

# **MASTER's THESIS - Integrated Water Resources Management**

Cologne University of Applied Sciences - Institute for Technology and  
Resources Management in the Tropics and Subtropics

## **INTEGRATED MANAGEMENT OF ECOSYSTEM SERVICES USING TREATED WASTEWATER: A CASE STUDY AT UPPER ZARQA RIVER, JORDAN**



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## List of Abbreviations

Al	Aluminium
APHA	American Public Health Association
AZB	Amman-Zarqa Basin
BOD <sub>5</sub>	Biological Oxygen Demand (Five Days)
Ca	Calcium
Cd	Cadmium
CFU	Colony-forming Units
Cl	Chloride
COD	Chemical Oxygen Demand
Cr	Chromium
Cu	Copper
DEM	Digital Elevation Model
<i>E. coli</i>	<i>Escherichia coli</i>
EC	Electrical Conductivity
EDC	Endocrine Disruptors Compounds
ESP	Exchangeable Sodium Percentage
FAO	Food and Agriculture Organization
GIS	Geographic Information System
HCO <sub>3</sub>	Bicarbonate
JS	Jordanian Standard
K	Potassium
MAR	Managed Aquifer Recharge
MCM	Million Cubic Metres
meq/L	milliequivalents per litre
Mg	Magnesium
MOE	Ministry Of Environment
msl	mean sea level
MWI	Ministry of Water and Irrigation of Jordan
N	Nitrogen
Na	Sodium
Ni	Nickel
NO <sub>3</sub>	Nitrate

P	Phosphorus
Pb	Lead
PDFs	Portable Document Formats
PO <sub>4</sub>	Phosphate
RBT	Riverbank filtration
SAR	Sodium Adsorption Ratio
SAT	Soil-aquifer Treatment
SO <sub>4</sub>	Sulphate
SWOT	Strength, Weaknesses, Opportunities, and Threat
TDS	Total Dissolved Solids
TOrC	Trace Organic Chemicals
TWW	Treated Wastewater
WHO	World Health Organization
WSP	Waste Stabilization Pond
WWTP	Wastewater Treatment Plant

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## **Abstract**

Jordan is deemed as one of the least water-endowed regions in the world. The acute water shortage, accompanied with changing climatic conditions have necessitated the increasing use of treated wastewater (TWW), predominantly in irrigated agriculture sector. This is especially true with the upper Zarqa River. The ample supply of TWW resources can be found there; paradoxically, the practical implementation of TWW reuse is hindered by the enforcement of irrigation water quality standard, compounding pressure on the dwindling groundwater resources. In light of the large potential source of TWW, this study aims to supply knowledge on maximizing the safe reuse of TWW while minimizing the environmental impacts within the local environment of the upper Zarqa River. A SWOT analysis was conducted to identify the strengths, weaknesses, opportunities, and threats of TWW reuse for agriculture in the local context. In recognition of the projected growth in the treated effluent to more than 135 MCM in the coming ten years, and how it would affect the water use on the study region, several plausible development scenarios were proposed based on expected developments on the ground. Considering the vital role of TWW in sustaining multiple ecosystem services, this study addresses the need to review current standard, encourages managed aquifer recharge with TWW, recommends crops type modification, and enhances knowledge on suitable practices at farm level. Each of these factors is needed in order to deliver a range of ecosystem services to sustain the local rural communities and to advance them in the face of profound challenges, thereby leading to its stability and increased productivity.



# 1. Introduction

Water scarcity is slowly invading on a global scale. The blooming of population growth, urbanization, and climate change are among the key drivers exacerbating the available freshwater resources, specifically in water-scarce countries (Abdulla et al., 2009). To date, agriculture accounts for the largest consumer of water in arid and semi-arid zones where irrigation is of paramount importance. More than 60%, in some countries over 80%, of the total available water is withdrawn by agriculture sector (Al-Wer, 2009; Kellis et al., 2013). The high population rate increases economic activities and enhances living standards, thereby provoking competition and conflicts over the limited freshwater resources (NWMP, 2003). The over-exploitation of groundwater, which is the major freshwater source for urban and rural regions around the world and Hashemite Kingdom of Jordan in particular, has led to undesirable effects on the surroundings, including natural environment and local agriculture setting (Ta'any et al., 2009). This scenario, if coupled with the likely effect of highly variable climatic changes, have a large tendency to hamper food and water security in the long run (Al-Qaisi, 2010).

More than 90% of Jordan's area is dominated by arid and semi-arid climate, and the persistent water shortage faced by the country is well documented (Abdulla et al., 2009; MWI, 2009; Grover et al., 2010). Jordan suffers from water scarcity because of the variability in rainfall, which water resources mainly depend on. The rainfall is flashy sporadic and only about 2% of the territory receives a rainfall of exceeding 350 mm annually (Al Mahamid, 2005); thus, food production severely relies on irrigated agriculture, constituting about 64% of the overall water uses (NWMP, 2003). Due to the vast area of steppe and desert in the country, accompanied with extremely less reliably available water resources, Jordan is deemed as one of the ten most water-deprived countries in the world with a very limited annual renewable freshwater resources of approximately 145 m<sup>3</sup> per capita as of 2008, remarkably lower than the water poverty line of 1000 m<sup>3</sup> per capita per year (MWI, 2009; Ulimat, 2012). The limitation of conventional water supplies in the Kingdom has brought about depletion and deterioration of groundwater basins, resulting from over-pumping by governmental and private wells in fulfilling the increasingly high domestic and agricultural demands since the early 1970s. This phenomenon has magnified the strains on the freshwater resources (Salameh, 2008; Al-Zyoud et al., 2015).

One solution to alleviate these negative effects and ensuring the sustainability of the water source is treated wastewater (TWW) reuse. As reuse emerges as an alternative, TWW becomes a beneficial resource (Abu-Sharar et al., 2003). The adoption of this practice not only bridges the supply and demand gap but also as a means to adapt water scarcity. In fact, owing to population growth, agricultural development, and successive waves of guests from neighbouring countries, the Ministry of Water and Irrigation of Jordan (MWI) has crystalized methods to consider the non-conventional resources as an option in their water management and development strategies (Husain, 2010).

The biggest supply of this resource can be found in Zarqa River which is enclosed in Amman-Zarqa Basin (AZB). In the context of this study, TWW reuse is the recapture of secondary treated domestic effluent for beneficial purposes release from As Samra Wastewater Treatment Plant (WWTP) located upstream of the river that receives all TWW discharges. As the As Samra plant serves two major cities, Amman and Zarqa, it is the largest WWTP in Jordan and the treated municipal wastewater is increasingly used for crop irrigation. This is especially true with the upper part of the Zarqa River Basin. The growing food market in Jordan, resulting from deteriorating regional political situation

and turmoil in the region especially in the last two years, has driven most of the farmers to intensify agricultural activities in the river basin (Ta'any et al., 2009). According to MWI (2016), with Jordan's population of 9.5 million as of 2015, the figure is expected to almost double by 2050. This statement inevitably exerts certain degree of influence on the water use at the upper Zarqa River area.

Ecosystem services, as expressed by Millennium Ecosystem Assessment (2005), are benefits that human derive from ecosystems. These benefits encompass four classes: provisioning services such as provision of food and water; regulating services such as climate regulation, flood protection, disease prevention, and water purification; cultural services comprising recreational, aesthetic, and spiritual values; and supporting services such as nutrient cycling and soil formation. To put that into the framework of this study, ecosystem services pertain to irrigated crops, soil, and groundwater, as each of these ecosystem components, if well managed by TWW, renders a range of valuable ecosystem services that helps to sustain the livelihood of the local community, especially in the rural areas. Recognizing the agricultural landscape ruled by the upper course of the river, irrigated crops, soil, and groundwater become of high concern due to the irrigation process of the TWW likely affecting crops production, soil profile, and groundwater resources to some extent. Considering the amount of effluent accepted by the upper Zarqa River, along with the reuse of the TWW with respect to different ecosystem components, the interrelationships must be addressed in a holistic approach before maximizing the plentiful resource (Grover et al., 2010). In this respect, a crucial area of the upper course of the Zarqa River near the As Samra plant becomes the limelight to address this interaction to enable a sustainable and safe reuse of TWW resources in the future.

The presented study is, therefore, a step forward in incorporating current information and supplying knowledge on maximizing the safe reuse of the abundant TWW resources in the section of the river basin part adjacent to the WWTP by identifying the strengths, weaknesses, opportunities, and threats (SWOT) of TWW reuse in agriculture, with respect to various ecosystem components. In recognition of the projected population growth leading to an increase in the TWW rates, several plausible development scenarios will be proposed based on the developments on the ground followed by guidelines and recommendations. With the high demand for the TWW resource and its vital role in sustaining multiples ecosystem services, the outcome is to provide insights into the integrated management of irrigated crops, soil, and groundwater to deliver a range of ecosystem services, acting as crucial drivers in supporting the livelihood of the local community in the long run.

## 1.1 Treated Wastewater Reuse and the State of the Art

TWW reuse has been an interesting and beneficial alternative water source worldwide. The benefits of this practice are widely recognized. A number of scholars have agreed upon its high potential in mitigating water scarcity, especially in water-deprived countries (Kellis et al., 2013; Lonigro et al., 2015).

Irrigation by TWW is practiced in many parts of the world. As the world is becoming more insecure about adequate food supplies, many countries have harnessed the use of this plentiful resource as it can narrow the gap between supply and demand (Abu-Sharar et al., 2003). The reuse in the agriculture sector can be distinguished into two practices as defined by the following:

**Direct reuse:** Use of TWW at sites in the immediate vicinity or adjacent to WWTP or reclaimed water that has been conveyed from the point of treatment to the point of use without an intervening discharge to waters (McCornick et al., 2004)

**Indirect reuse:** Discharged TWW is mixed or blended or diluted with another water body such as reservoirs, rivers or canals before use (WHO, 2006)

The reuse of TWW is viewed as a positive means of preserving scarce water resources, gaining agronomic benefits, and enhancing soil-formation, attributed to nutrient enriched TWW (Toze, 2006). A pilot project in regard to the cultivation of forage crops by applying TWW was undertaken in Oman (SQU & UJ, 2015). Lonigro et al. (2015) utilized treated municipal wastewater for irrigating different vegetable crops. Both studies yielded promising agronomic result resulted from TWW irrigation. In Italy, Lubello et al. (2004) investigated the potential irrigation of nursery ornamental plants with tertiary treated municipal effluent. The direct use of reclaimed water from a sewage treatment facility as a source of irrigation water in conjunction with groundwater was explored by Al Khamisi et al. (2013) in Oman. As a result, the irrigated area increased by 323%.

In view of environmental protection, water quality issues concerning TWW is of paramount importance to the public. The quality of the TWW itself affects its suitability in various applications, which should be assessed before reuse. Kretschmer et al. (2006) stated in a review paper that the different applications of TWW reuse rely on specific water quality guidelines. In this context, many studies have focused on the quality of TWW discharge into rivers and its use in irrigation, and long-term research results have demonstrated that TWW can safely be reused for irrigation purposes. Kamel and Nada (2008) proved that the highly performed conventional and modified activated sludge treatment plants in Jordan produce considerably good quality municipal TWW for reuse, compared to the waste stabilization pond (WSP) method. Al-Abdallat (2011) had also informed the research community about the positive improvements along the Zarqa River, entailing strong reductions in both biochemical oxygen demand (BOD) and chemical oxygen demand (COD).

Studies of plant-uptake based on contaminants as a result of TWW irrigation are a subject of interest to environmentalists seeking to ensure the protection of public health and environment. In Jordan, Al-Ansari et al. (2013) showed that treatment of crops with TWW caused different uptake rates of heavy metals, namely zinc, iron, lead, and nickel for various vegetables. Remarkably, a five-year study at Monterey County in California by Burau et al. (1987) revealed no significant public health risk associated with irrigation of raw-eaten vegetable crops with reclaimed domestic wastewater. Furthermore, pollutants of emerging concern accruing from pharmaceuticals and personal care products in the domestic wastewater discharge into the river is a major undertaking of society when the water is used as irrigation water. In this regard, Riemenschneider et al. (2016) conducted a broad plant-uptake studies in relation to micropollutants under TWW irrigation regimen at Zarqa River Basin. Still, studies of the existence of micropollutants based on plant-uptake in the region of interest remain scarce.

The intentional recharge of water into an aquifer either by injection or infiltration and recovery by planned extraction is termed managed aquifer recharge (MAR) (Lumb, 2006). In this respect, TWW can be considered as suitable water sources for MAR (Gale, 2005). Drewes (2009) reported the replenishment of groundwater with secondary or tertiary TWW will result in additional water quality improvements due to the percolation process. In Saudi Arabia, the researchers agreed that the

reclaimed water can be maximized by means of restoring dwindling wadi aquifers by artificial recharge with aquifer recharge and recovery system (Missimer et al., 2012). Artificial recharge of aquifer with treated municipal water, in combination with reduced groundwater extraction have also prompted in North China plain for groundwater resources protection and aquifer recovery (Han, 2003). Interestingly, to build on the existing MAR technique, proper conjunctive use of surface water and groundwater has been receiving immense limelight in the research platform. Ejaz and Peralta (1995) established a simulation-optimization model to determine the use of reclaimed water in conjunction with river and groundwater, while taking water quality constraints into considerations. In Iran, Karamouz et al. (2004) developed conjunctive use planning for irrigation purpose to satisfy agricultural water demands.

Different groundwater models are applied to study the groundwater-surface water interactions in the Zarqa River Basin, but current research of such interactions within the study area remains limited. Although there is a variation in the reported recharge rates, the results of the former studies act as a precursor for the implementation of further action plan. Schulz et al. (2013) estimated the temporal and spatial distribution of groundwater recharge in the Zarqa River catchment by applying J2000, a hydrological model from the years 1977 to 2007. The estimated groundwater recharge is 105 million cubic metres (MCM) per year which accounted for 21 mm annually. The outcome indicates a fairly modelled safe yield estimation of groundwater resources. Al Mahamid (2005) calculated the average annual direct recharge for normal and wet years which are 22.4 to 60.4 MCM respectively, based on mathematical modelling. El-Rawy et al. (2016) developed a groundwater flow model, MODFLOW 2005, for the upper Zarqa River Basin to assess the water budgets of the subjacent unconfined aquifer and the Zarqa River itself, by establishing different simulated scenarios. In short, this knowledge stresses the significant role of releasing TWW in recharging the unconfined aquifers in the area.

Ultimately, the knowledge of TWW safe reuse practice can be maximized in multiple applications such as agriculture and groundwater recharge. TWW reuse, if managed properly, provides a viable mechanism to increase water availability for different uses in many parts of the world, especially in arid and semi-arid regions where water is a precious commodity.

## 1.2 Problem Description

Regardless of long history of pronounced water scarcity, AZB remains as one of the major water arteries at the northwestern part of Jordan. Being one of the largest rivers in Jordan (Al-Ansari et al., 2013), Zarqa River is located in the central part of the basin. The selected study area extends from the discharge site of As Samra plant carrying more than 78% of the TWW quantities (Al-Zboon & Al-Suhaili, 2009). At present state, the upper course of the river receives a maximum TWW discharge of 364,000 m<sup>3</sup> daily (MWI, 2013) from the plant, which is a major resource of water in the river. Figure 1 exhibits the general location of the AZB and study area.

Water has been a vital source of life in the basin, especially for the upper Zarqa River ecosystem where agricultural activities are accentuated. As a matter of fact, agricultural water demand represented almost 51% of the total demand in the basin. Despite the high availability of the TWW, the upstream Zarqa River is prohibited for direct reuse from the river due to restricted regulation (Al-Omari et al, 2009). The enforcement of the regulation exerts pressure on the rural farming communities and results in rampant illegal TWW reuse.

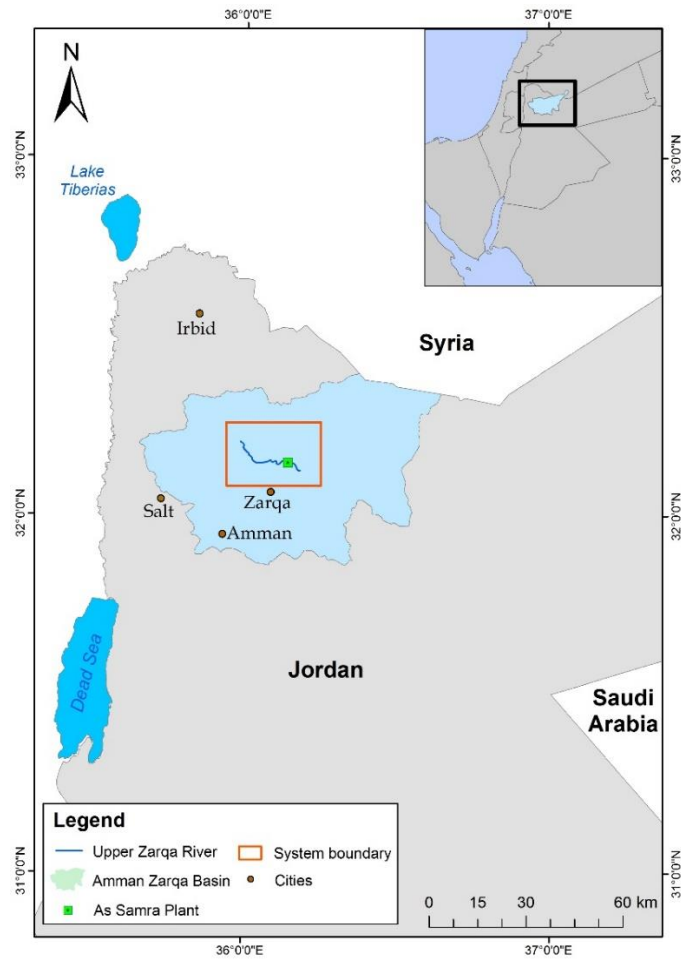


Figure 1. General location of AZB and upper Zarqa River.

*Data source: shapefiles from MWI, 2016b*

Over-exploitation of groundwater resource stocks is a severe problem in the Zarqa River catchment (Schulz et al., 2013). This implies that additional replenishment from an external water source has become an issue in need of addressing. Dated back to '80s before the establishment of As Samra plant, the natural discharge of the seasonal river was low and often dry. With sporadic rainfall, the scarce groundwater furnished from basalt and limestone aquifers are viewed as primary source of water supply in the basin (Salameh, 2008) for agricultural and domestic uses on one hand, and accommodating the unanticipated influx of refugees from neighbouring countries on the other (Al-Qaisi, 2010).

The historical continuous over-abstraction of the precious commodity has plunged the basin into a deepening water crisis. Ta'any et al. (2009) found the degradation of groundwater system in the catchment is manifested by an annual drop of groundwater levels ranging from 0.47 to 1.68 m in most observed wells for the period of 2001 to 2005. A study conducted by Al-Zyoud et al. (2015) in the centre of the AZB revealed an average drawdown of 1.1 m yearly for the last 15 years and they concluded that no sustainable water management is applied until now. Bajjali and Al-Hadidi (2017) evaluated the groundwater quality and an elevated groundwater salinity, as high as 4000 mg/L, in some wells is being reported. Loss of groundwater and restriction of law threaten the future of water availability, hindering agricultural productivity and potentially impeding further development (Abu-Sharar et al., 2003).

Despite the growing body of literature on the relation of TWW and crops productivity, TWW quality and its environmental impacts (Abu-Sharar et al., 2003; Carr et al., 2011; Al-Ansari et al., 2013), the single focus of one ecosystem from the perspective of reusing TWW, contributes to scattered management of ecosystem in the region. The TWW irrigation activity has a high tendency to influence irrigated crops, soil profile, and groundwater system to a certain degree; however, these interactions has been marginally discussed in a holistic approach and lead to limited studies on the integrated management of ecosystem services at the study area. On the other hand, Al Mahamid (2005), MWI (2009), and El-Rawy et al. (2016) projected an increase in the production rate of effluent from the As Samra plant the near future as a result of rapid population growth and increased sewerage area (Ammary, 2007). Nevertheless, scarce studies have been conducted on the future development scenarios with respect to increased TWW discharge to more than 135 MCM.

In view of the study area is expected to receive extra discharge of TWW, this projection amount will affect the water use at the upper Zarqa River. Considering the practice of TWW reuse is interconnected with regards to different ecosystem components, scattered management of the ecosystems will lead to degradation of ecosystem services being delivered to the local communities that depend on them.

### 1.3 Justification of Study

The river passes through a vast area of high socio-economic importance to the upper region where irrigated agriculture is predominant (Al Mahamid, 2005). These areas include Wadi Dhuleil, Al-Hashemieh, Al-Sukhnah, and Tawaheen Al Adwan (see Figure 2). More than 60% of the population occupied the basin (Al-Wer, 2009), and the farming communities are heavily reliant on the irrigated agriculture that contribute to food security.

Water availability is a crucial factor controlling human's wealth and prosperity, particularly in arid and semi-arid areas (Al-Zyoud et al., 2015). Considering the deteriorating condition of the groundwater reserves, the continuous supply of the treated municipal wastewater discharge from the As Samra plant into the river serves as a principal source of surface water (Ammary, 2007; Al-Wer, 2009; Al-Zboon & Al-Suhaili, 2009). TWW is independent of winter season, year-round, and even in the years of droughts, wastewater is generated constantly as long as people drink and use potable water (Yaqob et al., 2015). In this respect, the TWW is seen as a renewable and reliable water source in view of the erratic rainfall in the study region (Toze, 2006; Ulimat, 2012).

Food production is by far the main water consumer. According to Abdulla et al. (2009), the water scarcity is expected to aggravate due to the increasing demand from the growing population. This implies that the growing food demand will fuel the food production. As such, this available non-conventional resource is the backbone of the agricultural activities in the study area safeguarding food security in the entire region (El-Rawy et al., 2016; MWI, 2016).

Considering the growing importance of the upper region in sustaining the livelihood of the rural communities, the TWW is considered the major source of food security especially for the poor. The prohibition of direct use of TWW from the upriver (Al-Omari et al., 2009; El-Rawy et al., 2016) is viewed as a limiting factor for further economic development (Yaqob et al., 2015) and puts remarkable pressure on the local farmers who depend on TWW for agricultural purpose. In

recognition of the projected rise in the effluent, the demands on the planners to maximize beneficial use of TWW and its reuse capacity are therefore expected to intensify in Jordan. As stated in the national water reallocation policy, TWW is becoming a resource for agriculture gradually replacing freshwater. In other words, irrigated agriculture is most likely to expand where TWW is available (MWI, 2016). Recognizing the need to increase water supplies to unlock Jordan's potential for economic growth (Salameh, 2008), TWW reuse at the upper Zarqa River is sought-after to make the best use of the abundant non-conventional resources.

Given the densely irrigated area and presence of unconfined aquifers in the study region, the study area becomes an interesting subject for elaboration. The plentiful of the TWW resource, fittingly, offers an optimal opportunity to replenish the depleted groundwater supplies and simultaneously augment the water availability for agricultural activities (Al Mahamid 2005; Schulz et al., 2013; El-Rawy et al., 2016). In this regard, the upper Zarqa River is a potential region to maximize the safe reuse of TWW for future developments. Considering the vital role of TWW reuse in sustaining multiple ecosystem services, the local environment of the upper river becomes a pertinent perspective for understanding the ecosystem as a general interaction with TWW (Grover et al., 2010).

In arid and semi-arid regions, assessment of the current local environment in respect to TWW reuse is essential for advanced planning. Consideration of ecosystem services is essential in developing integrated management strategies (Li et al., 2016). The ecosystem components are interconnected because TWW irrigation has an effect on the irrigated crops and soil profile, consequently influences the groundwater system to a certain extent. These ecosystem elements interact as a functional unit. With an integrated approach of ecosystem services management in the study area, it promotes better planning and management of TWW resources (Al-Wer, 2009). In addition to that approach, it optimizes the delivery of a range of ecosystem services to the communities that depend on them which in turn helps sustaining the livelihood of the local communities in the long run.

For these reasons, the study area offers a valuable research case study to deliver knowledge that maximizing the safe reuse of the abundance of TWW and how likely it is to be continued in the coming ten years concerning the provisioning of extra TWW discharge. Therefore, the SWOT of TWW reuse in the local context are sought. The interaction of TWW reuse with respect to different ecosystem components addressed in the SWOT analysis has considerable value to inform decision-making on reuse issues. Notwithstanding the restricted standard, this study also attempts to highlight this situation and draw guidelines and recommendations that are able to adapt to the local climate and environment at the upper Zarqa River.

## 1.4 Research Questions and Objectives

Considering the increasing agricultural demand in the region, the future impacts on the upper Zarqa River will determine, to some extent, a major part of water use in Jordan. Subsequently, the following research questions arise.

1. How could the reuse of TWW be maximized within the upper course of the river with respect to different ecosystem components?
2. What are the feasible development scenarios based on the projected increase in effluent in the near future?

The research questions are answered by addressing the interaction of TWW reuse with the ecosystem services within the study area. Therefore, the objectives of the study are:

1. To identify the strengths, weaknesses, opportunities, and threats of TWW reuse for agriculture.
2. To supply knowledge on maximizing the safe reuse of TWW while minimizing the environmental impacts.
3. To propose development scenarios based on the expected growth in the treated effluent to more than 135 MCM in the coming ten years.



## 2. Upper Zarqa River Inventory

Recognizing the interface between human development and ecosystems in the study region, it is utterly important to understand the local dynamic environment. In this chapter, upper Zarqa River refers not only to the physical area of the upper course of the river with its associated climatic conditions, unique geological characteristics, and biophysical and ecological elements, but also to the people living within the region and the features of their socio-economic development.

### 2.1 Geography, Topography, and Climate

The geographical area, topography, and climate characteristics of the study area will be elaborated within this sphere. The climate patterns are highly influenced by the geographical location and its topographic features. The interrelationships between these parameters generate unique ecosystem, and as a result contribute to distinct landscape with mixed patterns of human use in the area of concern.

#### *Geography*

Figure 2 illustrates the study area map of the Zarqa River in the AZB. With a coverage area of roughly 4025 km<sup>2</sup>, it is a transboundary basin shared by two riparian countries. Larger portions of the basin are located in Jordanian territory than those in Syria, which are 89% and 11% respectively (Al Mahamid, 2005). The areas in Jordan includes the capital Amman and the second largest city in Jordan, Zarqa.

The river course traverses 65 km before joining the Jordan River (El-Rawy et al., 2016). The headwaters of the Zarqa River originate in the Ain Ghazal spring on the eastern side of the Gilead Mountain northeast of Amman (Al-Ansari et al., 2013). It flows westward, passing through King Talal Dam halfway downstream. Being the main tributary of the Jordan River, it feeds the King Abdullah Canal and lastly empties into the Jordan River at Deir Alla confluence. Notably, the river discharge is primarily contributed from a secondary TWW from the As Samra plant located 50 km east of Amman with an annual discharge rate of 110 MCM.

The present study is carried out at the upper part of the Zarqa River which, represents the first 22 km of the river. Geographically, the study area lies between 32° 9' and 32° 12' North latitude and 35° 5' and 36° 9' East longitude. It extends from the discharge point of As Samra plant through Wadi Dhuleil, Al-Hashimiya Village, and the cultivated areas along the banks of the Zarqa River to Tawaheen Al-Adwan region (El-Rawy et al., 2016).

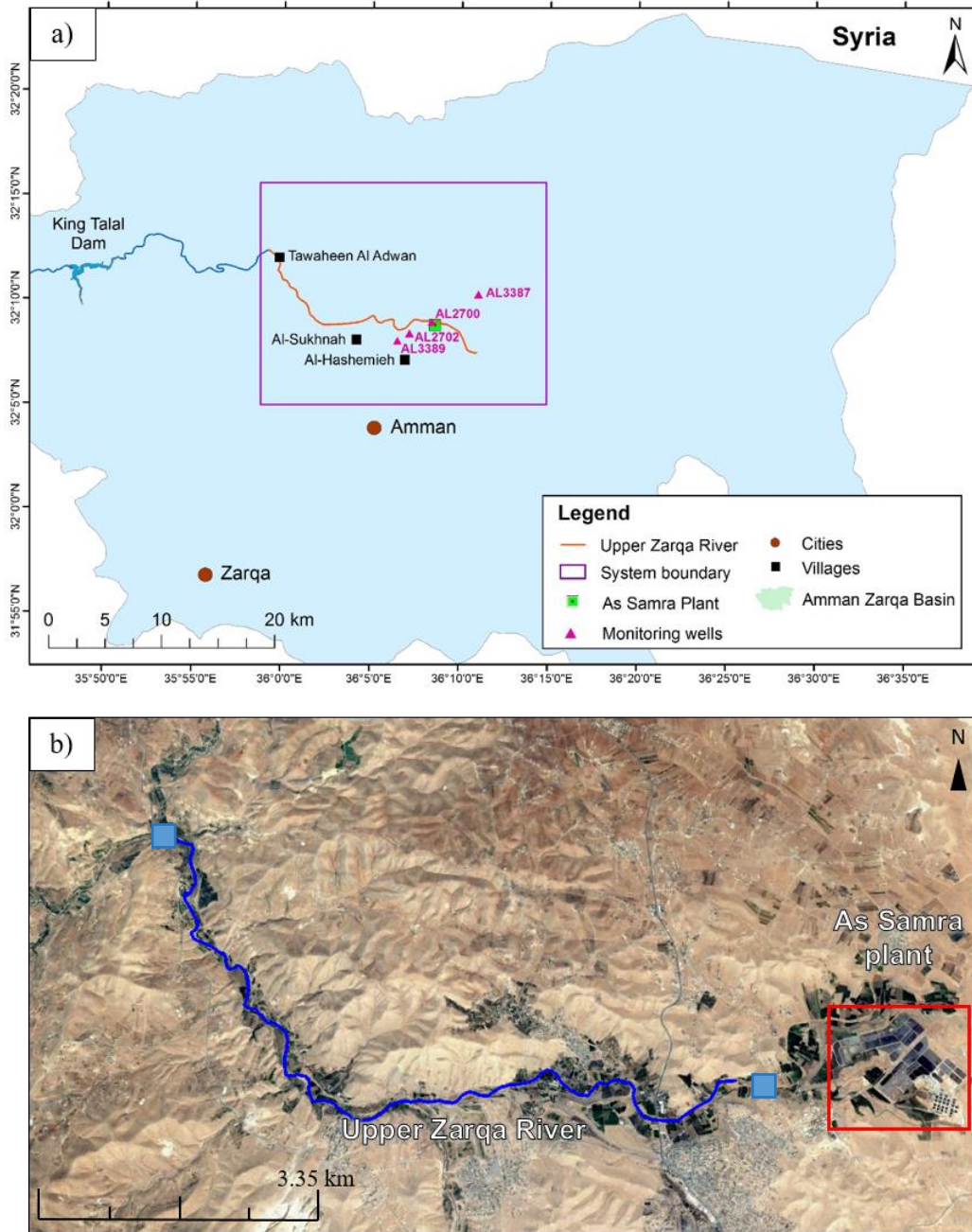


Figure 2. Study area map of upper Zarqa River: a) area of interest with monitoring wells, b) aerial view of study area.

*Data source: shapefiles from MWI, 2016b; after Google Earth image, 2017*

### Topography

The elevation of the upper Zarqa River ranges between 292 m and 950 m, as portrayed in Figure 3. The upper basin is characterized by high elevation of about 500 m. The adverse inclination upstream limits efficient TWW reuse to a certain extent. The general slope in the basin differs from west to east where hilly areas dominate a major part of the western and surrounding areas along the basin boundary. The altitudes gradually decrease towards the centre of the basin ranging from 1,200 m mean sea level (msl) in the east to -366 m msl towards the outlet of the catchment to Jordan Valley near Deir Alla in the west (Al Mahamid, 2005; Schulz et al., 2013).

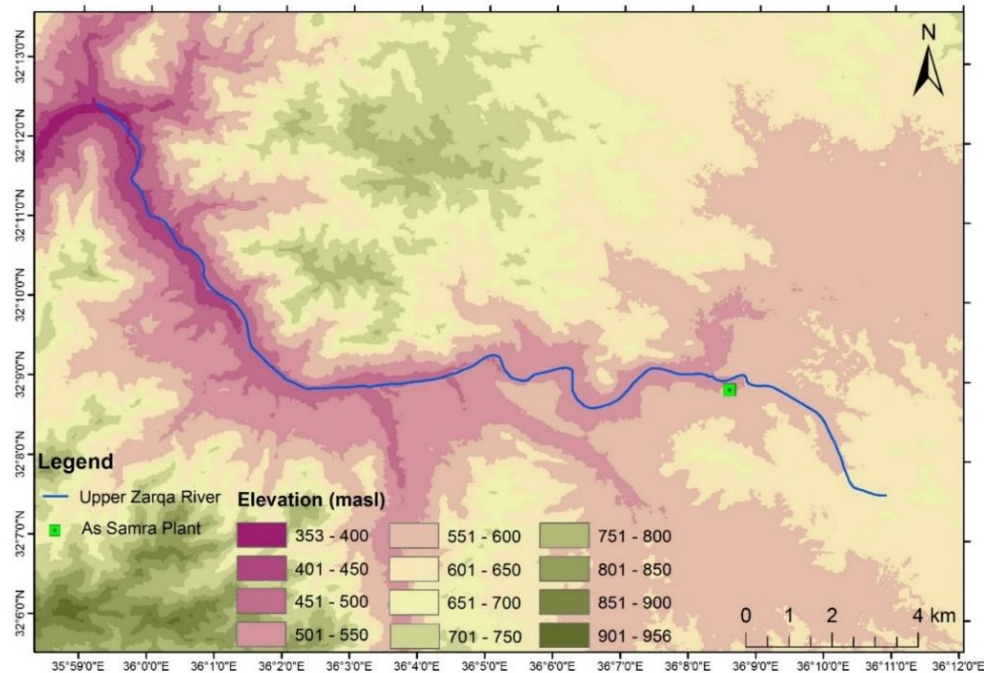


Figure 3. Topographical map of upper Zarqa River.

*Data source: shapefiles from MWI, 2016b*

### Climate

The climate of the catchment is characterized by a Mediterranean climate with hot, dry summers and moderately cool, wet winters (Hammouri et al., 2015). The AZB receiving an average annual precipitation of about 237 mm is bordered by Jordanian Northern highlands in the west and foothills of the Jabal Al Arab in the northeast that signify the water divide of the basin. Therefore, the basin is situated in a rain-shadow region where the moist air masses can only enter through Zarqa River Valley from the west and near Mafraq 20 km north of the study area (Al Mahamid, 2005).

The catchment extends across arid and semi-arid zones. The eastern catchment, which comprises around half of the total catchment area, receives a yearly average amount of precipitation of 182 mm, whereas the western catchment, comprising the highlands and Jordan Valley area, receives a yearly average precipitation rate of 397 mm (MERWRA, 2015). This scenario explains the variability of climates varying from semiarid in the western highlands to arid in the eastern parts of the study area (Al Mahamid, 2005). Figure 4 clearly stipulates the high spatial variability of precipitation from the east to the west region.

The average daily temperature in the basin is 12.4 °C during the wet season, which runs from November to April, and 23.2 °C from May to October during the dry season. In the study area, the prevailing wind direction is west-southwestern in winter and shift to west-northwestern in summer. The average daily relative humidity varies from 65.2 to 82.6% in winter and from 59.2 to 71% in summer (Al Mahamid, 2005). The unique transitional climate, as a result, creates an ideal microclimate which favours continuous agricultural activities along the river.

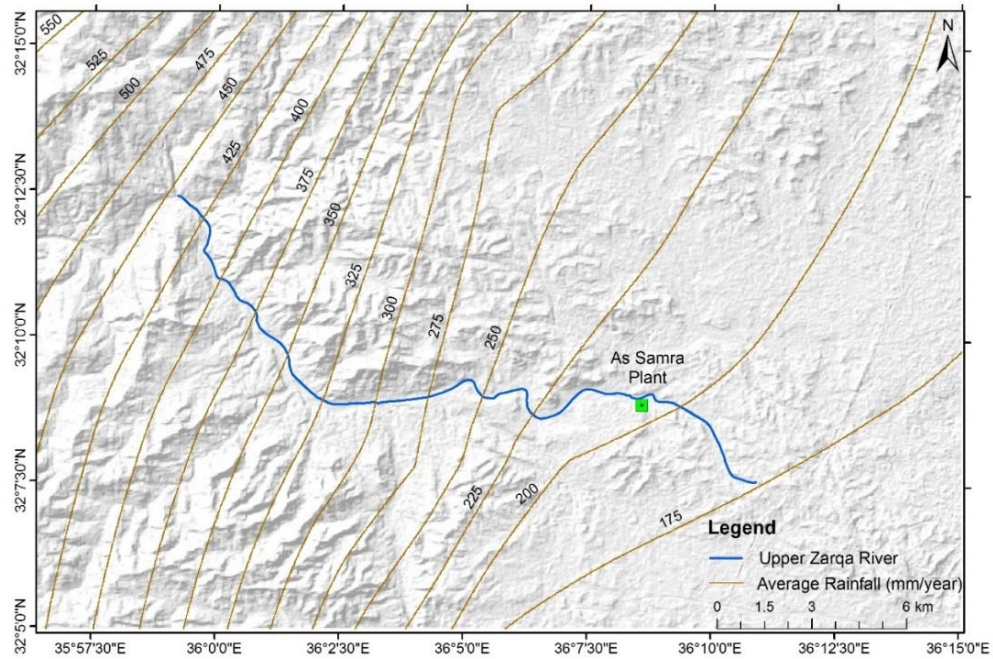


Figure 4. Precipitation of upper Zarqa River.

*Data source: averaged rainfall rates over 40 years obtained from MWI, 2016b*

Owing to high temperatures, low topographic elevation, and presence of green cover, it is estimated that the evapotranspiration within the study area is high (El-Rawy et al., 2016). The potential evaporation ranges from 1600 mm annually along the western highlands to 2000 mm annually in the eastern part of the study area. In fact, the lack of water does not satisfy the needs of the evaporation force of the climate, which is less during the winter months than the summer months. This occurrence enables the infiltration of precipitation water and recharges the groundwater during rainy season (Al-Abdallat, 2011).

## 2.2 Geological Setting

The outcropping formations in the AZB range from Triassic sandstone to recent alluvium. Figure 5 demonstrates the simplified geological map of the upper Zarqa River, derived from the local names listed in Table 1.

Hummar Formation, also known as the Late Cretaceous carbonates, are prevalent in the surface geology of the catchment. This unconfined limestone Hummar unit forming the upper aquifer in the study region is poorly karstified and is directly fed by the streaming water. Thus, the porous medium is subjected to main water-bearing formation. The Na'ur Formation representing the aquitard that is dominated by clay and silt layers, separate the upper aquifer system of Hummar from deep sandstone aquifer system, containing saline water with a high salinity of 2500 mg/L (El-Rawy et al., 2016).



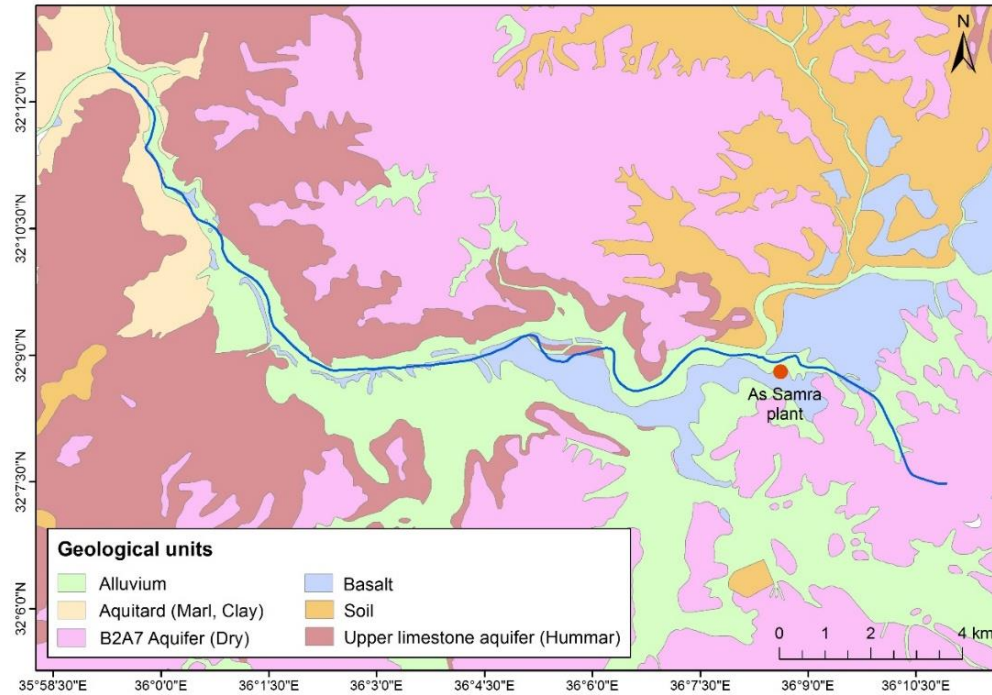


Figure 5. Simplified geologic map of upper Zarqa River.

*Data source: shapefile from MWI, 2016b*

Table 1. Composition of geological units in study area based on local names.

Acronym	Geological unit	Rock type	Group
ASL	Amman Silicified Limestone	Calcium carbonate, $\text{CaCO}_3$	B2/A7
WSL	Wasi as Sir Limestone		
WG	Wadi Umm Ghudran		
NL	Na'ur Limestone	Marl, clay, silt	Aquitard
PI	Fluviatill and Lacustrine Gravels	River gravels, superficial gravels, silts	Alluvium
Alf	Alluvial Fan		
AI	Alluvium and Wadi Sediments		
AOB	Abed Olivine Phyric Basalt	Scoriaceous basalt, volcanic plugs	Basalt
H	Fuhays/Hummar/Shu'ayb	$\text{CaCO}_3$	Hummar

*Source: Self-elaborated based on Al-Qaisi et al., 2010; El-Rawy et al., 2016*

## 2.3 Land Cover and Land Use

Figure 6 represents the classification of land cover in the upper course of the river. The region of interest represents a transitional area between semi-arid highlands in the west and arid desert in the east (Hammouri et al., 2015). The variation in altitudes is not only reflected in the climatological changes but also in various land use patterns. Prevalent irrigation activities can be seen along the river. Its minimal inclination compared to downstream, the presence of productive land, and the ideal microclimate resulting from different climatic zones allows high irrigable areas.

The distribution of soil types in the basin includes Huwaynit (WAY) and Zumlat (ZUM) soil, which dominate the eastern and northeastern parts of the study area (Al Mahamid, 2005). There is abundance of lime and gypsum. The surface layers of most of these soils composed of various kinds of deposits that are coarse textured and low in organic matters.

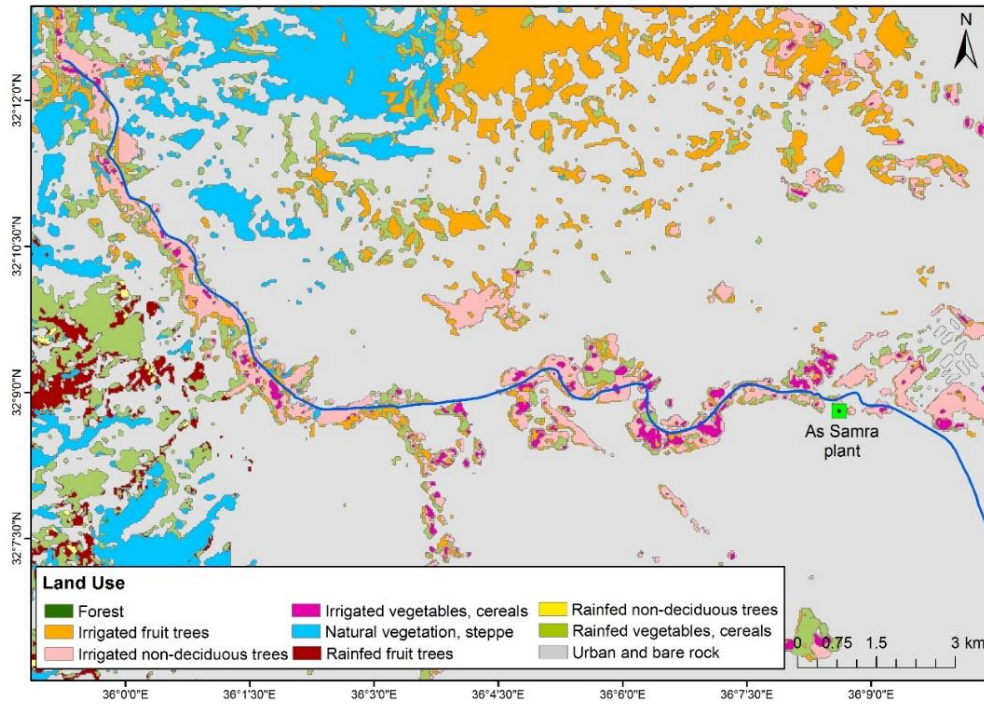


Figure 6. Land use map of upper Zarqa River.

*Data source: shapefiles from MWI, 2016b*

## 2.4 Water Resources

Figure 7 exhibits the tributaries of the upper Zarqa River. The river system contains two divisions: Wadi Dhuleil drains the eastern part of the study area for flood flow, while Sail Zarqa drains the western part of the study region for flood and base flows (Al-Abdallat, 2011). The constant supply of treated municipal wastewater emanates from the As Samra WWTP is the biggest share in water resources which carries more than 78% of the TWW quantities (Al-Zboon & Al-Suhaili, 2009). Spring, which gains groundwater along its whole source, and runoff water also contribute to the source of inflow to the river.

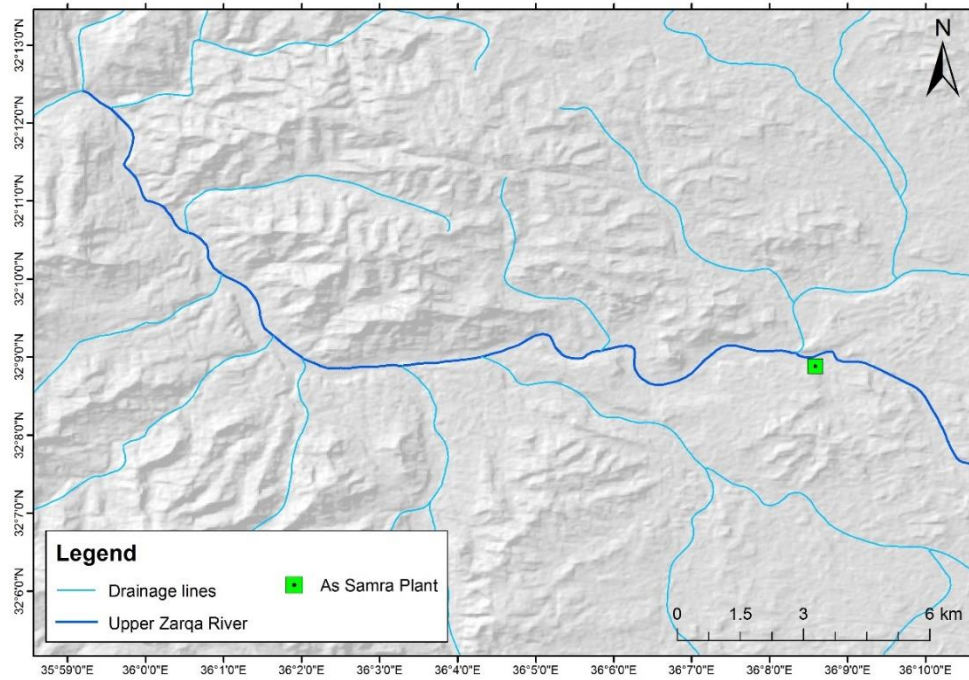


Figure 7. Wadis at upper Zarqa River.

Data source: shapefile from MWI, 2016b

## 2.5 Hydrological Features

Relating to the special hydrological regime of the Zarqa River system, losing and gaining sections of the river can be identified (El-Rawy et al., 2016). Figure 8 illustrates the cross section of the river from upstream to downstream.

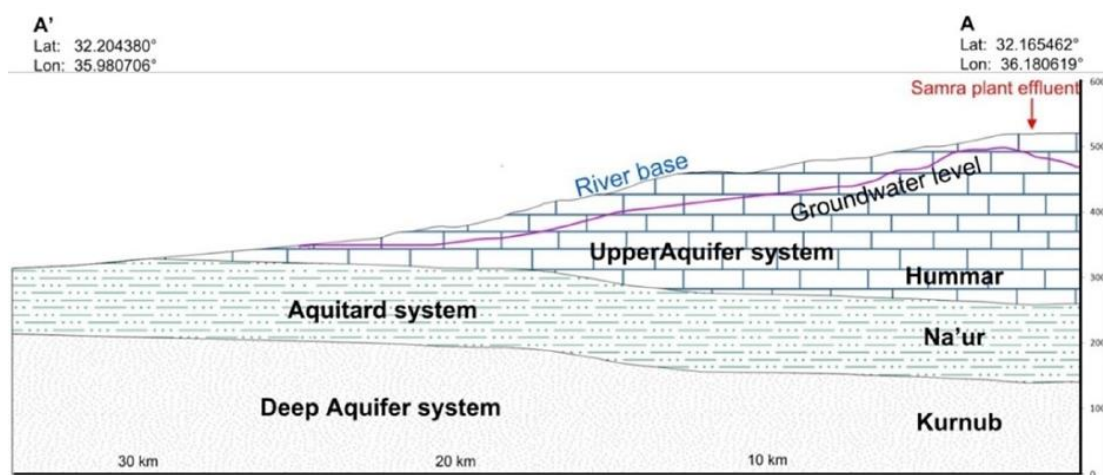


Figure 8. Cross section along the Zarqa River.

Source: El-Rawy et al., 2016

It is worth mentioning that the river regime of Zarqa River has two different unique systems, namely:

**Losing stream:** The first 22 km represents the losing section, where groundwater level is low and the river water feeds the groundwater.

**Gaining stream:** Further downstream represents the gaining section of the river, where water level is high in the groundwater, wherein the groundwater from deep aquifer feeds the river.

The phenomenon of losing and gaining depends on the water table which is based on dry or wet seasons. For instance, in the winter time, groundwater increases due to the recharge from precipitation. As a consequence, the elevated groundwater table feeds the river, and vice versa.

## 2.6 Socio-economic Features

The AZB, which makes nearly four percent of Jordan's region (Al-Omari et al., 2009), is the most heavily populated basin in Jordan. It hosts more than 60% of the total population of Jordan (Al-Wer 2009). The distinct climate variation from wet to dry leads to different land use patterns, higher accumulation of communities, and large changes of the presence of the habitat, as well as various socioeconomic practices such power generation and oil refining (Al Mahamid 2005; Al-Abdallat, 2011). Nonetheless, agricultural sector is still dominating the socio-economic landscape of Zarqa River Basin.

Within the study area, TWW is used predominantly for irrigation activities such as trees, vegetables, and cereals, which are subjected to soil suitability and the farmer's culture (SQU & UJ, 2015). The irrigated areas in the Zarqa River region is enumerated in Table 2, providing an overview of the agricultural development in the region. Figure 9 demonstrates the upstream and downstream irrigated areas within the Zarqa River area. Due to extreme upstream and downstream topographic difference, upstream mountain has more irrigated areas compared to the steep downstream which has scattered and scarce agricultural land.

Table 2. Proportion of irrigated areas in the Zarqa River region.

<b>Farming activity</b>	<b>Area (m<sup>2</sup>)</b>	<b>Percentage Coverage (%)</b>
Irrigated non-deciduous trees	15499.10	43.45
Irrigated fruit trees	12150.38	34.06
Irrigated vegetables, cereals	6559.74	18.39
Forest	1465.85	4.11

Source: SQU & UJ, 2015



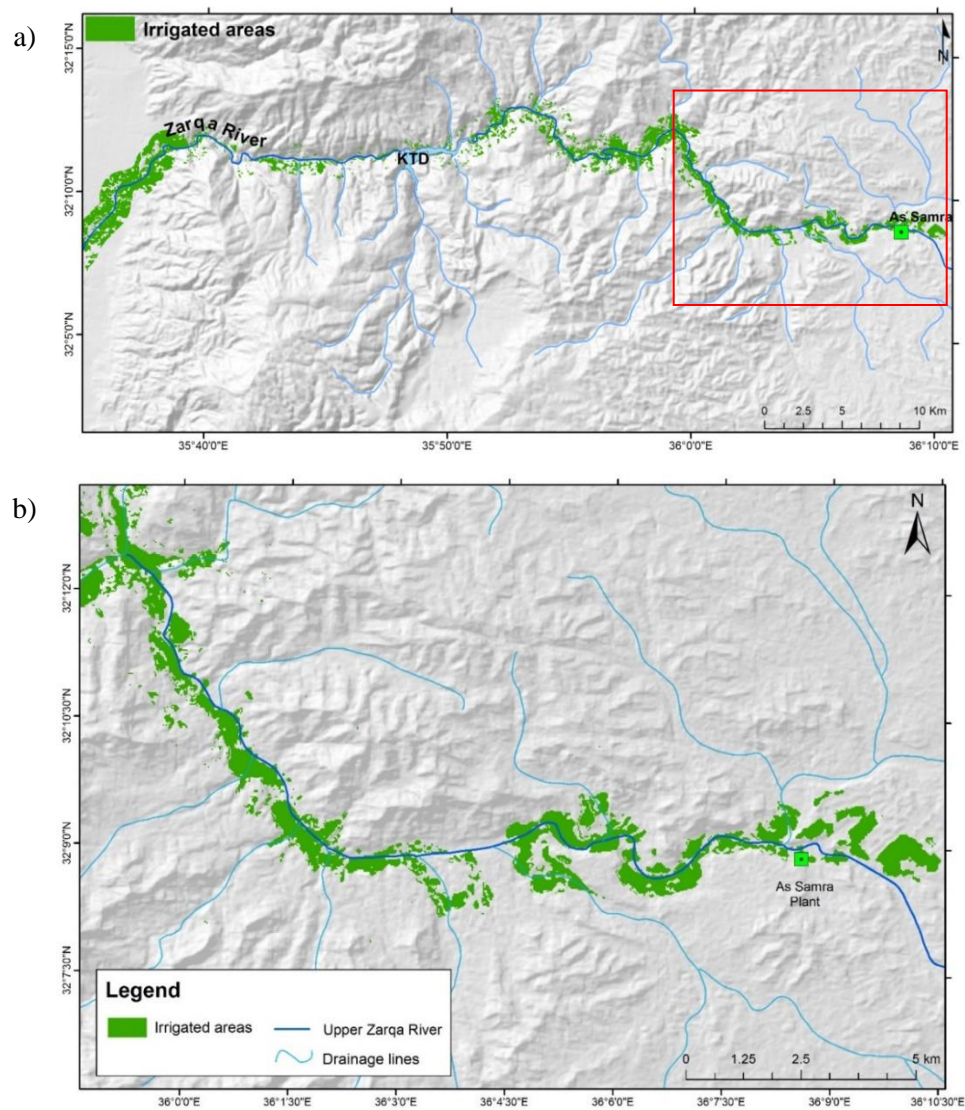


Figure 9. Comparison of irrigated areas along the river course: a) downstream and b) upstream of study region.

*Data source: shapefiles from MWI, 2016b*

## 2.7 Historical and Current Situations

The upper Zarqa River was confronted with severe environmental degradation in the past. The changes of the state of the river pertaining to quality and quantity are evident before and after the establishment of the As Samra plant.

### *Quality wise*

Dated from 1985 to 2008, the remarkable impact of the effluent from the As Samra plant was reflected negatively on the water quality of the Zarqa River and its ecosystems. The basin was intensely industrialized as it hosted about 85% of the industries (Al-Wer, 2009): for instance, paint, textile, pigment, and Pepsi Cola industries, where industrial effluents were discharged into the river. High level concentration of toxic components can be detected in the Zarqa River. The deteriorated water quality, as evidenced by high COD, high total nitrogen, and high total phosphorus, has

prompted the Jordanian Government to close down most of the industries. Apart from that, prior to the construction and expansion of As Samra WWTP, the small designed capacity of WSP was often overloaded. The occurrence of flood tended to wash untreated sewage from the WSP into the river. By the end of 2008, the upgrade of As Samra plant to activated sludge system producing better effluent quality has prevented the water quality from further declining (Myszograj & Qteishat, 2011; Al-Omari et al., 2013).

#### *Quantity wise*

Before 1950s, the natural springs gained GW along its whole course constituted as prime input to the river (Al-Wer, 2009). Groundwater pumping activities in the catchment escalated since 1960s and triggered severe drop in the groundwater level. The interaction or intersection between groundwater table and topography was lowered to a lower level and the springs were diminished. The Zarqa River system was nearly dried in the late '80s and the discharge of low productivity springs along the river was the only water in the system. Figure 10 exhibits the historical discharge records from the Zarqa River. In 1960s, the baseflow was  $2.0 \text{ m}^3/\text{s}$ . The baseflow is further declined to less than  $0.2 \text{ m}^3/\text{s}$  in the early 1980s. After the establishment of As Samra plant in mid-1980s, the river is heavily affected by the treated effluent from the plant, which is now a vital resource of water in the Zarqa River Basin. The availability of more than 110 MCM of permanent annual flow within the river system recovered the discharge along the river course (Myszograj & Qteishat, 2011). This, in turn, augments the groundwater levels through recharge which will be discussed in section 6.5.

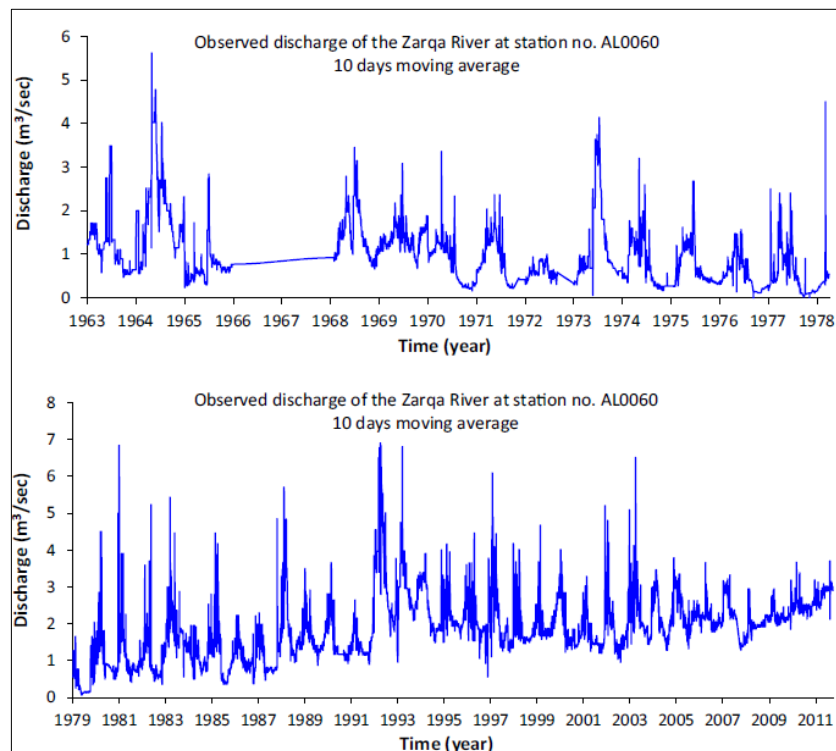


Figure 10. Historical discharge records of Zarqa River.

Source: El-Rawy et al., 2016

### 3. Literature Review

Chapter 3 aims at providing information related to TWW reuse, based on the presented research orientation for readers to gain an overview on the development of TWW reuse in a local context. This review is designed to provide the readers with an understanding of the past, current, and future issues concerning TWW reuse practice.

#### 3.1 Wastewater Treatment Plant and Reuse in Jordan

The first sewerage system in Jordan was established in 1970. Dated back to early the 1980s, the general approach has been to treat the wastewater and either: discharge it to the environment where it blends with fresh water or; reuse it directly or indirectly (Ulimat, 2012). Since 1994, Jordan has doubled its wastewater treatment capacity. The population in Jordan has increased dramatically from 0.58 million in 1950 (Kamel & Nada, 2008) to 9.5 million in 2015, including 2.9 million guests (Ghazal, 2016). This phenomenon, in combination with an expanding urban development resulting from rural to urban migration and increased modernization (Ammary, 2007), has contributed to the growth of wastewater production from the wastewater treatment facilities. Today, about 62% of the population are equipped by sewerage systems producing nearly 100 MCM effluent per year (MWI, 2009). Figure 11 portrays the rising volume of TWW coming from the domestic source due to high population growth and increased sewerage area.

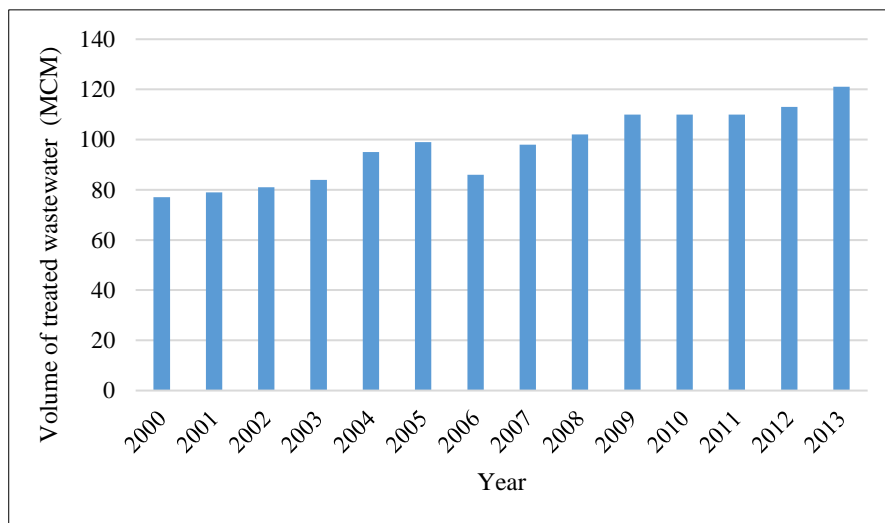


Figure 11. Volume of TWW from municipal source from 2000 to 2013.

*Data source: MWI, 2013*

As of 2013, the country has 31 operating wastewater facilities applying different types of treatment systems (MWI, 2013). Figure 12 illustrates the existing WWTPs in Jordan. The most important of these, the As Samra WWTP with a designed maximum capacity of 364,000 m<sup>3</sup>/day (MWI, 2013), treats more than 70% of the total wastewater treated in Jordan (World Bank, 2016) which forms a crucial component of Jordan's water resources. The treatment processes of this largest WWTP will be described at section 3.3.

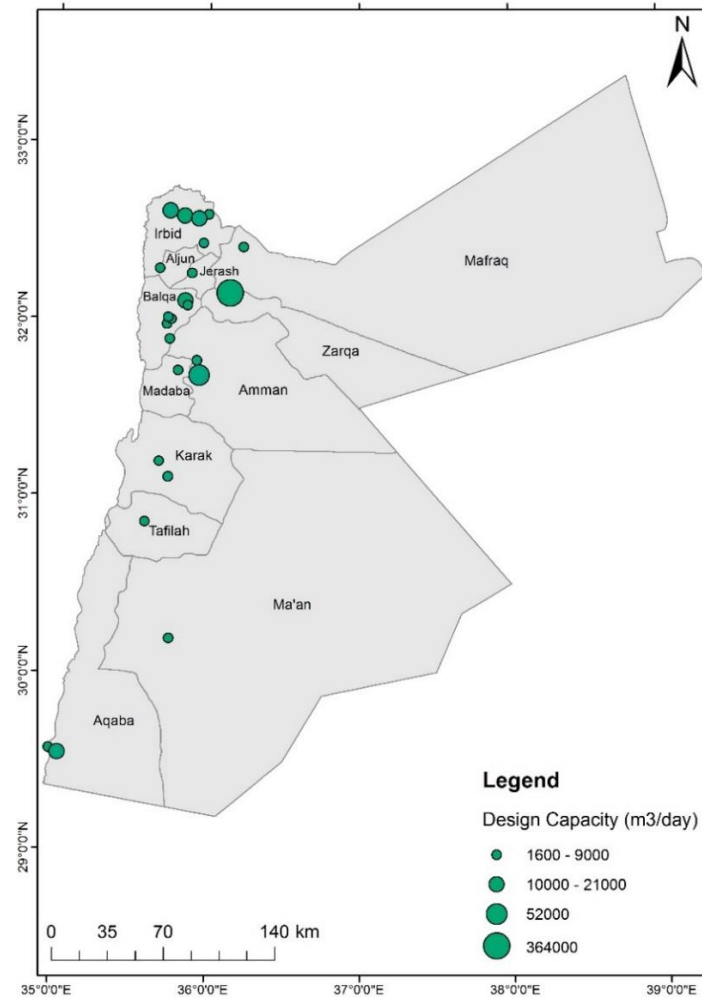


Figure 12. Location sites of main wastewater treatment facilities in Jordan.

*Data source: shapefiles from MWI, 2016b; geographical coordinates of WWTPs obtained from Google map, 2017*

The applied technologies and their design capacities are listed clearly in Appendix 1. Referring to Appendix 1, the systems are mainly composed of activated sludge, tricking filter, and WSP. Most of the treatment facilities with WSP system have been replaced to activated sludge processes in order to produce better quality of effluent on one hand, and increase the public acceptance for wastewater reuse on the other (Ulimat, 2012).

Jordan's mastery over TWW reuse in irrigation has lasted more than 30 years (Carr et al., 2011). Considering the prevailing aridity in the country, accompanied by increasing water demand, wastewater reuse has gained growing attention. The effort from the highest level of Jordan government integrating the adaptation of non-conventional water as part of the water supply-demand budget has urged the decision makers in the water sector to make use of the TWW economically and effectively to promote further development (Husain, 2010; MWI, 2016).

In order to meet the current standards and World Health Organization (WHO) guidelines as a minimum requirement, the wastewater is treated up to the secondary level, primarily for agricultural use. The irrigation water usage in Jordan had constituted about 66% of the overall uses in 2004 (NWMP, 2003). Figure 13 illustrates the practice of direct and indirect reuse of TWW in the AZB.





Figure 13. Illustration of TWW reuse practice in AZB.

*Source: after Google Earth image, 2017*

Indirect TWW reuse is exemplified in Jordan Valley. The reclaimed water generated from the As Samra WWTP discharges into the Zarqa River, mixing with freshwater in King Talal Dam downstream the river. The water that exits from the dam is further blended with water from King Abdullah Canal at Deir Alla area and is channelled to Jordan Valley. In fact, more than 60% of crops were irrigated with TWW in the Jordan Valley in 2011 (World Bank, 2016). On the other hand, direct TWW reuse is performed in the vicinity of As Samra plant where the upper Zarqa River receives the TWW without freshwater mixing, and is directed onto the land for irrigation activities.

In Jordan, approximately 61 MCM of the total TWW are impounded in reservoirs and are subsequently used indirectly for unrestricted agriculture in the Jordan Valley; conversely, roughly 45 MCM are used directly for restricted irrigation (Ulimat, 2012). The widespread application of TWW in Jordan has been realised by the development of guidelines and standards concerning TWW reuse, which will be discussed next.

### 3.2 Existing Guidelines and Standards in Jordan related to Treated Wastewater Reuse

For the past several decades, Jordan has worked to manage wastewater irrigation. Given the increasing population growth in the country, Jordan is in the process of rehabilitating and expanding its WWTPs as well as exploring alternatives for smaller communities. When the volume of TWW is increased, appropriate standards and guidelines need to be developed, revised, reviewed, and adopted to rely on reclaimed water as a resource. Suitable standards governing the water reuse are an important requirement because they serve to manage water reuse effectively (McCornick et al., 2004; Ulimat, 2012). Of primary importance is the need to protect environment on one hand, and guarantee public health on the other.

Several sets of realistic standards and guidelines have paved the way within this domain. To date, standards and guidelines regarding wastewater, sludge, and crops have been formulated from the

effort of several authorities and other related organizations that are MWI, Water Authority of Jordan, Ministry of Health, Ministry of Agriculture, Ministry of Environment (MOE), Jordan Valley Authority, and Jordan Food and Drug Administration. The control reuse of TWW is, thereafter, evident in the Jordanian legal documents such as Wastewater Management Policy of 1997 and Water Authority Law No. 18/1988 and its Amendments, highlighted that “*wastewater shall not be disposed of; instead, it shall be a part of the water budget*” (Seder & Abdel-Jabbar, 2011). This section focuses on the existing guidelines and standards that directly apply to wastewater reuse, which are as follows:

#### *Jordanian Standard 893/2006 for Discharge of Treated Domestic Wastewater*

Remarkably, the very first Jordanian Standard (JS) regulating the use of TWW was issued in 1995 (JS for Water Reuse, JS 893/1995), preceding the well-known Health Guidelines for the Use of Wastewater in Agriculture and Aquaculture published by WHO in 1989. The standard prescribed limits for specific reuses of TWW and discharge in different media (McCornick et al., 2004). In 2003, the water reuse standard is revisited, resulted in JS 893/2003.

The revision of JS 893/2003 had led to pronouncement of JS 893/2006, which is regarded as the principal requirements for establishing effective TWW reuse in productive agriculture (Husain, 2010). The updated standard describes the ideal quality of the TWW to be discharged into streams. Further, it defines the various use of TWW based on the quality of the water source, in terms of chemical and microbial qualities. The JS 893/2006 stipulated limits for each of the six following uses of treated domestic wastewater:

1. Irrigation of vegetables eaten cooked
2. Irrigation of fruit and forestry trees, crops and industrial products
3. Irrigation of fodder crops
4. Irrigation of cut flower
5. Discharge to streams, wadis and reservoir
6. Groundwater recharge

In other words, the raw wastewater discharged to 31 WWTPs has to be treated for minimum discharge standards, and reuse requirements promulgated in the JS 893/2006. The revised standards enable for a wide spectrum of water reuse dimensions including, where economic conditions permit, for landscapes, cut flowers and high-value crops, and for lower cost smaller-scale treatment and reuse activities with restricted cropping patterns (Ulimat, 2012).

#### *Jordanian Standard 1145/2006 Uses of Treated Sludge and Sludge Disposal*

Since 1996, the beneficial uses of treated sludge or biosolids have been enacted in the standard. The JS 1145/1996 for biosolids reuse in agriculture has been modified in 2006 in order to be applicable to the conditions of Jordan. The current standard specified the production and reuse of biosolids as organic fertilizer for enhancing soil fertility in agricultural lands or to be disposed of in landfills, applications procedures, and rates that are suitable in the context of local conditions as well as potential locations for land application (LeBlanc et al., 2009). The maximum elements concentrations in the biosolids including chemical, physical, and pathogenic concentrations of each type of biosolid

are stated in JS 1145/2006 for different applications. Notably, the existing standard requires the analysis of *Salmonella* and intestinal pathogenic nematodes counts.

Although the quality of treated sludge in connection with reuse practice is a major concern to the end users, systemic data concerning the quality and quantities of biosolids generated are not in place. Further, the treatment, handling, and management practices in general are not well documented (Suleiman et al., 2010). Therefore, the subject of reusing treated sludge is not favourable through public acceptance and in institutional and legal aspects.

### 3.3 As Samra Plant

In the 1980s, As Samra plant produced 30 to 40 MCM of TWW in the initial phase. The plant often overloaded, owing to insufficient capacity to treat the increasing TWW rates, and had contributed to deleterious effects on the Zarqa River water quality. Due to the low performance of the old treatment system, the plant was upgraded to activated sludge system by the end of 2008. At the present time, the TWW generated is more than 110 MCM. As Samra now treats all wastewater per JS, and the effluent water released into Zarqa River is of better quality than the water released during the initial stages of the plant. In general, activated sludge system produces effluent with low organic contents, medium nutrients (N, P), and medium to low pathogens (Kretschmer et al., 2006). Al-Omari et al. (2013) researched that the water quality of Zarqa River has improved significantly after the As Samra plant upgrade, showing reductions in the COD, total phosphorus, and total nitrogen. This has been a top priority for Jordan's Ministry of Environment and a key element of the country's long-term water resources management strategy. Figure 14 shows the aerial view of the plant obtained from Google Earth image.

The incoming wastewater from Zarqa and Hashimiyya pumping stations of the plant are distributed into grit and sulfide removal chambers:

- Each grit removal tank has an average hydraulic residence time of 17 minutes. Air is introduced at the bottom of the grit chamber, resulting from the settling of heavy particles. These particles are collected by a screw and discharged into grit classifier. Air bubbles cause oil, grease, and scum to float on the surface. It is then collected in a scum pit and pumped to the digesters.
- A sulfide removal tank is composed of two aerated zones in series. Ferric chloride acts as a catalyst is added for the sulfide removal. The settled water is then distributed into primary settling tanks.

These tanks remove about 65% of the total suspended solids and 40% of the BOD<sub>5</sub>. Oil and grease are skimmed and collected in the scum chamber. The settled water from the primary settling tanks is distributed into biological reactors consisting of three zones:

- i.) Anoxic zone for exogenous denitrification.
- ii.) Oxidic zone where air is introduced constantly through air diffusers to remove BOD<sub>5</sub> and initiate nitrification.
- iii.) Endogenous zone where air is introduced intermittently for complete nitrification.



Figure 14. Aerial view of the As Samra plant.

*Source: Google Earth image, 2017*

The effluent of the activated sludge process is then distributed into secondary clarifiers. Bio-suspended solids are separated, and the settled sludge is thickened and recycled to the aeration tanks. The clarified effluent of the secondary settling tanks flows to plug flow chlorine contact basins, where it contacts with chlorine for about 35 minutes for its final disinfection stage to meet the JS 893/2006 (Suez, 2008; Myszograj & Qteishat, 2011).

### 3.4 Treated Wastewater Reuse in Agriculture

As stressed beforehand, TWW reuse brings multifaceted benefits. This practice is viewed as a promising means to alleviate the escalating pressures on the freshwater resources, especially in water stress regions. On top of that, the high nutritive values of the reclaimed water supplies essential nutrients to the crops, contributing to high crops productivity. Rusan et al. (2007) revealed that the application of wastewater irrigation contributed to the diverse organic content in the soil due to the nutrients-containing TWW. The organic matter (Becerra-Castro et al., 2015) and the micronutrients are beneficial for soil integrity as they improves the water retention capacity of soil, which in turn affects the drainage properties. These valuable nutrients are necessary for the production of agricultural crop. A pilot project, in regard to the utilization of tertiary TWW from Saham WWTP in forage production, was conducted in Oman; in this project, the cultivation of forage crops such as sorghum, maize, and barley was monitored, and crop rotation and drip irrigation system were practised. It was observed that the forage yield of sorghum and maize was increased by 30%, and the barley crop produced, with taller plants and higher grain yield, grew 43% more, in comparison with that resulting from using fresh water. Notably, the contents of toxic elements in the plant tissues of the fodder produced were found to be below the safe limits recommended (SQU & UJ, 2015). Under the influence of TWW, fodder tends to show high productivity and tolerant to high salinity. The high agricultural outputs influenced by TWW irrigation regimen is also reflected in a studies conducted by Rusan et al. (2007), where an increase in biomass production barley was reported. In terms of agronomic benefits, a Palestinian case study was presented by Yaqob et al. (2015), who studied the cost and benefit analysis of TWW reuse. The results indicated that use of TWW in agricultural



irrigation is economically feasible, where the use of one MCM of TWW in palm cultivation resulted in financial returns of USD\$2 million. Meanwhile, irrigation of fodder, olive, and almond trees achieved about USD\$1 million per MCM of TWW.

Nevertheless, TWW reuse is often associated with environmental and health impacts in respect to pathogens, heavy metals, and micropollutants. This subject always remains to be the interest and priority of researchers, owing to the issuance of the standards and guidelines in relation with the reuse of such resources. The following parts describe the important health aspects in connection with the reuse.

### *Pathogens*

Domestic wastewater containing pathogens, if managed improperly, is most likely to cause disease spread (Westcot, 1997). A number of pathogenic microorganisms can be present in the wastewater including bacteria, viruses, helminths, and protozoa, which are capable of long survival, and even multiplication for days, weeks and at times months in various environmental domain (water, crop surface, soil) that come in contact with wastewater and allow transmission to humans (WHO, 2006). Therefore, understanding the survival time of pathogens and how they infect a host are of utmost importance. Table 3 exhibits the survival periods of a range of organisms to illustrate the fate of pathogens transmission.

Table 3. Survival times of the excreted pathogens.

<b>Pathogen</b>	<b>Survival time (days)</b>
<b>Viruses</b>	
Enteroviruses	<120 but usually <50
<b>Bacteria</b>	
Thermotolerant coliforms	<60 but usually <30
<i>Salmonella</i> spp.	<30 but usually <10
<i>Shigella</i> spp.	<30 but usually <10
<i>Vibrio cholerae</i>	No Data
<b>Protozoa</b>	
<i>Entamoeba histolytica</i> cysts	<30 but usually <15
<i>Cryptosporidium</i> oocysts	<180 but usually <70
<b>Helminths</b>	
<i>Ascaris lumbricoides</i> eggs	Years
Tapeworm eggs	Many months

Source: WHO, 2006

After gaining an overview of the survival intervals of various pathogens, it is also imperative to note the effectiveness of the organisms to induce infections. Table 4 outlines the epidemiological model of the related pathogens and their associated health risks. Notably, helminth eggs are the most resistant pathogens in the environment as the survival time last for years, especially in the soil.

Table 4. Effectiveness of enteric pathogens causing infections associated to their epidemiological characteristics.

Enteric pathogen	Persistence in environment	Minimum infective dose	Infection routes	Soil development stage	Potential health risks
Virus	Medium	Low	Home contact; Consumption	No	Gastrointestinal illness, gastroenteritis, diarrhoea, vomiting and cramps
Bacteria	Short/ Medium	Medium/ High	Home contact; Consumption	No	<i>Salmonella</i> spp.: Typhoid fever, Salmonellosis, gastroenteritis, diarrhoea, long-term sequelae (e.g. arthritis)  <i>Shigella</i> spp.: Shigellosis (dysentery), long-term sequelae (e.g. arthritis)  <i>Vibrio cholerae</i> : Cholera
Protozoa	Short	Low/ Medium	Home contact; Consumption	No	<i>Entamoeba histolytica</i> cysts: Amoebiasis (amoebic dysentery)  <i>Cryptosporidium</i> oocysts: Cryptosporidiosis, diarrhoea, fever
Helminth	Long	Low	Mainly soil contact	Yes	<i>Ascaris lumbricoides</i> eggs (roundworm): Ascariasis  Tapeworm eggs: Taeniasis

Source: after Shuval et al., 1986; WHO, 2006; EPA, 2016

According to WHO (2006), global mortality due to some diseases of relevance to wastewater use in agriculture, such as diarrhoea, 90% of deaths occur in children, especially in developing countries. However, research carried out by Lonigro et al. (2015) demonstrated that TWW irrigation is realistic. Treated municipal wastewater produced from membrane bioreactor treatment plant was utilized for irrigating different vegetable crops such as cucumber, lettuce, melon, and fennel. The crop water requirement was calculated, the crops were alternated, drip irrigation was applied, and agronomical practices such as fertilization, and pest and weed control were monitored. The outcomes from two years of such experimental field activities have shown a promising agronomic result, where crop yields irrigated with TWW were higher compared to those yielded from conventional water being pumped from the wells; the microbial indicators such as *Escherichia coli* (*E. coli*) and *Salmonella* were never found on edible parts of the TWW irrigated crops and in the soil during harvesting time.

## Heavy metal

Heavy metals pose another potential health threat that also stems from the plant-based uptake of contaminants. Heavy metal refers to any metallic chemical elements that have a relatively high density and are toxic or poisonous at low concentrations. Cadmium (Cd), copper (Cu), nickel (Ni) are often present in wastewater and can be mobilized easily and absorbed by plants. Figure 15 illustrates the heavy metal uptake mechanisms in phytoremediation technology. The uptake of heavy metal by plants are a complex mechanism. However, the main interest of this study is phytoextraction, the uptake and translocation of contaminants by the roots of plant into the plant shoots (Tangahu et al., 2011). In this regard, health risks arise with the consumption of these heavy metal-contaminated vegetables over a long period of time. The accumulation of toxic chemicals present in an elevated concentrations may result in significant morbidity and mortality to the crops and consumers in a long term.

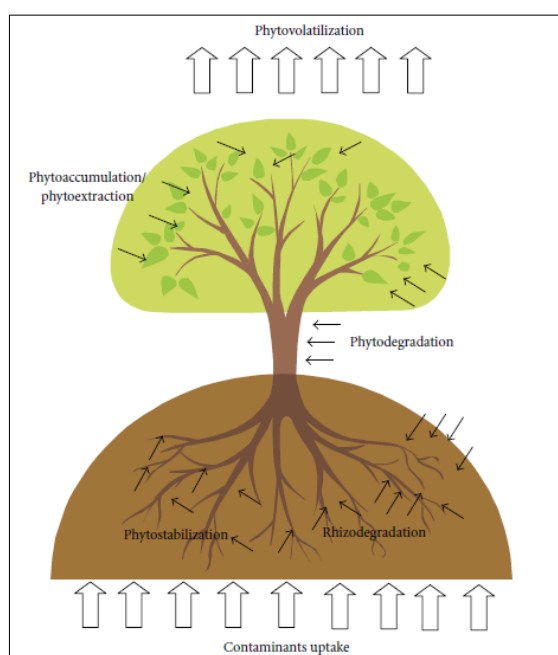


Figure 15. Schematic representation of plant-based contaminants uptake.

Source: Tangahu et al., 2011

Appendix 2 stipulates the recommended maximum concentrations of trace elements in irrigation waters by Food and Agriculture Organization (FAO). If the amount of heavy metal exceeds the action level, it may lead to fatality. Table 5 describes the signs and symptoms of diseases attributed to heavy metals, namely Cd, chromium (Cr), Cu, Ni and lead (Pb).

Table 5. Health implications caused by heavy metals.

Heavy metal	Sign and symptom
Cd	Kidney damage Softening of bone Skeletal damage Possibly cancer development

Cr	Allergic dermatitis
Cu	Short term exposure: gastrointestinal distress Long term exposure: liver or kidney damage
Ni	Higher chances of development of lung cancer, nose cancer, larynx cancer, and prostate cancer Sickness and dizziness after exposure to nickel gas Lung embolism Respiratory failure Birth defects Asthma and chronic bronchitis Allergic reactions such as skin rashes, mainly from jewelry Heart disorders
Pb	Infants and children: delays in physical or mental development; children could show slight deficits in attention span and learning abilities Adults: Kidney problems; high blood pressure

*Source: after Järup, 2003; Brenner & Hoekstra, 2012; Shivhare & Sharma, 2012*

### *Micropollutants*

Besides heavy metals, the discharged TWW from the As Samra plant has been a major pathway for the introduction of micropollutants to the river. Micropollutants, also known as emerging contaminants, are persistent and bioactive, and they cannot be removed completely in conventional wastewater treatment process. Notably, micropollutants are present in waters at low concentrations, ranging from a few ng/L to several µg/L. These include steroid hormones, pharmaceuticals, personal care products, pesticides, industrial chemicals, and many other emerging compounds. The occurrence of micropollutants in the aquatic environment has become increasing environmental concern as it leads to loss of certain aquatic biodiversity, which does not tolerate deteriorated water quality. The feminization of aquatic wildlife is also likely to happen due to the mutagenic effects of pharmaceutical compounds such as estrogen existing in TWW in trace concentrations (Luo et al., 2014).

Therefore, the abovementioned pathogens are the major considerations in response to dealing with TWW irrigation process. Otherwise, there exists the possibility of upsetting the health of TWW users as well as consumers, as described below:

### *Direct use impact*

Direct use of TWW is centred on the rural health and safety problems of those living and working on wastewater irrigation field such as farmers or agricultural workers. Soil is the helminths' intermediate host prior to re-infecting humans (Toze, 2006). Therefore, soil-transmitted helminth infections or parasitic worms frequently pose the greatest health risk for these target groups. Even with a minimal dose of helminths, it is adequate to infect the vulnerable group (refer Table 4). Due to the repeated exposure of pathogens, particularly in occupational exposure regions, these target groups inevitably get contaminated soils on fingers. When coupled with low sanitation and hygienic practices, soil particles may be ingested. Subsequently, the intestinal nematodes (roundworms) or hookworm resulting from involuntary soil ingestion may cause intestinal obstruction and gastrointestinal upset (WHO, 2006).

### *Indirect use impact*

On the other hand, the public health conditions associated with indirect wastewater use is the risk that contaminated crops, which are irrigated with TWW, may eventually infect humans or animals through consumption or handling of the foodstuff. Also, secondary human contamination, resulting from consumption of animals or animal products that have been contaminated via exposure to wastewater, exists (Westcot, 1997). These vulnerable groups may be subjected to parasitic protozoa on irrigated vegetables surfaces, typhoid, and shigellosis outbreaks (WHO, 2006).

## 3.5 Managed Aquifer Recharge

As previously defined in section 1.1, MAR practice can be taken as an agent to alleviate climate change effects on water resources (Al-Qaisi, 2010). MAR system can be achieved by riverbank filtration (RBT), surface spreading operations (e.g. soil-aquifer treatment (SAT), and aquifer recharge and recovery), or direct injection into a potable aquifer. To demonstrate the feasibility of MAR in Jordan, Wolf et al. (2008) investigated individual test sites in Wadi Kafrein by infiltrating a mixture of TWW and fresh water. The results demonstrated an excellent infiltration capacity of the unconsolidated gravel sediments at the site. El-Rawy et al. (2016) assessed the long-term unconfined aquifer recharge by TWW discharged into the river at field scale at the Zarqa River Basin. Provided the groundwater-surface water interactions, conceptual model was developed, several management scenarios were evaluated, and the studies demonstrated that banking of the TWW coupled with water use management offer a promising practice to enhance the agricultural community in the region.

Although Abdel-Raouf et al. (2012) mentioned that the undesirable constituents present in TWW can cause adverse environmental effects during the implementation of MAR, Mansell et al. (2004) conveyed that endocrine disruptors compounds (EDC) such as steroidal hormones were removed efficiently via SAT through laboratory experiments. These suggested that subsurface systems i.e. RBT or SAT are able to remove EDC, which are of environmental concern. Rauch-Williams et al. (2010) conducted column experiments to illuminate the metabolic removal of trace organic chemicals (TOC) during soil infiltration. This study revealed that the organic matter naturally available in aqueous environment managed to degrade the TOC within the first 2 m of porous media infiltration under aerobic or oligotrophic condition.

To put a final note on that, Drewes (2009) suggested that surface spreading and direct injection are the common techniques for recycled water. As stated by Schmidt et al. (2011), SAT is likely to take advantage of physical and biogeochemical processes during infiltration of secondary wastewater effluent. Depending on local conditions, the simplest and cheapest form can occur where the aquifer is unconfined, soils are permeable, and land is available to construct infiltration ponds (Dillon, 2009).

## 3.6 Limitations of Treated Wastewater Reuse

The safe reuse of TWW for agriculture is constrained to certain practices. In order to maximize the benefits of TWW reuse and protecting public health at the same time, a series of control measures that are listed below must be deliberated. There are, in fact, a host of factors affecting safe TWW

reuse. However, the following points stemming from the review of literature underscore some of the major concerns for safe reuse in agriculture.

*Wastewater treatment:* The impurities that must be removed are subject to the intended use of the water. The chief criteria in the reuse domain, including pathogens, salinity, nutrients, organic matters, and trace metals removal [see WHO (2006, pp. 65) for pathogens reduction (log units) by different combinations of health protection measures]. As previously noted, the required treatment level is highly reliant on the local standards. In general, the recommended treatment in the Mediterranean region for irrigation without restrictions is stabilization ponds with polishing steps and reservoirs; or secondary: filtration (or equivalent) and disinfections; for irrigation of restricted crops, stabilization ponds in series or aerated lagoons, followed by stabilization reservoirs are necessary (Kretschmer et al., 2006).

*Irrigation technique and crop type:* In view of the existing irrigation methods, monitoring of cropping pattern (type of crops to be planted) becomes an important component in case of reuse wastewater for agriculture. In that perspective, the distance of harvested part to the soil shall be minimized to curtain public health risk (Becerra-Castro et al., 2015). Drip irrigation is recommended for low-growing produce. If spray irrigation is employed, crops restriction will be a major consideration. In addition to that practice, a buffer zone of 50 to 100 m is required to protect the residents living in the vicinity (WHO, 2006).

*Pathogen die-off between last irrigation and consumption:* This idea is specifically targeted at the farm level i.e. the farmers' harvesting period. Referring to Table 3, to reduce crop contamination, the provided time for pathogen die-off naturally (the interval between final irrigation and consumption) on crop surfaces shall be sufficient. The other critical factors influencing the die-off are climate, time, crop type and etc. (WHO, 2006).

*Crop handling:* Literature search revealed that water quality is not the solely factor in case of wastewater reuse for agriculture. Crops handling at farm level, for example the technique of crops being harvested, hygienic practices of farmers, and the storage of produce (post-harvesting measures) before they are transported to consumer chain largely affect the likelihood of pathogens regrowth during the entire process (WHO, 2006).

*Food preparation measures:* The particular food preparation practices at household level, for instance washing produce (salad crops and fruits as examples) with clean water, use of a weak disinfectant solution for disinfection purpose, peeling, and/or cooking produce thoroughly with boiling water are one of the approaches to interrupt the flow of pathogens to consumers (WHO, 2006).

In short, a large-scale of safe application and reuse of TWW can be realistic when the above major concerns are taken into considerations in the planning and management of such resource.

### 3.7 Projected Future Scenarios in Zarqa River and As Samra Plant

In the AZB, there are four WWTPs that discharge wastewater into the Zarqa River. Jerash and Baq'a WWTPs are rather small-scale treatment facilities; however, the increase discharge of TWW in the future from these two plants shall be taken into consideration. Reviewing the present situation and

the rapid population growth in the main cities, Amman and Zarqa, and the mega project bringing more than 50 MCM of domestic water to the AZB (Al-Omari et al., 2013), it is implied that by 2025, As Samra being the largest WWTP is projected to reach its maximum capacity i.e. 135 MCM in the coming ten years. As such, the Zarqa River will be likely to accommodate these additional discharge as the volume of the TWW discharge from As Samra plant is projected to increase manifold (MWI, 2001; El-Rawy et al., 2016). Figure 16 stipulates the current and projected discharged effluent to the Zarqa River from different WWTPs.

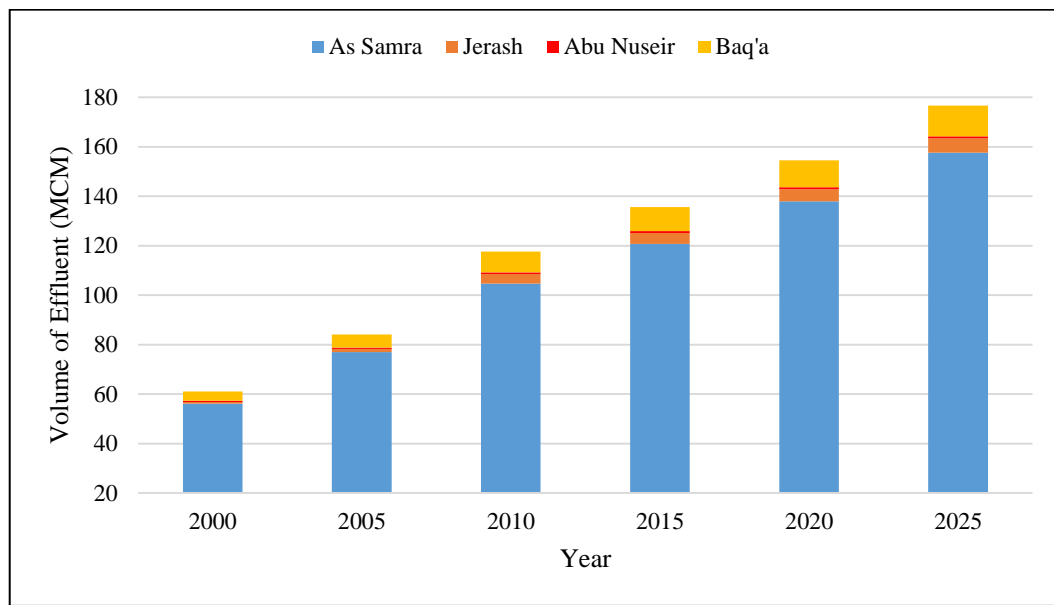


Figure 16. Present and projected quantity of effluent discharge to AZB from different WWTPs.

*Data source: MWI, 2001*

As it was proved that Jordan is facing a raise in temperature and a decrease in precipitation rates, specifically a decrease in rainfall by 20% and a 1 °C rise in the temperature, will likely result in reduction in the recharge to groundwater by 29% (Al-Raggad, 2014). This phenomenon indispensably affects AZB indirectly, particularly the Zarqa River region. Therefore, AZB is subjected to the expected impacts from climate change. Although the effects of climate change remain largely unknown (MWI, 2009), the studies undertaken by Hammouri et al. (2015) in the Zarqa River Basin using SWAT model delivered results that precipitation is the principal factor that had upset the availability of surface runoff water, predicting that the future amounts of runoff are expected to decrease. Al-Qaisi (2010) deduced that the climate change is taking place since early years with an evidence of 12% reduction in annual rainfall in AZB correlated with a decrease in evaporation amount with 1%. This negatively impacts the natural recharge of aquifer from precipitation and surface water runoff, which helps to maintain the water level of producing aquifers. In regards to the abovementioned future scenarios, the knowledge to maximize the use of TWW in a safe manner are opt in order to cope with the expected impact of climatic changes.

## 4. Methodology

This chapter illuminates the steps that were undertaken to achieve the intended objectives as specified in Chapter 1.

### 4.1 Data Acquisition and Analysis

To initiate a research, data collection is inevitably the principal component for the initial phase of a study. The main activities of this study are subdivided into field work and office work. Figure 17 describes briefly how data are collected from various sources.

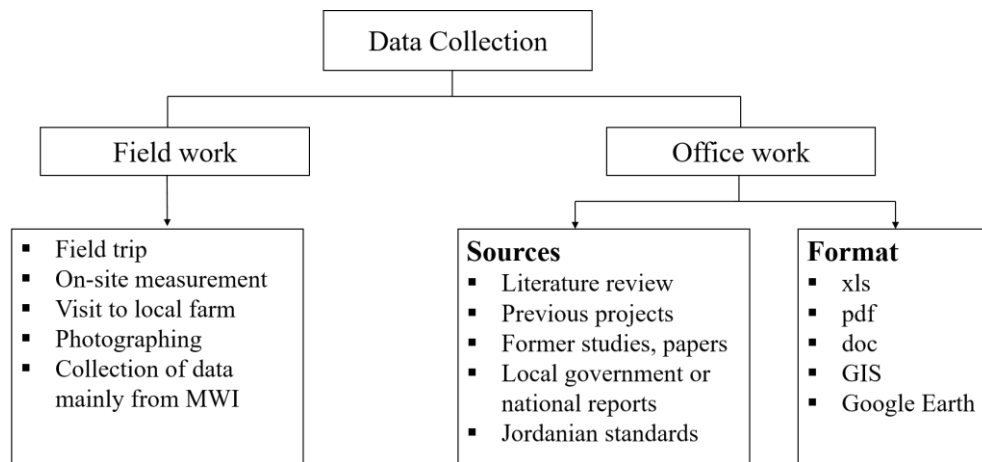


Figure 17. Components of data collection in the present research.

*Source: Self-elaborated*

#### *Field work*

Field trips were carried out in December 2016 and January 2017 to observe the present state of the ground situation of the upper Zarqa River, and to validate the collected secondary data. A professional digital multi meter for mobile measurement (Multi 3410 Set KS1) was used to measure the electrical conductivity (EC) of water samples (treated effluent and groundwater) instantly at the site, as demonstrated in Figure 18.

In order to observe the irrigated crops and have an overview of the current practices of the local community farmer, several visits were made to Abu Shadi's Farm (see Figure 19), which is located approximately 5 km from the discharge site of the As Samra plant. Considering that the farmer invest in his family's land for vegetables irrigation, field measurement was performed in situ by measuring the EC of irrigation water source i.e. the groundwater well in the farm, with the use of the potable water quality kit. Simultaneously, photographs were taken throughout the field trips for the purpose of documenting the study.





Figure 18. Potable water quality kit used for on-site measurement.

*Source: Chan, 2017*



Figure 19. Visit to Abu Shadi's Farm.

*Source: Chan, 2017*

Apart from that, field data, including the questionnaire data, were obtained from Mitigating Environmental Risks of Wastewater Reuse for Agriculture (MERWRA) project (MERWRA, 2015). The questionnaire used focuses mainly on the irrigation water source, irrigation activities, and the farmers' knowledge on TWW reuse (SQU & UJ, 2015). The interview data are used to describe the current practices of a total sample of 27 farms using TWW for different crops within the study area. Furthermore, the observations from the conducted field trips are also incorporated in this section (see section 6.2) to understand the mechanism of TWW reuse at the farm level.

For the purpose of this study, all secondary quality data summarized herein was acquired from the MERWRA project, namely the TWW, irrigated crops, soil, and groundwater to describe the current condition in terms of quality based on various parameters. Besides those sources, the shapefiles of the study area, digital elevation model (DEM), topography, rainfalls, geological units, land cover,

irrigated areas, and groundwater levels of the monitoring wells (AL2700, AL2702, AL3387, and AL3389) were collected from the MWI in Jordan for the purpose of developing inventory of the study region, as elaborated in Chapter 2.

#### *Office work*

Different sources of data were obtained via literature review. This included the previous projects, former studies, and research papers. Local government or annual national reports and Jordanian standards were also reviewed. The related data were acquired in different formats such as Microsoft Excel spreadsheet forms (xls), Portable Document Formats (PDFs), Microsoft Word document files (doc), Geographic Information Systems (GIS) tools, and Google Earth maps.

The questionnaire data were subjected to pie charts. The shapefiles obtained from the MWI are transformed in the GIS environment. GIS tool, ArcMap version 10.3.1, was utilized to delineate the natural settings and the characteristics of the study area in the form of maps, such as the geographical, geological, land use maps, et cetera, based on the data source from the MWI.

#### *Analysis of treated wastewater data*

The TWW samples were interpreted based on chemical and physical parameters. Data for physico-chemical parameters of TWW samples collected by Al-Abdallat (2011) and MERWRA project (MERWRA, 2015) in 2009 and 2010 were used to evaluate the hydrochemical situation. The concentration of the parameters were reported in milliequivalents per litre (meq/L). All the water quality parameters such as pH, EC, BOD<sub>5</sub>, sodium (Na<sup>+</sup>), calcium (Ca<sup>2+</sup>), potassium (K<sup>+</sup>), magnesium (Mg<sup>2+</sup>), bicarbonate (HCO<sub>3</sub><sup>-</sup>), sulphate (SO<sub>4</sub><sup>2-</sup>), nitrate (NO<sub>3</sub><sup>-</sup>), chloride (Cl<sup>-</sup>), phosphate (PO<sub>4</sub><sup>3-</sup>), and chemical oxygen demand (COD) were sampled and analyzed as per standard method of American Public Health Association (APHA). The total dissolved solids (TDS) were calculated mathematically (TDS mg/L = EC  $\mu$ s/cm \* 0.64). Therefore, the interpretation for EC is reflected similarly to TDS.

The hydrochemical data were then subjected to statistical analysis for summarizing the huge amount of data and thereby obtaining chemical relationships between different water quality variables (Bhat et al., 2014). In order to identify the possible source of ions in the surface water samples, it is necessary to investigate the type of water being generated. For this reason, Piper diagram was selected (Piper, 1944). Piper diagram is a multifaceted plot in which milliequivalents percentage concentrations of major cations (Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup> and K<sup>+</sup>) and anions (HCO<sub>3</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, and Cl<sup>-</sup>) are plotted in two triangular fields, which were then projected further into the central diamond field. AquaChem Scientific software (version 2014.2) was used to plot this diagram.

Due to discrete data (absence of measurement in January 2010), the physico-chemical parameters of TWW during the observation period were represented using graphical method i.e. bar charts, combining with MWI data from year 2010 to investigate any water quality changes along the river course in terms of spatial and temporal variations. To assess the quality of TWW, each water quality parameter was compared with the desirable limit of that parameter stipulated for discharge into water body as prescribed by JS 893/2006. The discrete water quality data represents one of the shortcomings of this study. Nonetheless, the present work still serves as a precursor to underscore the importance of giving guidelines to help policymakers in managing water reuse activities effectively in the study region.

#### *Analysis of irrigated crops data*

The crop quality is investigated in this study based on the concentration of trace elements, i.e. aluminium (Al), chromium (Cr), copper (Cu), and lead (Pb), in the most frequently consumed foodstuff in the upper Zarqa River, namely tomato, green pepper, eggplant, cauliflower, cucumber, corn, lettuce, rocca, carrot, and green onion.

Based on the collected data, the system parts of each crop are examined based on the heavy metals plant-uptake. The data were subjected to bar charts in order to compare the uptake of contaminants to address the interaction between TWW irrigation and heavy metal uptake and accumulation by plant in different parts in respect of Al, Cr, Cu, and Pb. The main interest of this study is to gain insight into how ions from the irrigation water are translocated to the system parts of various crops. Subsequently, the *E. coli* and trace elements concentrations are compared with the microbial guideline in WHO and FAO (see Appendix 2) trace elements in irrigation water guidelines respectively, to evaluate for trace element toxicity hazards that could affect the growth of plant, as well as to consumer. In particular, the spatial distribution map of *E. coli* was prepared by ArcGIS (version 10.3.1), to identify if there is any changes in the concentration due to specific reasons, so that safe reuse of TWW can be recommended.

#### *Analysis of soil data*

The elemental concentration in the soil samples with parameters EC, pH, ESP, Na, Ca, HCO<sub>3</sub>, Cl, K, and P, at different soil depths vary from 0 to 20 cm, 20 to 40 cm, and 40 cm to 60 cm were obtained from MERWRA project (2015). The obtained soil texture data was projected into soil triangle. Presentation of soil data was done in the form of graphical charts using Microsoft Excel 2016. Within this domain, the interest is to find out the effect of irrigation on soil at different depths. More specifically, the behaviour of different ions accumulation given various depths. Subsequently, this will be connected to current practices of farmers and its associated consequence to groundwater system. From the irrigation soil use point of view, the soil physical properties vary accordingly due to ionic exchange between irrigation water and soil structure. In view of the significant effect of soil physical properties on the plants and soils itself, exchange sodium percentage (ESP) indicator becomes a primary concern when the soil, particularly clay is used for cultivation. ESP is the amount of sodium as a proportion of all cations in a soil and is often used to measure the soil sodicity (Richards, 1954). The sodium content is often expressed as soluble sodium percentage and can be calculated from chemical soil tests using equation below:

$$\text{Na \%} = (\text{Na}^+ + \text{K}^+) / (\text{Na}^+ + \text{K}^+ + \text{Mg}^{2+} + \text{Ca}^{2+}) * 100$$

where ionic concentrations are conveyed in meq/L.

Excess Na concentrations interrupt the physical structure of soils and hence reducing water infiltration and drainage. The chemical characteristic of saline, sodic, and saline-sodic soil are then classified as per Table 6.

Table 6. Classification of saline and sodic soils.

Soil	EC (dS/m)	ESP	pH
Saline	> 4	< 15	< 8.5
Sodic	< 4	> 15	> 8.5
Saline sodic	> 4	> 15	< 8.5

Source: Richards, 1954

#### *Analysis of groundwater data*

Groundwater quality parameters samples from the wells in close proximity to the river collected from MERWRA project in 2015 were applied in this study. All the samples were analyzed according to standard procedure (APHA, 1995). These parameters include EC, pH, Ca, Mg, Na, K, Cl, SO<sub>4</sub>, NO<sub>3</sub>, HCO<sub>3</sub>, total coliform, and *E. coli*. Most of the major cations and anions were reported in meq/L.

Statistical and correlation analyses were conducted for groundwater datasets. Data were inputted into Microsoft office Excel 2013 and statistically analyzed using Pearson's correlation coefficient matrix. The correlation coefficient was calculated using an Excel add-in program, Analysis ToolPax in Excel 2013, to establish the relationship between two parameters at a time (Shammi et al., 2016). The hydrochemical water type of the groundwater samples from the study area is represented by Piper plot (Piper, 1944) to understand the origin of water. Cluster analysis is a group of multivariate methods, aiming to classify groups based on a similar hydrochemical characteristic (Shrestha & Kazama, 2007). Thus, the groundwater samples were classified into water groups based on EC values. This analysis was conducted to identify the water types and variation in their water quality so that the practise of specific kind of agriculture can be defined.

Sodium Adsorption Ratio (SAR) represents the alkali or sodium hazard. It is an essential parameter in agricultural system as it affects the agricultural soil structure. This index quantifies the proportion of Na to Ca and Mg ions in a sample. The sodium hazard was calculated by the following equation provided by Richards (1954):

$$SAR = \frac{Na^{2+}}{\sqrt{\frac{Mg^{2+} + Ca^{2+}}{2}}};$$

where all the ions concentrations are expressed in meq/L.

To determine the suitability of the water for different agricultural practices, the calculated SAR was then projected in Wilcox Diagram according to United States Salinity Laboratory's diagram (Richards, 1954), wherein the groundwater samples were classified based on sodium hazard and salinity hazard, as depicted in Table 7.

Table 7. Classification of SAR and EC as per Wilcox Diagram.

<b>SAR</b>	<b>Conductivity (<math>\mu\text{S/cm}</math>)</b>
S1: Low (0-10)	C1: Low (0-249)
S2: Medium (10-18)	C2: Medium (250-749)
S3: High (18-26)	C3: High (750-2249)
S4: Very high (>26)	C4: Very High (2250-5000)

*Source: Richards, 1954*

## 4.2 SWOT Analysis

SWOT is a form of analysis of a process that comprises strengths, weaknesses, opportunities, and threats - the four words from which the acronym SWOT is created. In the present research, SWOT analysis is employed to discern the strengths, weaknesses, opportunities, and threats of TWW reuse in agriculture with special reference to the upper Zarqa River ecosystem, particularly in connection with health aspects, crops productivity, and ecosystem as general interaction. The terms inscribed in the SWOT analysis, based on the context of this study, are defined as follows:

- Strengths:** Advantages of TWW reuse on the ecosystem at present time
- Weaknesses:** Existing events or factors related to reuse practice that hinder the ecosystem from thriving
- Opportunities:** Occurrence of future circumstances enabling the ecosystem to capitalize and improve
- Threats:** Potential risk or forecasted scenario that is likely to arise to impair the ecosystem

(adapted from Osita et al., 2014)

The SWOT method was primarily developed by Humphrey in 1960 is a broadly used and accepted means for a business venture. Researchers have applied the SWOT analysis to a wide spectrum of situations as a tool for business management (Humphrey, 2005). The use of the analytical tool has been extended beyond companies, as there are a couple of examples of the successful application of SWOT analysis in the aspects of municipal solid waste management (Srivastava et al., 2005) and regional energy planning (Terrados et al., 2007). Research also supports SWOT analysis as a tool for planning purposes and decision-making, particularly in water resource management (European Commission, 2004; Diamantopoulou & Voudoris, 2008). For instance, some countries (such as Cyprus and Portugal) utilized the tools for the selection of policy priorities and development of their sustainable development strategy. These successful examples indicate that SWOT analysis can be undertaken for any idea, project, program, development, or management plan, as each of these components has its strengths and weaknesses, along with opportunities and threats (Arslan & Er, 2008; Mainali et al., 2011). Nevertheless, scarce paper can be found in the literature applying SWOT method in TWW reuse issues, particularly in the study region.

For this reason, the current study advocated to SWOT analysis aims to pinpoint the potentials and pitfalls of the end use (reuse of TWW for agriculture). The data inputs of the SWOT framework are derived from Figure 17. Briefly, the process of the SWOT application encompasses the following steps (Hill & Westbrook, 1997):

- Recording of the present situation in the research area.
- Examination of the possible acts for the current problems that were identified.
- Analysis of the opportunities and threats that arise from external environment.
- Analysis of the strengths and weaknesses of the system.
- Categorizing of the proposed actions.

Strengths and weaknesses are regarded as factors of the system (internal issues), whereas opportunities and threats refer to factors of the external environment (external issues) (Diamantopoulou & Voudouris, 2008), as depicted in Figure 20. Microsoft PowerPoint is then used as a visual aid to present the outputs of SWOT analysis in a representative manner.

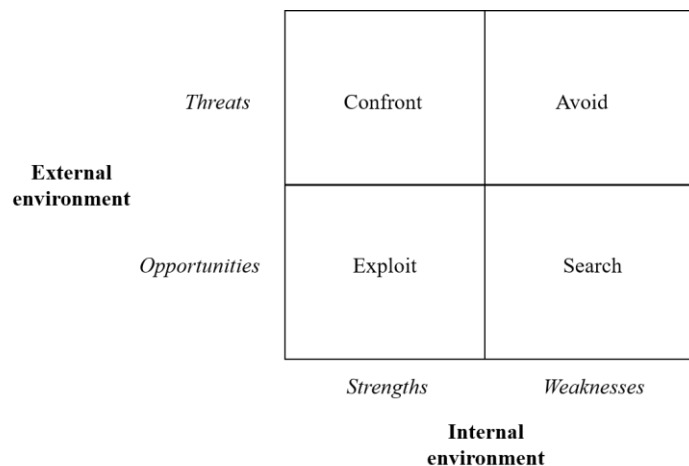


Figure 20. Basic dimension of SWOT analysis.

*Source: Rowe et al., 1994 as cited in Richards, 2001*

With the aid of this tool, SWOT analysis renders knowledge to maximize the safe reuse of TWW by delivering an insight to the ways and means of converting the threats into opportunities, and also offsetting the weaknesses against the strengths (Arslan & Er, 2008). As such, strategic alternatives can be formulated from the situation analysis. From a practical point of view, this tool offers strategic planning to prevent higher future costs result from mismanagement of water resources and agriculture (Michailidis et al., 2015). SWOT additionally serves as a complementary tool to draw recommendations and development strategies that are suitable in the context of the upper Zarqa River, so as to enhance ecosystem services. Therefore, the relevant decisions toward ecosystem management should become at least tangible, which then compliments the concept of integrated management in this research. Figure 20 summarizes the research methodology structure for SWOT technique.

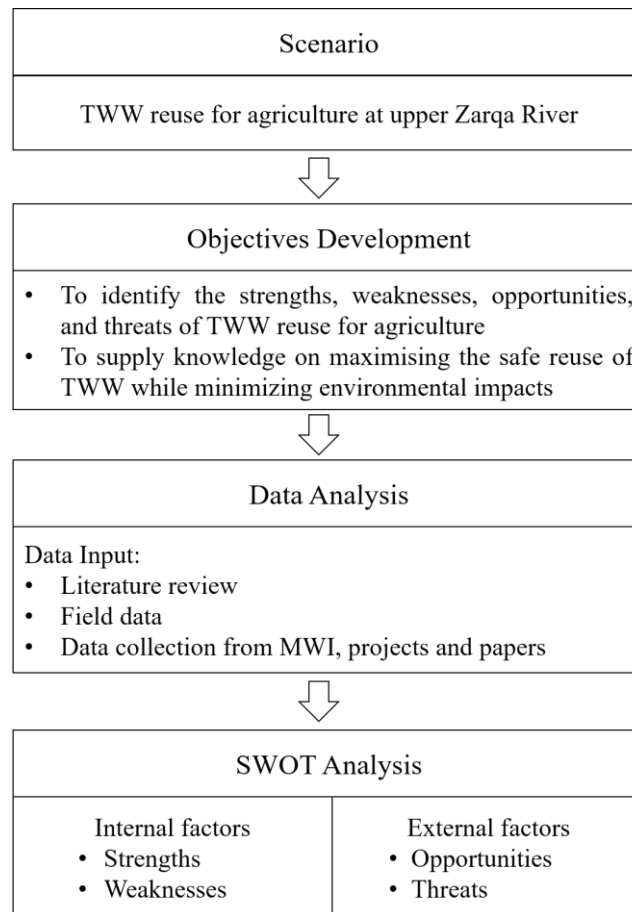


Figure 21. Research methodology structure for SWOT analysis.

*Source: adapted from Hill & Westbrook, 1997*

### 4.3 Proposition of Development Scenarios

Following the diagnosis of the existing and prospect situations of TWW reuse within the area of interest, development scenarios are suggested based on expected developments on the ground. As justified by the expansion plans of the WWTP, the upper Zarqa River is projected to receive an increase in the TWW volume from the As Samra plant in the near future. In addition to that observation, studies undertaken by Al Mahamid (2005), MWI (2009), and El-Rawy et al. (2016) demonstrated that the effluent discharge from the As Samra plant is expected to increase to more than the maximum capacity of the plant itself. In this respect, possible development scenarios are proposed in line with the expected growth in the treated effluent to more than 135 MCM in the coming ten years. The proposed development scenarios are visible and justifiable scenarios, derived from the observed base case conditions and real facts from the review of existing literature, local government reports, previous projects, water reuse standards, and outcomes from the former studies.

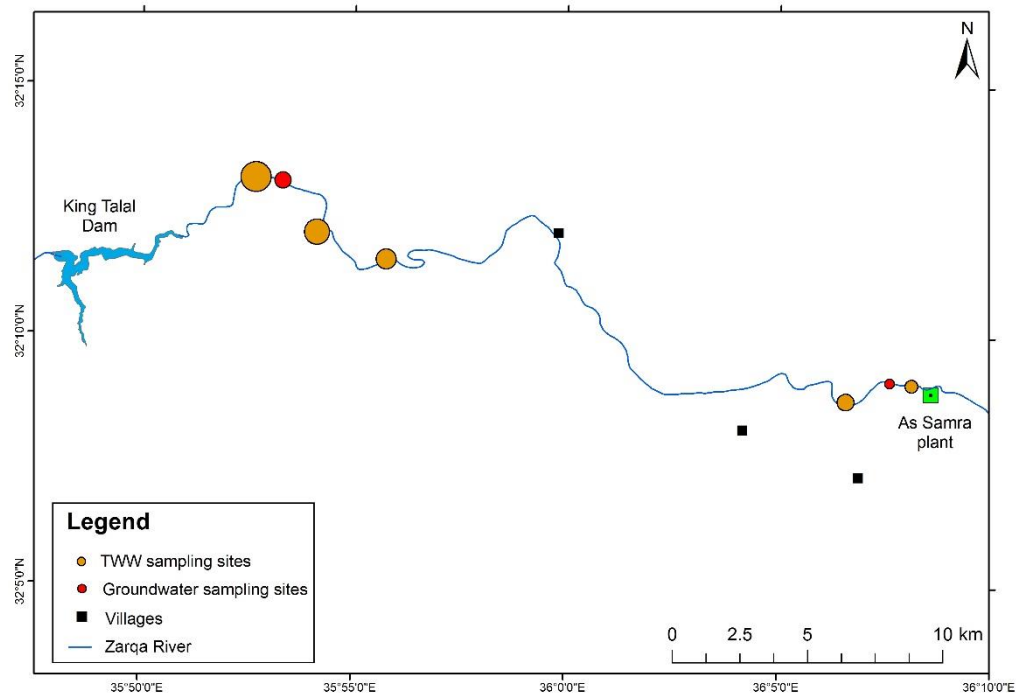
In the long run, provided the projected growth in the effluent, the targeted contribution of the development scenarios is to present insights into the potential development associated with its ecosystem and provide valuable information that is compatible with local settings on maximizing the safe reuse of TWW in the long term, while minimizing the environmental impacts at the upper course of the river.

## 5. Results

This chapter aims to display, interpret, and visualize the collected raw data related to the field of the research work in an understandable manner.

### 5.1 In-situ Measurement

Figure 22 displays the field measurement locations of the TWW and groundwater. The measured EC of the TWW and groundwater samples at the respective locations are enumerated in Appendix 3. The EC was measured directly in the field for better accuracy of the readings. As seen from the figure, the EC of the TWW increases downstream.



*Note.* The bigger the symbol of sampling sites, the higher the EC.

Figure 22. Field measurements of EC for TWW and groundwater samples.

### 5.2 Treated Wastewater

Figure 23 represents the sampling sites of TWW. The various data sets of physical and chemical analyses of the TWW for Site I, Site II, Site III, Site IV, and Site V are depicted in Appendix 4, Appendix 5, Appendix 6, and Appendix 7 respectively.



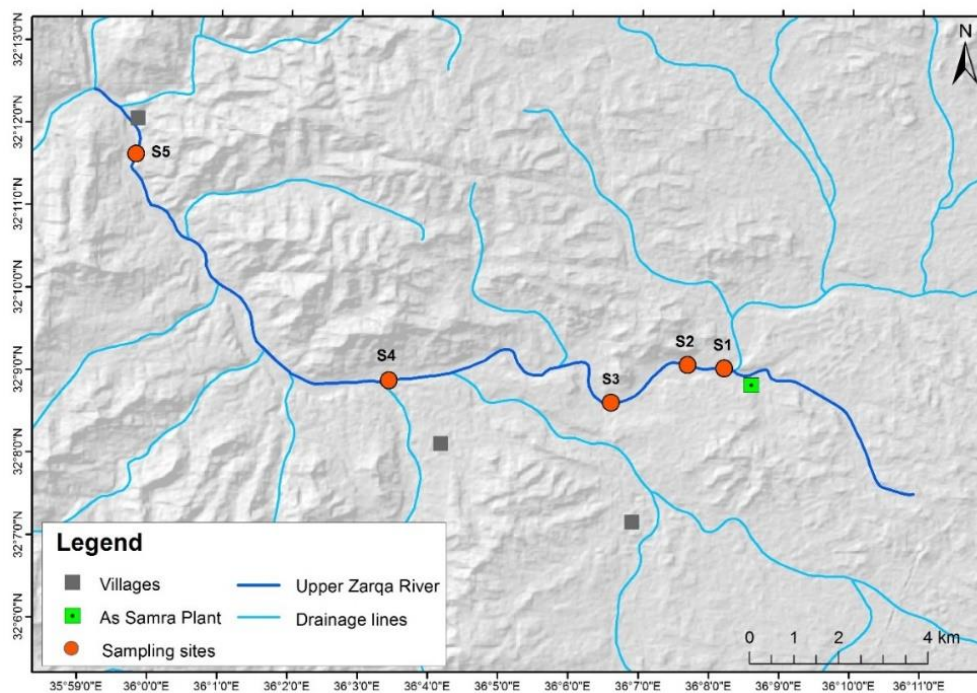


Figure 23. TWW sampling sites.

### Statistical Analysis

The descriptive statistic (arithmetic mean, standard deviation, minimum, and maximum values) pertaining to the TWW quality data, along with the allowable levels postulated in the JS 893/2006 for treated domestic wastewater to be discharged to wadis are presented in Table 8. The values in bold indicate that the parameters do not conform the quality requirements of the discharge standard.

Table 8. Descriptive statistic for the concentration of major cations and anions of TWW and the comparison of the values with JS 893/2006.

Parameter	Unit	Descriptive statistic	Sampling location				JS 893/2006
			Site I & Site II	Site III	Site IV	Site V	
pH		Mean	7.7	8.2	7.9	8.2	6 - 9
		Std. Dev.	0.3	0.6	0.4	0.2	
		Minimum	7.3	7.4	7.6	8.0	
		Maximum	7.9	8.7	8.4	8.4	
EC	µs/cm	Mean	1920.5	2434.8	2185.0	2455.6	-
		Std. Dev.	27.3	508.2	309.5	374.7	
		Minimum	1880.0	1914.0	1772.0	2148.8	
		Maximum	1951.0	3000.0	2500.0	3090.0	
BOD <sub>5</sub>	mg/L	Mean	7.5	14.5	18.5	15.0	60 mg/L
		Std. Dev.	2.5	0.5	5.0	4.1	
		Minimum	5.0	13.9	11.9	9.8	
		Maximum	11.4	15.1	25.7	21.1	

Na	meq/L	Mean	10.0	13.3	11.6	12.1	200 mg/L
		Std. Dev.	1.3	3.0	1.5	1.4	
		Minimum	8.4	<b>10.1</b>	<b>9.6</b>	<b>10.3</b>	
		Maximum	<b>12.3</b>	<b>16.7</b>	<b>13.3</b>	<b>13.9</b>	
Ca	meq/L	Mean	4.5	7.0	5.9	7.5	200 mg/L
		Std. Dev.	1.2	1.0	0.7	1.6	
		Minimum	3.0	5.9	4.8	5.2	
		Maximum	6.0	8.4	6.5	9.7	
K	meq/L	Mean	1.5	1.1	1.1	1.2	-
		Std. Dev.	0.3	0.1	0.3	0.4	
		Minimum	1.1	1.0	0.8	0.9	
		Maximum	1.8	1.3	1.4	1.9	
Mg	meq/L	Mean	3.0	2.8	3.2	3.4	60 mg/L
		Std. Dev.	0.7	1.3	0.7	1.1	
		Minimum	2.2	1.4	2.4	2.5	
		Maximum	3.9	4.5	3.9	4.8	
HCO <sub>3</sub>	meq/L	Mean	5.9	7.7	7.6	8.6	400 mg/L
		Std. Dev.	0.9	2.1	0.6	1.8	
		Minimum	4.8	5.8	6.7	7.4	
		Maximum	<b>7.5</b>	<b>10.2</b>	<b>8.1</b>	<b>11.7</b>	
SO <sub>4</sub>	meq/L	Mean	1.2	2.0	1.5	2.1	300 mg/L
		Std. Dev.	0.7	0.3	0.6	0.3	
		Minimum	0.2	1.8	0.8	1.7	
		Maximum	2.0	2.5	2.1	2.4	
NO <sub>3</sub>	meq/L	Mean	0.7	0.4	0.3	0.4	30 mg/L
		Std. Dev.	0.4	0.1	0.1	0.1	
		Minimum	0.3	0.3	0.2	0.2	
		Maximum	<b>1.1</b>	<b>0.6</b>	0.4	0.5	
Cl	meq/L	Mean	11.1	13.8	12.4	13.1	350 mg/L
		Std. Dev.	1.1	2.9	1.9	1.4	
		Minimum	9.6	10.3	9.9	<b>11.3</b>	
		Maximum	<b>13.0</b>	<b>17.2</b>	<b>14.3</b>	<b>14.8</b>	
PO <sub>4</sub>	meq/L	Mean	0.045	0.080	0.032	0.076	15 mg/L
		Std. Dev.	0.021	0.005	0.004	0.013	
		Minimum	0.011	0.074	0.026	0.061	
		Maximum	0.072	0.086	0.037	0.096	
COD	mg/L	Mean	109.8	129.8	60.5	92.6	150 mg/L
		Std. Dev.	20.2	26.3	18.1	52.3	
		Minimum	82.0	97.0	40.0	55.0	
		Maximum	132.0	155.0	82.0	<b>182.0</b>	
TDS	mg/L	Mean	1229.1	1558.3	1398.4	1571.6	1500 mg/L
		Std. Dev.	17.4	325.3	198.1	239.8	
		Minimum	1203.2	1225.0	1134.1	1374.7	
		Maximum	1248.6	<b>1920.0</b>	<b>1600.0</b>	<b>1977.6</b>	

Note. Std. Dev. = Standard Deviation.

Figure 24 exhibits the Piper plot for TWW classification in the study area.

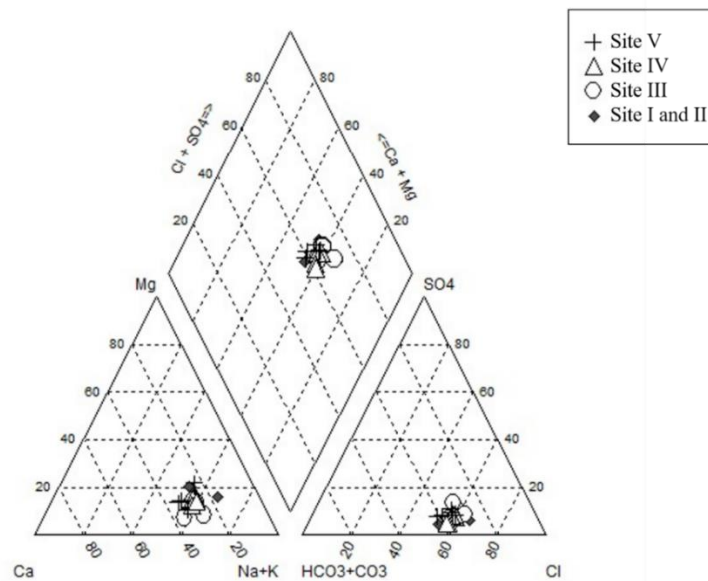


Figure 24. Piper trilinear diagram for TWW classification.

The spatial and temporal variations of pH, EC, biological parameters, the concentration of major cations and anions of the TWW are graphed in Figures 25 to 28.

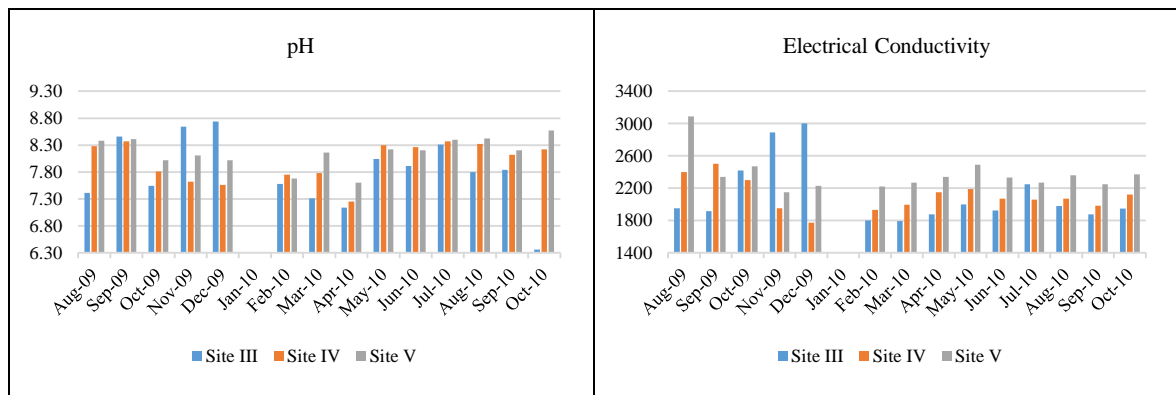


Figure 25. pH values and EC of TWW along the river (combined with MWI data).

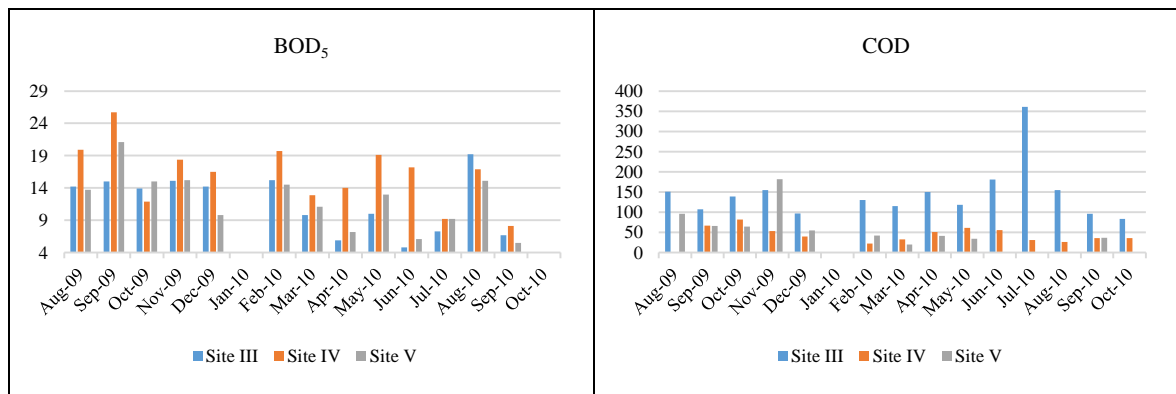


Figure 26. Concentration of BOD<sub>5</sub> and COD of TWW (combined with MWI data).

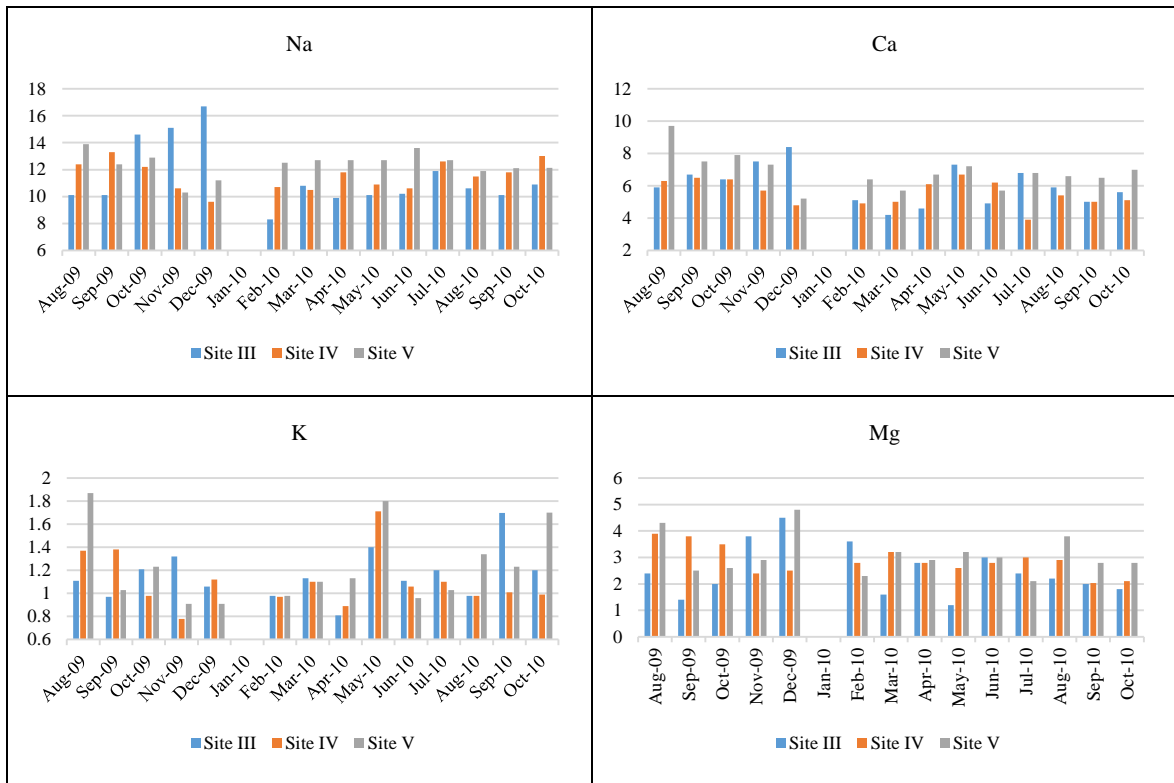
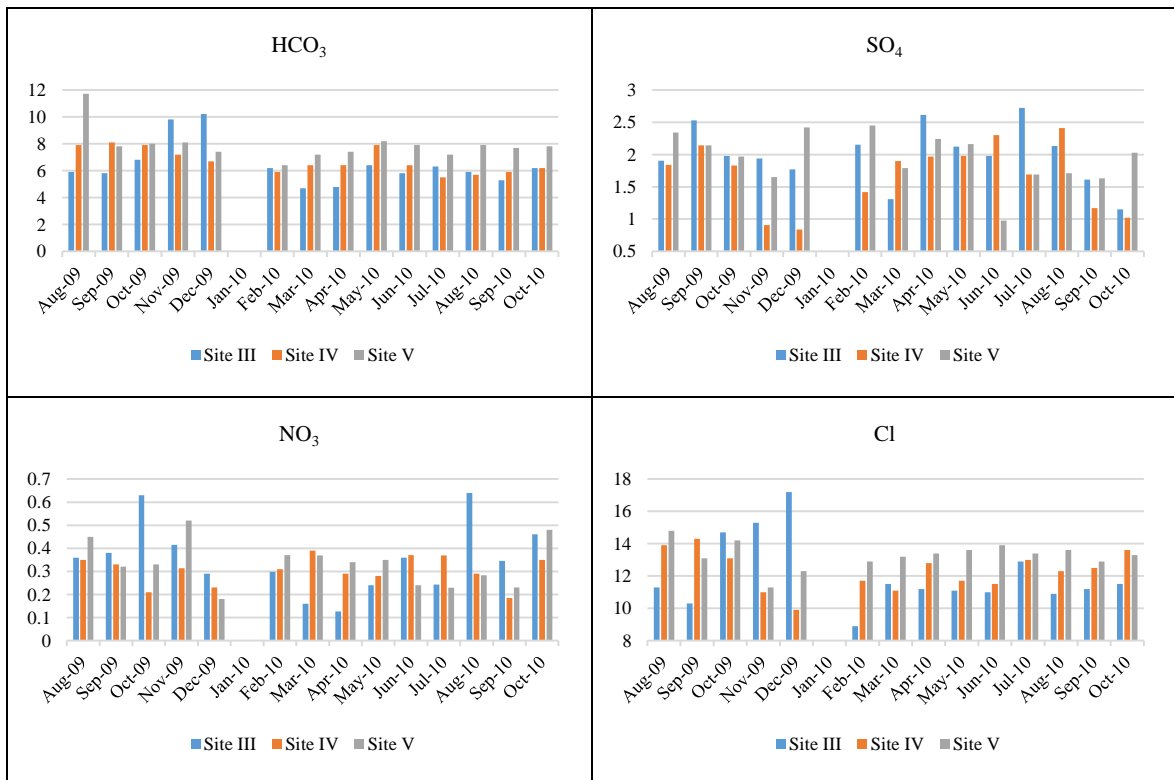


Figure 27. Concentration of major cations of TWW along the river (combined with MWI data).



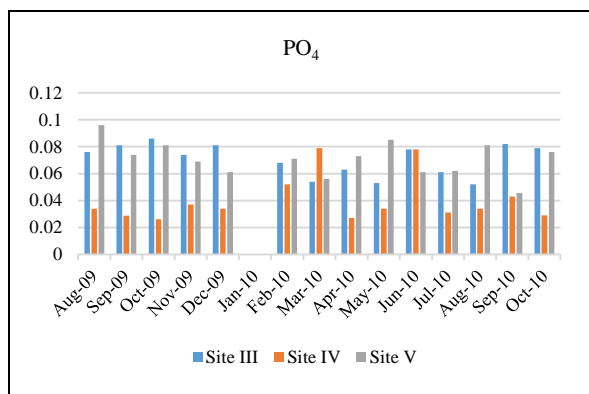


Figure 28. Concentration of major anions of TWW along the river (combined with MWI data).

### 5.3 Irrigated Crops

The location of ten different crops under TWW field irrigation along the study area is demonstrated in Figure 29.

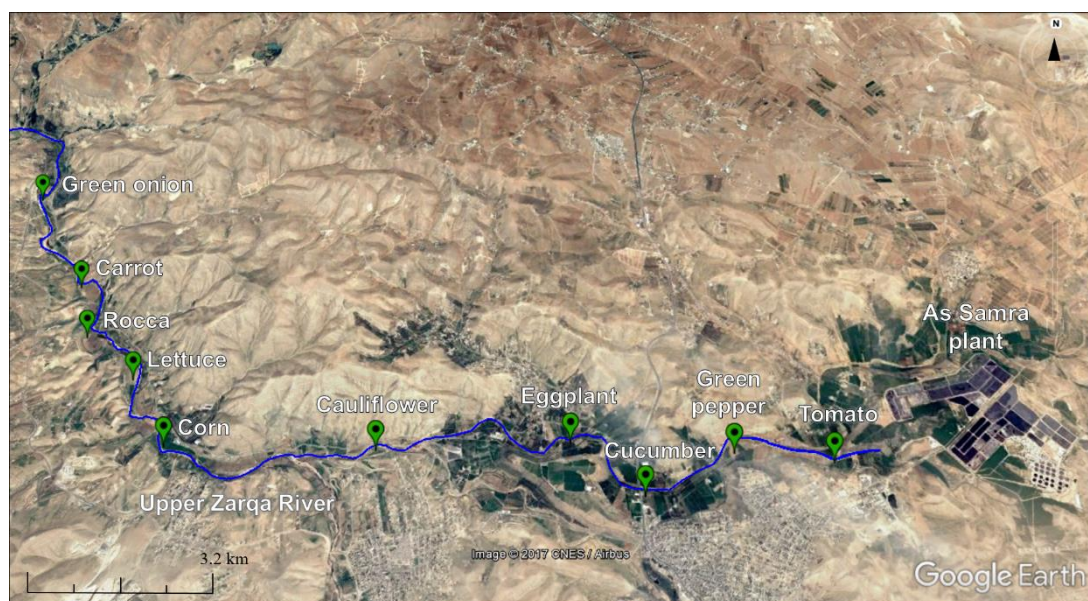


Figure 29. Location of irrigated crops with TWW along the river course.

*Source: after Google Earth image, 2017*

Appendix 8 represents the trace elements and *E. coli* concentrations in the source of irrigation water, root, stem, and leaves and fruit of ten different field-grown vegetable species. The content of the trace elements in the source water used for crops irrigation, as exhibited in Appendix 8 are compared with the permissible limits of trace metals and *E. coli* concentrations in irrigation water established by FAO and WHO respectively. The values in bold imply that the parameters exceed the threshold limits.

In the domain of irrigation water, Figure 30 and Figure 31 represent the amount of trace elements and the concentration of *E. coli* in the source water used to irrigate different crops respectively.

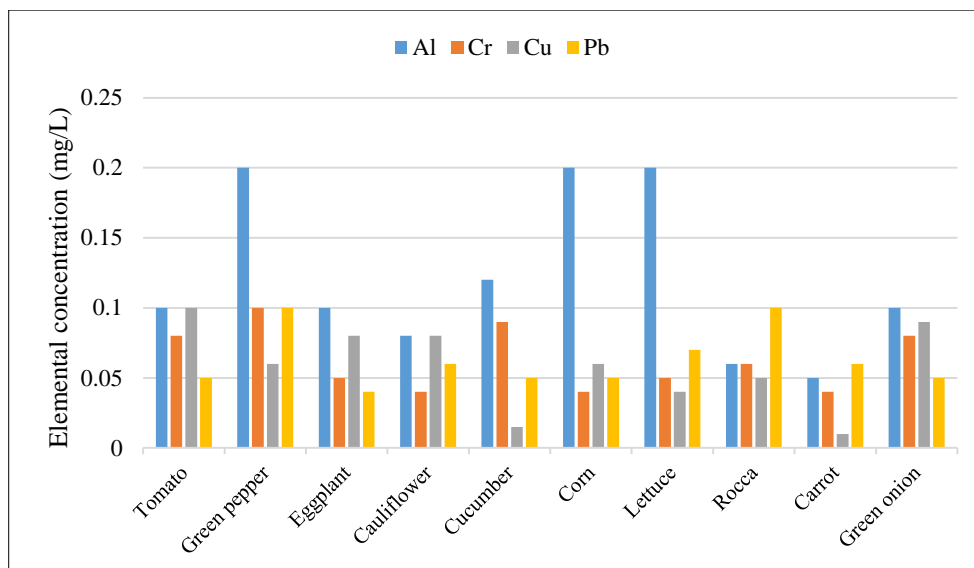


Figure 30. Trace element contents in the applied irrigation water for various crops.

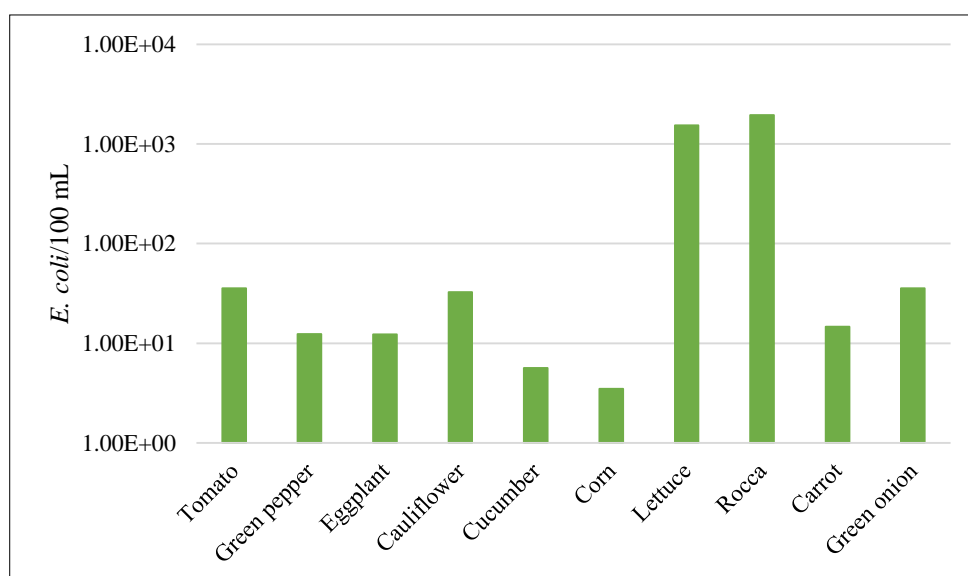


Figure 31. Concentration of *E. coli* in the irrigation water of ten different crops.

Figures 32 and 33 illustrate the concentration of trace elements as well as *E. coli* in different parts of plants for tomato, green pepper, eggplant, cauliflower, cucumber, corn, lettuce, rocca, carrot, and green onion.

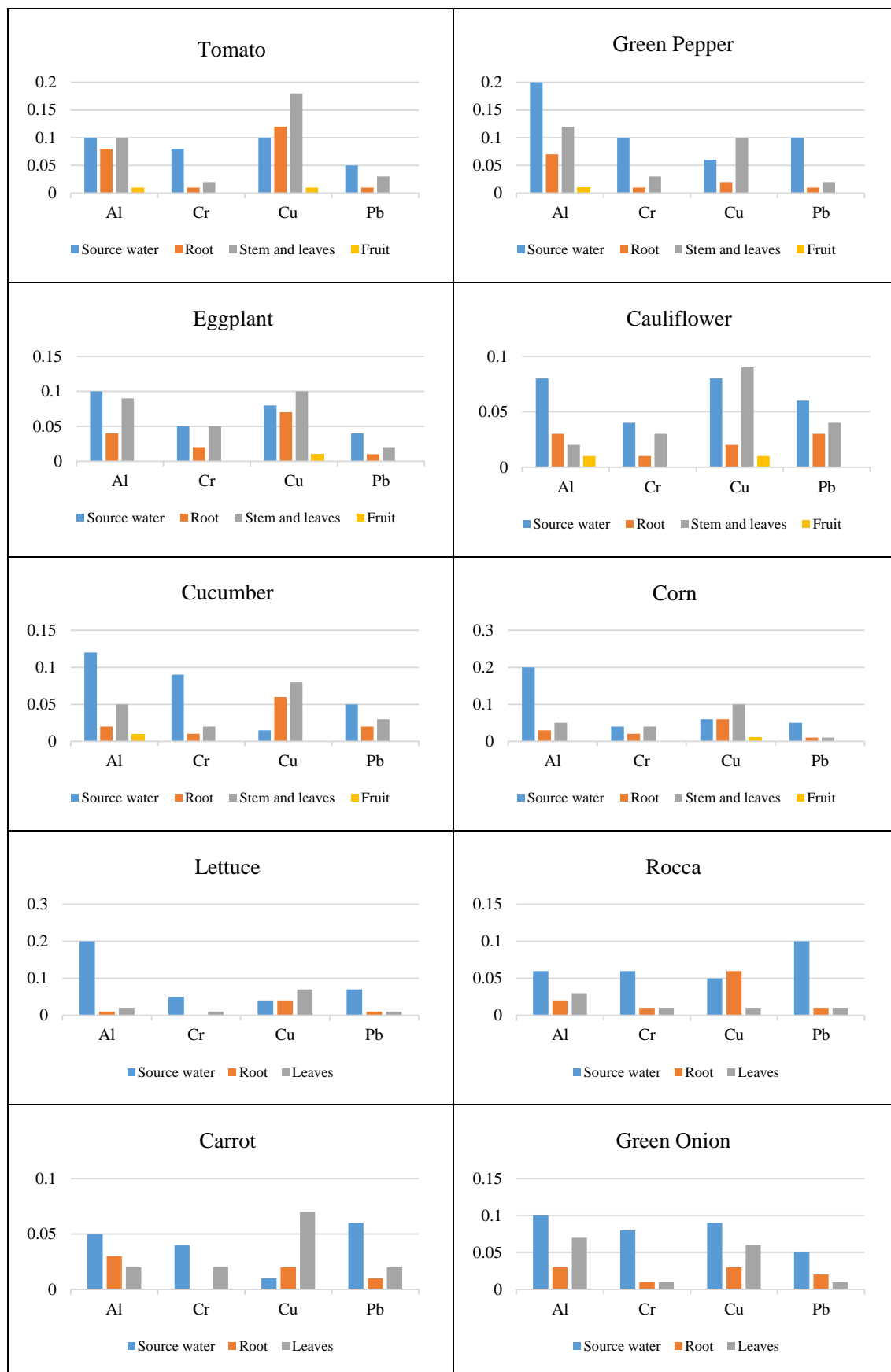


Figure 32. Concentration of trace elements in the irrigated crops (mg/kg) with respect to different system parts.

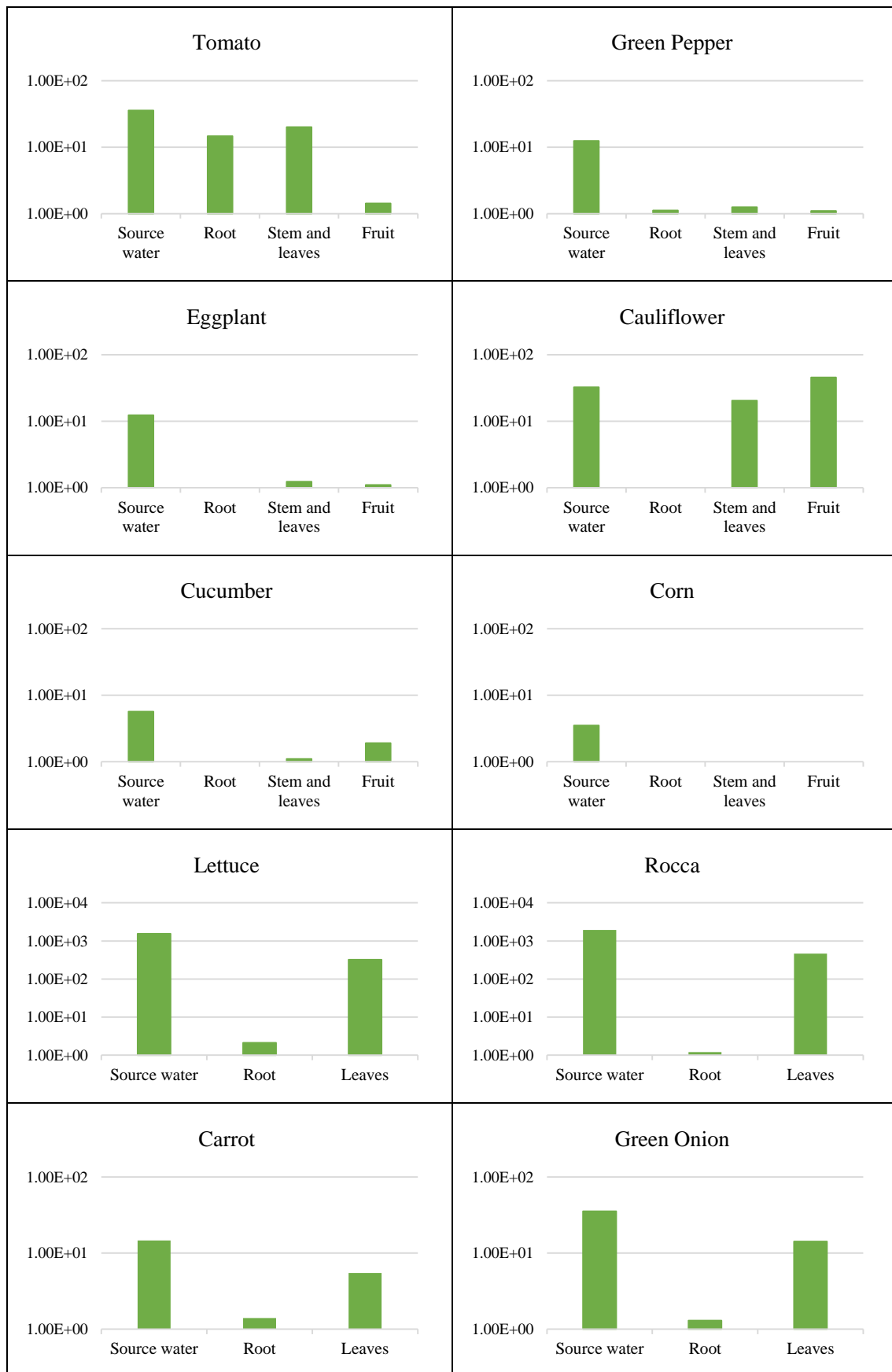


Figure 33. Concentration of *E. coli* in the irrigated crops (*E. coli*/100 mL) with respect to different system parts.



Figure 34 and Figure 35 show the distribution of trace elements and *E. coli* concentration in the plants' edible parts.

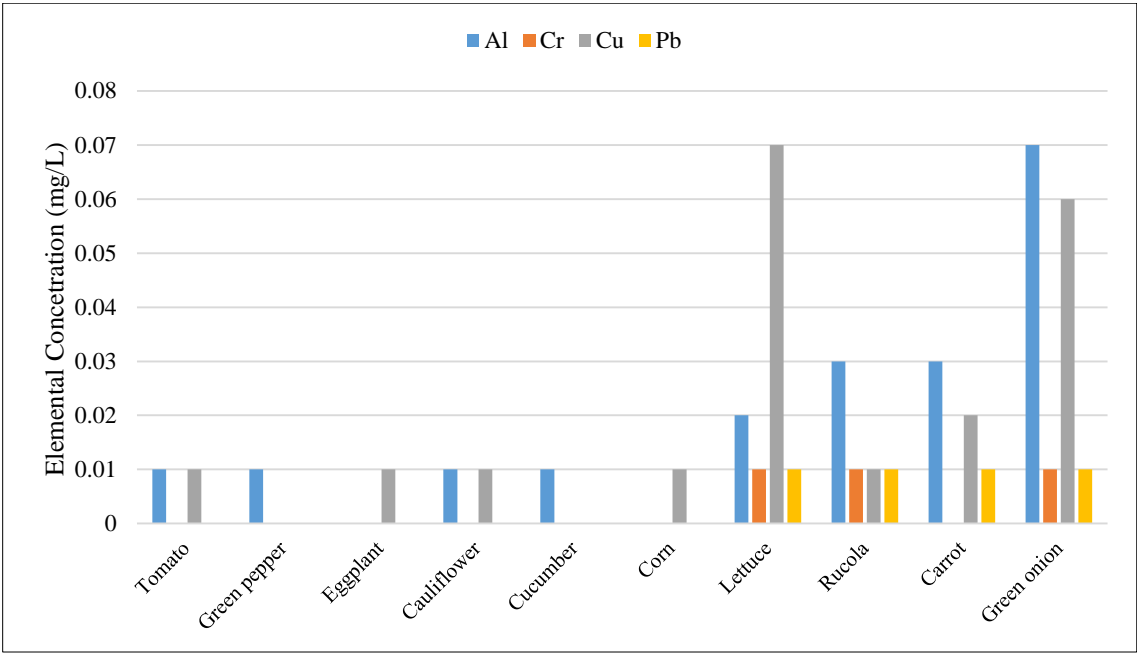


Figure 34. Concentration of trace elements in the edible parts of the irrigated crops.

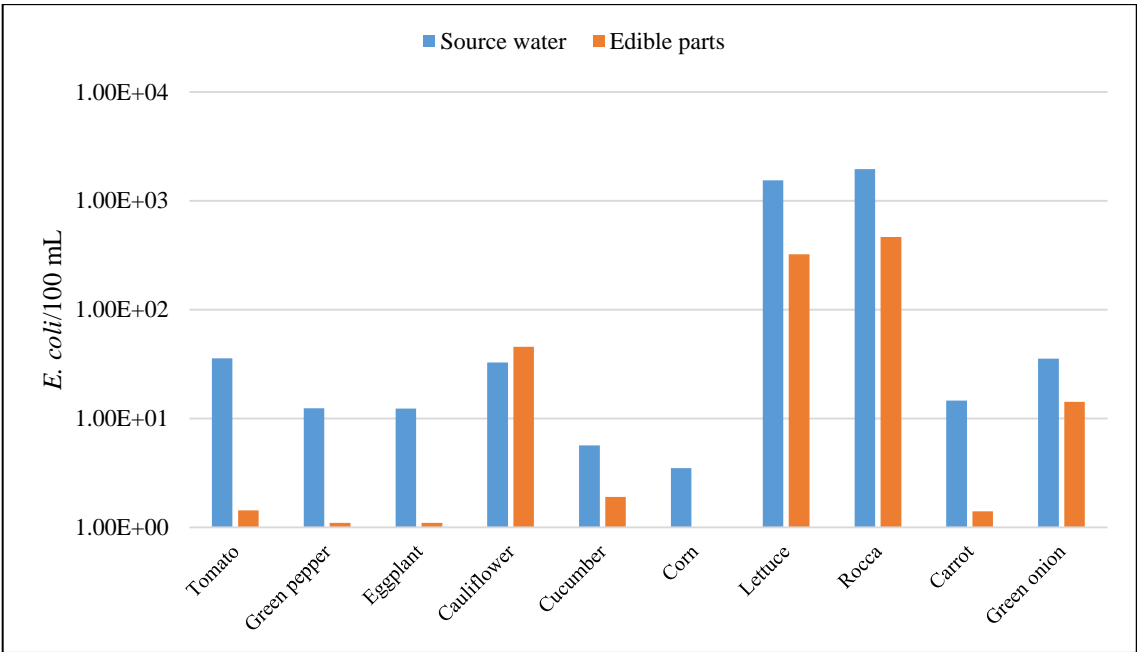


Figure 35. Concentration of *E. coli* in the edible parts of the irrigated crops.

Figures 36 to 40 demonstrate the spatial distribution of different constituents i.e. Al, Cr, Cu, Pb, and *E.coli* along the river, in terms of irrigation water and edible parts of plants.

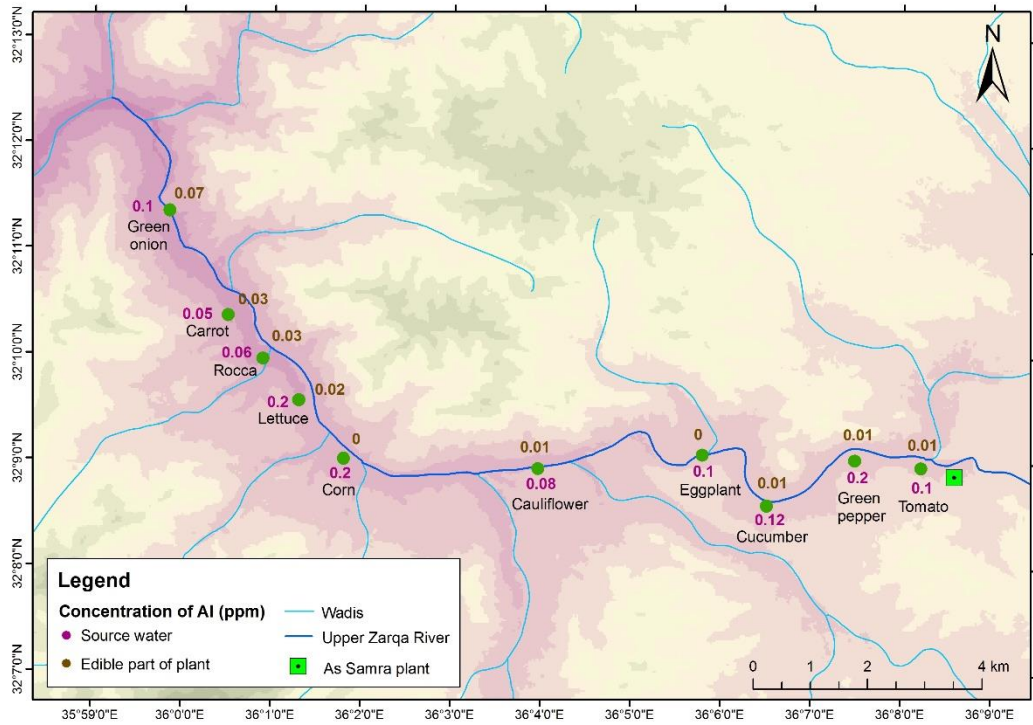


Figure 36. Aluminium concentrations in source water and plants' edible part along the river.

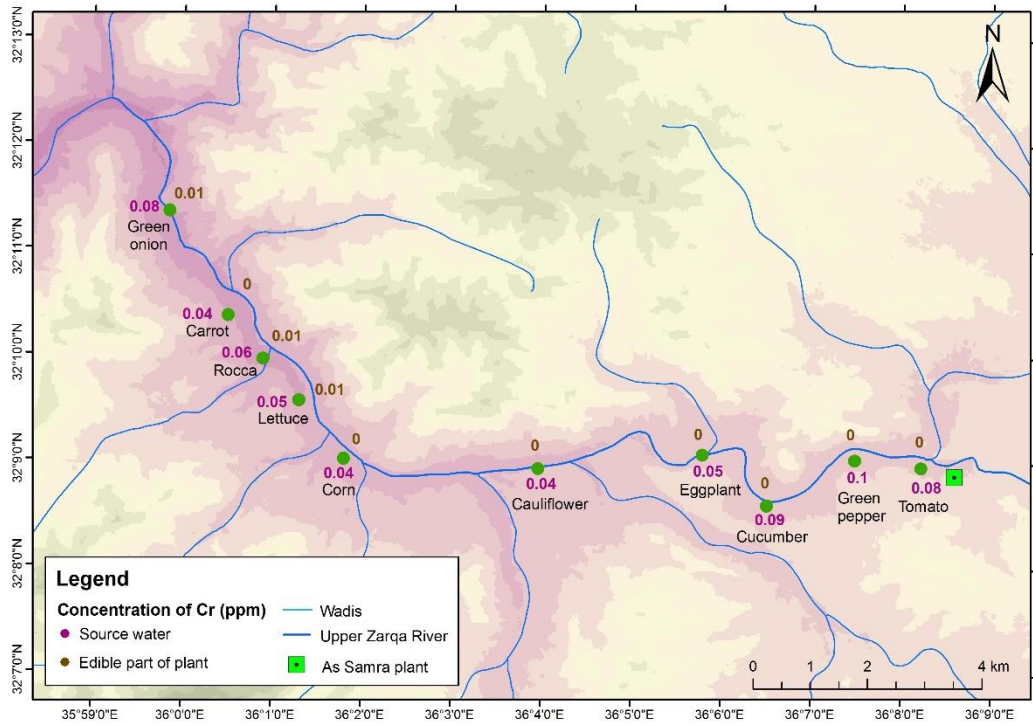


Figure 37. Chromium concentrations in source water and plants' edible part along the river.

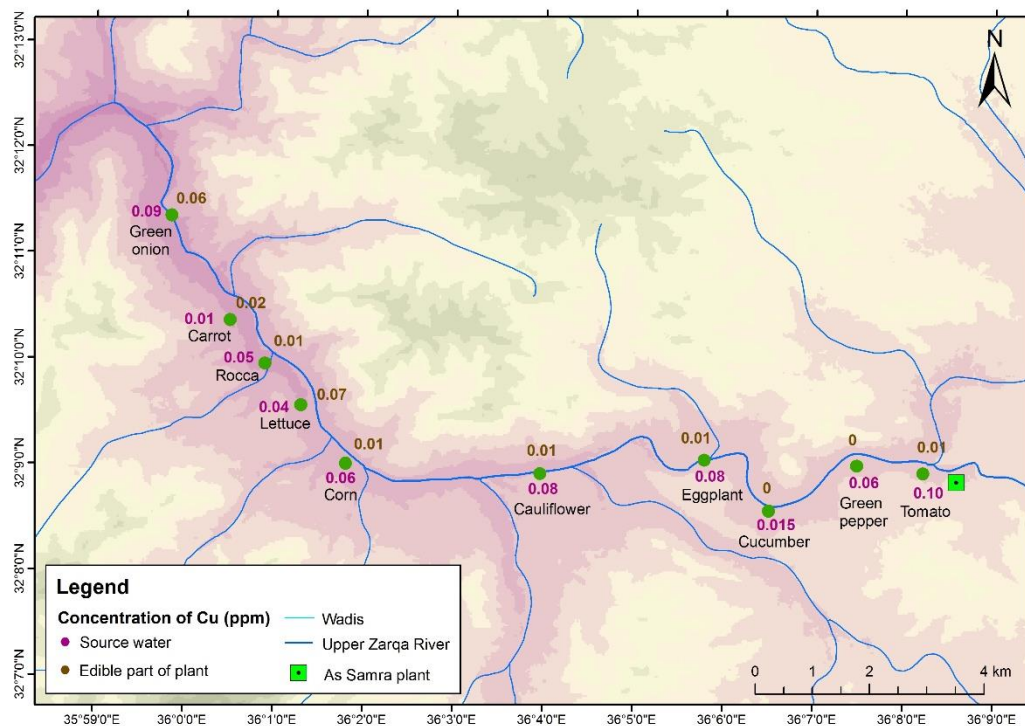


Figure 38. Copper concentrations in source water and plants' edible part along the river.

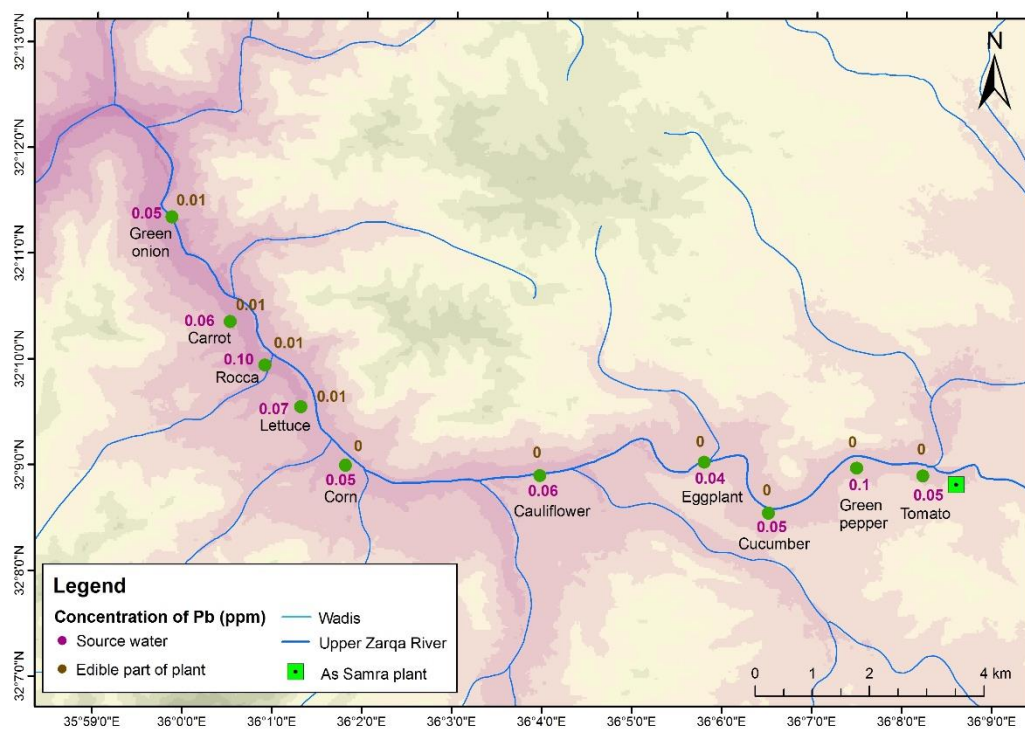


Figure 39. Lead concentrations in source water and plants' edible part along the river.



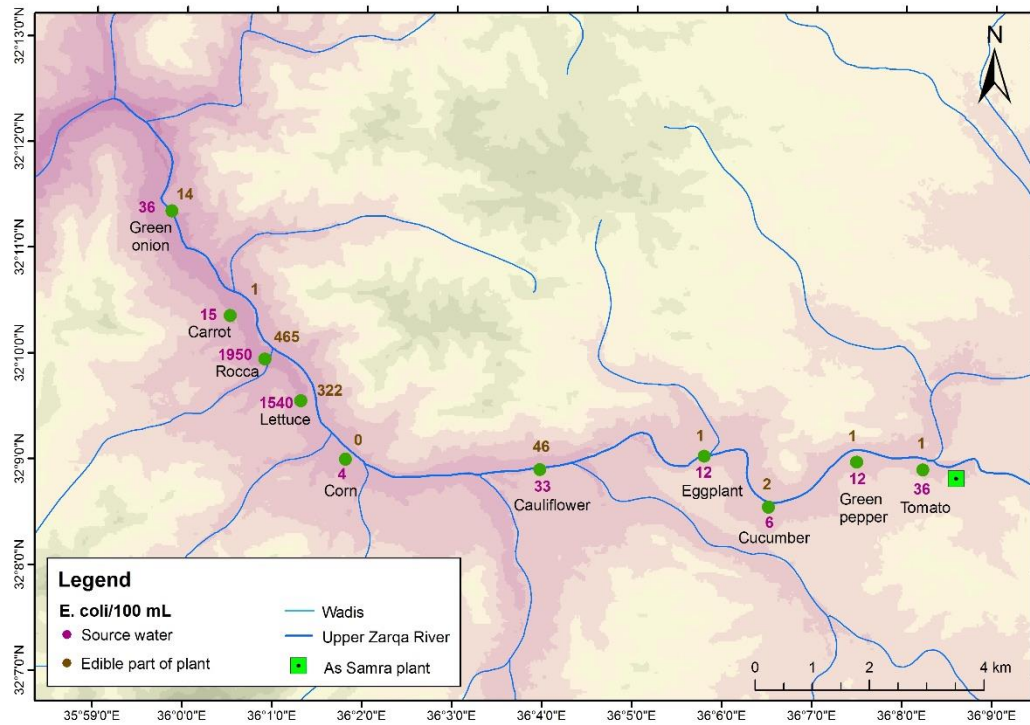


Figure 40. *E. coli* concentrations in source water and plants' edible part along the river.

## 5.4 Soil

Figure 41 shows the soil sampling sites within the upper course of the river. The samples indicated from S1 to S6 reflects the existing soil situation in the area of concern. Appendix 9 demonstrates the soil texture based on the composition of clay, silt, and sand of each soil sample. Subsequently, the soil type is obtained using the soil triangle depicted in Figure 42. The chemical properties for soil samples collected along the study area are described in Appendix 10.

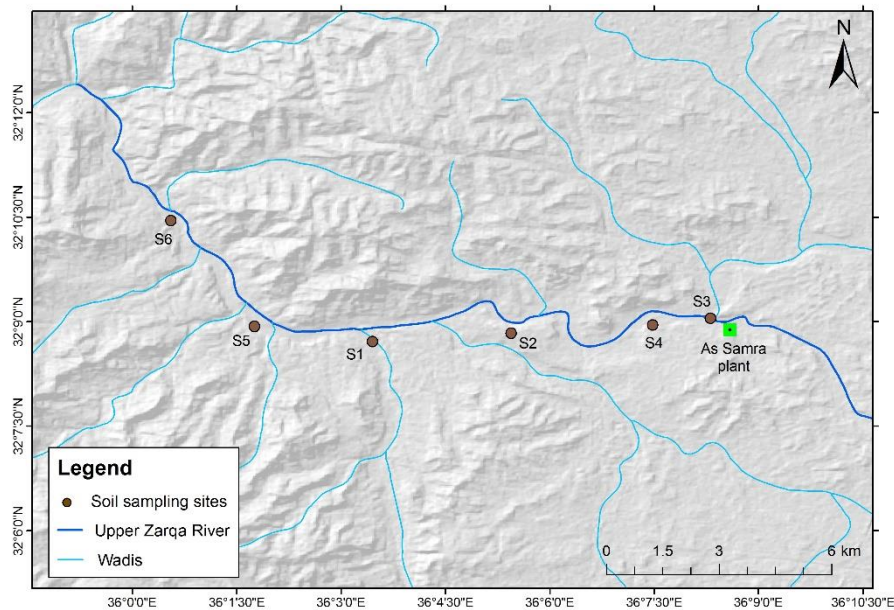


Figure 41. Soil sampling sites along the study area.

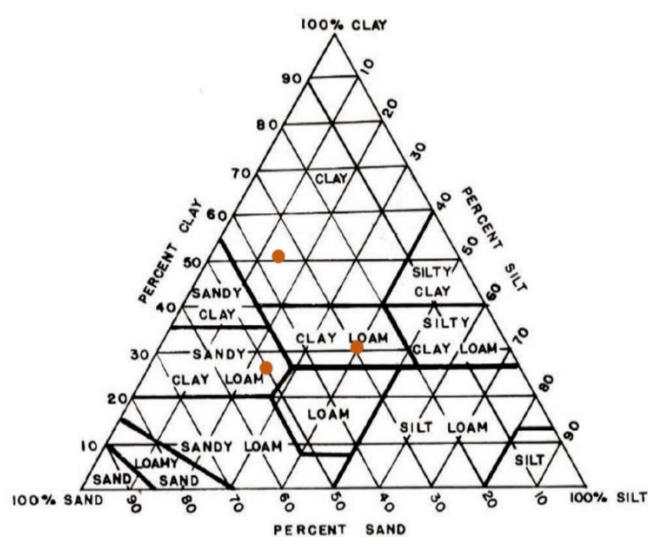


Figure 42. Classification of soil samples based on soil triangle.

Figure 43 depicts the EC, pH, and ESP of the soil samples.

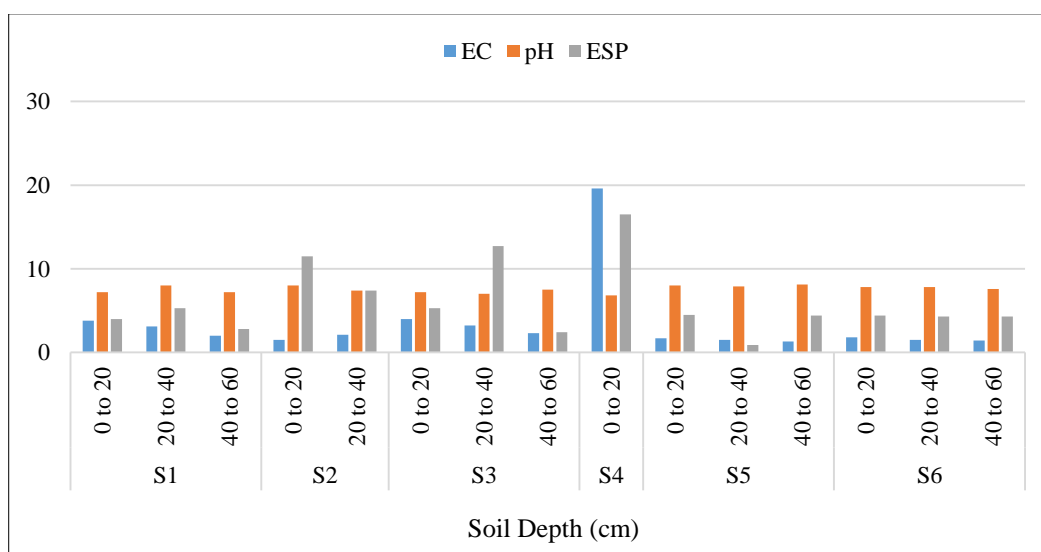


Figure 43. EC, pH, and, ESP of soil samples at various depths.

Figures 44, 45, and 46 illustrate the concentration of major cations, anions, and phosphorus in the soil samples.

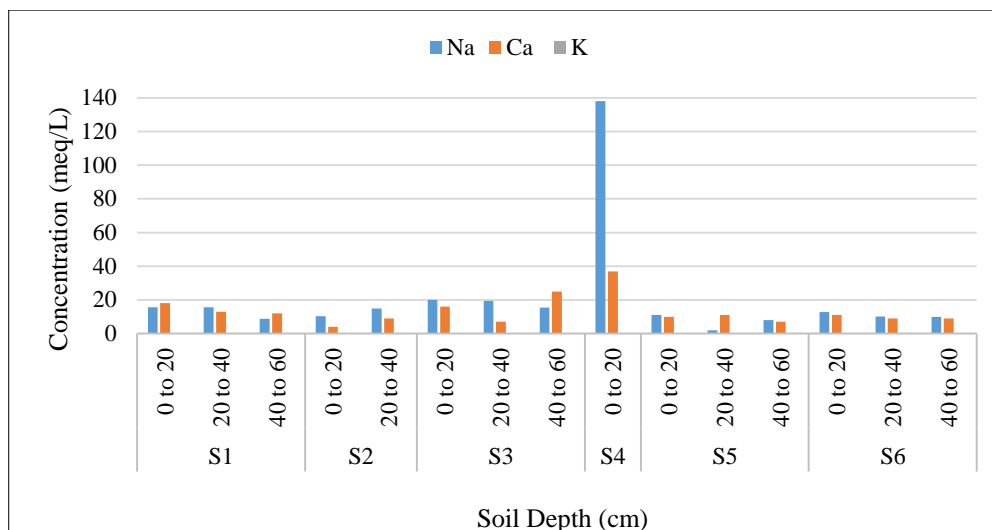


Figure 44. Concentration of major cations in the soil samples at different depths.

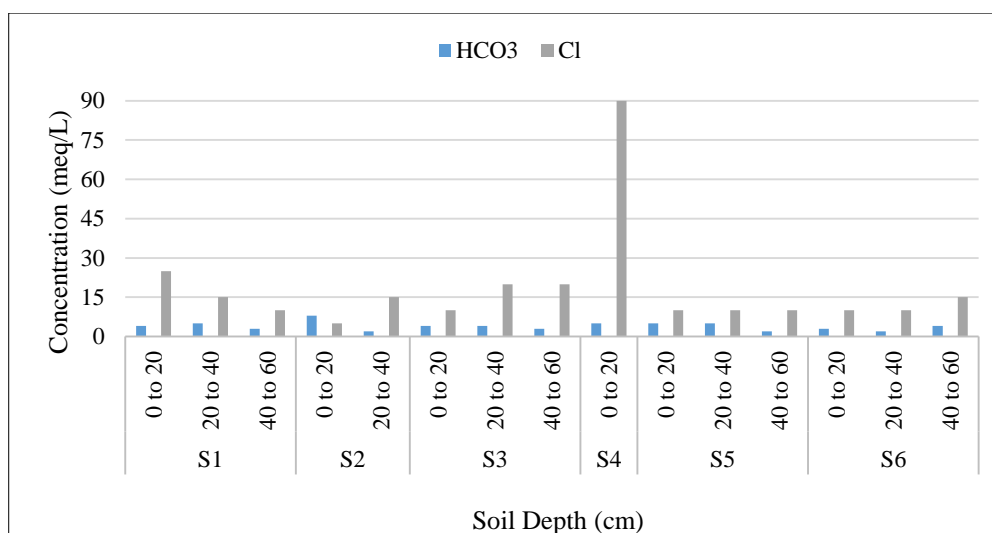


Figure 45. Concentration of major anions in the soil samples at different depths.

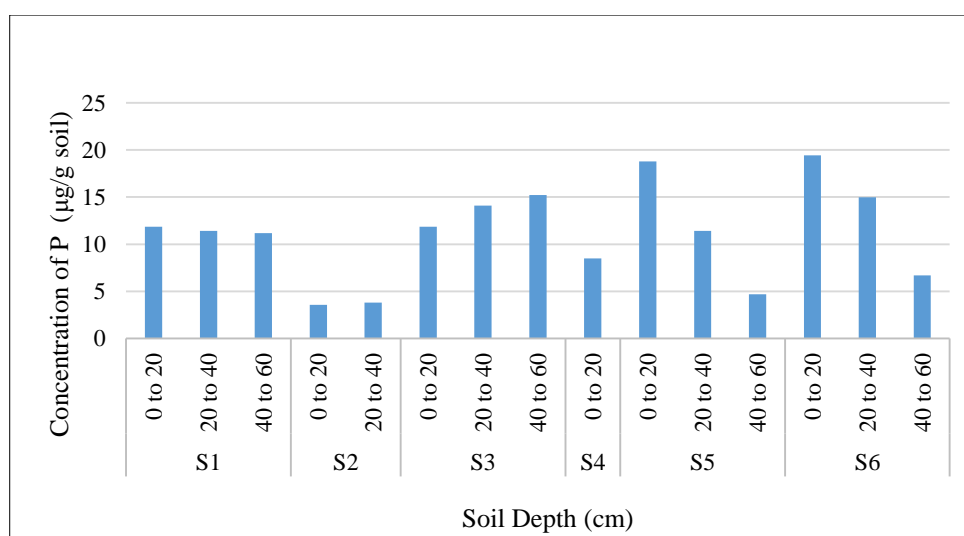


Figure 46. Concentration of phosphorus in the soil samples at different depths.

## 5.5 Groundwater

The water quality parameters of groundwater samples obtained from 43 studied wells along the upper Zarqa River are exhibited in Appendix 11. Figure 47 illustrates the distribution of the studied groundwater stations at the upper reach of the river.

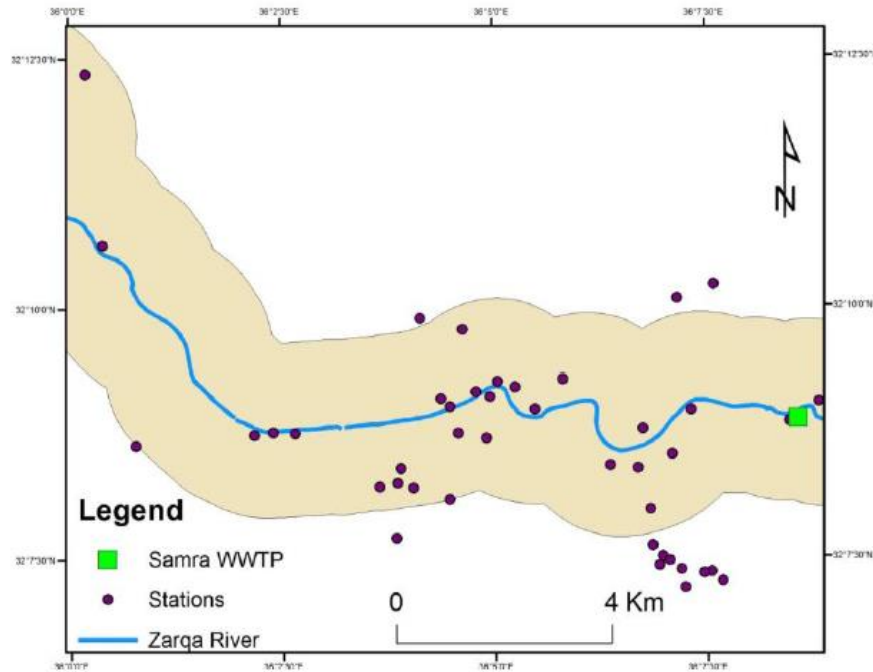


Figure 47. Map of the studied groundwater stations along the study area.

Source: MERWRA, 2015

### *Statistical analysis*

A basic statistical analysis is conducted to understand the range of different parameters. The physicochemical characteristics of the groundwater samples were statistically analyzed and the obtained results for the parameters considered in this work are summarized in Table 9, along with their mean values, minimum and maximum values, and standard deviation.

Table 9. Statistical summary of hydrochemical parameters of groundwater.

Parameter	Mean	Minimum Value	Maximum Value	Standard Deviation
EC, $\mu\text{S}/\text{cm}$	3346.2	759.0	8180.0	1931.0
pH	7.3	6.3	8.6	0.4
Ca	10.0	0.9	33.6	7.1
Mg	10.0	0.6	42.1	9.3
Na	14.2	0.1	44.4	10.0
K	0.9	0.1	20.0	3.0
Cl	20.3	0.9	59.6	14.8
SO <sub>4</sub>	8.7	0.3	40.9	8.5
NO <sub>3</sub>	1.6	0.1	7.2	1.7
HCO <sub>3</sub>	4.3	0.2	7.4	1.6

*Note.* All units are meq/L unless otherwise stated.

### Correlation analysis

Pearson's correlation coefficient between the different parameters was calculated, as enumerated in Table 10. In general, the high correlation coefficient (close to 1 or -1) signifies a good relationship between the parameters whereas low values (close to zero) denotes no relationship between them. A correlation coefficient of more than 0.7 ( $r > 0.7$ ) represents a strong relation between the variables while the value between 0.5 and 0.7 implies moderate correlation. On the other hand, the negative value means that the parameters are inversely correlated (Shammi et al., 2016).

Table 10. Correlation matrix of variables.

Parameter	EC	pH	Ca	Mg	Na	K	Cl	SO <sub>4</sub>	NO <sub>3</sub>	HCO <sub>3</sub>
EC	1.00									
pH	-0.14	1.00								
Ca	<b>0.60</b>	-0.31	1.00							
Mg	<b>0.56</b>	-0.30	<b>0.82</b>	1.00						
Na	<b>0.50</b>	-0.37	<b>0.80</b>	<b>0.59</b>	1.00					
K	0.02	-0.13	-0.06	0.41	-0.18	1.00				
Cl	<b>0.65</b>	-0.29	<b>0.93</b>	<b>0.78</b>	<b>0.88</b>	-0.09	1.00			
SO <sub>4</sub>	0.46	-0.40	<b>0.90</b>	<b>0.75</b>	<b>0.87</b>	-0.09	<b>0.83</b>	1.00		
NO <sub>3</sub>	0.47	-0.08	0.44	0.48	0.44	0.03	0.47	0.45	1.00	
HCO <sub>3</sub>	0.11	-0.09	0.15	0.19	0.34	0.27	0.13	0.22	0.28	1.00

*Note.* The values in bold indicate good relationship.



Bivariate diagrams (Figure 48, Figure 49, and Figure 50) are plotted to demonstrate the correlation between different hydrochemical elements.

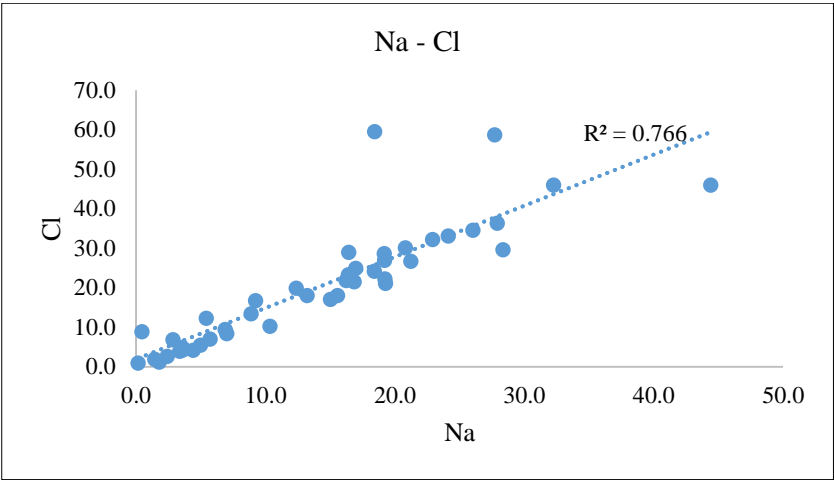


Figure 48. Scatter plot for the relationship between sodium and chloride in meq/L.

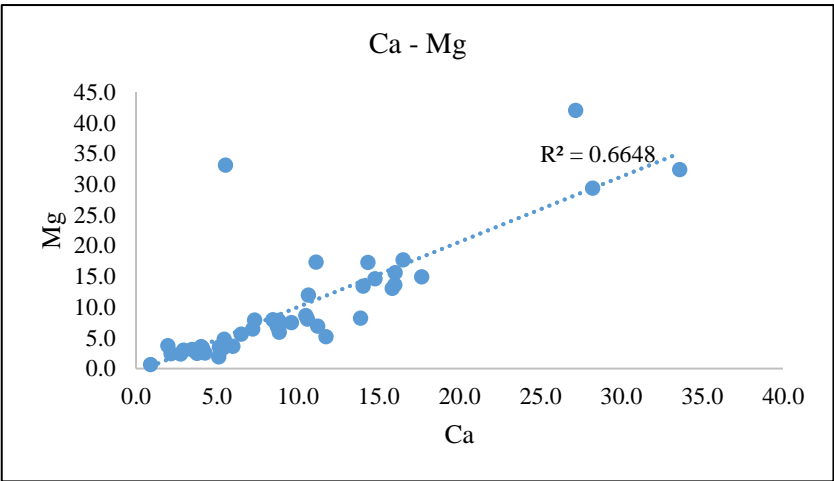


Figure 49. Scatter plot for the relationship between calcium and magnesium in meq/L.

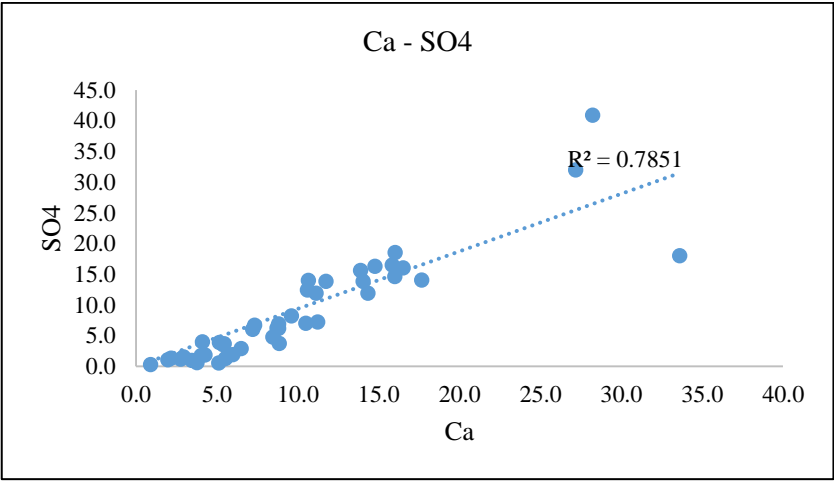


Figure 50. Scatter plot for the relationship between calcium and sulphate in meq/L.

Figure 51 exhibits the Piper diagram for groundwater samples in the study area.

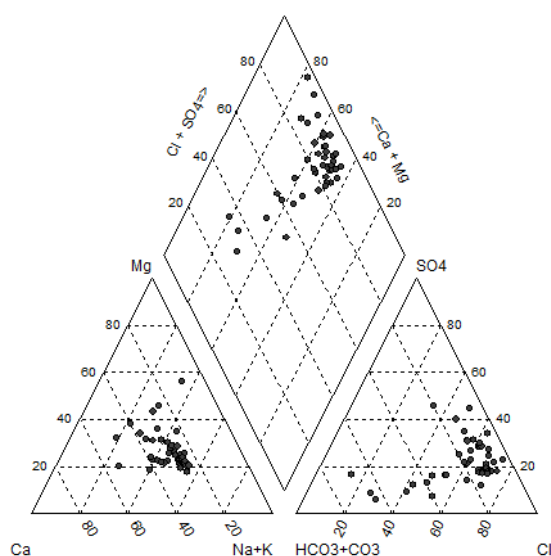


Figure 51. Piper trilinear diagram demonstrating type of groundwater facies.

#### Cluster analysis

Table 11 depicts the arithmetic mean of parameters in each water group. The order of abundance of the major cations and anions for each water group is as follows:

**Water group 1:** Cation:  $\text{Na} > \text{Mg} > \text{Ca} > \text{K}$ ; Anion:  $\text{Cl} > \text{SO}_4 > \text{HCO}_3 > \text{NO}_3$

**Water group 2:** Cation:  $\text{Na} > \text{Mg} > \text{Ca} > \text{K}$ ; Anion:  $\text{Cl} > \text{SO}_4 > \text{HCO}_3 > \text{NO}_3$

**Water group 3:** Cation:  $\text{Na} > \text{Ca} > \text{Mg} > \text{K}$ ; Anion:  $\text{Cl} > \text{SO}_4 > \text{HCO}_3 > \text{NO}_3$

**Water group 4:** Cation:  $\text{Na} > \text{Ca} > \text{Mg} > \text{K}$ ; Anion:  $\text{Cl} > \text{HCO}_3 > \text{SO}_4 > \text{NO}_3$

Table 11. Arithmetic mean of water parameters in each water cluster.

Parameter	Water Cluster			
	1	2	3	4
EC	6362.5	3763.9	2115.7	1042.7
pH	7.3	7.3	7.2	7.6
Ca	16.5	10.8	9.5	3.8
Mg	17.5	11.2	8.1	3.2
Na	20.1	17.4	13.8	4.1
K	0.5	1.5	0.4	0.4
Cl	33.2	24.1	16.8	5.6
SO <sub>4</sub>	14.4	9.4	10.3	1.9
NO <sub>3</sub>	3.3	1.7	0.6	0.9
HCO <sub>3</sub>	4.2	4.9	4.0	3.5

Figure 52 shows the distribution of water groups along the river.

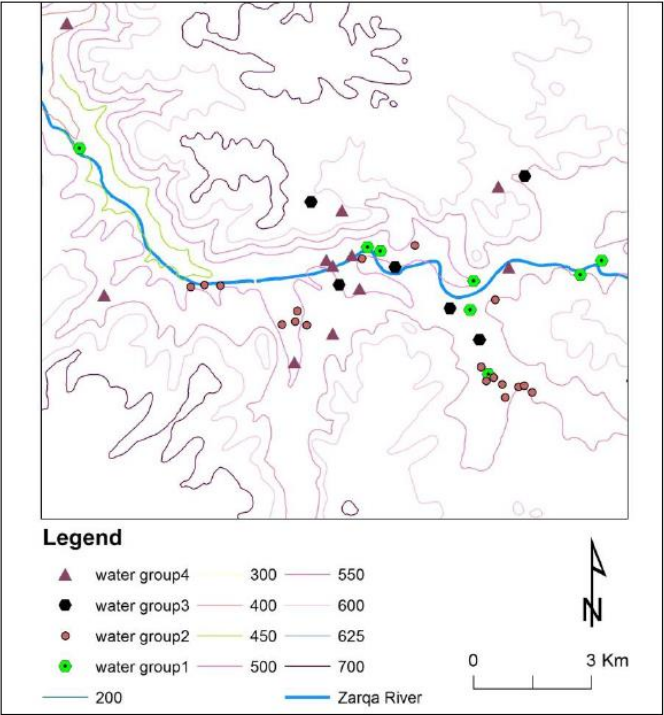


Figure 52. Distribution of water groups based on EC.

Source: MERWRA, 2015

Figure 53 shows the Wilcox diagram of groundwater samples according to EC and SAR. The calculated SAR values are displayed in Appendix 11.

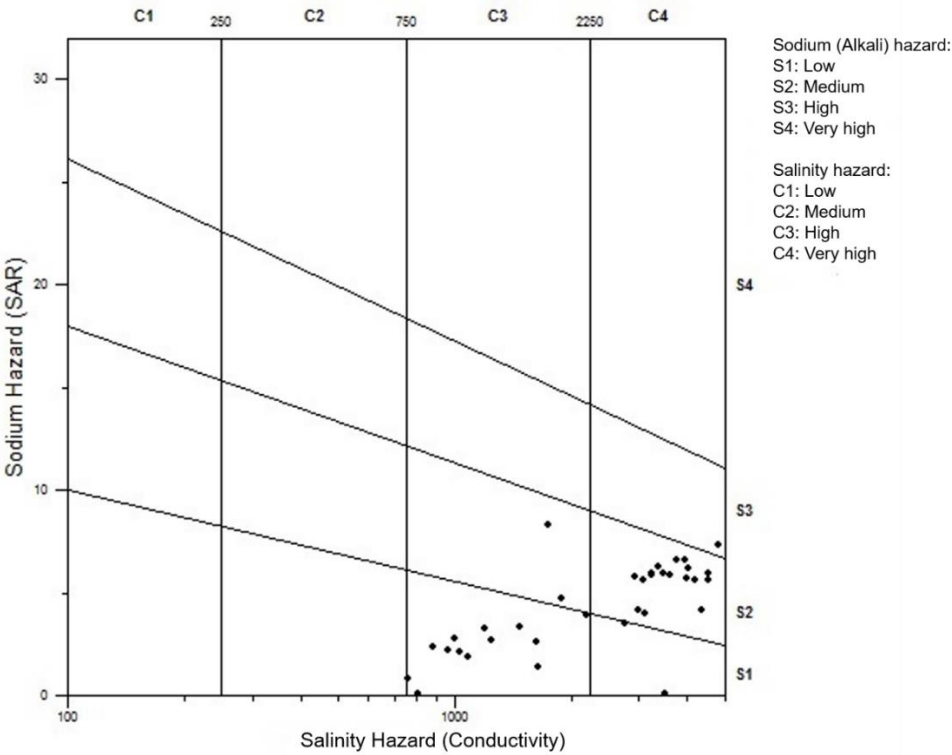


Figure 53. Wilcox plot for the classification of groundwater samples.

## 6. Discussion

The SWOT analysis in this study stems from the situation analysis in the local context. Therefore, based on the presented results in Chapter 5, the current situation in regards to quality will be described. The present practices of farmers using TWW for various crops are also an important input in determining the quality of the ecosystems. The following sections will then elaborate the TWW reuse performance concerning health aspects, crops productivity, and ecosystem as general interaction. Lastly, development scenarios, in connection with expected growth in treated effluent, will be proposed.

### 6.1 Description of Current Situation in terms of Quality

Within this domain, the existing situation in terms of quality with respect to different ecosystem components, including irrigated crops, soil, and groundwater, will be described based on various parameters.

#### *Treated wastewater quality*

Being one of the principal water resources supporting diverse agricultural activities in the catchment area, it is imperative to describe the quality of water source and identify possible sources of ions in the surface water samples before any development project or reuse activity takes place. The ample and yet the vital TWW resource discharged from upstream As Samra plant is depicted in Figure 54.



Figure 54. Clear discharged upstream TWW from physical appearance.

*Source: Chan, 2017*

The pH value of a water body influences the solubility of substances. A high pH of more than seven is able to dissolve sandstone. Conversely, a pH lower than seven tends to dissolve limestone. The average pH value of the TWW discharged into the river system ranges from 7.7 to 8.2, indicating an alkaline water type. These values fall within the desirable limit set out in the standard (JS 893/2006). Figure 25 depicts an increasing pH from the upstream (Site III) to downstream (Site V). In general, slight fluctuation of pH values with time is observed. More specifically, there is an upsurge of pH during November and December over the period at Site III. The rise of pH is associated with returned

irrigation water from farms located on both banks of the river. The large deviation of pH demonstrated in October 2010 can be possibly explained by measurement inaccuracy.

The EC reflects the TDS in the samples. The average EC of the TWW samples during the observation period (from August 2009 to December 2009) varies from 1921 to 2456  $\mu\text{S}/\text{cm}$ . The EC at Site III varies from 1914 to 3000  $\mu\text{S}/\text{cm}$ , whereas the EC at Site IV changes from 1772 to 2500  $\mu\text{S}/\text{cm}$ . The reduction of EC can be attributed to the dilution effect as a result of seepage of freshwater entering into the system. Remarkably, the EC has spatial distributions that increases from the upstream to downstream. By the same token, similar trend is found based on the measured EC during the field trip. The measured salinity of the TWW on the field at the upper stretch of the river is about 1650  $\mu\text{S}/\text{cm}$  (see Appendix 3), which is lower than the groundwater salinity. On the contrary, the salinity at the lower reach of the river measured on the field can reach as high as 3990  $\mu\text{S}/\text{cm}$ . Correspondingly, some of the samples slightly surpass the desirable limit of TDS (1500 mg/L) layout in the standards, and the highest value (1978 mg/L) is recorded at downstream site. The local increases in EC suggests that some anthropogenic effect is taking place. Run-off from agricultural land has a major role to increase the salinity and pH of the surface water. Linking this point to the land use map in Figure 6 (see section 2.3), irrigated areas are mainly along the side beds of the river. Irrigation return flow from agricultural system as a result from the practices of farmers is the main culprit of the arising salinity along the river course, along with illegal dumping and sewage discharge activity.

Nonetheless, a fluctuation of EC is detected throughout the months. More particularly, there is a rapid increase of EC at Site III in November and December, which are the wet seasons. This reflects the effect of rainwater or flood flow carries the runoff into the river system during winter time. The changes in the salinity of the river system are also partly as a consequence of groundwater seepage as spring. The fluctuation of the EC might also have been associated with the local source of farming activities and illegal discharge of impaired industrial wastewater along the river course (El-Rawy et al., 2016).

The BOD<sub>5</sub> and COD are regarded as biological parameters. The BOD<sub>5</sub> is a measure of oxygen used for microbiological decomposition, while COD measures the contents of organic and inorganic components in the water samples. There is a fluctuation in the temporal variation of BOD<sub>5</sub> and COD, showing no clear increasing or decreasing trend with time, as seen from Figure 26. During the observation period, the rise of BOD<sub>5</sub> concentration from Site III to IV to more than 40%, indicating an input of organic load at that specific location. The BOD<sub>5</sub> at Site IV varies from 11.9 to 25.7 mg/L, while the BOD<sub>5</sub> at Site V ranges from 9.8 to 21.1 mg/L. The decrease of BOD<sub>5</sub> is presumably attributed to the self-purification of river. The presence of algae and natural re-aeration of river as a result of travel distance from Site IV to V promotes the oxidation process. In terms of COD, a trend of decreasing can be observed at most of the sites along the river course. This observation is corroborated with the water quality studies undertaken by Al-Omari et al. (2013). The lower COD concentrations are most probably emerged from the oxidation of organic matter, resulted from the natural re-aeration as TWW travels along the sampling sites. More specifically, an upsurge of COD concentration in July 2010 is clearly noticed. Illegal waste dumping, in addition to possible discharge of high organic content wastes are responsible for such increase. Ultimately, the indicated values for BOD<sub>5</sub> and COD (with an exception at Site V, which slightly exceeds the limit) conform the quality requirement of discharge standard (60 mg/L). This reflects the positive performance, high efficiency of the As Samra plant, and its associated optimistic impact on the river water (Al-Abdallat, 2011).

On the basis of molar concentrations among the cations, Na and Ca are dominant in the measurements, while Mg and K are detected in minor concentrations. The concentration of Na ranges from 8.4 to 16.7 meq/L, while Ca concentration varies from 3.0 to 9.7 meq/L. The concentration of the major cations of the TWW demonstrate spatial distributions that increase from the upstream to downstream. On the other hand, Cl is the most prevailing anion, followed by  $\text{HCO}_3$ ,  $\text{SO}_4$ ,  $\text{NO}_3$ , and  $\text{PO}_4$ . The concentration of Cl can be found in the TWW samples from 9.6 to 17.2 meq/L. It is noticed that most of the study sites do not comply the JS 893/2006. The concentration of  $\text{HCO}_3$  changes from 4.8 to 11.7 meq/L. A trend of increasing  $\text{HCO}_3$  content in the samples can be observed from the sampling locations based on Figure 28; where most of the locations surpass the standard limit. The source of the cations and anions is partly associated with weathering of the sedimentary and igneous rocks in the region (Al-Ansari et al., 2013). The leaching from soils and rocks in the study region are the major input calcium sources in the river system, leading to changes in the Ca concentrations across the space and time. As per Piper diagram, the plot indicates that the water is alkaline with a prevailing sulphate-chloride. Chloride salts are known to have high solubility. Furthermore,  $\text{SO}_4$  is derived from gypsum. Low concentration of sulphate can be found in the TWW samples from 0.2 to 2.5 meq/L. This reflected that their origin in river is related to the nature of high dissolution of gypsum.

Time series plots demonstrate that there are no generalized trends in the cation and anion parameters under study over the months as shown in Figures 27 and 28. Noticeably, in November and December, Site III exhibits higher concentration of cations than the downstream. This may be due to the interaction between groundwater and surface water during winter time. Discharge of aquifers can be in the form of wells, springs or seepages. During winter season (from November to April), the groundwater level is elevated and high water table feeds the stream as a result of recharge from precipitation. Taking into consideration the cross section of the river, the river water composition presumably mixes with inflowing groundwater (i.e. spring) which contributes partly to the changes in different concentration of cations. Additionally, the fluctuation of the Cl concentration with time shows no clear changes of temporal variation. Nevertheless, during November and December 2009, high concentration of Cl is observed at Site III. This scenario is associated with the mixing of spring resulted from elevated groundwater table during winter time. Due to geothermal gradient, high temperature of spring is able to dissolve more salts. Thus, the composition of river water changes. The raised Cl concentration might also have been affected by agricultural runoff during these two months.

The average concentration of  $\text{NO}_3$  ranges from 0.3 to 0.7 meq/L, with the highest value recorded at Site I and II (see Table 8), exceeding the permissible limit (30 mg/L) as per JS 893/2006. In terms of spatial distributions, the reduction of  $\text{NO}_3$  contents is possibly due to bacterial and algal uptakes, besides denitrification. The fluctuation of  $\text{NO}_3$  concentrations throughout the months as demonstrated in Figure 28 can be explained by different agricultural practices. More specifically, the  $\text{NO}_3$  concentration at Site III in October 2009 and August 2010 exhibits an abrupt concentration jump. The presence of  $\text{NO}_3$  in the surface water is deemed as unfavourable contaminant because  $\text{NO}_3$  does not exist naturally. This pollutant originates typically from manure or fertilizers and is an indicator of organic activity (Bhat et al., 2014). Livestock are one of the major income sources for some of the local farmers and shepherds, as shown in Figure 55. The cattle access to the river system may also partly contribute to such pollutant's occurrence.



Figure 55. Cattles as farmers' livestock.

*Source: Chan, 2017*

Manure from animals such as cows, goats, and sheep has also been observed as the source of fertilizer in agricultural activities, as captured in Figure 56 during the field trip.



Figure 56. Animal manure used as fertilizer.

*Source: Chan, 2017*

The application of nitrogen (N) fertilizers and pesticides used in agricultural field is also the reason explains the increased concentrations of different cations and anions in the surface water due to more return flow from drainage. There are two main types of fertilizer commonly utilized in the region. The locally known urea is widely applied as a fertilizer amongst the farming communities. Urea is composed of high concentration of N, enhancing the green cover of plants. This chemical is added into a main water pond or mixed with another water source before being used for vegetable irrigation; this is a process known as fertigation. Another kind of fertilizer is N, P, K, which catalyzes the growth of roots and plant foliage simultaneously. The reckless use of organic and inorganic fertilizers in the agriculture dominated watershed, accompany with sewage discharged from septic tanks have given rise to the presence of such anthropogenic pollutants in the river system.

Overall, the effluent composition changes with time due to mixing with agricultural return flow and spring, interaction between surface water and groundwater, and self-purification of the river. The discharged effluent met the allowable limits for wastewater discharge into wadis, streams, and water bodies as stipulated in the JS 893/2006 for Reclaimed Domestic Wastewater, except Na,  $\text{NO}_3$ ,  $\text{HCO}_3$ , and Cl. The impact of human activities on the river ecosystem is evident. The river body as an open



system that promotes anthropogenic input into the river, such as how illegal waste dumping contributes to the existence of undesirable pollutants. The other sources of surface water contamination can include cattle access, loads from septic tanks, and agricultural run-off. The upper Zarqa River is characterized by unique anthropogenic impacts, hence, water quality must be monitored in a regular manner so that it does not surpass the removal carrying capacity of Zarqa River. Continuous timely measures serve in accurately identifying the source and impact, if any, of the contamination.

### *Crops quality*

Figure 57 displays a wide spectrum of vegetable species irrigated under TWW setting. The vegetable crops, if perceived by the sense of sight, are mostly succulent. The healthy green foliage observed from the promising physical appearance of the crops from the field is deduced from the nutritive value of the TWW.

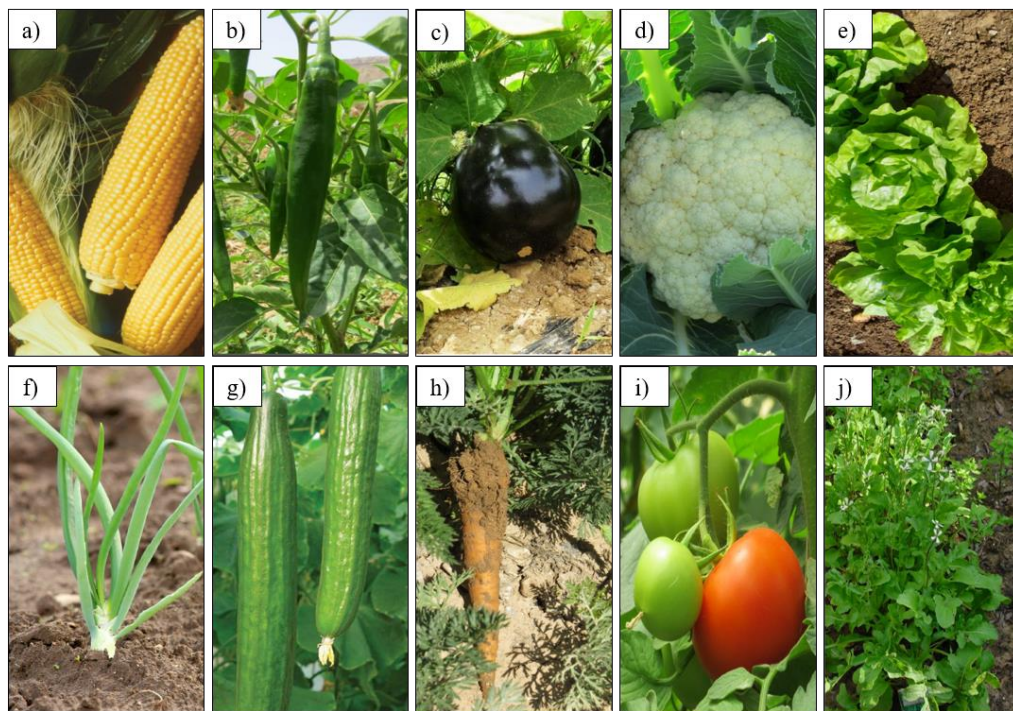


Figure 57. Luscious vegetable crops grown under TWW irrigation: a) corn, b) green pepper, c) eggplant, d) cauliflower, e) lettuce, f) green onion, g) cucumber, h) carrot, i) tomato, and j) rocca

*Source: MERWRA, 2015*

### *Trace elements*

The major difference of the various studied vegetable species are their crop types, which can be categorized into fruit-bearing crops (tomato, green pepper, eggplant, cauliflower, cucumber, and corn), leafy crops (lettuce, rocca, and green onion) and root vegetable (carrot).

There are two main processes involved in the mechanism of heavy metals uptake by plants: phytoaccumulation and phytodegradation (Tangahu et al., 2011), affecting the contaminants uptake in the system parts. The uptake of different toxic materials from irrigation water is initiated from the



root system, and, subsequently, translocates to the green parts of a plant. Figure 32 implies that phytoaccumulation is taken place in the irrigated crops, where the uptake rate of metals varies between leaves and fruits of crops. As low as 0.01 mg/L, and even absence of trace elements can be detected in the fruit-bearing crops. In fact, the leafy vegetable crops tend to accumulate more trace elements than the fruit-bearing vegetables. This is due to phytoaccumulation, the mechanism that filters and traps most of the trace elements in the green part of the plant without letting any residuals disseminate to the fruits, which enables the fruit-bearing vegetables to be safe for consumption. This condition is attested by a plant-uptake studies of micropollutants under TWW irrigation regimen at the Zarqa River Basin conducted by Riemenschneider et al. (2016), where the studies' outputs reflected that leafy crops such as lettuce, followed by parsley and rucola, have highly elevated concentration of pollutants in its edible portions.

As can be observed in Figure 32, some of the system parts of the plants are found to have higher concentration of trace elements than the source water, such as the concentration of Cu in eggplant, cucumber, and tomato as an example. It is likely due to the application of microfertilizer or antifungal pesticide in the field. Microfertilizer comprised of minor amount of trace elements that should be provided in a small amount as a means to stimulate plants' growth health, while the use of antifungal pesticide reduces the effect of fungi on the plant. Hence, these additional nutrients are being uptake by the crops causing the concentration of Cu in the system part to be higher than the water source.

The threshold levels of trace elements in the irrigation water are imperative not only for crop production but also on consumers' health. An elevated trace elements concentration induces high accumulation of toxic chemicals in edible portion of the plants, which could adversely affect the health of consumer through consumption. FAO suggests that more than 5 mg/L of Al in the irrigation water results in non-productivity. High amounts of Cu of more than 2 mg/L can cause toxicity to plants, whereas excessive Pb (more than 5 mg/L) impedes plant cell growth. Cr is not acknowledged as an essential growth element, thus, the recommended value for Cr is less than 0.1 mg/L. The trace metals observed in the Table 14 show that the levels of Al, Cr, Cu, and Pb in the irrigation water remain below the FAO permissible limits. It is worth mentioning that the value of Cr, particularly in green pepper irrigation zone nearly exceed the recommended maximum concentration (0.1 mg/L). Therefore, this area requires special attention if intensive cultivation is practised. A regular irrigation water quality monitoring concerning the specific farm that uses the water for irrigation activity would minimize the health risk on crops and humans.

Overall, the observation that plant-based uptake of trace contaminants are detected at measurable concentration in the edible part of crops based on the crop quality indicates a potential pathway of contaminants entering into food chain.

### *E. coli*

The microbiological quality of crops are also an important aspect for human health. Bacterial contamination of crops is a real issue dealing with TWW. *E. coli* becomes highly concern because of existing high contents of *E. coli* between irrigation water and the plant system, as indicated in Figure 33. The concentration of *E. coli* in the plant system is highly reliant on the technique of growing. Some farmers practised drip irrigation equipped with plastic mulch, preventing the crops contact with soil and evaporation effect, while other farmers grow their crops in a green house where the crops are hanged with small ropes away from the ground. However, practising in an open field,

the fruit, due to its weight, may be in contact with the TWW irrigated soil and therefore subjected to contamination.

Comparing tomatoes and green peppers, the phytoaccumulation behaviour is similar with respect to the accumulation of trace ions in the leaves. However, in terms of microbial activity, green peppers are subjected to less contamination than tomatoes are. The fruit yielded by a green pepper is not heavy. Furthermore, green peppers can grow up to 50 to 60 cm above the soil profile, preventing it from reaching the ground. Due to the light weight of its fruit and the distance from the ground, green peppers are less contaminated than tomatoes. In contrast, the heavy fruit of tomatoes facilitates the soil contact with the fruit. Hence, the *E. coli* crops contamination depend on the types of crops and its distance to the TWW irrigated soil profile.

Interestingly, cauliflower has exceptionally high contamination, considering an increase of 40% of the *E. coli* content in the fruit compared to the source water. In this domain, the structure of the crops itself is the main determinant. Vegetable crops such as tomatoes, green peppers, eggplants and cucumbers have smooth surface and the low surface area restrains bacterial accumulation. On the other hand, the large surface area of cauliflower (see Figure 57(d)) serves as a breeding ground for bacteria inside the crop, if coupled with suitable environment. The texture of the crop harbors pathogenic strains of *E. coli* and is susceptible to the accumulation of microbes. Thus, this produce must be washed thoroughly before consumption. From this point of view, high surface area of the plant is one of the pathways for *E. coli* contamination. Correspondingly, it is noted a high detection rate of *E. coli* among low-growing leafy vegetable crops such as lettuce, rocca, and green onion. These vegetable crops have large surface areas and grow near to the soil profile; thereby their leaves are subjected to microbes contamination. Additionally, carrots are also susceptible to contamination because of the direct contact with soil. The bacteria can infiltrate the upper 20 to 30 cm of a carrot but not past 30 cm, indicating no accumulation and thereby that the health of such product is not affected.

*E. coli* concentration is not high in cucumbers and corn, as can be seen from Figure 33, especially where the *E. coli* content is absent in the root and stem and leaves. The surface of corn is elevated from the ground. Due to its salt-tolerant characteristic, farmers practice corn plantation in saline soil, and this condition reduces the activity of *E. coli* due to high salinity.

Figure 35 shows different comparison between *E. coli* in irrigation water to the edible part of the system. There is a reduction of *E. coli* in most of the edible portions as compared to source water, but this presence nonetheless, indicates risk. The presence of this faecal indicator bacteria implies that a contamination pathway is present between the irrigation water source and the products. Pathogenic strains may be introduced to food chain via this route.

#### *Spatial distribution of trace elements and E. coli concentrations*

Based on Figures 36 to 40, an understanding of whether there exist any changes in the concentrations of trace elements and *E. coli* along the river due to specific reasons can be elaborated. The trace elements concentrations in the irrigation water show no trend from upstream to downstream. There is no drastic change in the levels of the trace elements, implying that no industrial activities in close proximity to the river.

Different *E. coli* concentrations are based on different activities along the river course. WHO recommended a microbial guideline for effluent to be used for irrigation purpose. The organization has placed a total coliform limit of 1000 colony-forming units (CFU) per 100 mL for irrigation water (WHO, 2006). However, the rocca and lettuce irrigation zones exceed the suggested target values. The high *E. coli* concentrations in the irrigation water of rocca and lettuce serves as an indicator of contamination sources in the area, which might be contributed by manure practice in the region. This is also attributed to the source of untreated wastewater discharge from the river and some urban activities that are not connected to treatment plant but to septic tank.

### *Soil quality*

As per soil texture, 67% of the samples belong to sandy clay loam, one sample fall in clay loam, and one sample is classified as clay. The mineral in the soil's parent material is one of the inherent factors affecting soil pH. In view of the dominant natural limestone geological formation in the region, this explains the prevailing calcareous soil with a pH of ranging from 7.8 to 8.6. The pH of soil plays an instrumental role in the plant development, concerning nutrient availability in the soil needed for the plants' growth. Many necessary nutrients are not readily available to plants in highly alkaline soil. Consequently, pesticides and herbicides will not be adsorbed by the plant and end up as run off and introduces to the waterbody.

The degree of soil salinity is commonly expressed in EC. The parameter implies the concentration of total soluble salts in the solution. There is a difference of EC and ESP among soil samples in Figure 43. According to Richards (1954) classification, S4 has EC value above four, representing a saline soil. The salinity is likely due to natural processes such as weathering, deposition by water or wind, or anthropogenic factors such as irrigation practices, tillage practices, or fertilizer usage (Richards, 1954). Likewise, S4 has an ESP value of more than 15, implying a sodic soil.

Additionally, sample S4 has an upsurge concentrations of Na and Cl (see Figures 44, 45). An increased amount of Na and Cl impairs plant growth as it is likely to form insoluble NaCl, which is difficult for the plant to absorb the elements. The higher concentration of Na and Cl ions at the upper soil profile than that in the lower soil profile indicates that soil salinity is taking place at the upper soil profile. This is especially true with agricultural soil experiencing low rainfall, high evaporation rate, and restricted leaching, in relation with improper agricultural practices. The incessant application of excess amounts of water during irrigation practices is the large contributor to such circumstances. When the irrigation process ceases, the high evaporation effect resulting from the local climatic setting induces the accumulation of high amount of salts on the top layer of soil. Relating to the profile interaction of soil and groundwater, rain or the subsequent irrigation water can carry soluble salts down through the soil, which diffuse into groundwater. When the rainfall comes, the upper soil profile will gain a higher saline content. As the water percolates through the soil, it dissolves more minerals and gains more salinity during the time it takes to reach the groundwater body. The infiltration process represents the crossing of soil profile and ultimately leaching to groundwater system. Subsequently, the groundwater is more saline. In support of this statement, Bajjali and his colleagues (2017) stated the same within the scope of their work. This linked consequence concludes that mismanagement of irrigation create environmental problem to the ecosystem.

Crops tolerance to the abiotic stress (i.e. salinity) are major consideration. Salinity control with the selection of crops type must be taken into consideration at Site 4. High soil salinity is an important concern for irrigation because most tree crops are sensitive to high saline soil; such plants include citrus, grapes, avocado, strawberries, and some ornamentals. Contrarily, vegetable crops such as tomatoes and cucumbers are tolerant to this circumstance (WHO, 2006).

The presence of P and K is derived from the application of pesticides or fertilizer containing K,  $K_2SO_4$ , KCl,  $KNO_3$ . The concentration of K decreases with depth. This is attributed to uptake by plants; thus, less K escapes to lower profile. Nonetheless, the existence of high amount of calcium in the soil has the tendency to suppress the absorption of K, which is an essential macronutrient for plant growth. Similarly, high Ca is also most likely to prevent absorption of phosphorus which in turn promotes the formation of insoluble  $CaHPO_4$  compound. Figure 46 shows that mobilization of phosphorus tends to be at higher depth (0 to 40 cm), as indicated at S5 and S6. As nutrient uptake occurs at less than 20 cm, it will not mobilize deeper because it is a nutrient for plants; most of it will be consumed by plants at the upper part.

In short, the quality of soil within the study region has been affected by the spread of secondary salinization resulted from poor irrigation practice. Large scale of frequent irrigation stimulates high soil salinity, which markedly influences the productivity of soil in the long run. In such setting, the application of mulch can be suggested to alleviate high evaporation effect in the region. An adjustment of amount of water added to the land can certainly help in mitigating soil salinization. Therefore, proper management of irrigation and monitoring of soil quality parameters assures safe and long term TWW reuse.

#### *Groundwater quality*

The EC values of the groundwater samples in the studied area range from 759 to 8180  $\mu S/cm$ , with an average of 3346  $\mu S/cm$ , and the pH values vary from 6.3 to 8.6 (average value is 7.3), indicating an alkaline type of groundwater. The remarkable observation from Table 9 is high electrical conductivity. An elevated EC, as high as 8000  $\mu S/cm$  can be observed in some wells. Also, it is observed that the order of abundance of the major cations is  $Na > Ca > Mg > K$ , while for anions is  $Cl > SO_4 > HCO_3 > NO_3$ .

As exhibited in Table 10, there are correlations between different water parameters of more than 50%. This relationship denotes a significant correlation or good relation that can be justified due to different reasons. EC shows moderate correlation of over 50%. Most of the parameters have a good relation with EC because EC represents the amount of dissolve solids in water samples (except K because it is found in minor concentrations). Correspondingly, the correlation coefficient between Na and Cl is 0.88, indicating a high correlation. This is because dissolution of halides, which are Na and Cl minerals, a 1:1 stoichiometry of (Na + Cl) should exist, producing one Na ion and one Cl ion, resulting in a positive correlation ( $r^2 = 0.77$ ) in most of the samples as depicted in Figure 45. This relationship can be explained by high evaporation effect and high irrigation process in the area due to climatic setting. The highest correlation among elements is found between Cl and Ca with 0.93. This implies that during mining practices, many CaCl components are being dissolved, resulting in this high correlation of parameters. The high correlation of more than 85% between  $SO_4$  and Ca is justified by gypsum dissolution. Based on the knowledge on the local geological understanding, the Mg-Ca relation is justified by the limestone system or carbonate system present in the region.

As per cluster analysis, the EC of the water groups varies from 1043 to 6363  $\mu\text{S}/\text{cm}$ , with group 4 having the least EC. The prevailing salinity is presented by the dominant Na and Cl ions in all the water groups. The others reasons behind the different concentrations of cations and anions are attributed to the limestone setting in the area. On the basis of Piper classification, the origin of water belongs more to Na-Cl type due to high Cl concentration in the samples, indicating that groundwater system is strongly affected by anthropogenic activities. This implies the irrigation effect on groundwater system due to evaporation of irrigation water, which results in accumulation of NaCl in the soil profile, then reaching groundwater system through incessant irrigation process. In parallel, Bajjali et al. (2017) have reported similar finding associated with geochemistry evaluation of groundwater. The different recorded EC can be apply to different practices at the location of reuse for agricultural activities. EC is a good measurement of salinity hazard to crop. Excess salinity provokes a reduction in the osmotic activity of plants and thus restricts access of plants to water and nutrients from the soils (Richards, 1954). With the classification of water types, agricultural water uses can be defined by practising specific kind of agriculture at certain areas, as indicated in Figure 52. For instance, forage crops and corns have good salt-tolerant which can be irrigated with saline water.

The SAR values of the samples vary from 0.08 to 8.27 meq/L. The Wilcox plot (Figure 53) illustrates that most of the samples are classified within the S1 and S2 zones. About 40% of the groundwater samples fall in S1C3 quality, representing low Na and high salinity water. This water type is suitable for specific crops that are salt-tolerant. C4 represents high salinity hazard that is more than 5000  $\mu\text{S}/\text{cm}$ . Two samples fall within the zone S1C4, which defines a low Na hazard and very high salinity. This interpretation limits the water for certain use (for instance, salt-tolerance crops). Nearly 46% of the samples belong to the zone of S2C4, with medium Na hazard and very high EC. One sample is located within S3C4 zone, with high SAR and very high salinity hazard. Only plants that are able to resist salinity can thrive in such given environment. High Na concentration in irrigation water tends to block the soil and jeopardize soil permeability. As a consequence, roots will not be able to absorb water from the soil profile and thus retard the plants growth.

A noteworthy observation from the field trip is demonstrated in Figure 58, where the rust-coloured iron minerals are observed. This suggests that the leakage of saline groundwater well from deep aquifer downstream. The salinity tested on the spot is around 4900  $\mu\text{S}/\text{cm}$  (see Appendix 3), which exceeds the tolerable salinity value for plants and potentially affects crops productivity.



Figure 58. Downstream appearance of saline groundwater well.

*Source: Chan, 2017*

Linking to the cross section of the river in Figure 8, the upward leakage of saline water (more than 3000 mg/L) from deep sandstone aquifer is the major source of salinity downstream. Recognizing the high salinity effect downstream accompanied with sparse and limited land availability (see Figure 9), these observations stress the importance and suitability of agricultural activities to be conducted at the upper stretch of the river; which has more suitable land and most importantly, less salinity effect and more water available.

Salinity is the main considerable aspect in the groundwater quality evaluation. Water is deemed as an excellent solvent as it has high tendency to dissolve salts, chemical constituents, and rock-forming materials due to its dielectric constant (Tölgyessy, 1993). This suggests that the groundwater hydrochemistry is controlled by water-rock interaction. As groundwater flows through the rock pore spaces and subsurface soil, it is most likely to dissolve substances due to the factor of water-rock interaction. For this reason, the dissolved solids concentration increases from the upper soil layer downward. Further, the long residence time of water in the groundwater system results in higher saline groundwater than the surface water. As such, groundwater is often comprised more dissolved substances than the surface water. Owing to anthropogenic pollution, primarily agriculture, the upper aquifer is highly affected by agrochemical residues resulting from farmers' practices, particularly the use of nitrogen fertilizer. The residues indicate a contamination risk in the area, which may deteriorate water quality locally in the high vulnerability zones. In addition, the enhanced salinity zones are results from the existence of evaporates (gypsum) and lime at the study area. The high evaporation force concentrates the salt content in the soil profile to be washed out by the rainfall and, ultimately, reach the groundwater system.

Ultimately, the groundwater quality modelled to be with a medium sodium hazard and high salinity hazard, derived from high evaporation rate and the saline soil. The sources of ions into the groundwater originate from cation exchange, anthropogenic activities, and dissolution and leaching from source rocks. For that reason, it is important to study the geology of the area and thereafter understand the resulting composition or quality of water with respect to different values. Achieving these goals serves as a basis for developing an appropriate monitoring program and thereby enhances management of the groundwater resources of the study region.

## 6.2 Current Practices of Farmers using Treated Wastewater

Farmers are the key stakeholders in the reuse of TWW for irrigation (Carr et al., 2011). The irrigation practices of the farmers have capacity to influence the quality of the ecosystem service delivered to the farm. Under TWW irrigation setting, the farmers' practices tend to have a loop effect. The unsustainable agricultural practices invariably affect the delivery of a range of ecosystem services; further down the line, the vulnerable local farmers are highly afflicted with the derived implications resulting from their irrigation practices. Hence, their current practices are sought to ensure a sustainable agricultural productivity.

The local existing practices of the farming communities using TWW for different crops will be highlighted within this realm. These includes water sources, crop types, irrigation activities, land use practice, and the knowledge of farmers on such reuse.

### Source of water

Figure 59 depicts the origin of the irrigation water. The sourcing of water is from both well and surface water i.e. the TWW.

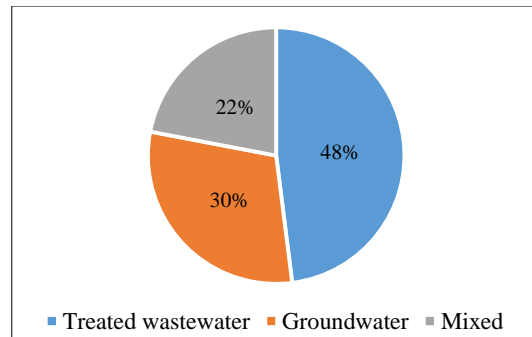


Figure 59. Source of irrigation water.

*Data source: SQU & UJ, 2015*

As indicated in Figure 59, 48% of individuals amongst the farming communities consider TWW as the primary water source for irrigation. The sourcing of TWW directly from the river by pumping can be observed in the field as demonstrated in Figure 60. Illegal pumping of TWW was spotted for reuse purpose in irrigated agriculture. Dated in the middle of 1990's, the implementation of the provisions of the groundwater by-law 1985-2002 had prohibited the drilling of private groundwater wells for private and agricultural uses. As such, the farmers stopped drilling groundwater wells when considering the high cost incurred from the groundwater exploration and high groundwater salinity (Naber, 2009). Ultimately, TWW has become the only alternative for the local farmers to practice agriculture, in view of the climate variability and drought events.

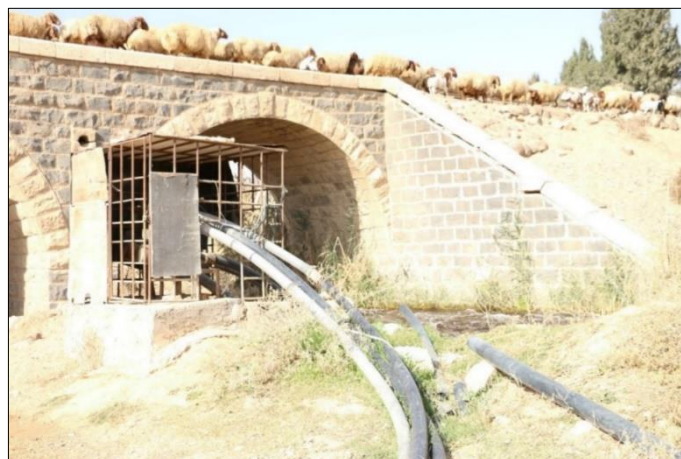


Figure 60. Illegal pumping of TWW from river.

*Source: Chan, 2017*

Notably, there is still a portion of farmers (30%) that owns private groundwater wells for agricultural practices. The irrigation wells penetrates the upper limestone aquifer, generating 50 m<sup>3</sup>/hr in average (SQU & UJ, 2015). As stated by the farmers, this is to secure the farms due to unfulfilled water demand, under the controlled agricultural water supply.

### *Conjunctive use of TWW and groundwater*

After identifying the water sources, Figure 61 illustrates the mixing ratio of different water sources within the study group. The conjunctive use of groundwater and surface water is practised in the irrigation setting.

Some mixing practices in varying proportions are observed amongst farmers when the water sources are limited. About 33% of the study sample are recorded with a mixing ratio of groundwater to TWW of 2:1. The salinity of groundwater well measured in situ in Abu Shadi's Farm was about 3680  $\mu\text{S}/\text{cm}$ . It can be deduced that the mixing of TWW and groundwater reduces the salinity of the irrigation water as the groundwater system has higher salinity than TWW. Without mixing, it would adversely affect the productivity of less salt-tolerant crops. However, the irregular mixing of groundwater and TWW may lead to uncontrolled changes of the irrigation water quality (Al-Ansari et al., 2013).

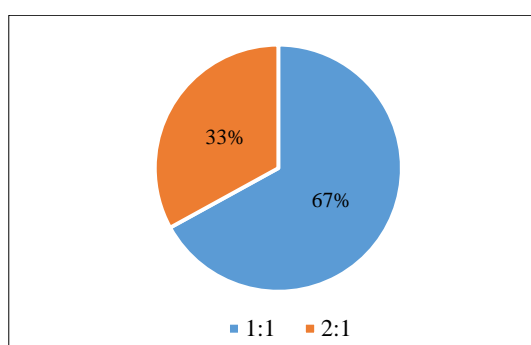


Figure 61. Water mixing ratio of different sources (groundwater :TWW).

*Data source: SQU & UJ, 2015*

### *Type of crops*

Figure 62 shows a variety of crops present in the local farms, including vegetables, fruit trees, and cereals. Within the study sample, about 40% of olive, citrus, and grape tree farming exists in the area. These types of farming are regarded as old practices amongst the local community in the region.

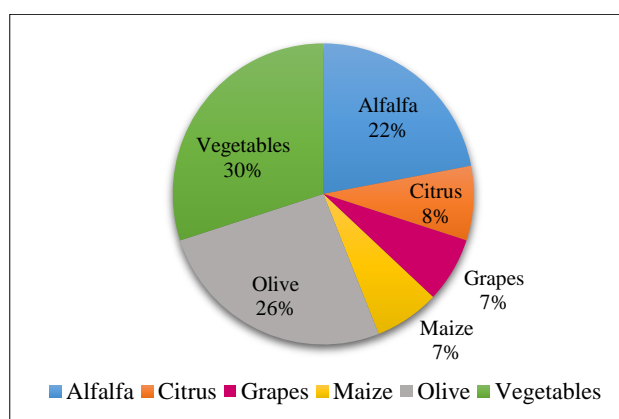


Figure 62. Distribution of crop types.

*Data source: SQU & UJ, 2015*



On the contrary, 30% of the water is reused to irrigate vegetable crops, including but not limited to cucumber, green pepper, eggplant, onion, lettuce, ladyfinger, and tomato. These crops are mostly ready for human use without cooking. In irrigation setting, TWW can be reused in restricted agriculture. As specified in the Jordanian regulations, TWW reuse in irrigated agriculture is constrained for certain crops that are normally cooked and, in particular, crops that grow 80 cm above soil profile. However, most of the crops irrigated by TWW in the local farms can be consumed raw, and this signifies a potential health risk. Figure 63 captures some samples of the crops in the study area, indicating various agricultural activities being taken place in the region.

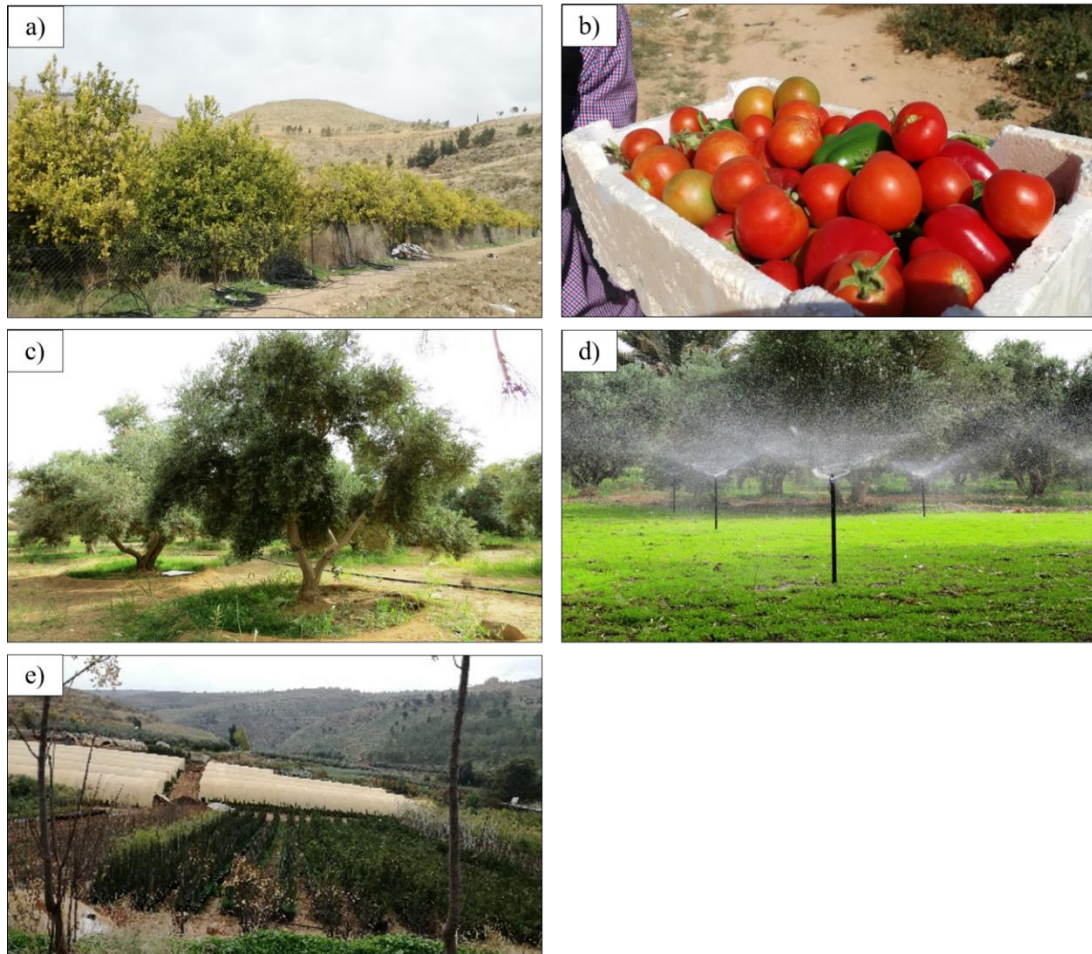


Figure 63. Observed agricultural activities from the farm: a) citrus trees, b) tomatoes and bell peppers, c) olive trees, d) Alfalfa crop, and e) nursery ornamental plants.

Source: MERWRA, 2015; Chan, 2017

#### *Knowledge on treated wastewater reuse*

The limelight of this question is directed at the awareness and previous knowledge of the farmers concerning wastewater reuse impacts, as represented in Figure 64. It can be concluded that awareness of TWW reuse is not high among farmers.

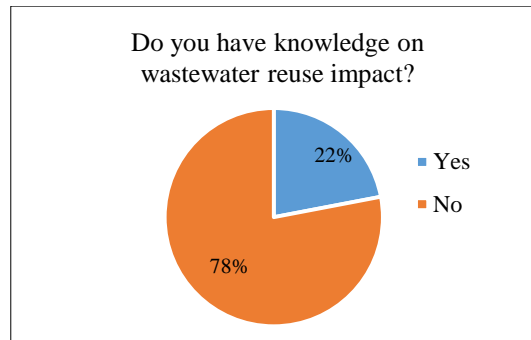


Figure 64. Knowledge of farmers on wastewater reuse impacts.

*Data source: SQU & UJ, 2015*

From Figure 64, 22% of the study sample responded that they have knowledge on the environmental and health impacts resulted from different awareness programs conducted in the past years. Remarkably, 78% of the farmers have no existing knowledge on the impacts of the reuse. This is presumably due to limited awareness campaign and little effort bring done by the minister and researchers on the education of farmers using TWW.

Due to insufficient existing knowledge and awareness of farmers on wastewater reuse impact, illegal reuse of TWW for irrigation purposes is rampant. Furthermore, the over dosage of fertilizers added into the pond containing nutrient-rich wastewater leads to eutrophication and triggers harmful microalgal blooms. This striking phenomenon is illustrated in Figure 65, where the water reservoir is loaded with inorganic nitrogen and phosphorus. This suggests the inadequate knowledge of farmers on TWW reuse leading to inorganic pollution.

Naturally, the fertilizers entail a sufficient amount of N and P, which are prominent for plants growth. The excess application of nutrients into a body of nutrient-rich TWW results in algal growth and subsequently the formation of algal blooms. Phosphorus and Nitrogen are considered the main culprit of eutrophication because these inorganic constituents stimulates the growth of undesirable plants for instance algae and aquatic macrophytes (Abdel-Raouf et al., 2012). These oxygen-demanding plants create anaerobic environment and jeopardize the water quality in the pond with time.



Figure 65. Eutrophication of water environment due to excessive nutrients.

*Source: Chan, 2017*

These unwanted environmental perturbations invariably raise a multitude of agricultural challenges, including contamination of water sources and low crops yield owing to unsuitability for irrigation water. Discharge of these nutrient-enriching waters into another water environment is likely to cause adverse effects in receiving bodies of water and disrupt the sensitive aquatic system. Hence, low knowledge of farmers on wastewater reuse impacts indicates a weakness in the area of interest.

#### *Perception of farmers on water and soil quality*

Within this sphere, an understanding of what farmers think about the water quality pertaining to physicochemical properties and what agricultural challenges they experience at the farm level were sought, in order to address the concern of farmers. Figure 66 demonstrates the farmers' perception in the aspect of water quality. It was found out that the major water quality issues are salinity and turbidity.

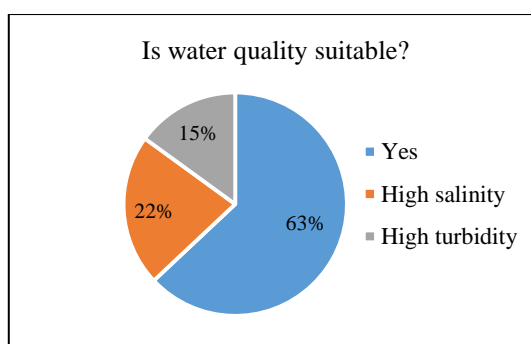


Figure 66. Perception of farmers on water quality.

*Data source: SQU & UJ, 2015*

More than 60% of the total farms described TWW positively. The salinity of the TWW generated from As Samra plant measured on the field is about 1900  $\mu\text{s}/\text{cm}$ . This value is equivalent to 1200 mg/L, and it is accepted by the local farmers. On the other hand, 22% claimed salinity issue and 15% recognized turbidity problem. The salinity problem is likely to correspond to the effect of gypsum mining taking place in the local areas along the river causing increasingly saline river water to more than 2000 mg/L. This situation exceeds the plant tolerant and affect productivity severely. Further, the presence of saline wells and springs also distress the river system.

Figure 67 shows the farmers' perception on soil quality based on their farming experience. Within the sample, 56% responded positively on the soil quality. In contrast, 44% of the recorded sample viewed the soil resource negatively, of which 26% of them declared high soil salinity.

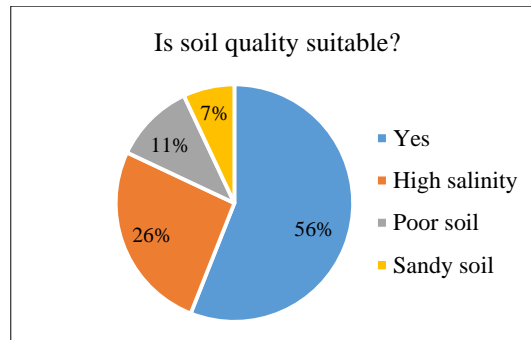


Figure 67. Perception of farmers on soil quality.

*Data source: SQU & UJ, 2015*

These farmer related aspects of soil quality to crop health damage, and less than 20% of the total sample is accounted for poor and sandy soil. Figure 68 shows the environmental concerns in agricultural production as experienced by farmers, in which the repercussion of saline soil is reflected on the plants' health, with yellow spots appearing on the plant's surface. This is a clear indication of high salinity environment.



Figure 68. Effect of over-irrigation with saline water supply on soil and plant's health.

In conclusion, the implications of the current practices of farmers can form a feedback loop. It will ultimately reflect the quality of the ecosystem services being delivered. Consequently, the farmers are the ones who bear the detrimental impacts. In light of these sobering observations, communication of research and education targeting TWW reuse practice and impacts to local farmers should be strongly enhanced via awareness campaign, among others to promote knowledge on best practices. Smallholder farmers who do not have access to this type of information are unaware of the potential harm that high salinity will cause to their key crops or microbiological contamination will cause to them or the general public. Lack of vertical communication (between governments and/or researchers and farmers) exacerbates this condition.

In that perspective, dissemination of the available quality information potentially alleviate negative environmental pollution. Prior to that strategy, researchers or authorities should develop a relationship of trust with farmers, also taken into consideration the sensitive issue of illegal usage of TWW. The research community should solicit input from farmers regularly to ensure that farmers are obtaining the information necessary to effectively manage agricultural issues. The conclusion that can be drawn with respect to this last point is that research that informs action are needed as this channel improves farmers' capabilities to manage agricultural problems. This rapport relationship is imperative to bridge the gap between science and agricultural productivity in the farm level.

### 6.3 Health Aspects

The health impact of TWW reuse is directed on the type of pollutants and the connection between irrigation process, products, and humans. Microbial parameters and pathogens are the key issues in this realm due to high expected effects on human beings within low contact time. Generally, pathogenic organisms may survive on the plant surface for approximately ten to 50 days. The pathogen die-off time between last irrigation and consumption is important for determining the relative health risk. Considering a maximum time of ten days between harvesting and consuming the crops, the microbial impact is most likely to take place. As stressed beforehand, the awareness and knowledge of farmers on the practice of TWW reuse concerning pathogen die-off time is pertinent in this domain.

Connecting to the high *E. coli* concentrations of water source in the lettuce and rocca irrigation zones (see Figure 40) and the health aspect, farmers dealing with type of water are susceptible to bacterial infections, resulting from direct physical contact of such water. Hence, implementation of rural health and safety measures for agricultural workers practising direct reuse are important to minimize health risk and avoid low productivity of workers. This strategy, couples with enhanced TWW reuse knowledge likely improve the sustainability of agricultural system.

In the aspect of indirect reuse, post-harvesting practices, i.e. food preparation in terms of washing, peeling, and cooking, determine majorly how disease transmits amongst consumers. The high *E. coli* concentration on the big surface area of the cauliflower crops exerts indirect effect on consumer chain. Proper washing of produce, e.g. cauliflower in the household reduces contamination and potential exposures to pathogens and some chemicals. Thus, hygienic practices potentially prevent the spread of cholera or gastrointestinal diseases.

#### *Heavy metals and pathogens*

As discussed in former section 6.1, the green pepper irrigation area requires prompt attention as the trace metals in the irrigation water almost exceed FAO guideline. If the condition is not well-addressed, the consumers will then be subjected to health implications, as listed in Table 5 (see section 3.4) with time via secondary consumption. In light of this potential threat, application of bioindicators as a reliable measure for assessing water quality can be incorporated in the water quality monitoring program. The bioindicators respond rapidly and sensitively to environmental stresses, indicating the presence of certain undesirable pollutants, such as heavy metals within the ecosystem. Specific fish kind used as a bioindicator can be monitored for any quality changes in the river system, with no cost of chemical analysis. Besides, comprehensive study of bioindicators in water quality over entire basin can significantly contribute to adjust and optimize agricultural practices.

Additionally, this study recommends the establishment of TWW reuse area, so that agricultural activities can be defined. Based on the discussion in section 6.1, phytoaccumulation is efficient enough in reducing different parameters of trace elements in the crops itself. Nevertheless, it poses risk for the leafy crops, considering the process of filtering and accumulating toxic materials in the green parts of plants. Relating to that observation, the types of crops can be modified. Fruit-bearing crops can be cultivated instead to minimize the health risks. Further, based on the root system of the crops, if high concentration of trace elements are concentrated at high depth, deep root plants shall



not be planted but with shallow root plant. These measures are helpful in defining and optimizing TWW reuse activities.

Based on the spatial variation of *E. coli* concentration in the irrigation water source (see section 6.1), different types of crops can be introduced at different areas of the study region. It is feasible to have the water used for irrigation at specific area rather than using the same source of water. By establishing a defined TWW reuse area, the contamination sources in the area can be reduced, thereby reducing the crops contamination. A well-defined area with sufficient crop monitoring such as crop types, also increases farming land use efficiency. It is also important to bear in mind that the source of *E. coli* contamination not always stems from the water source but also results from how the crops are being harvested, handled, stored, and processed. Hence, the practices and awareness of farmers play an important role in determining the crop quality.

### *Micropollutants*

Albeit micropollutants are not researched in this study, this section aims to highlight the occurrence and uptake of emerging micropollutant in the aquatic system and plant-based system respectively, within the study region. Plant-based uptake of anthropogenic micropollutants is evident in the research undertaken by Riemenschneider et al. (2016). Moreover, literature search revealed that at present time, regulations on the occurrence of these trace pollutants are absent in the study region and this exacerbates the present conditions. The existence of these contaminants in the Zarqa water body is viewed as a potential threat to the study area due to its pernicious mutagenic effects on the aquatic system even in trace concentrations, such as fish feminization. When it enters into the food chain, the bioaccumulation effect is likely to disrupt the functioning of human system through secondary consumption. In spite of that consequences, this subject is marginally discussed in the research community with respect to the study area. Thus, micropollutants shall be regulated in the standards or guidelines for public health concern. Research on the fate of micropollutant uptake by plants and in aquatic environment must be enhanced in order to avoid deteriorating water quality and loss of aquatic biodiversity.

## 6.4 Crops Productivity

At the upper Zarqa River area, diverse agricultural activities can be observed. A variety of crops such as vegetables, Alfalfa (fodder for animals feeding), olives, citrus, and maize (see Figure 63) are planted. In the last few years, the knowledge exchange and development of TWW reuse in agricultural practices has largely improved the economic return for local farmers. Figure 69 shows the performance of crops and its associated economic return.

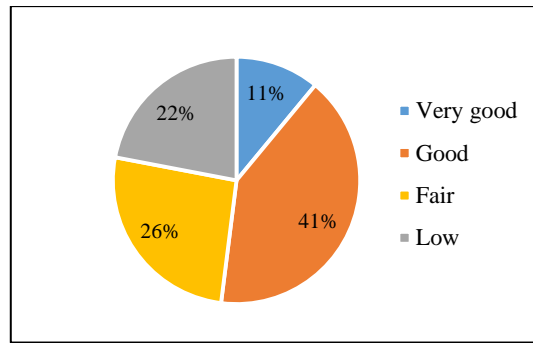


Figure 69. Crop performance and economic return

*Data source: SQU & UJ, 2015*

TWW reuse in irrigation often has direct agronomic and economic benefits. More than 50% of the study sample recognized the nutrient benefits from the TWW and acknowledged good to very good economic return. The macronutrients-containing TWW produced from the As Samra plant is a good fertilizer source for farmers as it comprises high value of organic and inorganic nutrients such as nitrogen, potassium and phosphorus which are fundamental for crop health. In addition, if TWW is applied optimally, the valuable components of nutrients improves soil conditions. In this respect, the application of synthetic fertilizers can be greatly reduced and subsequently facilitates economic efficiency in fertilizer savings. Conversely, less than 50% of the farmers are below expectations and stated a low economic return. Relating this statement to section 6.2, this could possibly due to low education, traditional practices, and soil-water quality. Farmers are not aware of the saline soil and perform crops cultivation that are not salt-tolerant. This practice contributes to low crops performance.

Despite the tangible benefits for crop productivity, inappropriate agricultural routine such as excessive input of urea for field irrigated with TWW may cause fertilization surplus in affected soils and recession in plant cover. Hence, the education and agricultural practices of farmers are markedly important. An improved soil conditions combined with sustainable land use can achieve a win-win scenario for environments and farmers itself.

#### *Supply and demand factor*

Water availability is also one of the factors in increasing crop productivity, the supply and demand factor that influences the availability of TWW and its uses in the area under cultivation (SQU & UJ, 2015). The inflow of discharged TWW into the Zarqa River not only potentially reduces the water conflicts among farmers but also assures water security in the region by mitigating water shortages. It helps greatly the small farmers to improve crops productivity. The continuous supply of precious commodity sustains the livelihood and lower the tendency of rural-urban migration, which in turn maintains the agricultural productions all year long.

#### *Effect of climatic changes*

Nonetheless, the crops in the hilly areas of the study region are prone to climate risk which adversely afflict the crop yield. The crops tend to freeze and shrink during the winter season when low temperature strikes. Figure 70 shows the burning part of the crops leave exposed to low temperatures

under cold stress conditions, which is represented as one of the weaknesses in the study area. Crop harvest has been decimated by a cold winter and a late freeze with calamitous consequences. Therefore ability to adapt to cold temperature has an impact on the distribution and survival of the crops. In that perspective, frost or cold tolerance crops, for example carrot, radishes, which possess cold acclimation can be introduced by the decision makers as a potential practical applications to assist farmer proactively manage climate risks to agriculture to protect their livelihoods. By diversifying crops and varieties as a means of tackling unpredictable climatic changes can certainly help reducing vulnerability of local agriculture to climate-related extreme events. Another feasible alternative including farming in green house against the climate hazard potentially lessen crop losses.



Figure 70. Shrinkage of crops owing to climatic changes.

*Source: Chan, 2017*

## 6.5 Ecosystem as General Interaction

An ecosystem is a dynamic environment of living communities in conjunction with the non-living environment, interacting as a functional unit (MEA, 2005). The release of TWW and its reuse inextricably interact with the ecosystems as a delivery mechanism of ecosystem services to the local communities. Considering the upper Zarqa River system as a whole, the implications of the discharge and reuse practice of TWW influence the state of the existing local ecosystem to a certain dimension, either in a positive or negative manner. Therefore, understanding the interface between TWW discharge into the river basin and its reuse, and ecosystems in the region of interest, provides options to manage ecosystems sustainably.

### *Rehabilitation of ecosystem*

One of the most noteworthy positive interactions from the generated TWW and ecosystem itself is the restoration of the Zarqa River, associated with its quality. As described in section 2.7, Zarqa River was notorious for its water quality up until the '90s. With a significant 70% reduction of COD from 224 mg/L to 69 mg/L, Al-Omari et al. (2013) concluded an improvement of the river water quality, after the upgrade of the As Samra plant. The extra discharge of good quality TWW results in ecosystem recovery. For instance, the relocation of fish, aquatic organisms, and other wildlife to the river rejuvenates the river ecosystem. The expansion of vegetation cover due to availability of



river water as water source for irrigation can be observed prior to and after the operation of the As Samra plant with Google Earth data, as demonstrated in Figure 71. These recoveries indicate the water quality of the river has improved dramatically.

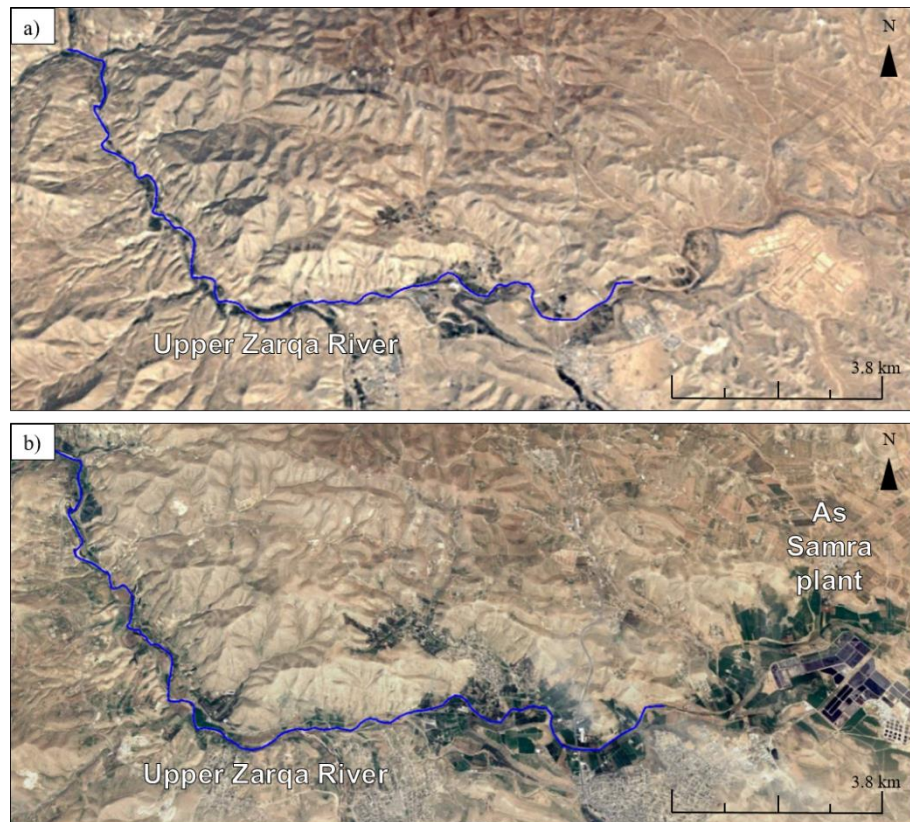


Figure 71. Historical and current satellite observations on the ground in terms of green cover expansion along the river in a) 1984, before the establishment of As Samra plant and b) 2017, after the establishment of the plant.

*Source: after Google Earth image, 2017*

#### *Improved flow conditions*

As discussed in section 2.7, prior to the construction of As Samra plant, the river and springs were running dry. The flow of the river was relatively small in the '80s (see Figure 10), exacerbated by intensive groundwater withdrawal and agricultural activities. Starting in the mid-1980s, the additional discharged TWW volumes from the plant continues to improve the flow conditions (El-Rawy et al., 2016) along the river tremendously and thus stabilises the base flow (Al-Wer, 2009). An increase of the water availability not only supports the economic means, i.e. irrigated agriculture sector along the river, but also enhances and sustains the regional ecosystem services, e.g. through the formation of additional springs, which in turn contributes to the inflow of the Zarqa River. Recognizing the rapid-MAR induced aquifer changes as exhibited in Figure 72, the intersection between groundwater table and topography (a high drop in topographic elevation) is elevated to a higher level and the springs are revived. As a result, these scenarios increase the carrying capacity of the local environment.

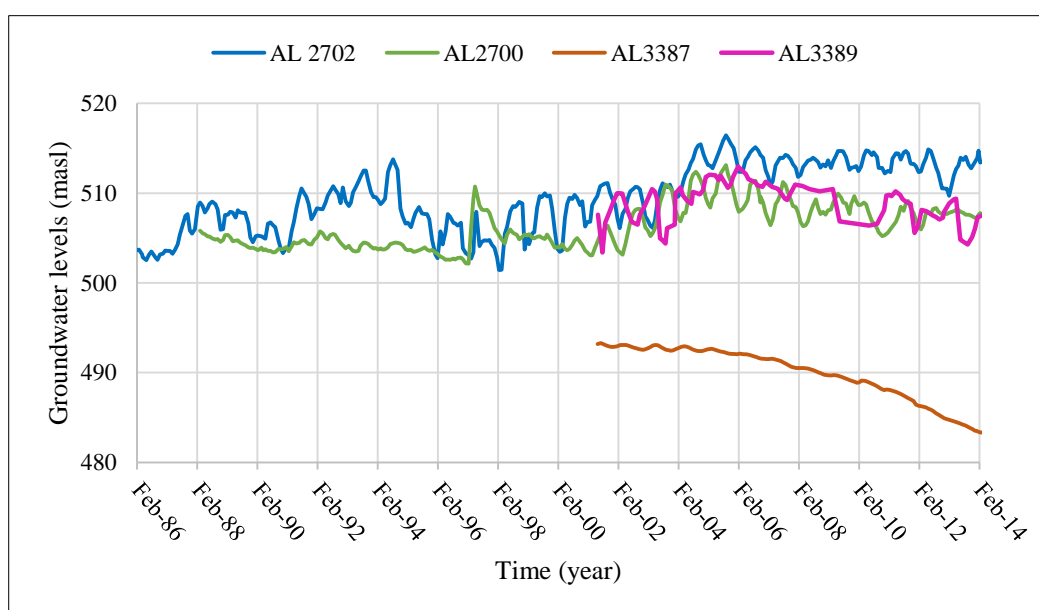
### *Suitable microclimate for human settlements*

The greater water quality of the river not only has benefited the local farmers who use the river water for irrigation purpose, but the improved environmental condition also creates a suitable local climate for human settlements in the vicinity of the river. This point will be used to address and highlight the linkages between ecosystems and human well-being in the area of interest.

The interaction of the altitudes and climatic conditions (as described in section 2.1) causes humid conditions in mountainous regions because the air is saturated with water. A 400 m drop in the elevation in less than 2 km (refer Figure 3), in addition to its semi-closed area, cause the temperature in the region to be 3 to 5 °C more than the surrounding temperature. The humid air has a low tendency to escape due to the unique mountainous range in the study area, thus, heat can be trapped. Owing to variation in altitudes in the study region, 10 to 15% of humid air retains and the resulted atmospheric humidity generates an ideal microclimate. This localized climatic structure promotes the simulation to a green house, which is important to sustain regional food security. Further, considering the factor of erosion and transportation of soil materials, these materials accumulate at the bottom of the basin. As such, the thick soil enriched with substantial amount of organic matter in the region is fertile and suitable for agricultural activities. The strategic location of the river and the productivity area indirectly increase the relevance of the river for people, contributing to agricultural sustainability. Consequently, it maintains a continuous agricultural production, enhancing the livelihood of the rural communities and thereby strengthening the food security in the region.

### *Augmentation of groundwater storage*

An elevated groundwater table has been observed at the upper Zarqa River. This is evident in the groundwater levels of the monitoring wells situated close to the As Samra plant and downstream as demonstrated in Figure 72.



Note. For well locations, see Figure 2.

Figure 72. Groundwater levels in observation wells AL2700, AL2702, AL3387, and AL3389

Data source: MWI, 2016

As revealed from the figure, the water table levels within the As Samra plant and downstream areas (AL2700, AL2027, and AL3389) have been recovered by more than 8 m from mid-1990s due to the effect of recharge from the TWW. As a result of groundwater-surface water interaction, the TWW seeps through the riverbed, forming a groundwater recharge mound in the Hummar Aquifer. Likewise, this statement is supported by Bajjali et al. (2017). Conversely, the monitoring well AL3387 east of the plant demonstrated a declined water level due to over-pumping. This suggests that the underlying unconfined limestone Hummar Aquifer at the upper section of the Zarqa River has a high potential for aquifer recharge by TWW. The upper aquifer system is composed of basalt and limestone. These water-bearing aquifers are characterized by a good recharge mound. In specific, the basaltic joints or fractures favour recharge because such structures contribute to water movement and thus enhance water infiltration to aquifer.

The dramatic water level recovery demonstrated a positive scenario as a response to continuous recharge from the river (El-Rawy et al., 2016). Thus, the groundwater recharge by the TWW is considered as an optimistic opportunity for long term aquifer recharge to relieve stress on the existing groundwater stocks on one hand and provide large reserve in the times of drought on the other.

#### *High aquifer resilience*

Resilience is the amount of perturbation a system can absorb to sustain its fundamental function and its ability to reorganize and renew itself for adaptation, subject to disturbance and change (Elmqvist et al., 2003). Within this domain, it is the degree to which the aquifer can rebound from setbacks such as over-pumping activities and climate change. With a high recharge rate, the system is characterized to have a high resilience. The augmentation of groundwater storage ensued from TWW discharge has a high tendency to increase the aquifer system resilience in terms of quantitative water abstraction. For instance, the aquifer with a thickness of 400 m is more resilient than an aquifer with a thickness of 100 m because it is more saturated and capable of holding a large amount of water, thereby potentially achieving more recharge. In other words, a resilient groundwater system is desired. Therefore, investing on a thick aquifer is viewed as a feasible alternative or an adaptation scenario to cope with the climate change and over-pumping scenario. Nevertheless, sustainable agricultural practices play a pivotal role in sustaining the aquifer system resilience. For instance, calculation of optimal abstraction rates of irrigation water would induce minimum damage to the aquifer and Zarqa River Basin, without losing their ability to provide valuable ecosystem services.

#### *High groundwater vulnerability*

Vulnerability has various connotations, depending on research orientation and perspective. In the field of ecosystems, vulnerability is defined as the degree to which an ecosystem is sensitive to change, along with the degree to which the sector that depends on this service is incapable of adapting in response to changes (Metzger et al., 2006). Thus, Figure 73 is provided to elaborate the high vulnerability of the groundwater system to quality degradation in respect to agricultural activities and the depth to groundwater level.

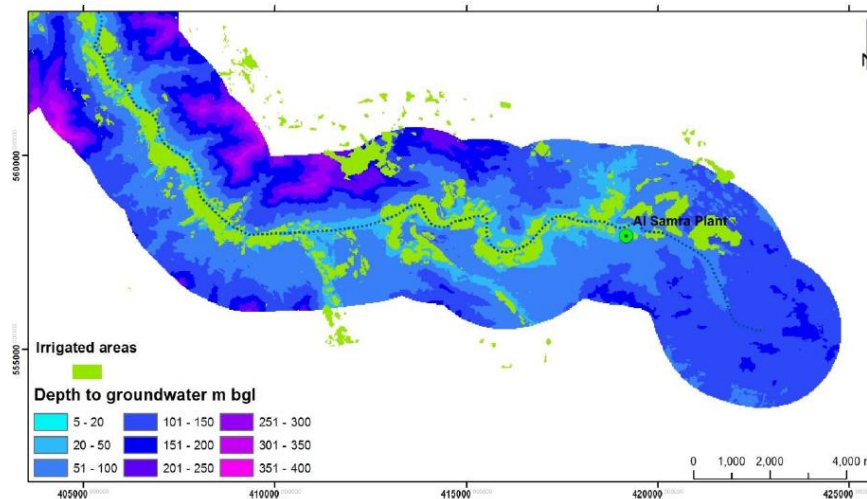


Figure 73. Irrigated areas and depth to groundwater table below ground level (mbgl).

Source: MERWRA, 2015

It is observed that a depth of 5 to 20 m to the level of groundwater is attenuated along the river, but a high depth to groundwater, up to 400 m is found in the highland. Farmers tend to go to shallow water table to extract water due to low cost pumping. This indicates that the return flow from agriculture activities will be closer to the groundwater system. This scenario causes long term contamination of the groundwater body. The difficult recovery of the contaminated groundwater system results in long term damage on the water security. Also, Lumb (2006) points out that the return flow containing high nitrogen content increases the likelihood of eutrophication if it finds its way to groundwater system. Hence, the shallow water table is more vulnerable to contamination than the deep groundwater due to the short distance.

In other words, high resilience of the aquifer system is also subjected to high vulnerability, in terms of high recharge rate. The feeding of young water from the river to the groundwater due to the losing and gaining systems of the river has a potential threat to trigger unfavourable environmental effects. Further, the groundwater table is too high that contaminants travel shortly to the groundwater body.

Figure 74 demonstrates the spatial distribution of groundwater recharge over the study area estimated by El-Rawy et al. (2016). They also estimated the return flow to be 17% of the total irrigation water. In light of the irrigated areas in the study region, the return flow is added to the groundwater recharge (green and yellow zones in Figure 74).

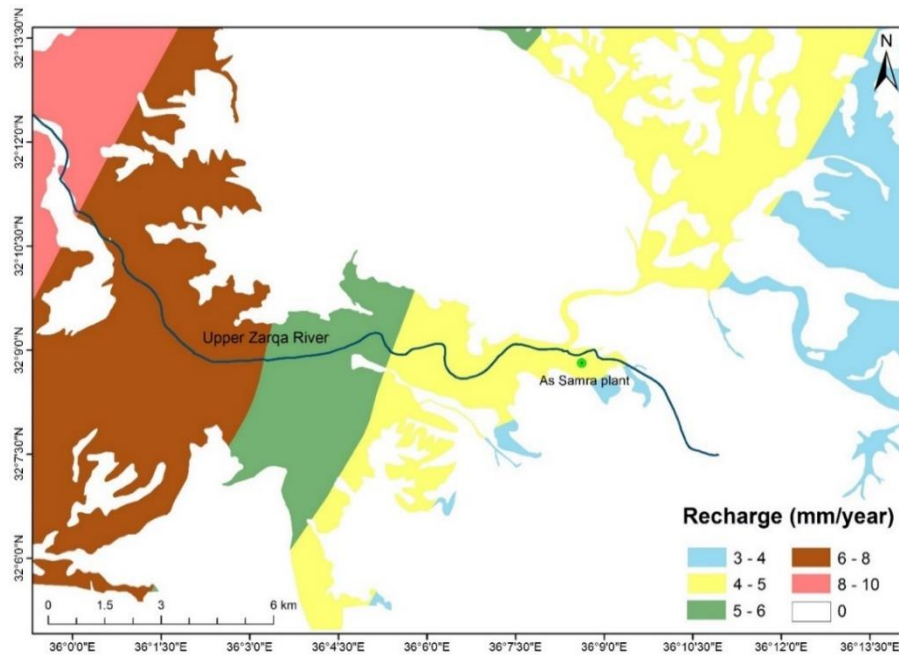


Figure 74. Estimated distribution of the groundwater recharge rate.

*Data source: recharge rate shapefile from MWI, 2016b*

Albeit the karstic features of the groundwater system spur a high recharge rate, the fractures also indicate high vulnerability of groundwater to contamination. This is because TWW may comprise heavy metals, pathogens, pharmaceuticals and other undesirable constituents (Abdel-Raouf et al., 2012) which contributes to a possible risk of groundwater contamination. Therefore, the joints within the groundwater body are considered as weakness points as the channels helps the transmission of contaminants.

Considering the farmer's activities and groundwater ecosystem, there is a relation between social vulnerability and environmental vulnerability within the river basin. Over-pumping activities induce severe drawdown in the groundwater level and leads to high saline wells. The farmers are afflicted directly with this scenario. In other words, farmers are plagued with high investment cost on the ground, as they are forced to dig into deeper groundwater levels which triggers high energy consumption. With time, they are burdened with high operational and maintenance cost, for instance, cleaning and changing the pumps or infrastructure. Not to mention, the high salt contents in the saline wells contributes to high salinity effect on agricultural activities. In that perspective, these circumstances add stress to local communities who are vulnerable in deepening wells. Apart from losing freshwater availability and the possible risk of losing the well, the pernicious consequence are most probably associated with agricultural productivity. Provided this point, social vulnerability and environmental vulnerability are correlated in the study region, in terms of high cost incurred on farmers level when groundwater table dwindles.

Relating to the above observations, groundwater protection measures can be applied for instance groundwater protection zone can be expanded to safeguard the groundwater system from over-drafting and minimize farmers' vulnerabilities to high operational cost.



### *Flood risk*

The upper Zarqa River is susceptible to flood risk. Climate change may complicate the usage of TWW incorporated with its non-predictable changing weather, e.g. through severe flash floods, with particularly severe flood afflicting the country back in November 2015. As the flood water will ultimately reach the Zarqa River channel, the potential overflow of nutrients into the system may contaminate sensitive adjacent areas with TWW on a wide spatial scale. Alternatively, check dams can be constructed in order to counteract the torrential flow and curtail the flood effect in the catchment area (see Figure 77).

### *Undercutting*

It is observed that the river undercuts the geological rocks. The erosion by the river wears down the soil and produces an overhang over a period of years. When such undercutting takes place, the rock making up the overhang will eventually collapse or slump due to lack of support. Figure 75 demonstrates the typical jointing in the study area. This is because when the rock is under stress, it fractures in the same direction. The deep long fractures are the weakness points that may collapse due to instability. This contributes to one of the threats in the area. Bearing in mind that the production of TWW continues to increase, strong water flux may stimulate the detachment.



Figure 75. Vertical joints in the geological rocks.

*Source: Chan, 2017*

Ultimately, all of the abovementioned points address the connectivity of ecosystems and the provision of ecosystem services in regard to TWW discharge and its reuse, while also addressing mitigation and adaptation to potential shock such as climate change and intensive groundwater withdrawal. Investing in high resilience ecosystems and concurrently reducing and protecting high vulnerability area through different measures, must be considered in land use management and planning. Albeit increasing resilience of the ecosystem promotes high vulnerability in the area, this situation can be counteracted through applied environmental law and regulations. Hence, enhancing resilience itself is a successful story and it can help immensely in defining more water availability for different practices.

## 6.6 SWOT Analysis

Based on the previous discussion at each section, the elaborated existing quality situation, current practices of farmers using TWW for various crops, health aspects, crops productivity, and ecosystem as general interaction, render a comprehensive understanding on the study system. To achieve one of the objectives stated in this research, this section aims to categorize the related major concerns according to the definitions being fixed in the section 4.2. The major inputs projected into the SWOT analysis depicted in Figure 76 supplies diverse array of knowledge in the sphere of TWW reuse for agriculture.

In the following analysis, the strengths, weaknesses, opportunities, and threats of TWW reuse for agriculture targeting at the upper Zarqa River will be highlighted, providing wide-ranging insights (immediate and future situations) into the local environment of the upper Zarqa River system. How the safe reuse practice of TWW can be maximized for agriculture, while minimizing the environmental impacts can be achieved in practical terms should be made apparent by the next SWOT analysis.



Figure 76. A SWOT analysis of TWW reuse for agriculture.

Source: Own-compilation

Under the umbrella of the integrated management of ecosystem services, the developed SWOT analysis supplies information and knowledge on maximizing TWW reuse by offsetting the strength and weaknesses, and simultaneously examining the prospective opportunities and threats. Future strategies pertaining to ecosystem services improvement are sought to leverage the present key features of the system that are already strong, addressing existing shortcomings, minimizing potential threats and harnessing the opportunities that are available to the upper Zarqa River. Subsequently, the outputs from the SWOT analysis will be used to generate recommendations in the context of the local environment of the upper Zarqa River for maximizing the safe reuse of TWW by means of ecosystem services improvement.

## 6.7 Proposition of Development Scenarios

Development scenarios describe plausible events that would be taking place within the study area, with respect to the projected increase in the volumes of TWW to more than 135 MCM per year, which is the maximum design capacity of the As Samra plant. The anticipated change in the TWW amount has a high tendency to affect the water use at the upper Zarqa River in the future. Based on the expected development on the ground, several development scenarios in connection with the expanding TWW discharge volume during the coming ten years are proposed.

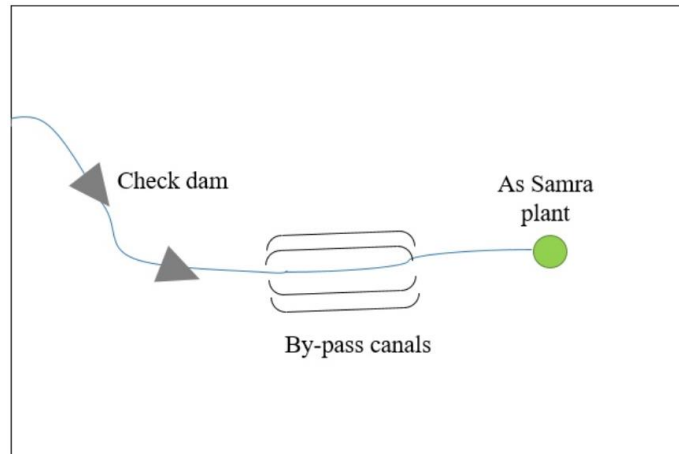
### *Implementation of managed aquifer recharge*

MAR is one of the water management alternatives to increase water availability. It is regarded as one of the probable development scenarios because the aquifer will be able to accommodate additional TWW discharge, as evident in Figure 72, where the groundwater table is restored following the inception of the As Samra plant. The increment in the TWW discharge rates will raise the depth of flowing water in the river. Taking into consideration the losing section of the river regime (see section 2.5), more river water tends to infiltrate into the aquifer, resulting from strong hydraulic connection between surface water-groundwater interactions. As a consequence, the river helps to raise the water table and promotes long term aquifer recharge.

The changes in the groundwater level are used as an indicator of the recharge effect, as reported by El-Rawy et al. (2016). An increase in the average water river depth from 0.63 m at the present state (110 MCM per year of permanent flow) to 0.77 m in the coming future (more than 135 MCM per year) elevates the groundwater level from 0.12 m to 0.55 m. Recharge from the river to the aquifer by 0.55 m tackles declining yields, which in turn improves and sustains the functioning of the ecosystem.

Hence, to augment the groundwater storage, by linking to the losing and gaining river sections in Figure 8, by-pass canals can be constructed at the losing segment of the upstream river, as suggested in Figure 77. The canal serves the function of diverting additional water on the aquifer surface, thus enhancing MAR activity and ultimately elevating the groundwater table. When the water quality constraints are met, MAR using TWW is viewed as viable and feasible mechanism for adaptation and resilience building of aquifer from quantitative water abstraction.





Note. Map not to scale.

Figure 77. Depiction of by-pass canals and check dam construction at upstream site.

Source: Self-elaboration

### *Geological instability*

The acknowledgement that the production of the TWW continues to increase; this condition will exacerbate the rock undercutting as mentioned in section 6.5. The strong water flux increases the rate of undercutting on the stability of slopes with time, and it highly leads to rockfall. In this respect, check dams can be constructed, as proposed in Figure 76. Check dams have the ability to reduce the flow of the water and therefore minimize the erosion of rivers.

### *Expansion of agricultural development*

An expansion in the irrigated areas is projected. At the present time, the only reason limiting local farmers from agricultural activities is the regional topography of the land. According to the conceptual aquifer model developed by El-Rawy and his colleagues (El-Rawy et al., 2016), the infiltration of river water into the aquifer increased by 11% as a result of additional TWW discharge. This value denotes approximately 30% of the irrigation abstraction volume from groundwater wells. Correspondingly, the irrigated areas are expected to expand by 30% based on the availability of farming land. This represents an irrigated area of nearly 15.55 km<sup>2</sup>, in contrast to the present area of 11.96 km<sup>2</sup>, allowing more farming activities and crops production. In this respect, farmers are likely to extend agricultural activities by making use of the terrace in mountainous stretches. The relationship between agricultural productivity and rural employment opportunities is linear; as the productivity increases, opportunities of employment also increase, which in turn raises incomes of farming communities. Also, considering the political unrest in the Middle East region, Jordan may constantly face an inflow of guests in the near future, in which the proliferation of population will result in a growing food market. The expansion of agriculture not only maintains a sustainable agricultural production chain in a long term, but also enhances overall development and social stability of the region.

### *Increase in groundwater withdrawal*

The anticipated expansion of irrigation activities will induce an increase of water extraction by 30%. In fact, this circumstance is addressed due to restricted regulation. The prohibition of direct use of TWW from the river accruing from the enforcement of irrigation water quality standard is expected to shift the farmer's dependency for irrigation water to groundwater. As such, farmers are likely to restart abandoned wells or invest in the development of new groundwater wells, and they have to bear the malicious effect from the high operational cost of withdrawing groundwater. Moreover, indiscriminate pumping activities trigger the lowering of water table by 0.36 m (El-Rawy et al., 2016). These scenarios amplified the pressure on the groundwater assets. Further down the line, the enactment of the standard could internally displace local farmers, who are poor and land-dependent, to search for another alternative water source. If legislation remains, the livelihood of the inhabitants in the region, whose economic means depend mostly on agriculture are under threat. The forced rural-urban migration of the community of farmers is another threat that intensifies food insecurity in the region. This prompts the need to review current standard.

Albeit expanding irrigated activities enables more crops production, it is inevitable that this development provokes groundwater drawdown. To alleviate this situation, it is suggested that the local planners shall consider developing and implementing conjunctive use policies in the study region. Conjunctive use is the process of using water from two different sources as an input to the irrigation system. Currently, the managed conjunctive use of scarce water resources in the study area is not in place (El-Rawy et al., 2016). Thus, it is suggested that direct use of river water, particularly in the times of drought, is recommended in order to alleviate stress on the groundwater system. At resource level, conjunctive use practice is viewed as sustainable management of groundwater and surface water. In parallel, there are a host of successful examples of conjunctive use of surface and groundwater resources including Karamouz et al. (2004) and Al Khamisi (2013), and these examples can be applied in the local context of the study region to increase water use efficiency, increase water availability, and minimize stress on groundwater system on one hand, and reduce pumping cost and maximize crops production on the other. Hence, an integrated approach to the surface and groundwater resources allocation is a useful tool for irrigation planning, especially in water-stressed region specifically in the upper stretch of the Zarqa River.

Nevertheless, the practical implementation of TWW reuse within the study region is hindered by the standard. As previously noted in section 6.2, conjunctive use is practicing in the local irrigation setting, thus, with a change in the standard, TWW reuse can be safely maximized. Given the local farmers who have settled in the region for more than three generations (before the construction of As Samra plant), the restricted standard jeopardizes the local riparian water rights, especially when the agriculture dominated watershed is a major water consumer. For this reason, the MOE should take farmers into consideration and be responsible in providing them options. As such, an initiative (such as this study) must be taken to draw information that may assist in giving recommendations to enhance the livelihood of the local inhabitants by addressing the need to change current standard in order to sustain agricultural productivity in the area that will enhance food security in Jordan and avoid migration from countryside to city.

Recognizing the prioritized effort of Jordanian government by integrating the adaptation of TWW resource into its national water budget as a means of tackling the country's persistent water scarcity (MWI, 2016), to effectively managing water reuse, including revisit existing irrigation water quality standard can maximize TWW reuse and complement the aforesaid effort. Relaxing the standard, in

addition to enhanced application of existing standard (such as enabling the cultivation of high value crops e.g. vegetables), will increase the benefits of agricultural TWW usage. If the Jordanian government is not in favour to legalize TWW reuse for vegetables, the downstream experience can be applied similarly to upstream, for example, through cultivation of cutting flowers and nursery activities. Hence, adjusted TWW legislation plays an instrumental role in sustaining the agricultural system within the study region.

#### *Increase in sludge production*

In line with the increasing TWW generation, sludge production from treatment processes will increase accordingly. If the local authorities are convinced with the quality and the true value of the produced sludge rendered, along with public acceptance, the application of sludge is seen as an optimistic scenario in irrigated agriculture sector. The treated sludge can be harnessed to enhance organic matter of the soil profile and thereby improve the farming activities in the region.

#### *Further extension of As Samra plant*

With the projection rate of TWW to more than 135 MCM in the coming years, the As Samra plant will be highly extended. It is important to note that the increasing freshwater supplied to Amman and Zarqa cities, resulting from the impact of Red Dead Canal project implementation, will cause an additional wastewater volume (Al-Omari et al., 2009). This implies that the WWTP will soon reach its maximum capacity, and it has a high tendency to experience overloading owing to unparalleled growth. This phenomenon heightens the risk of contaminated wastewater inflow and also raises a concern regarding the TWW quality due to the insufficient capacity of treating the increasing volume of TWW. In view of the increasing attention of the occurrence of emerging contaminants in the aquatic system, the advanced level for the removal of micropollutant shall also be considered. Nevertheless, the upgrade of the WWTP depends heavily on the available financing mechanism.

Taking into consideration that certain barriers and challenges can terminate the discharge of TWW into the river such as the risk of contaminated wastewater inflow, and the risk of As Samra plant being neglected by people stems from political issues or safety concerns. These reasons could impede the flow of TWW and affect the reuse practice in the area.

Ultimately, recognizing the links between the expected TWW discharge and human development, the above development scenarios represent future potential scenarios that reflect the expected changes. Proposing the possible development scenarios enables policy makers to pre-empt the impact of increasing TWW volume, respond to potential changes, and manage water resources effectively.

## 7. Recommendations

Based on the outcomes of this study, several recommendations for further work or research priorities are listed below, in the context of the local environment of the upper Zarqa River:

- Considering some of the threats such as increased groundwater withdrawal rate, the opportunities of long term aquifer recharge with TWW, alongside constant groundwater quality monitoring and expansion of groundwater protection zone, can be done to strengthen water security and minimize the environmental impact.
- Integrated management of groundwater abstraction with MAR using TWW can be incorporated; the calculation of optimal irrigation water abstraction rate and conjunctive use of TWW and groundwater would induce minimum damage to the aquifer.
- Revisit the standard by permitting direct use of TWW from the river, in addition to the enhanced application of existing standard (such as allowing the cultivation of vegetables eaten raw), will increase the benefits of water use.
- Through proposing the need to review current irrigation water quality standard, this study attempts to recommend specific kind of agricultural practices that can be defined within the study region through the establishment of well-defined TWW use area. Specifically, the potential to modify type of crops could suggest the safe reuse and sustainable practice of agricultural wastewater reuse.
- Further research studies on the occurrence of micropollutants in the water body and its associated uptake based on plant system are needed to ensure public health.
- The current practice of TWW reuse can also be strengthened through leveraging on opportunities such as the awareness of farming communities on reuse knowledge and proper irrigation practices.

## 8. Conclusion

In the near future, the expansion of TWW reuse stems from a high focus on the TWW as a resource, not a waste. The interaction of TWW reuse with respect to different ecosystem components are outlined in the SWOT analysis. The outputs from the SWOT profile provide an insight to the means of converting the potential threats into opportunities, along with offsetting the weaknesses against strengths. The analysis furnishes knowledges during the preliminary stage of decision making and serves as a precursor for strategic management planning concerning safe reuse of TWW.

The results of the present investigation elucidate that TWW reuse recuperates dwindling water table, increases groundwater system resilience, rehabilitates the ecosystem, creates ideal microclimates, sustains agricultural production, and enhances rural livelihood. In contrast, illegal waste dumping, illegal reuse practice resulted from restricted standard, over-irrigation, secondary salinization of soil, continuous vicious return flow to aquifer from irrigation activities, reckless use of fertilizer, and the absence of regulation on the existence of micropollutants were the main weaknesses of the study region. The identified possible threats potentially influence the area of interest are increased rural-urban migration, potential health threats, increased groundwater vulnerability, and indiscriminate groundwater abstraction through pumping activities. Further, the development scenarios in connection with projected increase in TWW rates were also proposed. The main features of which are an implementation of MAR, the expansion of agricultural activities, and the increase in groundwater withdrawal.

Based on these sobering observations, this study suggests the communication of research to farmers at the farm level, in relation to appropriate agricultural practices; doing so would increase agricultural productivity, long term aquifer recharge, and improve research capacity on micropollutants. As highlighted in this study, the upper region is a river basin with an economy dominated by agriculture whereby the river serves as a life line to this region. The restricted standard that prohibits direct use from the river is a probable amplifier of local farmers' displacement and forced migration, thus threatening the regional food and water security. These ramifications can be plummeted by having a lenient standard. Therefore, this study recommends the review and possible revision of current irrigation water quality standard. Softening the standard, for instance, enables the cultivation of vegetable crops will increase the benefits of water use and securitizing productive land. Safe reuse of TWW can also be maximized on the modification of crop types, establishment of TWW use area, and the enhancement of groundwater system's resilience by implementing MAR, all while simultaneously expanding the groundwater protection zone.

In the long run, TWW reuse activity and the enhancement of ecosystem services are related in non-trivial ways in the local context. The positive aspects for TWW reuse are observed, particularly for ecosystem services improvement. The outcomes of the present study strongly emphasize the prominence and the benefits gained from safe TWW reuse. With an integrated management of ecosystems within the local environment of the upper Zarqa River by TWW, the delivery of a range of ecosystem services can be rendered to ensure its long-term viability and sustainability. Ultimately, the thriving ecosystem services enhance the livelihood of local community, especially in the rural area, and sustain the food and water security in the region. If well-managed, it can be a successful story and become role model for similar regions or for other catchments in Jordan.

## 9. References

- Abdel-Raouf, N., Al-Homaidan, A. A., & Ibraheem, I. B. M. (2012). Microalgae and wastewater treatment. *Saudi Journal of Biological Sciences*, 19(3), 257-275.
- Abdulla, F., Eshtawi, T., & Assaf, H. (2009). Assessment of the impact of potential climate change on the water balance of a semi-arid watershed. *Water Resources Management*, 23(10), 2051-2068.
- Abu-Sharar, T. M., Hussein, I. A., & Al-Jayyousi, O. R. (2003). The use of treated sewage for irrigation in Jordan: opportunities and constraints. *Water and Environment Journal*, 17(4), 232-238.
- Al-Ansari, N., Aldardor, W., Siergieiev, D., & Knutsson, S. (2013). Effect of treated wastewater irrigation on vegetables. *Journal of Environmental Hydrology*, 21, Paper-5.
- Al-Abdallat, G. A. (2011). *Effects of improved treatment in Khirbet As Samra plant and its effects on the recipient water bodies and irrigated soils* (Master thesis). University of Jordan Library.
- Al Khamisi, S. A., Prathapar, S. A., & Ahmed, M. (2013). Conjunctive use of reclaimed water and groundwater in crop rotations. *Agricultural water management*, 116, 228-234.
- Al Mahamid, J. (2005). *Integration of water Resources of the upper aquifer in Amman-Zarqa Basin based on mathematical modeling and GIS, Jordan* (Doctoral dissertation). Freiberg University, Germany. Retrieved on 24<sup>th</sup> April 2017 from <https://pdfs.semanticscholar.org/e7d0/32d385392a0880604ac64e33306be8c07926.pdf>
- Al-Omari, A., Al-Quraan, S., Al-Salihi, A., & Abdulla, F. (2009). A water management support system for Amman Zarqa Basin in Jordan. *Water resources management*, 23(15), 3165-3189.
- Al-Omari, A., Al-Houri, Z., & Al-Weshah, R. (2013). Impact of the As Samra wastewater treatment plant upgrade on the water quality (COD, electrical conductivity, TP, TN) of the Zarqa River. *Water Science and Technology*, 67(7), 1455-1464.
- Al-Qaisi, B. M. (2010). Climate change effects on water resources in Amman Zarqa Basin-Jordan. *Individual Project Report for Climate Change Mitigation and Adaptation, MWI, Amman*.
- Al-Raggad, M. (2014, June). Managed Aquifer Recharge (MAR) as an adaptation measure to climate variability effect on natural groundwater recharge in North Jordan. In Symposium on “*Disposal of Large Volumes of Water: challenges and opportunities for Arid Environments in MAR practices*”. Water Research Center, Sultan Qaboos University, Oman.
- Al-Wer, I. (2009). *The Zarqa River rehabilitation and sustainable management* (Master thesis). Department of Land and Water Resources Engineering, Stockholm, Sweden.
- Al-Zboon, K. K., & Al-Suhaili, R. H. (2009). Improvement of water quality in a highly polluted river in Jordan. *Jordan Journal of Civil Engineering*, 3(3), 283-293.
- Al-Zyoud, S., Rühaak, W., Forootan, E., & Sass, I. (2015). Over exploitation of groundwater in the centre of Amman Zarqa Basin-Jordan: Evaluation of well Data and GRACE satellite observations. *Resources*, 4(4), 819-830.
- American Public Health Association, APHA. (1995). Water Environment Federation. *Standard methods for the examination of water and wastewater*, 22.
- Ammary, B. Y. (2007). Wastewater reuse in Jordan: Present status and future plans. *Desalination*, 211(1), 164-176.
- Arslan, O., & Er, I. D. (2008). SWOT analysis for safer carriage of bulk liquid chemicals in tankers. *Journal of Hazardous Materials*, 154(1), 901-913.

- Bajjali, W., & Al-Hadidi, K. (2017). Water quality and geochemistry evaluation of groundwater upstream and downstream of the Khirbet Al-Samra wastewater treatment plant/Jordan. *Applied Water Science*, 7(1), 53-69.
- Becerra-Castro, C., Lopes, A. R., Vaz-Moreira, I., Silva, E. F., Manaia, C. M., & Nunes, O. C. (2015). Wastewater reuse in irrigation: A microbiological perspective on implications in soil fertility and human and environmental health. *Environment international*, 75, 117-135.
- Bhat, S. A., Meraj, G., Yaseen, S., & Pandit, A. K. (2014). Statistical assessment of water quality parameters for pollution source identification in Sukhnag stream: an inflow stream of lake Wular (Ramsar Site), Kashmir Himalaya. *Journal of Ecosystems*, 2014.
- Brenner, A., & Hoekstra, E. J. (2012). Drinking water quality standards and regulations. *Best Practice Guide on Metals Removal From Drinking Water By Treatment*, 1.
- Bureau, R., Sheikh, B., Cort, R., Cooper, R., & Ririe, D. (1987). Reclaimed water for irrigation of vegetables eaten raw. *California agriculture*, 41(7), 4-7.
- Carr, G., Potter, R. B., & Nortcliff, S. (2011). Water reuse for irrigation in Jordan: Perceptions of water quality among farmers. *Agricultural Water Management*, 98(5), 847-854.
- Chan, S. Y. (2017). Photographs taken during field trip for documentation purpose.
- Diamantopoulou, P., & Voudouris, K. (2008). Optimization of water resources management using SWOT analysis: the case of Zakynthos Island, Ionian Sea, Greece. *Environmental geology*, 54(1), 197-211.
- Dillon, P. (2009). Water recycling via managed aquifer recharge in Australia. *Boletín Geológico y Minero*, 120(2), 121-130.
- Drewes, J. E. (2009). Ground water replenishment with recycled water-water quality improvements during managed aquifer recharge. *Ground Water*, 47(4), 502-505.
- Ejaz, M. S., & Peralta, R. C. (1995). Maximizing conjunctive use of surface and ground water under surface water quality constraints. *Advances in water resources*, 18(2), 67-75.
- El-Rawy, M., Zlotnik, V. A., Al-Raggad, M., Al-Maktoumi, A., Kacimov, A., & Abdalla, O. (2016). Conjunctive use of groundwater and surface water resources with aquifer recharge by treated wastewater: evaluation of management scenarios in the Zarqa River Basin, Jordan. *Environmental Earth Sciences*, 75(15), 1146.
- Elmqvist, T., Folke, C., Nyström, M., Peterson, G., Bengtsson, J., Walker, B., & Norberg, J. (2003). Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the Environment*, 1(9), 488-494.
- Environmental Protection Agency, EPA. (2016). Table of regulated drinking water contaminants. Retrieved on 12<sup>th</sup> March 2017 from <https://www.epa.gov/ground-water-and-drinking-water/table-regulated-drinking-water-contaminants#Organic>
- European Commission. (2004). National sustainable development strategies in the European Union. Retrieved on 25<sup>th</sup> June 2017 from [http://www.eu-natur.de/attach/60/sustainable\\_development\\_strategies.pdf](http://www.eu-natur.de/attach/60/sustainable_development_strategies.pdf)
- Gale, I. (Ed.). (2005). *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas*. UNESCO.
- Ghazal, M. (2016, Jan 30). Population stands at around 9.5 million, including 2.9 million guests. *The Jordan Times*. Retrieved on 23<sup>rd</sup> December 2016 from <http://www.jordantimes.com/news/local/population-stands-around-95-million-including-29-million-guests>

- Google Earth. (2017). Google Earth satellite imagery of study area. Assessed on 4<sup>th</sup> April 2017.
- Google Map. (2017). Geographical coordinates of wastewater treatment plants in Jordan.
- Grover, V. I., Darwish, A. R., & Deutsch, E. (2010, December). Integrated water resources management in Jordan. In *Economic Research Forum, Cairo, Egypt*.
- Hammouri, N., Adbulla, F., Abu Qdais, H. & Freiwan M. (2015, May). Assessing the impacts of climate change on water resources of Jordan. Paper presented at World Water Congress XV IWRA: Sub-Theme-17: Climate Change, Impacts and Adaptations, Edinburgh, Scotland. Retrieved on 14<sup>th</sup> January 2017 from <https://eis.hu.edu.jo/deanshipfiles/conf103671554.pdf>
- Han, Z. (2003). Groundwater resources protection and aquifer recovery in China. *Environmental Geology*, 44(1), 106-111.
- Hill, T., & Westbrook, R. (1997). SWOT analysis: it's time for a product recall. *Long range planning*, 30(1), 46-52.
- Humphrey, A. (2005). SWOT analysis for management consulting. *SRI Alumni Newsletter*, 7-8.
- Husain, I. A. (2010). Reuse of reclaimed waste water in Jordan: A comparison study of the international vis-à-vis Jordanian standards. In *Fourteenth International Water Technology Conference, IWTC* (Vol. 14).
- Järup, L. (2003). Hazards of heavy metal contamination. *British medical bulletin*, 68(1), 167-182.
- Kamel, A. Z., & Nada, A. (2008). Performance of wastewater treatment plants in Jordan and suitability for reuse. *African Journal of Biotechnology*, 7(15).
- Karamouz, M., Kerachian, R., & Zahraie, B. (2004). Monthly water resources and irrigation planning: case study of conjunctive use of surface and groundwater resources. *Journal of Irrigation and Drainage Engineering*, 130(5), 391-402.
- Kellis, M., Kalavrouziotis, I. K., & Gikas, P. (2013). Review of wastewater reuse in the Mediterranean countries, focusing on regulations and policies for municipal and industrial applications. *Global NEST Journal*, 15(3), 333-350.
- Kretschmer, N., Ribbe, L., & Gaese, H. (2002). Wastewater reuse for agriculture. *Technology Resource Management & Development-Scientific Contributions for Sustainable Development*, 2, 37-64.
- LeBlanc, R. J., Matthews, P., & Richard, R. P. (Eds.). (2009). *Global atlas of excreta, wastewater sludge, and biosolids management: moving forward the sustainable and welcome uses of a global resource*. Un-habitat.
- Li, P., Chaubey, I., Muenich, R. L., & Wei, X. (2016). Evaluation of freshwater provisioning for different ecosystem services in the Upper Mississippi River Basin: Current status and drivers. *Water*, 8(7), 288.
- Lonigro, A., Montemurro, N., Rubino, P., Vergine, P., & Pollice, A. (2015). Reuse of treated municipal wastewater for irrigation in Apulia region: the “In. Te. RRA” project. *Environmental Engineering and Management Journal*, 14(7), 1665-1674.
- Lubello, C., Gori, R., Nicese, F. P., & Ferrini, F. (2004). Municipal-treated wastewater reuse for plant nurseries irrigation. *Water Research*, 38(12), 2939-2947.
- Lumb, K. (2006). Alternative urban water supplies regulatory review: managed aquifer recharge (MAR) technical Report, Victorian Government Report No: VC02161-01-MAR Rpt Final, Australia.



- Luo, Y., Guo, W., Ngo, H. H., Nghiem, L. D., Hai, F. I., Zhang, J., Liang, S. & Wang, X. C. (2014). A review on the occurrence of micropollutants in the aquatic environment and their fate and removal during wastewater treatment. *Science of the Total Environment*, 473, 619-641.
- Mainali, B., Ngo, H. H., Guo, W., Pham, T. T. N., & Johnston, A. (2011). Feasibility assessment of recycled water use for washing machines in Australia through SWOT analysis. *Resources, Conservation and Recycling*, 56(1), 87-91.
- Mansell, J., Drewes, J. E., & Rauch, T. (2004). Removal mechanisms of endocrine disrupting compounds (steroids) during soil aquifer treatment. *Water Science and Technology*, 50(2), 229-237.
- McCornick, P. G., Hijazi, A., & Sheikh, B. (2004). From wastewater reuse to water reclamation: progression of water reuse standards in Jordan. *Wastewater use in irrigated agriculture: Confronting the livelihood and environmental realities*, 153-62.
- Metzger, M. J., Rounsevell, M. D. A., Acosta-Michlik, L., Leemans, R., & Schröter, D. (2006). The vulnerability of ecosystem services to land use change. *Agriculture, Ecosystems & Environment*, 114(1), 69-85.
- Michailidis, A., Papadaki-Klavdianou, A., Apostolidou, I., Lorite, I. J., Pereira, F. A., Mirko, H., Buhagiar, J., Shiley, S., Michaelidis, E., Loizou, E. & Chatzitheodoridis, F. (2015). Exploring treated wastewater issues related to agriculture in Europe, Employing a quantitative SWOT analysis. *Procedia Economics and Finance*, 33, 367-375.
- Millennium Ecosystem Assessment, MEA. (2005). Ecosystems and human well-being: synthesis. *Island, Washington, DC*.
- Ministry of Water and Irrigation, MWI. (2001). Characterization of wastewater effluent in the Amman-Zarqa Basin (water reuse component). Ministry of Water and Irrigation, Jordan. Retrieved on 5<sup>th</sup> March 2017 from [http://pdf.usaid.gov/pdf\\_docs/Pnacp558.pdf](http://pdf.usaid.gov/pdf_docs/Pnacp558.pdf)
- Ministry of Water and Irrigation, MWI. (2009). Water for life: Jordan's water strategy, 2008-2022. Retrieved on 10<sup>th</sup> March 2017 from [http://www.mwi.gov.jo/sites/en-us/Documents/Jordan\\_Water\\_Strategy\\_English.pdf](http://www.mwi.gov.jo/sites/en-us/Documents/Jordan_Water_Strategy_English.pdf)
- Ministry of Water and Irrigation, MWI. (2013). Jordan water sector facts and figures. Retrieved on 24<sup>th</sup> February 2017 from <http://www.waj.gov.jo/sites/en-us/Hot%20Issues/Jordan%20Water%20Sector%20Facts%20and%20Figures.pdf>
- Ministry of Water and Irrigation, MWI. (2016). National water strategy of Jordan, 2016-2025. Retrieved on 7<sup>th</sup> January 2017 from [http://www.mwi.gov.jo/sites/en-us/Hot%20Issues/Strategic%20Documents%20of%20The%20Water%20Sector/National%20Water%20Strategy\(%202016-2025\)-25.2.2016.pdf](http://www.mwi.gov.jo/sites/en-us/Hot%20Issues/Strategic%20Documents%20of%20The%20Water%20Sector/National%20Water%20Strategy(%202016-2025)-25.2.2016.pdf)
- Ministry of Water and Irrigation, MWI. (2016b). Amman Zarqa Basin, upper Zarqa River in shapefiles, data bank on groundwater level in monitoring wells in Excel sheets.
- Missimer, T. M., Drewes, J. E., Amy, G., Maliva, R. G., & Keller, S. (2012). Restoration of wadi aquifers by artificial recharge with treated waste water. *Groundwater*, 50(4), 514-527.
- Mitigating environmental risks of wastewater reuse for agriculture, MERWRA project. (2015). Project conducted in Zarqa River, Jordan. Funded by USAID; award number PR&D 03-02. University of Jordan.
- Myszograj, S., & Qteishat, O. (2011). Operate of As-Samra wastewater treatment plant in Jordan and suitability for water reuse. *Inżynieria i Ochrona Środowiska*, 14, 29-40.
- Naber, H. (2009). Water scarcity, quality and environmental protection policies in Jordan. *Policy and Strategic Behaviour in Water Resource Management*, 29.

- National Water Master Plan, NWMP. (2003). Water sector planning support project in the framework of cooperation between the Ministry of Water and Irrigation and GTZ, with support from AHT, BGR, Engicon, Dr. Fritz Käser and Siegfried Holtkemper. Retrieved on 4<sup>th</sup> May 2017 from [http://gis.nacse.org/rewab/taggedDocs/National\\_Water\\_Master\\_Plan\\_of\\_2004\\_T.pdf](http://gis.nacse.org/rewab/taggedDocs/National_Water_Master_Plan_of_2004_T.pdf)
- Osita, C., Idoko, O. R., & Justina, N. (2014). Organization's stability and productivity: the role of SWOT analysis an acronym for strength, weakness, opportunities and threat. *International Journal of Innovative and Applied Resources*, 2(9), 23-32.
- Piper, A. M. (1944). A graphic procedure in the geochemical interpretation of water-analyses. *Eos, Transactions American Geophysical Union*, 25(6), 914-928.
- Rauch-Williams, T., Hoppe-Jones, C., & Drewes, J. E. (2010). The role of organic matter in the removal of emerging trace organic chemicals during managed aquifer recharge. *Water Research*, 44(2), 449-460.
- Richards, L. A. 1954. Diagnosis and Improvement of Saline and Alkali Soils. *Agriculture Handbook*, 60.
- Riemenschneider, C., Al-Raggad, M., Moeder, M., Seiwert, B., Salameh, E., & Reemtsma, T. (2016). Pharmaceuticals, their metabolites, and other polar pollutants in field-grown vegetables irrigated with treated municipal wastewater. *Journal of Agricultural and Food Chemistry*, 64(29), 5784-5792.
- Rowe, A. J., Mason, R.D., Dickel, K. E., Mann, R.B., and Mockler R. J. (1994). *Strategic Management: A Methodological Approach* (4<sup>th</sup> edition), Addison-Wesley, Reading, Massachusetts. As cited in Richards, H. (2001). Modelling and decision support tools. Department of Engineering, University of Cambridge.
- Rusan, M. J. M., Hinnawi, S., & Rousan, L. (2007). Long term effect of wastewater irrigation of forage crops on soil and plant quality parameters. *Desalination*, 215(1), 143-152.
- Salameh, E. (2008). Over-exploitation of groundwater resources and their environmental and socio-economic implications: the case of Jordan. *Water International*, 33(1), 55-68.
- Schmidt, C. M., Fisher, A. T., Racz, A., Wheat, C. G., Los Huertos, M., & Lockwood, B. (2011). Rapid nutrient load reduction during infiltration of managed aquifer recharge in an agricultural groundwater basin: Pajaro Valley, California. *Hydrological Processes*, 26(15), 2235-2247.
- Schulz, S., Siebert, C., Rödiger, T., Al-Raggad, M. M., & Merz, R. (2013). Application of the water balance model J2000 to estimate groundwater recharge in a semi-arid environment: a case study in the Zarqa River catchment, NW-Jordan. *Environmental earth sciences*, 69(2), 605-615.
- Seder, N., & Abdel-Jabbar, S. (2011). Safe use of treated wastewater in agriculture Jordan case study. *Arab Countries Water Utilities Association*.
- Shammi, M., Rahman, R., Rahman, M. M., Moniruzzaman, M., Bodrud-Doza, M., Karmakar, B., & Uddin, M. K. (2016). Assessment of salinity hazard in existing water resources for irrigation and potentiality of conjunctive uses: a case report from Gopalganj District, Bangladesh. *Sustainable Water Resources Management*, 2(4), 369-378.
- Shivhare, L., & Sharma, S. (2012). Effect of toxic heavy metal contaminated soil on an ornamental plant Georgina wild (Dahlia). *Journal of Environmental & Analytical Toxicology*, 2012.
- Shrestha, S., & Kazama, F. (2007). Assessment of surface water quality using multivariate statistical techniques: A case study of the Fuji river basin, Japan. *Environmental Modelling & Software*, 22(4), 464-475.

- Shuval, H. I., Yekutieli, P., & Fattal, B. (1986). An epidemiological model of the potential health risk associated with various pathogens in wastewater irrigation. *Water science and technology*, 18(10), 191-198.
- Srivastava, P. K., Kulshreshtha, K., Mohanty, C. S., Pushpangadan, P., & Singh, A. (2005). Stakeholder-based SWOT analysis for successful municipal solid waste management in Lucknow, India. *Waste management*, 25(5), 531-537.
- Suez. (2008). As Samra Wastewater Treatment Plant: Brochure prepared by Suez. Accessed on 25<sup>th</sup> May 2017 from [http://www.degremont.com/en/activities/references/references/?reference\\_id=57](http://www.degremont.com/en/activities/references/references/?reference_id=57)
- Suleiman, W., Gerba, C. P., Tamimi, A. H., Freitas, R. J., Al Sheraideh, A., & Hayek, B. (2010). Management practices of sludge and biosolid treatment and disposal in Jordan. *Journal of Residuals Science & Technology*, 7(1).
- Sultan Qaboos University Team & University of Jordan Team, SQU & UJ. (2015). Crops Identification Report (Oman and Jordan): *Mitigating Environmental Risks of Wastewater Reuse for Agriculture*.
- Ta'any, R. A., Tahboub, A. B., & Saffarini, G. A. (2009). Geostatistical analysis of spatiotemporal variability of groundwater level fluctuations in Amman–Zarqa basin, Jordan: a case study. *Environmental geology*, 57(3), 525-535.
- Tangahu, B. V., Sheikh Abdullah, S. R., Basri, H., Idris, M., Anuar, N., & Mukhlisin, M. (2011). A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. *International Journal of Chemical Engineering*, 2011.
- Terrados, J., Almonacid, G., & Hontoria, L. (2007). Regional energy planning through SWOT analysis and strategic planning tools.: Impact on renewables development. *Renewable and Sustainable Energy Reviews*, 11(6), 1275-1287.
- Tölgyessy, J. (Ed.). (1993). *Chemistry and biology of water, air and soil: environmental aspects* (Vol. 53). Elsevier.
- Toze, S. (2006). Reuse of effluent water-benefits and risks. *Agricultural water management*, 80(1), 147-159.
- Ulimat, A. A. (2012, May). Wastewater production, treatment, and use in Jordan. In *Second Regional Workshop Safe Use of Wastewater in Agriculture, New Delhi, India*.
- Westcot, D. W. (1997). Quality control of wastewater for irrigated crop production (Water reports-10). *Food and Agriculture Organization of the United Nations, Rome, Italy*.
- Wolf, L., Rapp, M., Zemmann, M., Werz, H., Sawarieh, A., Ali, W., & Hötzel, H. (2008, October). Artificial groundwater recharge in Jordan using various water qualities-Large scale potential map and individual test sites in Jordan. In Symposium to the International Year of Sanitation “Coupling sustainable sanitation and groundwater protection”. Hannover, Germany.
- World Bank. (2016). *Jordan - As-Samra wastewater plant expansion*. Public-private partnerships brief. Washington, D.C.: World Bank Group. Retrieved on 26<sup>th</sup> December 2016 from <http://documents.worldbank.org/curated/en/254401468187770179/Jordan-As-Samra-wastewater-plant-expansion>
- World Health Organization, WHO. (2006). *Guidelines for the Safe use of Wastewater, Excreta and Greywater: wastewater use in Agriculture* (Vol. 2). World Health Organization.
- Yaqob, E. Y., Al-Sa'ed, R., Sorial, G., & Suidan, M. (2015). Cost-benefit analysis model for treated wastewater use in agricultural irrigation: four Palestinian case studies. *Global Journal For Research Analysis*, 4(12).

## 10. Appendices

Appendix 1. Wastewater treatment plants in Jordan.

WWTP name	Technology	Service governorate	Design capacity (m <sup>3</sup> /day)
Aqaba - Natural	Waste stabilization ponds (WSP)	Aqaba	9000
Aqaba - Mechanical	Extended aeration	Aqaba	12,000
Baqa	Trickling filter (TF)	Amman, Balqa	14,900
Fuheis	Activated sludge	Amman, Balqa	2400
Irbid - Central	TF and active sludge	Irbid	11,023
Jerash - East	Oxidation ditch	Jerash	9000
Karak	TF	Karak	5500
Kufranja	TF	Ajloun	9000
Madaba	Activated sludge	Madaba	7600
Mafrq	WSP	Mafrq	6050
Ma'an	Extended aeration	Ma'an	5772
Abu Nuseir	Active sludge R, B, C	Amman	4000
Ramtha	Activated sludge	Irbid	7400
Sult	Extended aeration	Balqa	7700
Tafila	TF	Tafila	7500
Wai Al Arab	Extended aeration	Irbid	21,000
Wadi Hassan	Oxidation ditch	Irbid	1600
Wadi Mousa	Extended aeration	Ma'an	3400
Wadisseeer	Aeration lagoon	Amman	4000
Alekeder - Tankers	WSP	Mafrq	4000
Lajjon - Tankers	WSP	Karak	1200
Tal AlMantah - Tankers	TF and active sludge	Balqa	400
Al Jiza	Activated sludge	Amman	4500
As Samra	Activated sludge	Amman, Zarqa	364,000
Al Merad	Activated sludge	Jerash	9000
Shobak - Tankers	WSP	Ma'an	350
Mansorah - Tankers	WSP	Ma'an	50
South Amman		Amman	52,000
Mu'tah and Adnaniyyah		Karak	7060
Shallaleh		Irbid	13,700
ShounaShamaliyyah		Irbid	1200

Source: MWI, 2013

Appendix 2. FAO guideline for trace metals in irrigation water.

Element, symbol	Recommended maximum concentration (mg/L)
<b>Aluminum, Al</b>	<b>5.0</b>
Arsenic, As	0.10
Beryllium, Be	0.10
Cadmium, Cd	0.01
Cobalt, Co	0.05
<b>Chromium, Cr</b>	<b>0.10</b>
<b>Copper, Cu</b>	<b>0.20</b>
Fluoride, F	1.0
Iron, Fe	5.0
Lithium, Li	2.5
Manganese, Mn	0.20
Molybdenum, Mo	0.01
Nickel, Ni	0.20
<b>Lead, Pb</b>	<b>5.0</b>
Selenium, Se	0.02
Vanadium, V	0.10
Zinc, Zn	2.0

*Note.* The bold text indicates the element of interest.

*Source: after Ayers and Westcot, 1985*

Appendix 3. EC of TWW and groundwater at different sampling sites.

Parameter	Unit	Sampling location						
EC	µS/cm	S1	S2	S3	S4	S5	GW S1	GW S2
		1653	1650	1900	1907	3990	3680	4860

Appendix 4. Physicochemical parameters of TWW for Site I and II.

Parameter	Unit	Sample					
		Jun-10	Aug-10	Oct-10	Jun-10	Aug-10	Oct-10
		S1	S1	S1	S2	S2	S2
pH		7.4	7.3	7.6	7.9	7.8	7.9
EC	µs/cm	1920	1951	1900	1925	1880	1947
BOD <sub>5</sub>	mg/L	5.0	11.4	5.3	6.2	9.0	7.8
Na	meq/L	9.5	10.4	8.4	12.3	9.9	9.7
Ca	meq/L	5.0	6.0	5.0	3.0	3.0	5.0
K	meq/L	1.1	1.3	1.8	1.1	1.8	1.7
Mg	meq/L	3.8	2.2	3.9	2.8	2.8	2.6
HCO <sub>3</sub>	meq/L	5.9	5.7	7.5	5.4	4.8	6.2
SO <sub>4</sub>	meq/L	2.0	1.8	0.8	0.2	1.0	1.3
NO <sub>3</sub>	meq/L	0.3	0.4	1.1	0.4	1.1	1.0
Cl	meq/L	11.0	11.0	9.6	13.0	11.0	11.0
PO <sub>4</sub>	meq/L	0.061	0.049	0.038	0.072	0.011	0.039
COD	mg/L	126.0	100.0	132.0	109.0	82.0	N.A
TDS	mg/L	1228.8	1248.6	1216.0	1232.0	1203.2	1246.1

Note. N.A = Not Analysed.

Appendix 5. Physicochemical parameters of TWW for Site III.

Parameter	Unit	Sample				
		Aug-09	Sept-09	Oct-09	Nov-09	Dec-09
pH		7.4	8.5	7.5	8.6	8.7
EC	µs/cm	1950	1914	2420	2890	3000
BOD <sub>5</sub>	mg/L	14.2	15.0	13.9	15.1	14.2
Na	meq/L	10.1	10.1	14.6	15.1	16.7
Ca	meq/L	5.9	6.7	6.4	7.5	8.4
K	meq/L	1.1	1.0	1.2	1.3	1.1
Mg	meq/L	2.4	1.4	2.0	3.8	4.5
HCO <sub>3</sub>	meq/L	5.9	5.8	6.8	9.8	10.2
SO <sub>4</sub>	meq/L	1.9	2.5	2.0	1.9	1.8
NO <sub>3</sub>	meq/L	0.4	0.4	0.6	0.4	0.3
Cl	meq/L	11.3	10.3	14.7	15.3	17.2
PO <sub>4</sub>	meq/L	0.076	0.081	0.086	0.074	0.081
COD	mg/L	151.0	107.0	139.0	155.0	97.0
TDS	mg/L	1248.0	1225.0	1548.8	1849.6	1920.0

Data source: Al-Abdallat, 2011; MERWRA, 2015

Appendix 6. Physicochemical parameters of TWW for Site IV.

Parameter	Unit	Sample				
		Aug-09	Sept-09	Oct-09	Nov-09	Dec-09
pH		8.3	8.4	7.8	7.6	7.6
EC	µs/cm	2400	2500	2300	1953	1772
BOD <sub>5</sub>	mg/L	19.9	25.7	11.9	18.4	16.5
Na	meq/L	12.4	13.3	12.2	10.6	9.6
Ca	meq/L	6.3	6.5	6.4	5.7	4.8
K	meq/L	1.4	1.4	1.0	0.8	1.1
Mg	meq/L	3.9	3.8	3.5	2.4	2.5
HCO <sub>3</sub>	meq/L	7.9	8.1	7.9	7.2	6.7
SO <sub>4</sub>	meq/L	1.8	2.1	1.8	0.9	0.8
NO <sub>3</sub>	meq/L	0.4	0.3	0.2	0.3	0.2
Cl	meq/L	13.9	14.3	13.1	11.0	9.9
PO <sub>4</sub>	meq/L	0.034	0.029	0.026	0.037	0.034
COD	mg/L	N.A	67.0	82.0	53.0	40.0
TDS	mg/L	1536.0	1600.0	1472.0	1249.9	1134.1

Note. N.A = Not Analysed.

Appendix 7. Physicochemical parameters of TWW for Site V.

Parameter	Unit	Sample				
		Aug-09	Sept-09	Oct-09	Nov-09	Dec-09
pH		8.4	8.4	8.0	8.1	8.0
EC	µs/cm	3090	2340	2470	2148	2230
BOD <sub>5</sub>	mg/L	13.7	21.1	15.0	15.2	9.8
Na	meq/L	13.9	12.4	12.9	10.3	11.2
Ca	meq/L	9.7	7.5	7.9	7.3	5.2
K	meq/L	1.9	1.0	1.2	0.9	0.9
Mg	meq/L	4.3	2.5	2.6	2.9	4.8
HCO <sub>3</sub>	meq/L	11.7	7.8	8.0	8.1	7.4
SO <sub>4</sub>	meq/L	2.3	2.1	2.0	1.7	2.4
NO <sub>3</sub>	meq/L	0.5	0.3	0.3	0.5	0.2
Cl	meq/L	14.8	13.1	14.2	11.3	12.3
PO <sub>4</sub>	meq/L	0.096	0.074	0.081	0.069	0.061
COD	mg/L	96.0	66.0	64.0	182.0	55.0
TDS	mg/L	1977.6	1497.6	1580.8	1374.7	1427.2

Data source: Al-Abdallat, 2011; MERWRA, 2015

Appendix 8. Concentration of trace elements and *E. coli* in various system parts of analyzed vegetable species.

<b>Crop</b>	<b>System part</b>	<b>Al (mg/L)</b>	<b>Cr (mg/L)</b>	<b>Cu (mg/L)</b>	<b>Pb (mg/L)</b>	<b><i>E. coli</i> (<i>E. coli</i>/100 mL)</b>
Tomato	Irrigation water	0.1	0.08	0.1	0.05	3.56E+01
	Root	0.08	0.01	0.12	0.01	1.47E+01
	Stem and leaves	0.1	0.02	0.18	0.03	2.01E+01
	Fruit	0.01	0	0.01	0	1.43E+00
Green pepper	Irrigation water	0.2	<b>0.1</b>	0.06	0.1	1.24E+01
	Root	0.07	0.01	0.02	0.01	1.12E+00
	Stem and leaves	0.12	0.03	0.1	0.02	1.25E+00
	Fruit	0.01	0	0	0	1.10E+00
Eggplant	Irrigation water	0.1	0.05	0.08	0.04	1.23E+01
	Root	0.04	0.02	0.07	0.01	1.00E+00
	Stem and leaves	0.09	0.05	0.1	0.02	1.23E+00
	Fruit	0	0	0.01	0	1.10E+00
Cauliflower	Irrigation water	0.08	0.04	0.08	0.06	3.26E+01
	Root	0.03	0.01	0.02	0.03	0.00E+00
	Stem and leaves	0.02	0.03	0.09	0.04	2.05E+01
	Fruit	0.01	0	0.01	0	4.56E+01
Cucumber	Irrigation water	0.12	0.09	0.015	0.05	5.66E+00
	Root	0.02	0.01	0.06	0.02	0.00E+00
	Stem and leaves	0.05	0.02	0.08	0.03	1.10E+00
	Fruit	0.01	0	0	0	1.90E+00
Corn	Irrigation water	0.2	0.04	0.06	0.05	3.50E+00
	Root	0.03	0.02	0.06	0.01	0.00E+00
	Stem and leaves	0.05	0.04	0.1	0.01	0.00E+00
	Fruit	0	0	0.01	0	0.00E+00
Lettuce	Irrigation water	0.2	0.05	0.04	0.07	<b>1.54E+03</b>
	Root	0.01	0	0.04	0.01	2.10E+00
	Leaves	0.02	0.01	0.07	0.01	3.22E+02
Rocca	Irrigation water	0.06	0.06	0.05	0.1	<b>1.95E+03</b>
	Root	0.02	0.01	0.06	0.01	1.20E+00
	Leaves	0.03	0.01	0.01	0.01	4.65E+02
Carrot	Irrigation water	0.05	0.04	0.01	0.06	1.46E+01
	Root	0.03	0	0.02	0.01	1.40E+00
	Leaves	0.02	0.02	0.07	0.02	5.45E+00
Green onion	Irrigation water	0.1	0.08	0.09	0.05	3.55E+01
	Root	0.03	0.01	0.03	0.02	1.30E+00
	Leaves	0.07	0.01	0.06	0.01	1.42E+01

Data source: MERWRA, 2015



Appendix 9. Composition of clay, silt, and sand for respective soil samples.

Samples	% Clay	% Silt	% Sand
S1	25	25	50
S2	25	25	50
S3	25	25	50
S4	25	25	50
S5	30	40	30
S6	50	15	35

*Data source: MERWRA, 2015*

Appendix 10. Elemental concentrations in the soil samples at different soil depths.

Sample No.	Soil Depth (cm)	Na (meq/L)	Ca (meq/L)	HCO <sub>3</sub> (meq/L)	Cl (meq/L)	K (meq/L)	P (µg/g soil)
S1	0 to 20	15.6	18.0	4.0	25.0	0.07	11.8
	20 to 40	15.6	13.0	5.0	15.0	0.09	11.4
	40 to 60	8.8	12.0	3.0	10.0	0.07	11.2
S2	0 to 20	10.3	4.0	8.0	5.0	0.09	3.6
	20 to 40	14.9	9.0	2.0	15.0	0.07	3.8
S3	0 to 20	20.1	16.0	4.0	10.0	0.13	11.8
	20 to 40	19.5	7.0	4.0	20.0	0.13	14.1
	40 to 60	15.5	25.0	3.0	20.0	0.10	15.2
S4	0 to 20	138.0	37.0	5.0	90.0	0.10	8.5
S5	0 to 20	11.0	10.0	5.0	10.0	0.12	18.8
	20 to 40	2.0	11.0	5.0	10.0	0.12	11.4
	40 to 60	8.1	7.0	2.0	10.0	0.09	4.7
S6	0 to 20	12.7	11.0	3.0	10.0	0.13	19.4
	20 to 40	10.1	9.0	2.0	10.0	0.08	15.0
	40 to 60	9.9	9.0	4.0	15.0	0.07	6.7

*Data source: MERWRA, 2015*

Appendix 11. Groundwater quality parameters at different sampling locations.

Sample	EC ( $\mu\text{s}/\text{cm}$ )	pH	Ca ( $\text{meq}/\text{L}$ )	Mg ( $\text{meq}/\text{L}$ )	Na ( $\text{meq}/\text{L}$ )	K ( $\text{meq}/\text{L}$ )	Cl ( $\text{meq}/\text{L}$ )	SO <sub>4</sub> ( $\text{meq}/\text{L}$ )	NO <sub>3</sub> ( $\text{meq}/\text{L}$ )	HCO <sub>3</sub> ( $\text{meq}/\text{L}$ )	Total Coliform	<i>E. coli</i>	SAR
GW 1	5080	7.2	16.0	15.6	26.0	0.8	34.6	18.5	7.2	6.3	220	4	6.54
GW 2	4200	7.2	14.0	13.4	20.8	0.8	30.1	13.8	3.6	5.0	4	2	5.61
GW 3	4550	7.3	16.0	13.6	22.9	0.7	32.2	14.6	3.4	5.0	2		5.95
GW 4	3380	7.2	10.6	8.1	19.2	0.4	22.3	12.4	2.1	5.4	2	2	6.30
GW 5	4820	7.2	15.8	13.1	27.9	0.7	36.4	16.5	2.2	4.9		2	7.34
GW 6	5040	7.1	14.8	14.6	28.3	0.7	29.6	16.2	6.1	7.1	30	4	7.39
GW 7	3100	6.9	13.9	8.2	13.2	1.0	18.1	15.6	0.6	5.3	2	2	3.98
GW 8	3480	7.4	8.8	6.5	16.4	0.3	23.3	6.2	0.7	4.0			5.93
GW 9	4030	7.9	10.5	8.6	19.2	0.4	28.7	7.0	0.8	3.9			6.20
GW 10	6290	7.3	17.7	15.0	32.3	0.8	46.1	14.0	1.0	4.6			7.99
GW 11	3930	7.2	9.6	7.5	19.2	0.4	27.0	8.2	0.8	4.1			6.56
GW 12	2200	7.7	5.4	4.8	8.9	0.3	13.4	3.7	1.3	3.0	2		3.92
GW 13	3740	7.9	8.7	7.0	18.4	0.3	24.2	6.2	0.4	5.5			6.57
GW 14	2770	7.0	11.7	5.2	10.3	0.9	10.3	13.8	0.1	6.0	14	14	3.55
GW 15	4350	7.5	14.3	17.3	16.4	0.4	29.0	11.9	3.6	2.7	11	2	4.13
GW 16	4520	7.7	11.1	17.4	21.2	0.3	26.7	11.9	3.8	6.4			5.62
GW 17	1079	8.0	3.4	3.1	3.4	0.1	4.0	0.9	0.8	4.8			1.85
GW 18	759	7.7	3.8	2.5	1.4	0.1	1.9	0.6	0.9	4.6			0.81
GW 19	3080	6.9	7.3	7.9	15.6	0.3	18.0	6.7	0.9	4.7			5.64
GW 20	884	7.9	2.2	2.4	3.6	0.2	4.3	1.3	0.4	2.4			2.38
GW 21	3610	6.3	8.8	7.8	17.0	0.3	25.0	6.9	0.8	4.1			5.88
GW 22	1000	7.0	2.7	2.4	4.4	0.2	4.2	1.2	0.1	4.5			2.74
GW 23	6540	6.3	0.9	0.6	1.8	0.1	1.2	0.3	0.7	0.2			2.02
GW 24	3250	7.1	8.8	6.0	16.2	0.2	21.9	3.7	1.0	5.3			5.96
GW 25	3970	7.4	10.6	12.0	19.3	0.3	21.1	14.0	2.0	5.0			5.73

GW 26	5280	7.1	16.5	17.7	24.1	0.4	33.1	16.0	4.6	4.6	26	5.83
GW 27	802	7.7	2.0	3.8	0.1	2.4	0.9	1.0	3.2	4.2		0.08
GW 28	3490	7.0	5.5	33.1	0.4	20.0	8.9	1.2	1.4	6.7		0.10
GW 29	3250	7.0	8.4	8.0	16.8	0.2	21.6	4.7	0.4	7.4		5.88
GW 30	2940	7.2	7.2	6.4	15.0	0.2	17.1	6.0	0.8	5.1		5.75
GW 31	1033	7.6	2.9	3.0	3.6	0.1	5.0	1.5	0.6	2.7		2.06
GW 32	1740	6.4	28.2	29.4	44.4	0.8	46.1	40.9	0.2	5.1		8.27
GW 33	8180	7.2	27.2	42.1	27.7	0.5	58.8	32.0	4.1	3.3		4.71
GW 34	7100	7.3	33.6	32.4	18.4	0.6	59.6	18.0	2.4	2.1		3.20
GW 35	960	7.4	6.5	5.6	5.4	0.3	12.3	2.9	0.7	2.1		2.19
GW 36	7390	8.6	5.1	1.9	2.4	0.1	2.6	0.5	0.4	5.5		1.28
GW 37	1890	7.6	4.1	3.4	9.2	0.1	16.8	4.0	0.6	1.7		4.77
GW 38	3000	7.5	11.2	6.9	12.4	0.2	19.9	7.2	1.2	2.3		4.11
GW 39	1630	7.0	6.0	3.7	5.7	0.2	7.1	1.9	0.9	5.8		2.60
GW 40	1470	7.6	5.1	3.5	7.0	0.2	8.4	3.8	1.2	3.0		3.36
GW 41	1640	7.6	4.0	3.6	2.8	0.2	6.9	1.7	0.4	1.4		1.46
GW 42	1200	7.5	5.4	3.4	6.9	0.2	9.5	3.5	0.3	3.1		3.28
GW 43	1240	7.7	4.2	2.6	5.0	0.2	5.5	1.8	0.6	4.0		2.69

*Data source: MERWRA, 2015*

**Declaration in lieu of oath**

By

Sze Yie Chan

This is to confirm my Master's Thesis was independently composed/ authored by myself, using solely the referred sources and support.

I additionally assert that this Thesis has not been part of another examination process.

Köln, 14-08-2017

Place and Date

*Sze Yie Chan*

Signature

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