Suitability Mapping for Identification of Potential Riverbank Filtration Sites in Zarqa Valley, Jordan

An Internship Report

by

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June-August 2025

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Abbreviations

- **MAR** Managed Aquifer Recharge
- **TWW** Treated Wastewater
- **MWI** Ministry of Water and Irrigation
- **WWTP** Wastewater Treatment Plant
- **MCM** Million Cubic Meters
- **RBF** Riverbank Filtration
- **KTD** King Talal Dam
- **COD** Chemical Oxygen Demand
- **BOD** Biochemical Oxygen Demand
- **TDS** Total Dissolved Solids
- **EC** Electroconductivity
- **JISM** Jordanian Institution for Standards and Metrology

1 Introduction

1.1 Background

Jordan is one of the world's ten most water-scarce countries. It depends on groundwater to meet increasing demands, as surface water resources are relatively limited (Al Farajat et al., 2005). Over 90% of Jordan experiences an arid and semi-arid climate, creating significant stress on the country's limited water resources. Population growth, agricultural development, and the influx of refugees have exacerbated these pressures, compelling the Ministry of Water and Irrigation (MWI) to adopt and expand managed aquifer recharge (MAR) in their water management strategies (El-Rawy et al., 2016). One of the primary sources utilized in agricultural practice is treated wastewater (TWW). Jordan has 31 TWW plants, with the largest being the As Samra plant (Figure 1.1), which has a maximum capacity of 364,000 m^3/day, representing about 60% of the country's total TWW volume (El-Rawy et al., 2016). This plant serves Amman and Zarqa, the two major cities, and is located in the upper Zarqa River Basin, which receives all TWW discharges.

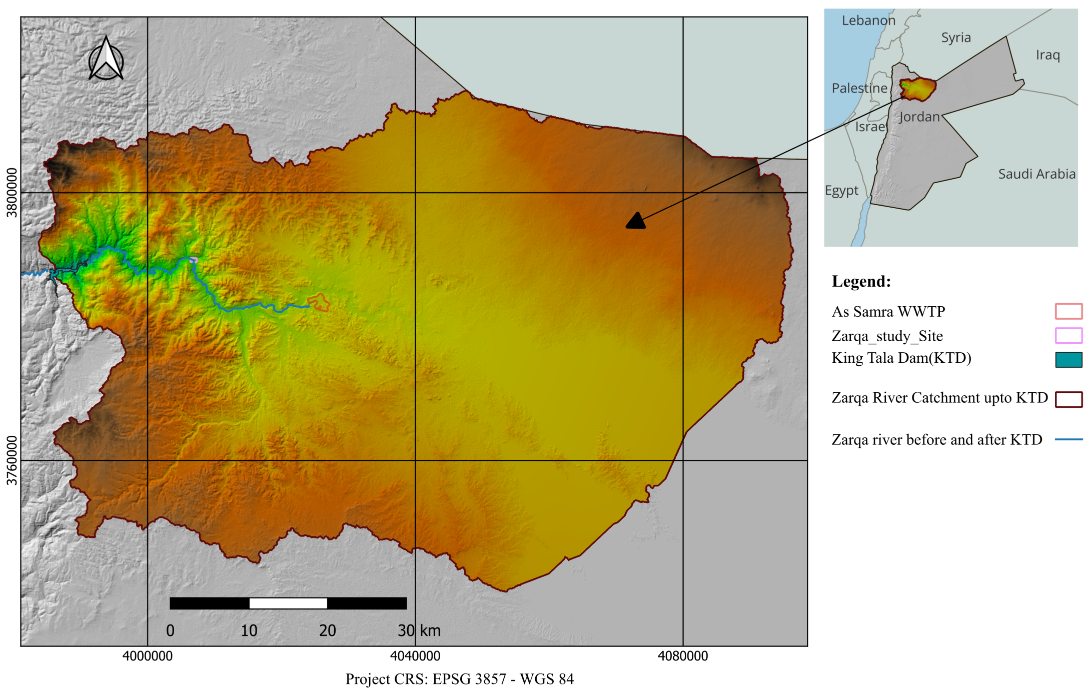


Figure 1.1: Location of Jordan and Zarqa Valley on the world map.

The identification of potential riverbank filtration (RBF) sites in the Zarqa region of Jordan necessitates a comprehensive understanding of the hydrological, environmental, and anthropogenic factors influencing water quality and availability. The Zarqa River, which is significantly impacted by TWW from the As Samra WWTP, serves as a crucial water resource in the area. This river receives approximately 110 million cubic meters (MCM) of treated wastewater annually, which contributes to its flow and influences the water quality downstream (Almanaseer et al., 2020).

The presence of contaminants, including pharmaceuticals and heavy metals, poses challenges for water quality in the Zarqa River. Studies have shown that the river is affected by various pollutants, including hexavalent chromium and other heavy metals, although recent evaluations indicate that their concentrations are within allowable limits. However, the historical context of pollution and ongoing discharges from urban runoff and untreated wastewater highlight the need for careful monitoring and management. The river's water quality is further complicated by seasonal variations in pollution levels, which can affect the suitability of sites for RBF (Al-Mashaqbeh et al., 2018).

1.2 Information about Current Study Site

A specific site along the course of the Zarqa River (Figure 1.2) has been selected to determine whether the area is suitable for RBF or not. There are existing monitoring wells to measure and evaluate the water quality parameters.

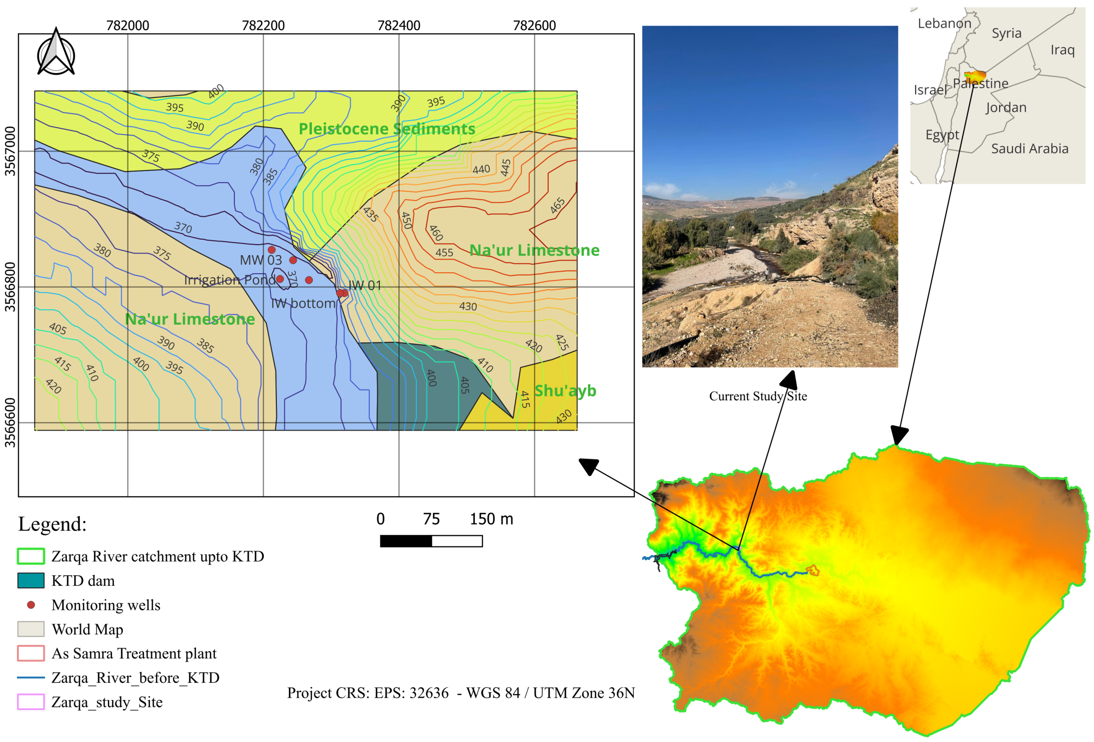


Figure 1.2: FEMAR Study site with information on lithological formations (Modified after Genzel et al., 2024).

1.3 Objective

The objective of this study is to identify potential RBF sites along the course of the Zarqa River, extending from the As Samra WWTP to the Jordan River in the far west.

2 Literature Review

2.1 Geology

The outcropping formations in the Amman-Zarqa basin range from Triassic sandstone to recent alluvium (Figure 2.1). When looked across Amman-Zarqa and Azraq basin, different geological formations can be found (2.2).They are arranged in such a manner that the youngest formations are on the top and oldest ones are in the bottom with respect to ground level. Regarding the site for FEMAR study project, geological formations like Quaternary Pleistocene sediments, Alluvium and Wadi sediments, Cretaceous Nau'r limestones can be found (1.2).

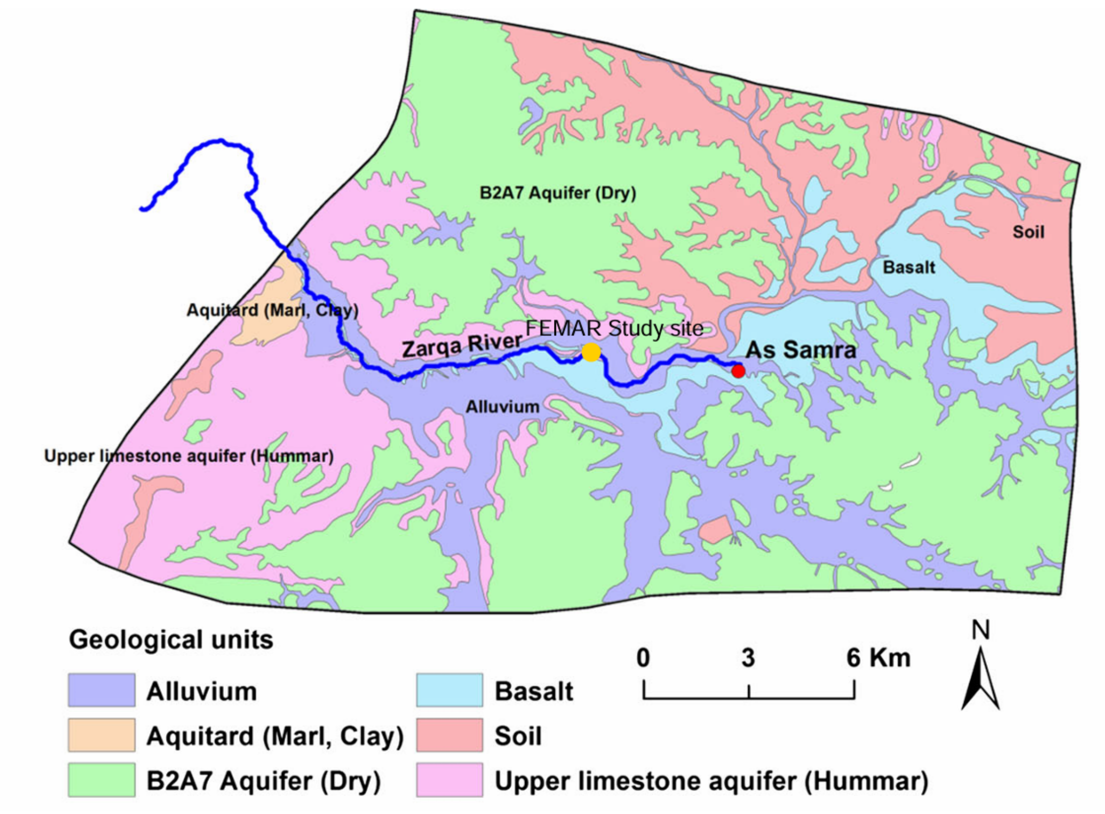


Figure 2.1: Overview of lithological formations in and around FEMAR study site (El-Rawy et al., 2016).

From the As Samra WWTP to King Tala Dam (KTD), the Hummar Limestone formation, with an average thickness of 150 m and a saturated thickness of 120 m, serves as the primary water-bearing layer in the upper aquifer system of the river basin (El-Rawy et al., 2016). This aquifer, crucial for agricultural and domestic water use, has recently been abandoned for domestic use due to increased salinity and contamination from treated wastewater. It is separated from the deeper Kurnub sandstone aquifer by a 100 m thick Na'ur marlstone layer. Kurnub aquifer system is not widely utilized for water supply due to its high salinity, which exceeds 2500 mg/L. It is believed that there is minimal interaction

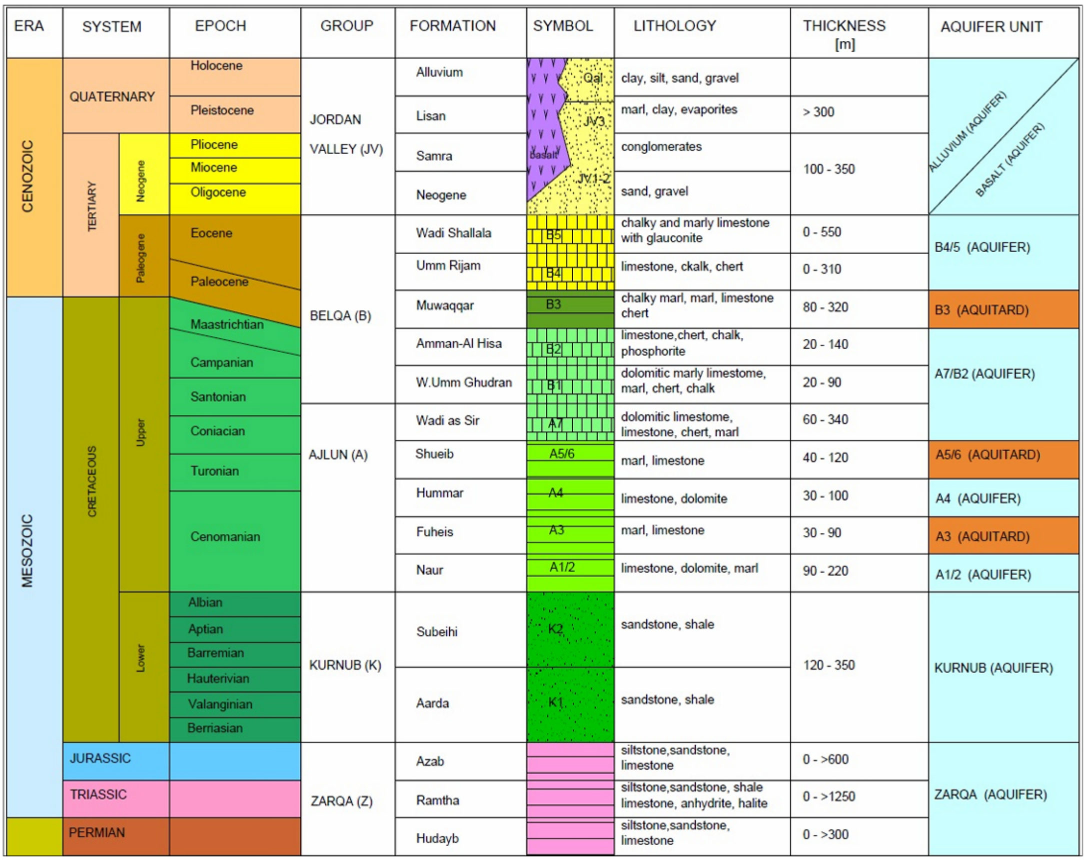


Figure 2.2: Lithostratigraphy and hydrogeological classification of rock units outcropping in Amman-Zarqa and Azraq basin (Steinel, 2012).

between the upper and deep aquifers, as the deep aquifer is not under significant artesian pressure. Additionally, downward leakage is considered negligible due to the very low hydraulic conductivity of the aquitard unit separating these aquifers (El-Rawy et al., 2016).

Artificial recharge of groundwater recharge includes resources such as irrigation return flow, physical losses, leakage from water supply networks, and effluent from WWTPs. However, groundwater recharge is more dominant in the upper Zarqa river area, particularly near the AS Samra plant. This conclusion is based on a water budget and changes in soil storage, which are influenced by land use and soil water holding capacity (El-Rawy et al., 2016). The natural recharge to groundwater in this region is estimated to be between 3 and 12 mm/year, primarily controlled by rainfall distribution and topographic slope.

Starting in the mid-1990s, water levels in the As Samra plant and downstream areas significantly recovered, forming a recharge mound in the Hummar Aquifer. The latest groundwater level map shows this mound extending 5 km downstream and 2 km upstream, with an average horizontal reach of 7 km. Upstream, the groundwater mound has caused the river to shift from losing to gaining (El-Rawy

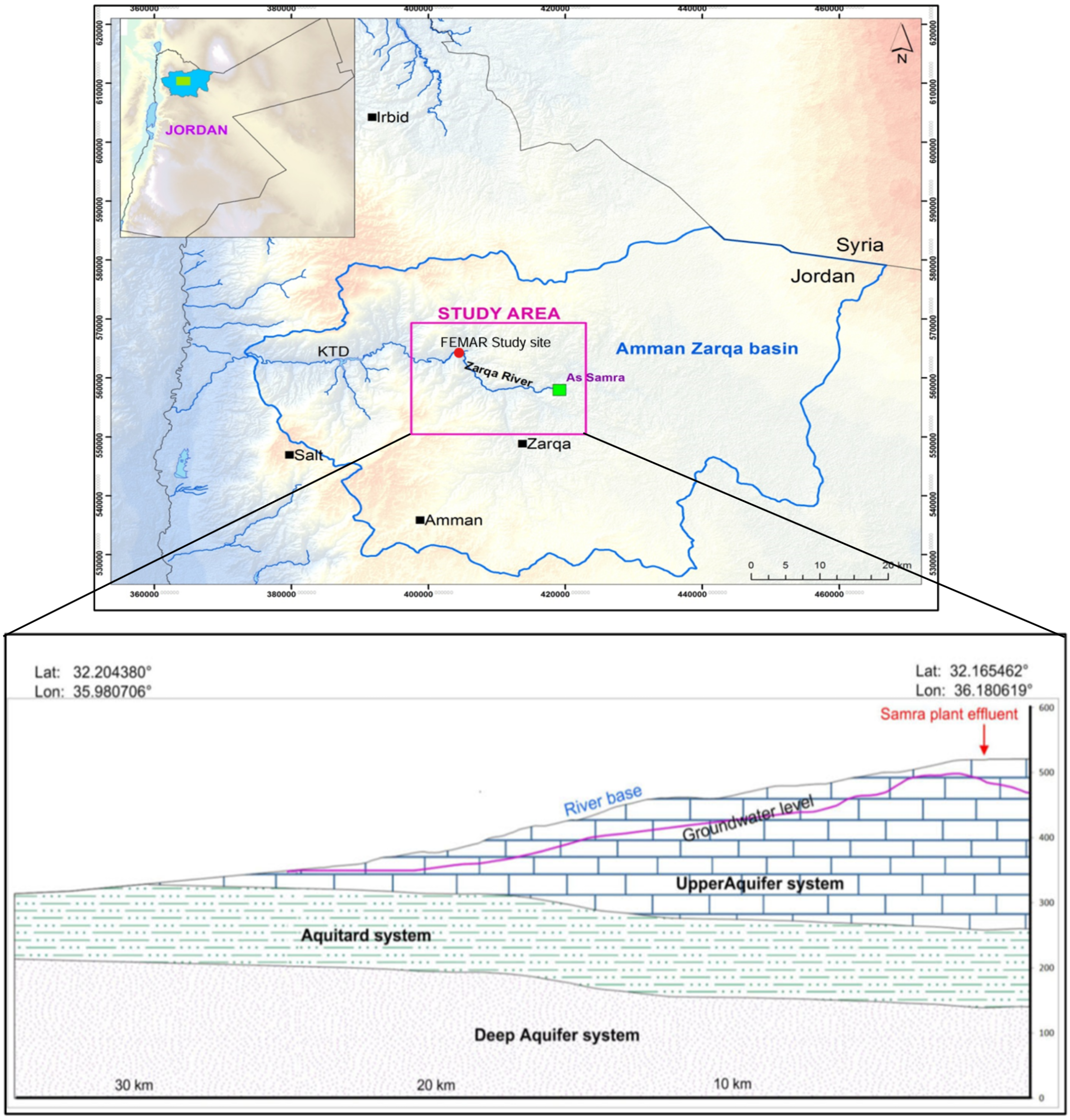


Figure 2.3: Location and cross section of the study area in the study done by Almanaseer et al., 2020.

et al., 2016). The development of recharge mound near As Samra WWTP as shown in 2.3 is also further explained by Figure 2.4.

The paper written by El-Rawy et al., 2016 highlights the role of TWW in augmenting both surface and groundwater resources by discharging it into rivers, significantly impacting hydrological dynamics. The conceptual model (Figure: 2.4) that they developed shows that TWW discharge is crucial for recharging aquifers, enhancing water availability in the Zarqa River Valley, and supporting agricultural expansion. Despite some simulation limitations, the study suggests using river water as an alternative to groundwater abstraction due to the strong surface-groundwater connection.

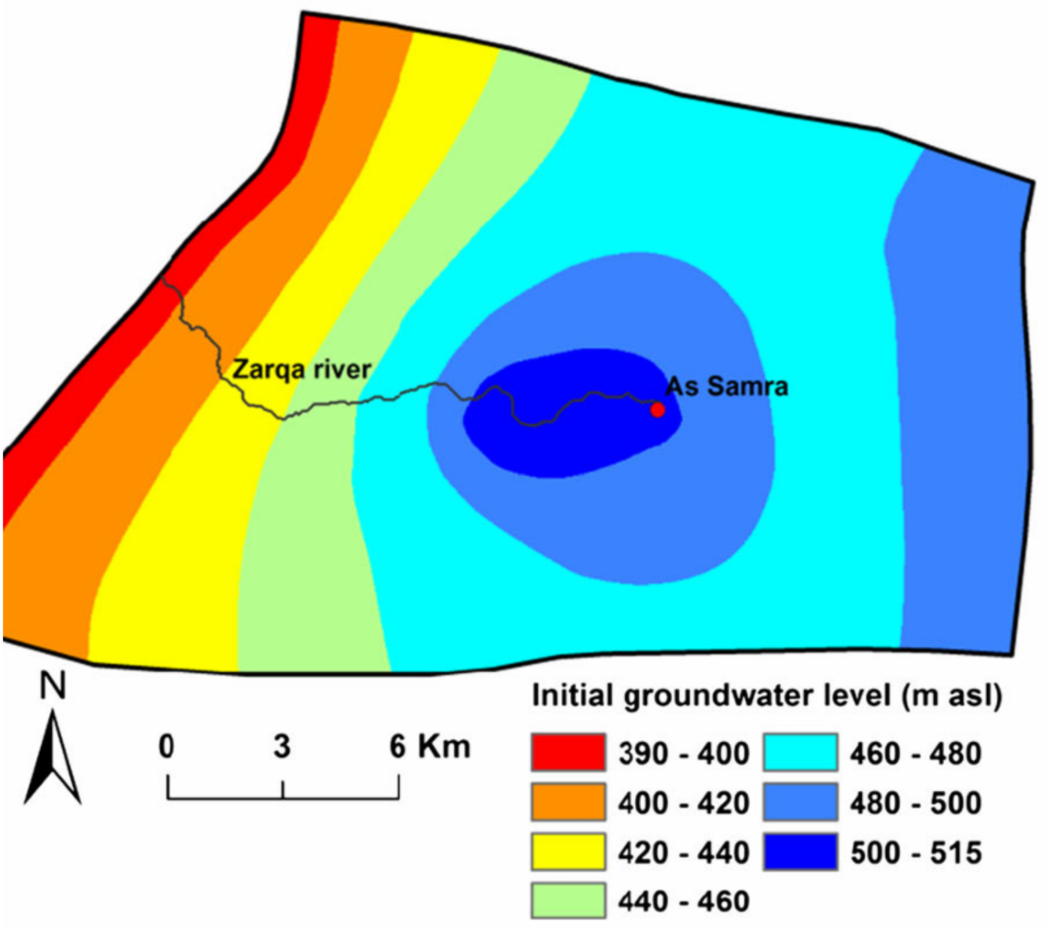


Figure 2.4: Initial groundwater level map for Hummar limestone aquifer in the upper Zarqa River area (m asl), El-Rawy et al., 2016

2.2 Water quality and vulnerability to groundwater

Almanaseer et al., 2020 in their study collected water samples at eleven defined points along the Zarqa River within their study area (Figure 2.3). These points were strategically selected based on existing data and a field survey, distributed over a 22 km stretch from As Samra treatment plant to Jerash bridge. The sampling locations were chosen to represent various crucial zones, including the effluent from As Samra plant, the mixing point with Ain Gazal water, areas with springs, spots with significant agricultural return flow, and zones where surface water and groundwater interaction occurs. The samples were collected by researchers and a master's student.They examined the effects of TWW with freshwater on water quality. The river's pH ranged from 7.5 to nearly 9, and turbidity varied between 21 to 126 NTU, with an increase in pH observed downstream. Chemically, most water samples met Jordanian standards, though elevated Chemical Oxygen Demand (COD) levels were noted, particularly at specific points.

Sodium (Na) and Chloride (Cl) levels were high, attributed to illegal irrigation practices and excessive fertilizer use. Pearson correlation analysis revealed a strong relationship between Na, Cl, and Total Dissolved Solids (TDS), indicating that salinity is primarily influenced by these ions (Figure: A.1). Electrical Conductivity (EC) values ranged from 1900 to 3100 µS/cm across the 11 sampling points. Specifically, EC ranged from 1938 to 2122 µS/cm (average 1987 µS/cm) at points 1 through 8, and increased to 2468 to 3060 µS/cm (average 2825 µS/cm) at points 9 through 11, indicating elevated salinity downstream, likely from brackish groundwater leakage. Microbiological analysis showed a decrease in E. coli levels downstream due to natural aeration. However, E. coli levels in irrigation water exceeded standards, with E. coli found in green crops like Rocca, cauliflower, lettuce, and green onion, but not in corn and potatoes. There was no consistent trend for trace elements in irrigation water related to sampling point distribution.

Alqadi et al., 2014 in their study observed notable spatial and temporal changes observed in pH, nitrate, and conductivity hotspot across the Zarqa region and surrounding areas. The Getis-Ord Gi* statistic was used to assess spatial clustering of well measurements like conductivity, nitrate, and pH. High z-scores (> 2) indicated hotspots with significantly higher values, while low z-scores (< 1) pointed to cold spots with lower values. Z-scores near zero suggested no significant clustering, implying a random distribution across the study area (Figure: 2.5,2.6)

According to Jordanian Institution for Standards and Metrology (JISM), the maximum allowable conductivity is 1,000 µS/cm, the nitrate is 50 mg/L, and the pH is between 6.5 and 8.5 mg/L. Medium pH areas (7–9 mg/L) in central and western Zarqa in 2004 expanded to include northern Zarqa by 2010, the areas in the south and east shifted to high levels, and low pH areas (5-6 mg/L) in central and western Amman increased to medium levels. High nitrate hotspots (57–78 mg/L) in central and western Zarqa in 2004 expanded northward by 2010 (58–137 mg/L), with medium hotspots spreading across southern Balqa and northeastern Amman, and low nitrate areas covering most other regions. High conductivity hotspots in central to northern Zarqa (3,000–3,267 µS/cm) intensified and expanded eastward by 2010 (3,740–6,775 µS/cm), while medium conductivity areas increased in western Zarqa and shifted towards western Amman, with low conductivity hotspots remaining consistent in eastern Zarqa, Balqa, and most of Amman.

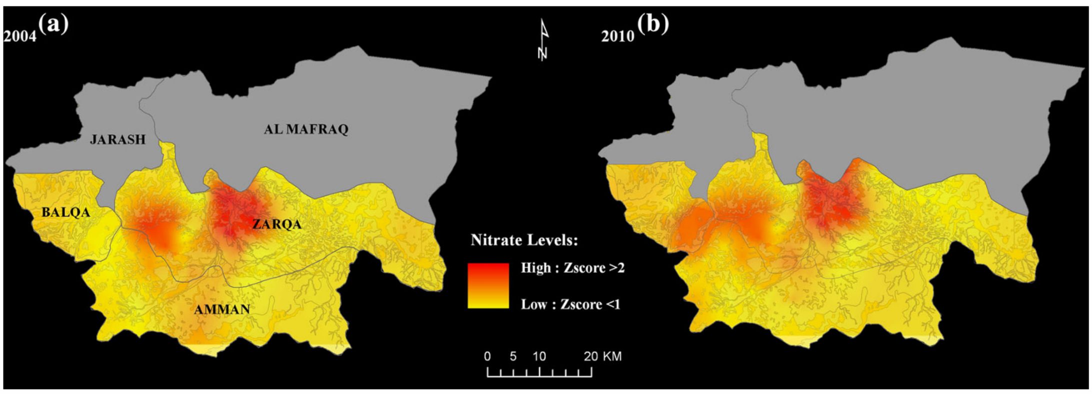


Figure 2.5: Changes in the nitrate level indicating hotspots between 2004 and 2010(Alqadi et al., 2014).

In one of the studies conducted by Blanford et al., 2010, a RBF well field was installed near the Zarqa River in Jerash, Jordan, consisting of six wells at various distances from the river (Figure: 2.7). The wells, averaging 22 meters in depth,

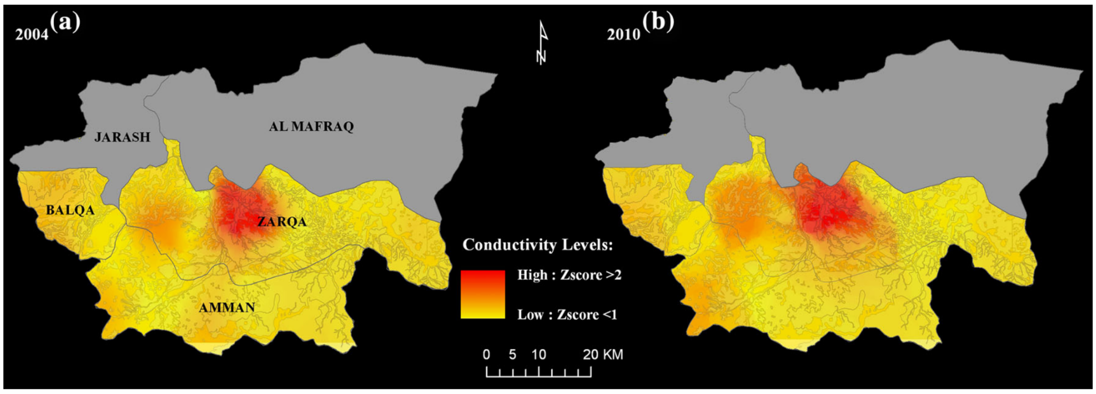


Figure 2.6: Changes in conductivity indicating hotspots between 2004 and 2010(Alqadi et al., 2014).

were drilled into a sandy and gravely alluvial aquifer. A conservative tracer test using table salt was conducted to measure water travel times. The tracer was released at the river's edge and monitored using an electronic data logger installed in a pumping well located 5 meters from the river. Additionally, water samples

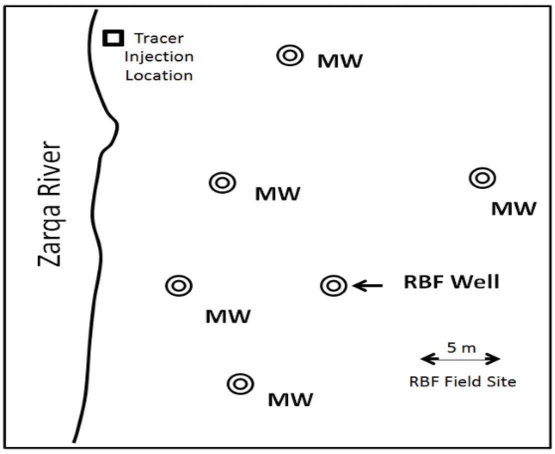


Figure 2.7: Layout of the RBF well field near the Zarqa River in Jordan (Al-Ghazawi and William Blanford, 2022).

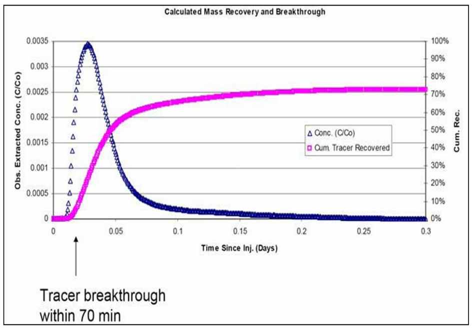
were collected from the wells and the river for analysis of microbial contaminants, including E. coli, Enterococci, somatic coliphages, somatic salmonella phages, and F-specific bacteriophages, with river samples serving as benchmarks for comparison.

The tracer test results, shown in Figure 2.8b, revealed a strong hydraulic connection between the RBF well and the Zarqa River, with rapid water travel times of 7 cm/min under pumping conditions. Microbial analysis demonstrated that the RBF system effectively removed fecal indicator bacteria and bacteriophages, achieving reductions of $3.4 - 4.2\ \log_{10}$ for bacteria and $2.7 - 3.3\ \log_{10}$ for phages (Figure:2.8a). This high level of microbial removal was particularly notable given the close proximity of the pumping well to the river, just 5 meters away.

El-Rawy et al., 2016 found the extracted water being primarily used for direct and conjunctive agricultural purposes. A total of 6.9 million cubic meters per year is pumped from 72 wells (Figure: 2.9), which tap into the upper limestone aquifer, Log$_{10}$ removal of *E.coli*, Enterococci, somatic coliphages, somatic salmonella phages and F-specific bacteriophages by river bank filtration

Indicator	RBF Removal
E. coli	>4.2
Enterococci	3.2
Somatic coliphages	3.3
Somatic Salmonella phages	>2.7
F-specific bacteriophages	3.3

(a) RBF removal efficiency for five microbial compounds during pumping



(b) Tracer concentration and mass recovery from extraction Well

Figure 2.8: Results from the study site located 5 m from river bank in the study by Blanford et al., 2010.

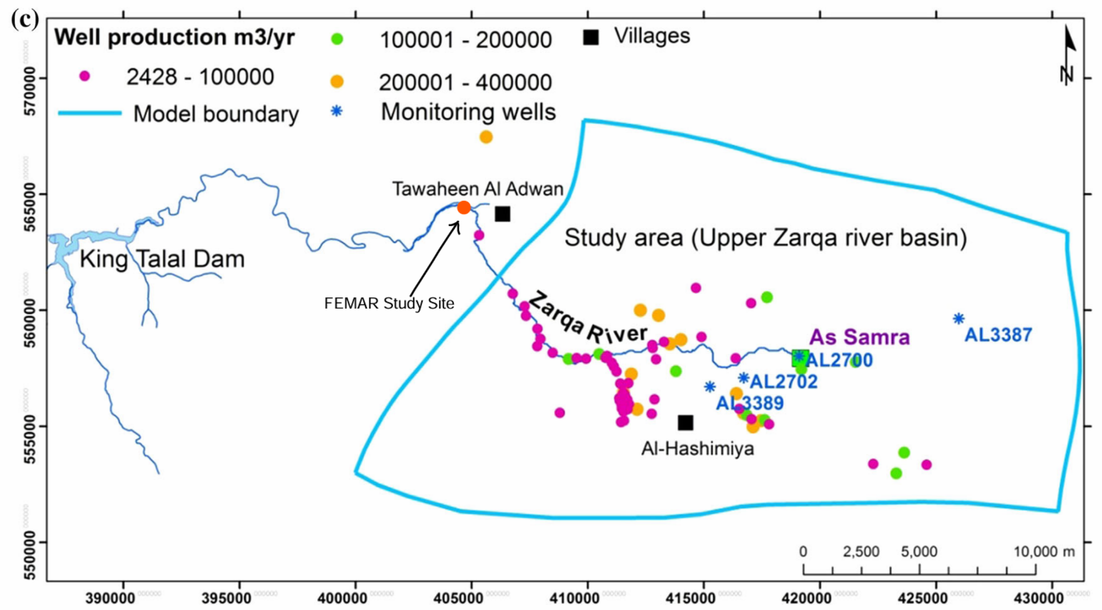


Figure 2.9: Area under investigation with irrigation and monitoring wells (well production rates obtained from MWI 2014) by El-Rawy et al., 2016.

known as the Hummar Aquifer. This aquifer extends to a depth of 200 meters below the ground surface, with an average well production capacity of 40 cubic meters per hour (MWI Data Bank, 2015).

3 Synthesis of Literature Review

The hydrogeology of the Zarqa river is studied through available literature. For identification of suitable RBF sites, similar sites as compared to the available monitoring wells in the study site of FEMAR project (Figure: 1.2) are selected by incorporating the lithology, land use and slope of the area. At the same time, by giving weightage and rating to different thematic maps and classes, suitability score is calculated. The score is divided into four groups: low, moderate, high and very high.

Lithology, Land use/Land cover and Topographic slope are given respectively weightage of 9, 6 and 5 based on their importance for RBF. For the ratings of Lithology, alluvium is given most importance as most of the riverbanks are situated above alluvial plains. And Hummar formation is also given more importance because the surface geology of the Zarqa River Basin is dominated by Late Cretaceous carbonates known as the Hummar Formation that represents the main water-bearing formation (El-Rawy et al., 2016). The idea for the assigned ratings were also taken from the paper written by Al-Shabeeb et al., 2018(Figure: A.4). For the rating of topographic slope, the study of Shukla et al., 2023 and Al-Shabeeb et al., 2018 were reviewed (Figure: A.5, A.4). Based on these information (Table: 3.1) and using equation 3.1, suitability scores were calculated for various classes. Then the calculated site suitability score was divided into four groups: low, moderate, high and very high (Table: 3.2).The location of potential RBF sites can be seen in Figure 3.1.

The Site Suitability Score S is given by:

$$S = L_{\mathrm{w}} \cdot L_{\mathrm{r}} + LULC_{\mathrm{w}} \cdot LULC_{\mathrm{r}} + S_{\mathrm{w}} \cdot S_{\mathrm{r}} \tag{3.1}$$

In this equation:

- S represents the Site Suitability Score.
- L_{w} and L_{r} are the weight and rating for Lithology L.
- $LULC_{\mathrm{w}}$ and $LULC_{\mathrm{r}}$ are the weight and rating for the Land Use Land Cover (LULC).
- S_{w} and S_{r} are the weight and rating for Topographic Slope (S).

Guideline for calculating Site Suitability Score				
Thematic Map	Weight (w)	Class	Rating (r)	w × r
Lithology (L)	9	Alluvium and Wadi Sediments	10	90
		Hummar	8	72
		Sand	7	63
		Kurnob Sandstone	7	63
		Wadi As Sair Limestone	6	54
		Hamam, Hamam Sandstone	4	36
		Wadi Umm Ghudran	2	18
		Amman Silicified Limestone	1	9
		Fuhays	1	9
		Shu'ayb	1	9
Land Cover/-Land Use (LULC)	6	Permanent Water bodies	9	54
		Herbaceous Wetland	8	48
		Grassland, Shrubland	7	42
		Cropland	5	30
		Bare/Sparse Vegetation	5	30
		Tree Cover	3	18
		Built-up	1	6
Topographic Slope (S)	5	<1	9	54
		1-3	8	48
		3-5	6	36
		5-7	5	30
		7-9	4	24
		9-12	3	18
		>12	0	0

Table 3.1: Thematic maps along with their classes, weight and ratings

Class	**From**	**To**
Low	0	24
Moderate	24	87
High	87	118
Very High	118	189

Table 3.2: Class Ranges

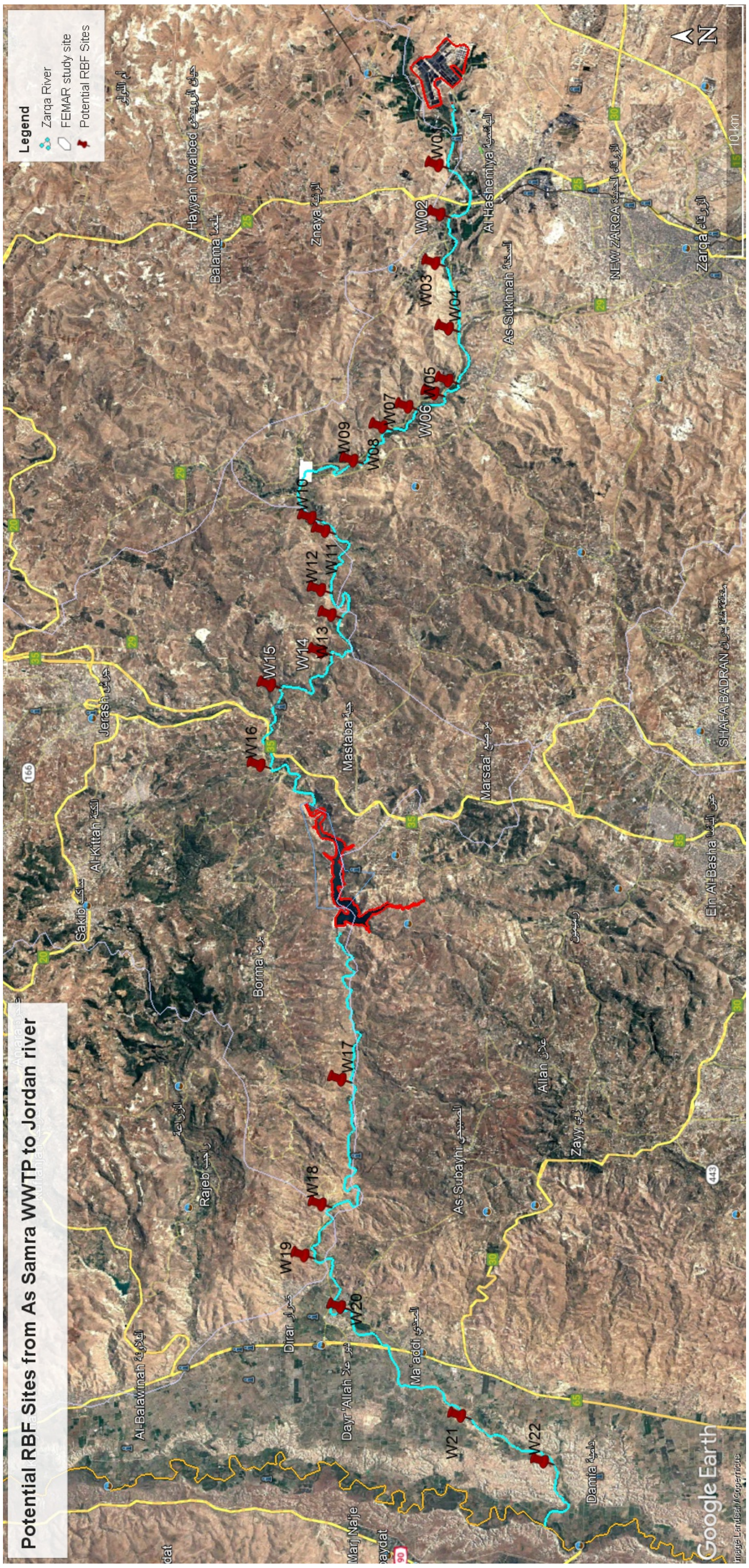


Figure 3.1: Potential RBF Sites

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Appendices

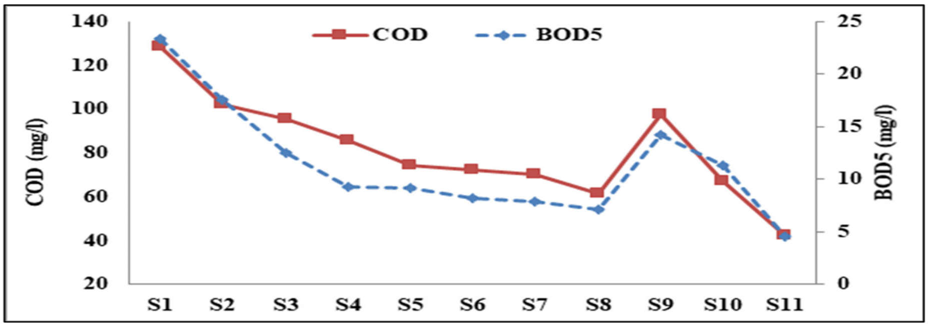

Figure A.1: BOD5 and COD values measured at 11 sampling points in the study area (Almanaseer et al., 2020).

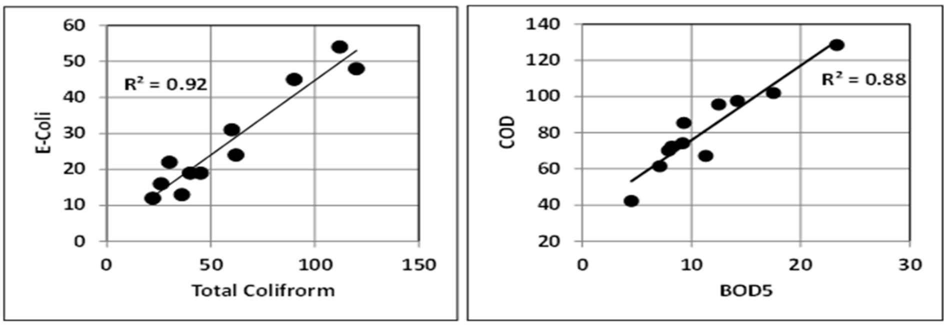

Figure A.2: Correlation between total coliform with E-Coli (left) and BOD5 with COD (right)(Almanaseer et al., 2020).

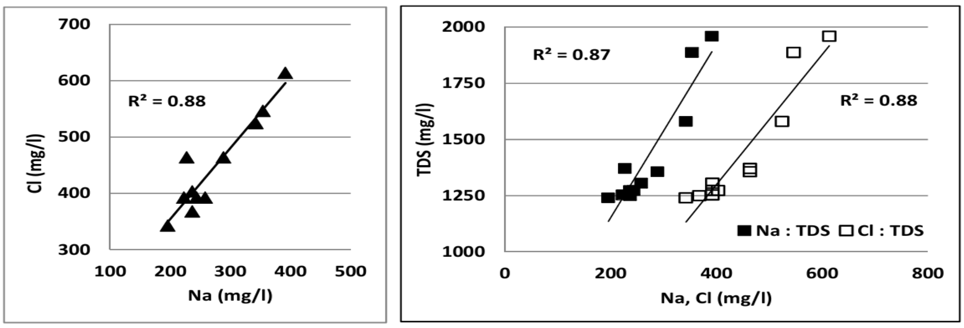

Figure A.3: Correlation between Na and Cl (left) and Na and Cl with TDS (right)(Almanaseer et al., 2020).

Map	Weight (w)	Class	Ratings (r)	w × r
Lineament Density ($km/\ km^2$)	9	> 0.0075	10	90
		0.0055–0.0075	8	72
		0.0035–0.0055	7	63
		0.0015–0.0035	5	45
		< 0.0015	4	36
Lithology	8	Schist, phyllite, slate, alluvium	9	72
		Limestone/ marble, basalt	8	6
		Schist,/phyllite, schist, volcano	6	48
		Acid intrusive, Mudflat	5	40
Rainfall (mm)	8	< 225	5	40
Slope (Degree)	4	< 5	8	32
		5–15	7	28
		15–25	5	20
		25–35	4	16
Elevation (m)	4	100–500	6	24
		500–1000	4	16
Soil	3	Sandy Clay/ Coarse Sandy Clay - Clay	7	21
		Sandy loam - Sandy clay	5	15
		Fine Sandy Clay loam/ Fine Sandy Clay	4	12
Drainage Density ($km/\ km^2$)	3	< 0.0010	9	27
		0.0010–0.0025	8	24
		0.0025–0.0040	6	18
		0.0040–0.0055	5	15
		> 0.0055	4	12
Land Use	2	Farms	7	14
		Other Crop/ Manmade dam	6	12
		Clear Land/ Urban Area	4	8

Figure A.4: Criteria-assigned ratings and weights (Al-Shabeeb et al., 2018)

Sl. No.	Thematic map	Class	Value
1	Geological map	River terrace with alluvium, gravel, and boulder	1
		Intermontane valley with alluvium, gravel, and boulder	1
		Old sided mass meta volcanic rock	Restricted
		Recently slide mass	Restricted
		High structural hills, Meta Volcanic rock	Restricted
2	Land use/Land cover map	Water	Restricted
		Forest	1
		Build area	Restricted
		Agricultural Land	1
		Open land	1
3	Slope map	5%	1
		10%	1
		15%	2
		20%	Restricted
		> 20%	Restricted
4	Stream network map	0rder 1	No data
		Order 2	No data
		Order 3	Restricted
		Order 4	Restricted

Note Value; 1 = Excellent, 2 = Good, Restricted = Unfit, No data = Unsuitable

Figure A.5: Scoring value of thematic layers for site suitability analysis (Shukla et al., 2023)