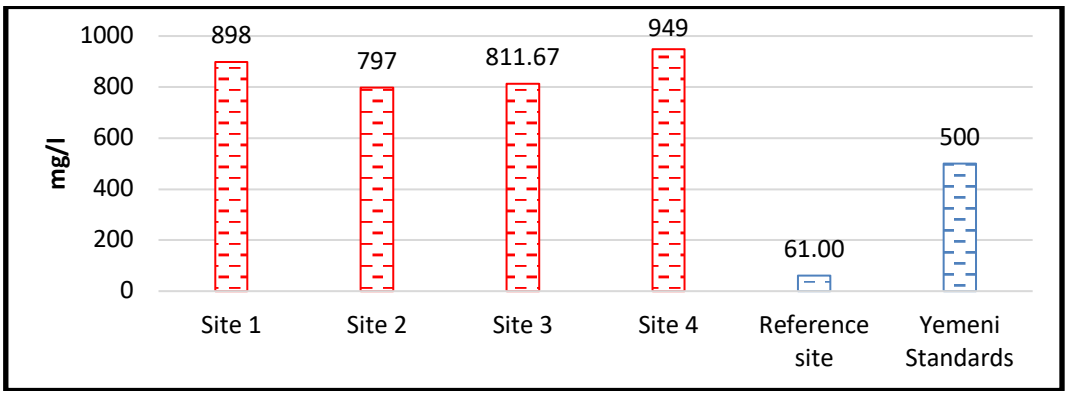

Fig. 4. The mean values of COD in four sites and reference site

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. 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 mentioning, that the percent coverage of sewerage networks across Sana'a city lies at about 48%[23].

Phosphorus and Nitrogen compounds are the most important nutrients and are relatively abundant in urban stormwater runoff[24]. 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 5.

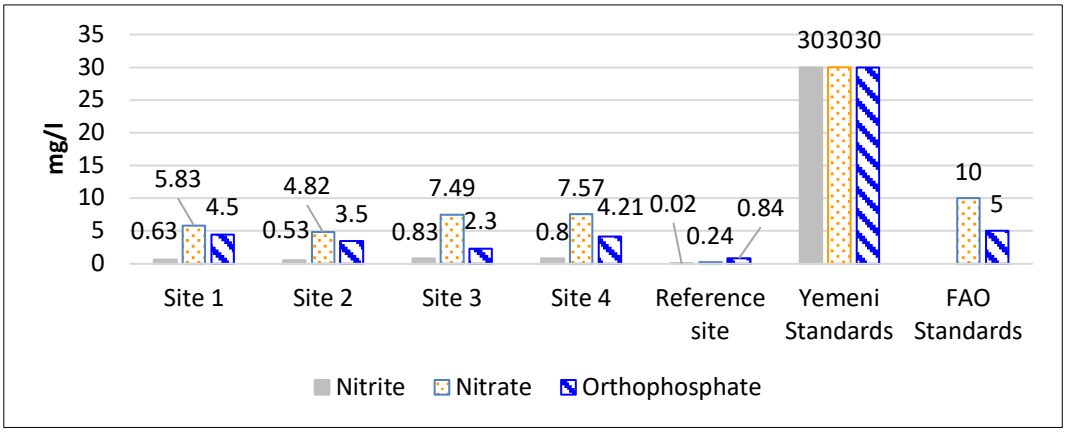

Fig. 5. The mean values of NO_2, NO_3, PO_4^{3-} in the four sites and reference site

Merghem[23] 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. 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.

It is unquestionable that the urban environment in Sana'a is adversely affected by a variety of anthropogenic activities that introduce numerous heavy metal pollutants (see high Zn, CU and Cr values, Figure.6) in stormwater runoff triggered by atmospheric deposition, intense traffic (fuel exhaust, brake pad wear, tire wear, engine wear, and engine oil as confirmed by Gupta[25]), sewer overflows, and weathering of structures. Vehicular movement of an estimated 450,000[26],can create heavy metal pollution and deposit on the road surfaces in Sana'a city.

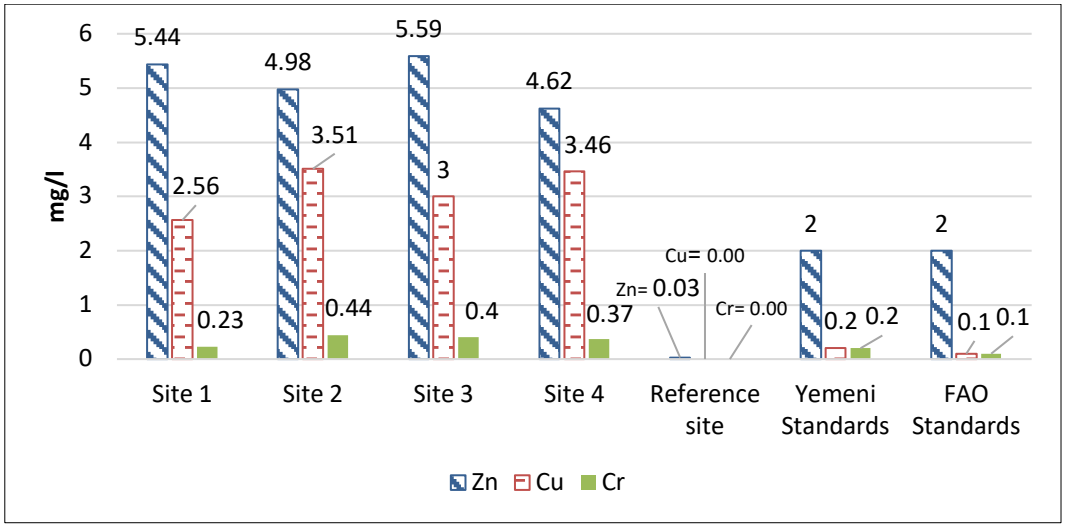

Fig. 6. The mean values of Zn, Cu, and Cr in four sites and reference site

The figure 7 shows the mean values of fecal coliform densities in the four sites that were exceeded the Yemeni and FAO wastewater reuse standards for irrigation.

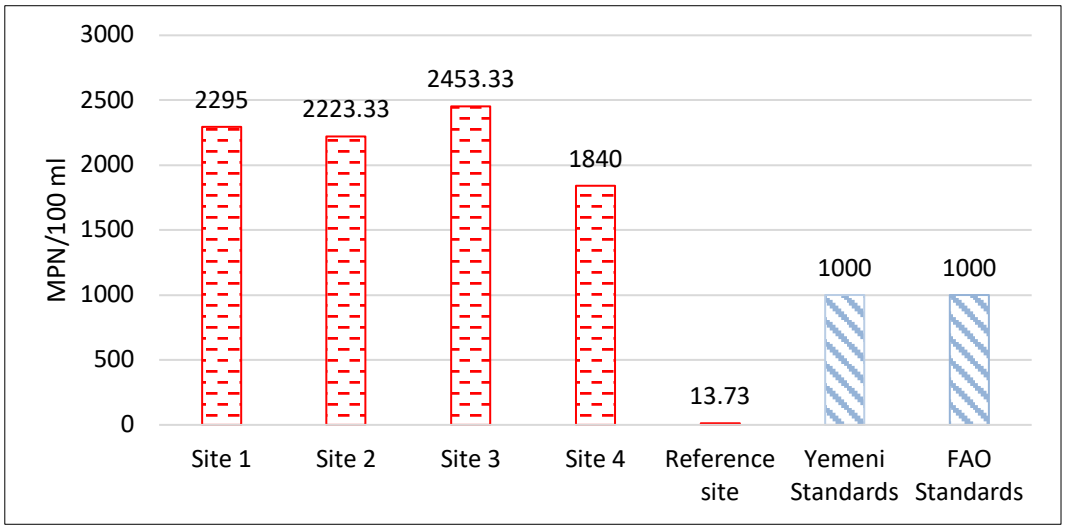

Fig. 7. The mean values of FC in four sites and reference site

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. 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. According to Sauvé *et al*[27], sewage spill over is a strong contamination driver that causes gastro-intestinal symptoms to humans. 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. Fadhl Ali Al-Nozaily [28] indicated that FC in raw wastewater in WWTP in Sana'a city exceeded 2400 MPN/100ml.

From the figure 8 All pH values are acidic (pH < 7) and fall in the common range of 4.5 to 8.7 moles/l [29] for stormwater. Monitoring the acidity is of key importance as stormwater runoff can influence the cation exchange process between soil and plant and soil microbiology[30].

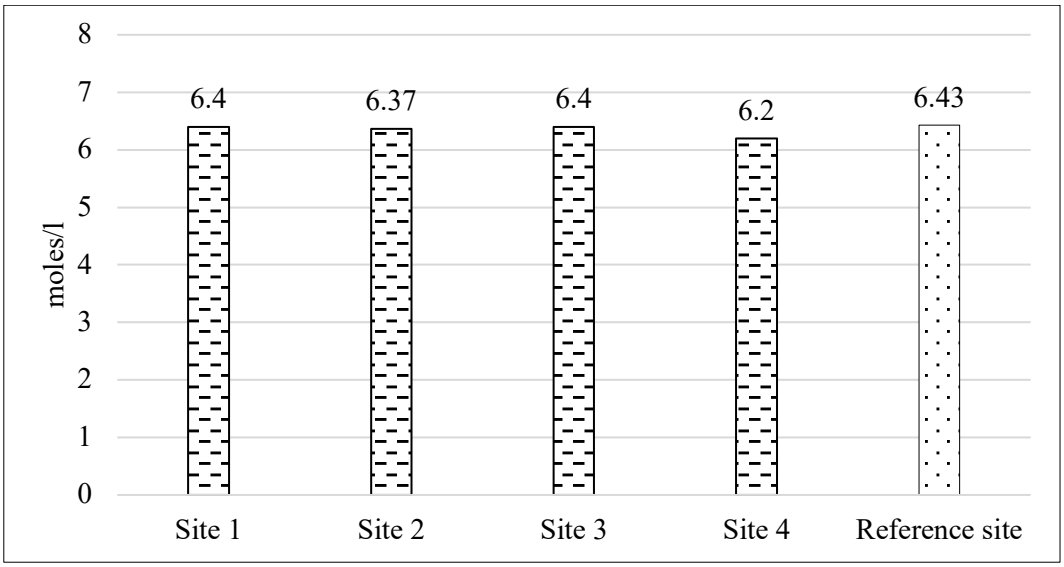

Fig. 8. The mean values of stormwater pH in four sites and reference site

3.2 Socio-Economic Dimensions of Stormwater

The focus group discussion with farmers revealed that they depend on stormwater retention ponds during and shortly after the rainy seasons in spring and summer to irrigate their farms. Outside seasons, they depend on groundwater extraction from wells. Main crops cultivated are vegetables which serve own consumption but to a larger extent for sales in Sana'a city. The lack or shortage of fuel, particularly diesel amid the ongoing war are drivers for a flourishing black market that in turn lead to soaring crop prices. Farmers indicated their need of only 200 litters of petrol to pump water out of retention ponds in comparison to 600 litters of diesel for groundwater pumping. According to them, they save about 70% of fuel consumption. Diesel savings contribute to less air pollution and groundwater depletion, less crop prices, food security and a sustainable income for farmers ie. escaping the poverty trap and protecting the environment. Coping measures as such can thus be considered as a good practice to be replicated. Government of South Australia[31], Amina and Kumud[32], and Borne, et al[33] indicated that that gross pollutant traps, detention basins, and floating treatment wetlands can mitigate stormwater pollution in urban and rural areas.

3.3 Legislative, Institutional and Policy Dimensions

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.

Article 54 of the Yemeni Water Law (YWL) addresses the dangers of various pollutants, regardless of their source. The assessment of Yemen's Water Law in 2002, addresses the unclear role of the National Water Resources Authority (NWRA) over monitoring the water quality at the level of water resources[34] but does not mention explicitly who should control stormwater pollution. The assessment report further states that "Experience elsewhere clearly shows that having the legal powers for pollution control is one thing, having the means to implement this responsibility is another, which is often ignored." The Ministry of Water and Environment (MWE) is obviously incapable to implement some proposed programs to mitigate and control nonpoint source pollutants in urban areas because of the scarcity of material and human resources. Coordination mechanisms among government institutions related to stormwater runoff management is weak. For example, there was no joint coordination in the planning and management of the stormwater harvesting ponds in Sana'a city between the Ministry of Agriculture and Irrigation and Ministry of Water and Environment. The proper policy formulation by water sectors can mitigate stormwater pollution efficiently[3].

4. Conclusions and recommendation

This research studied the quality of stormwater runoff in Sana'a city in terms of technical, socio-economic and legislative aspects. It can be concluded that non-point urban stormwater pollutants as TSS, COD, FC, Zn, Cu, and Cr threaten human health and the urban environment in Sana'a city. Furthermore, the quality of stormwater is not a standalone matter but environmental, socio-economic, and institutional aspects, etc. are closely interconnected and complex. Man-made nonpoint source pollution has severe consequences on human being and its environment. Weak legislations and human capacities, lack of funds and an unclear vision of priority policies in regard to capturing non-polluted stormwater instead of treating polluted runoff as a possible cheaper alternative water resource are of key importance and are challenges to be tackled urgently. Coordination mechanism between government institutions that are related to stormwater management in Sana'a city for management, control flooding, reducing erosion, and improving stormwater quality shall be put in place.

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