Research paper

The Zliten Groundwater Crisis: A Threat to Community Wellbeing and Sustainable Solutions

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Abstract:

The rise of polluted groundwater in Zliten, Libya, emerged as a crisis in early 2024, affecting over 2,000 families and posing significant health risks. This paper investigates the causes of this crisis by assessing the interactions between the man-made drivers and the natural environment of the Wadi Majer basin. GIS and remote sensing data for the years 2012-2024 have been used to analyse the spatial and temporal correlations between groundwater levels, Man-Made River Project (MMRP) water supply, precipitation, and the lack of a centralised wastewater system. The findings show that the uncontrolled water supply from the MMRP, along with wastewater contamination from faulty sewage systems, is a significant contributor to rising groundwater levels and contamination. The impact of natural geological and climate variations was found to be insignificant. We evaluate the effectiveness of current mitigation measures, such as drainage canals and water removal, and propose sustainable, long-term groundwater management options for Zliten, adopting Integrated Water Resources Management (IWRM) principles. These involve controlling MMRP supply management, investing in wastewater treatment facilities, and fostering public awareness. This research provides necessary information for policymakers and stakeholders to adopt beneficial strategies for mitigating the present crisis and ensuring that groundwater resources in Zliten are sustainable over the long run.

Keywords: Integrated Water Resources Management (IWRM) · Geographic Information System (GIS) · Man-Made River Project (MMRP) · Wastewater System

1. INTRODUCTION

1.1 Problem Statement

Groundwater crisis in Zliten, Libya, has emerged as a significant environmental and public health challenge, particularly since 2020, when residents began to notice rising levels of polluted groundwater. Starting in 2020, people in Zliten noticed a rise in polluted groundwater. The problem increased and became a crisis at the beginning of 2024 (Nazeer et al., 2025). Rising groundwater levels are causing an emergency affecting over 2,000 households in Zliten and posing significant health risks due to stagnant water and insect proliferation. According to the official media, 'people of Zliten observe the unusual phenomenon of the rising of groundwater levels in several neighbourhoods in the city' (The Libya Observer, 2024). Moreover, groundwater in the study has had some concerns regarding its quality (Jude & Nwankwoala, 2018; Nazeer et al., 2025).

Groundwater rising in the unsaturated zone with materialisation on the surface is one of the most dangerous phenomena affecting urban life in arid and semi-arid sites. Beyond property damage, waterlogging can, agricultural activities and infrastructure, which can lead to flooding, damaging property, disrupting daily life and negatively impact human health (e.g., spreading vector-borne diseases) (Becker et al., 2022; Bahir et al., 2022). In general, the reasons behind groundwater-related crises (pollution and rise) may include:

- Excessive pumping lowers water tables, causing saline intrusion (saltwater contaminating freshwater)
- Erratic rainfall patterns alter recharge rates, which leads to artificial recharge (Mostafa et el., 2021).

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- Fertilisers/pesticides seeping into aquifers (Abanyie et al., 2023),
- Poor Sewage/Wastewater Infrastructure that leads to leaking septic tanks or untreated sewage infiltration (Drah et al., 2023).

The affected area of Zliten is located at the lowest level of the surface water basin (Majer Basin) with a total area of 1,055 km² (Ben Issa & Saied, 2024). Regions experiencing groundwater discharge are part of the Wadi Majer basin, specifically encompassing the areas of Al-Nashia, Al-Mantarha, Al-Baza, and Al-Rumaiah, which collectively span 21 km². The rise in groundwater levels in Zliten has significantly damaged over 2,000 homes in the affected areas. Many of these homes have experienced cracked walls or collapse due to increased groundwater. This major issue has forced many residents to flee their homes to avoid the risks posed by the structural damage, as seen in Figure 1.

Figure 1. The Impact of Polluted Groundwater on Infrastructure (pictures were taken by the authors)

Moreover, the rise of contaminated groundwater has led to the accumulation of salts in the soil, damaged crops and destroyed agricultural yields in many areas of Zliten (Nazeer et al., 2025), as seen in Figure 2.

Figure 2. The Impact of Polluted Groundwater on Agriculture (pictures were taken by the authors)

1.2 The Geographic Information System (GIS) and Remote Sensing

The application of Geographic Information System (GIS) and Remote Sensing (RS) technologies to identify the natural characteristics of the basin is crucial. Since the latter half of the twentieth century, GIS-RS technologies have been integrated into numerous natural studies in developed countries, experiencing significant advancements over the past two decades (Abdelgiom, 2024). These technologies have provided significant capabilities in topographic studies, particularly in the analysis and interpretation of watershed characteristics. Investigating the natural features of the basin is essential for understanding and addressing various issues, including the phenomenon of groundwater discharge in the region. The models utilised in these technologies simplify complex realities, with each model serving a representational role based on mathematical language. These models are constructs that aim to depict reality; they do not merely represent existing conditions but rather create an interpretation of them (Chatrabhuj et al., 2024).

1.3 Water Resources

Water resources in Libya include surface water, groundwater and nonconventional waters, which include treated wastewater, desalinated water and the water coming from the MMRP (Brika, 2018), as seen in Figure 3.

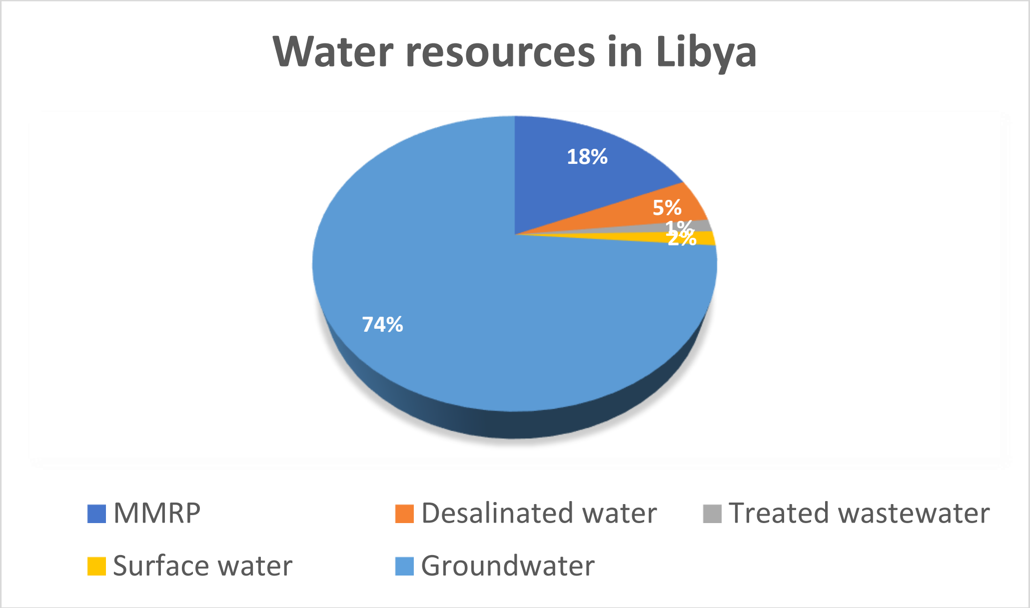

Figure 3. Water Resources in Libya

Surface water: There are limited resources for surface water in Libya (Rashrash & Farag, 2016). The three biggest dams are: Wadi Quattara, Wadi Kaam, and Wadi El-Magineen, with design capacities of 135 Mm^3, 111 Mm^3, and 58 Mm^3, respectively (Brika, 2019). Wadi Kaam Dam was constructed in Zliten in January 1974 within the Ka'am Region, approximately 25 kilometres southwest of Zliten city. It is strategically positioned. The conjunction of Wadi Al-Cusaiha and Wadi Targhlat forms Wadi Ka'am and Ka'am Lake in front of Ka'am Dam (Shushan & Abdeljalil, 2017). The dam receives an average annual rainfall of about 240 mm, contributing to its water storage capabilities. At the end of Wadi Kaam, a freshwater spring contributes to the local water supply (Ashmila et al., 2021).

Groundwater: Due to its arid climate and the lack of reliable surface water resources, Libya depends mainly on groundwater, which has many challenges (Abughlelesha & Lateh, 2014). This resulted in its extensive use (Brika, 2019). Groundwater resources in Libya come from six underground basins. Zliten is located in the renewable Al Hamada basin with a capacity of 4,000 Km^3 over 215,000 Km^2 (Brika, 2018) as shown in Figure 4.

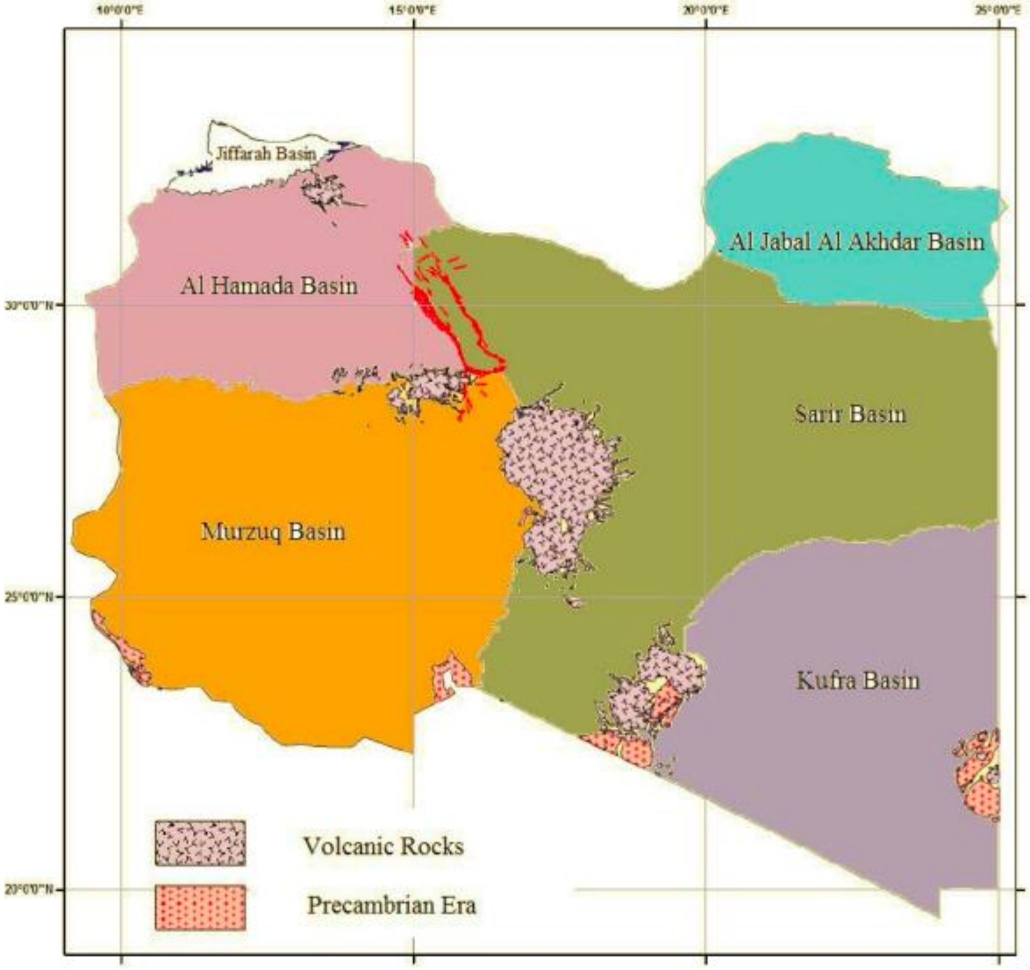

Figure 4. Underground Basins in Libya (Brika, 2018)

Wastewater: According to the General Company for Water and Wastewater (GCWW), 23 wastewater treatment plants (WWTPs) are distributed across Libya. Of these, only ten plants are currently operational, while eight plants are out of service, and the company's management teams are maintaining five plants. WWTPs in Libya were primarily designed to produce water suitable for agricultural use. The most significant operational wastewater treatment plants are in Tripoli, Misurata, and Sirte, with design capacities of 110,000, 24,000, and 21,000 m^3/day, respectively. The remaining wastewater facilities are primarily medium and small-sized plants, ranging from 370 to 6,700 m^3/day in capacity. The total amount of wastewater that requires treatment is 1,324,054 m^3/day. However, only 11% are treated. The remaining 89% of wastewater is being pumped into the sea, artificial lagoons, and black wells without any treatment (Brika, 2018).

Sea water Desalination: Sea water desalination was the second crucial non-conventional water resource adopted in Libya, which has been used in Libya since the early 1960s. There were 21 operating desalination plants, with a total capacity of 525,680 m^3/d (Brika, 2018). Thermal processes represent about 95% of the operable desalination plants, while reverse osmosis membrane technology represents about 5%. The overall contribution of desalination to the local water supply was 1.4% in 2002. However, the construction of the Man-Made River Project (MMRP) contributed to eliminating the importance of desalination technology in some areas, such as Zliten. Thus, only two desalination plants are currently in service.

The Man-Made River Project (MMRP): The MMRP, Figure 5, is the most extensive and most expensive groundwater pumping and conveyance project in the world; it was constructed and partially operated in August 1996 to meet the Libyan population's water needs by drawing water from aquifers beneath the Sahara – mainly the Nubian Sandstone Aquifer System and conveying it along a network of huge underground pipes to the Northern coastal cities. The MMRP aimed to produce and represent 2 Million Cubic Meters (MCM) of groundwater per day from the fields of wells in the Jabal Hasouna region. 80% of the water from the MMRP would be used for agricultural activities, 12 % for domestic and only 5% for industrial use.

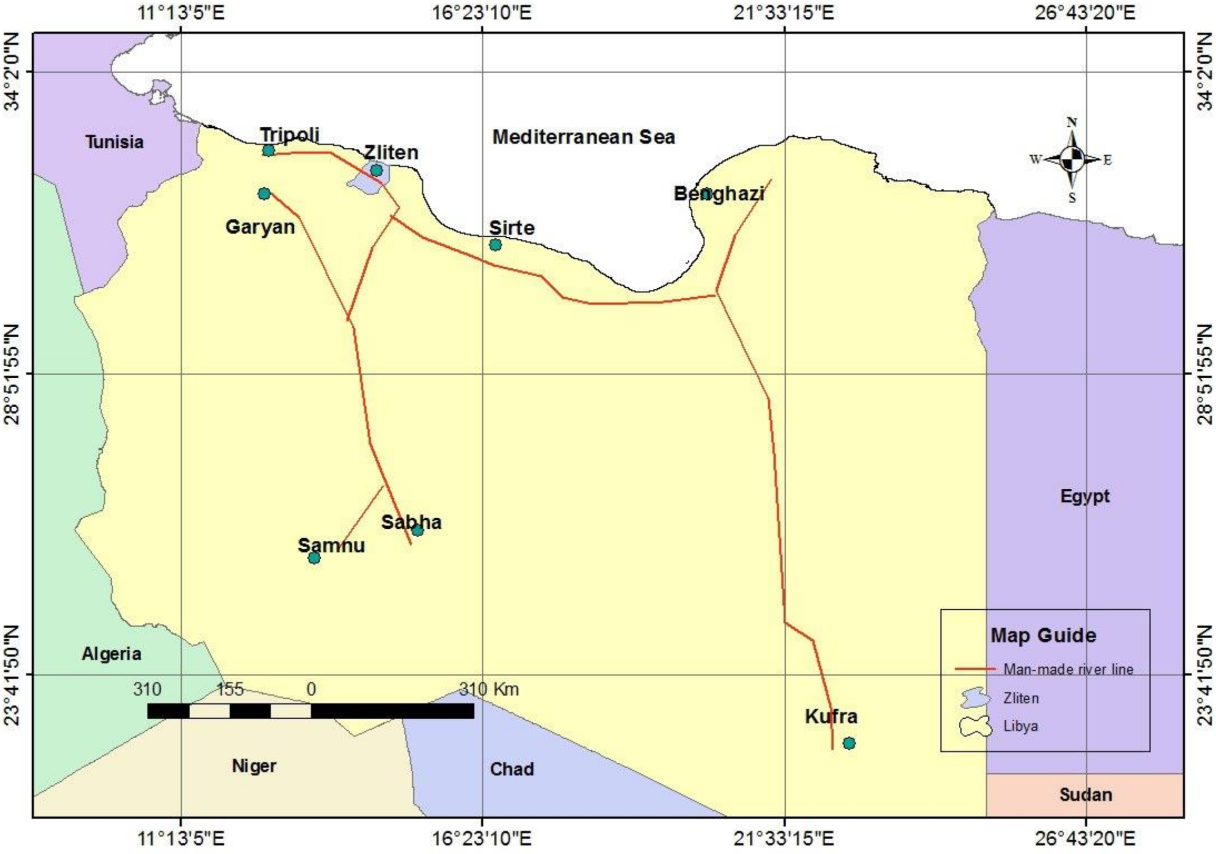

Figure 5. The MMRP Lines from South to North (created by the authors using ArcGIS)

1.4 Water Uses

Water resources in Libya cover three main users: agricultural, domestic and industrial:

1. Agricultural water use is Libya's largest consumer of water, accounting for approximately 85% of total water demand. In 2012, agrarian consumption was estimated at 4,850 million cubic meters, with many thousands of wells dug to support irrigation (Fanack Water, 2022). The irrigated area has expanded significantly, but rising groundwater levels in places like Zliten pose risks of waterlogging and soil salinisation, threatening agricultural productivity and food security. Despite its high-water consumption, the agricultural sector contributes minimally to the national economy, highlighting the need for sustainable practices (Ashmila, 2021).

2. Domestic water use is critical in urban areas, where average consumption ranges from 300-400 litres per capita per day, while rural areas have lower figures. Domestic water use was estimated at around 700 million cubic meters, serving a significant portion of the urban population (Fanack Water, 2022). However, rapid

urbanisation and population growth have increased demand, placing additional stress on water resources, particularly in regions like Zliten, where rising groundwater levels complicate access to clean water (Ashmila, 2021).

3. Industrial water use in Libya is relatively low, constituting less than 4% of total water demand. In 2012, industrial consumption was approximately 280 million cubic meters, with the primary industries being petrochemicals, textiles, and power generation. Although the industrial sector faces challenges related to water scarcity, its overall impact on total water use remains limited compared to the domestic and agricultural sectors. As Libya's economy diversifies, efficient industry water use will become increasingly important to address the country's water management challenges (Fanack Water, 2022).

1.5 Hypothesis and Objectives

1.5.1 Hypothesis

The observed rise in groundwater levels and associated contamination in Zliten are primarily driven by anthropogenic factors, specifically the uncontrolled water supply from the Man-Made River Project (MMRP) and the lack of a centralised wastewater management system, rather than natural variations in climate or geology.

1.5.2 Objectives

- Quantify the contribution of the Man-Made River Project (MMRP) to groundwater recharge in Zliten between 2012 and 2024.
- Assess the impact of the lack of a centralised wastewater system on groundwater quality in Zliten.
- Evaluate the effectiveness of current mitigation measures (water removal, drainage channels) implemented in Zliten.
- Propose sustainable, long-term solutions for groundwater management in Zliten.

2. METHODOLOGY

2.1 Study Area

The study area encompasses the Wadi Majer basin, situated within the administrative boundaries of Zliten. The basin lies between latitudes 32°09' N and 32°30' N, and longitudes 14°18' E and 14°53' E. The affected area experiencing groundwater discharge, Zliten, is located in the northwestern part of Libya on the picturesque Mediterranean coast, approximately 150 kilometres east of the bustling city of Tripoli, the capital of Libya, as illustrated in Figure 6.

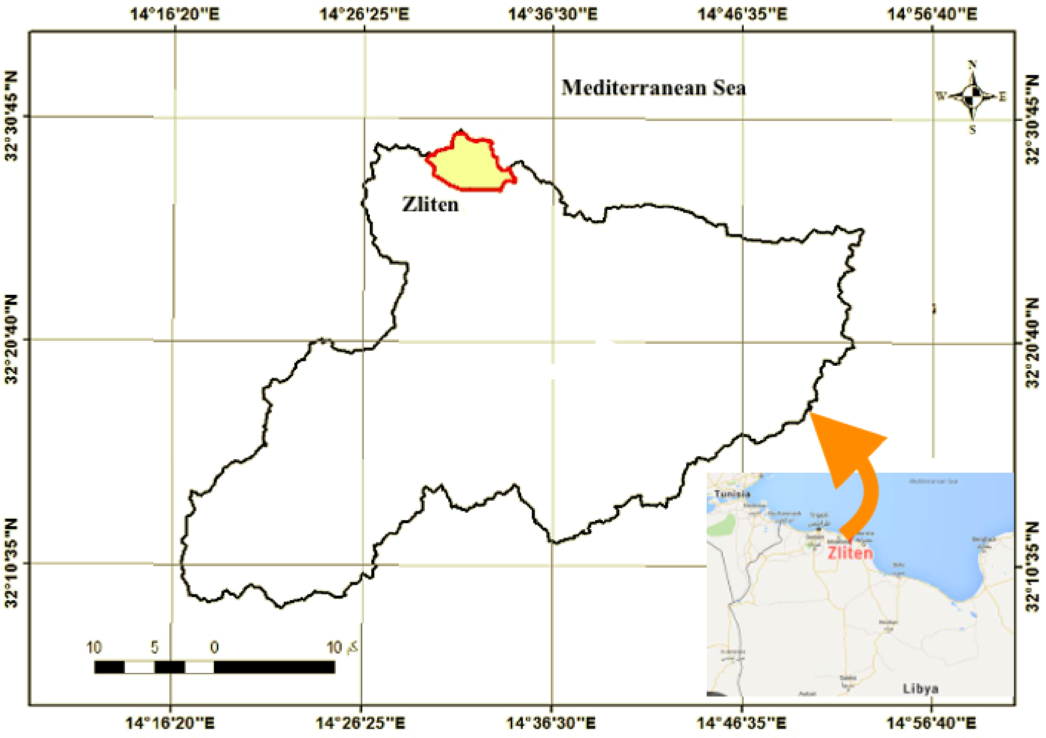

Figure 6*. Wadi Mager Basin and Zliten, the Damaged Area (created by the authors using ArcGIS)*

According to the official records of the Zliten Civil Registry Office, as of December 31st, 2023, the total population of the city of Zliten was estimated at 335,371 individuals (Zliten Civil Registry, 2023). This figure represents a 5.7% increase compared to the population count in 2021, across the 39 administrative districts (Muhallas) that comprise the city. Annual population growth in Zliten was 2% before 2012; then it became 4% between 2012 and 2020.

2.2 GIS and Remote Sensing

The digital elevation Model (DEM) of the basin was downloaded from NASA, and then the topographical maps and the spatial analysis were performed using a Geographical Information System (GIS). Moreover, the geological map was generated from the Libyan National map to assess the geological impacts on the geomorphological characteristics of the study area.

2.3 Desk Review and Consultation

The assessment of socioeconomic factors was based on a desk review and consultation with national stakeholders, including local experts. The consultations were performed using WhatsApp and Microsoft Teams. Rainfall data was obtained through personal consultation from the Meteorological Authority, Climate Department, Tripoli, Libya.

The desk review focused on utilising all available data from online publications, social media and the results of the geological surveys done by the Ministry of Water Resources (MoWR) in 2024, drilling 31 monitoring wells and establishing a "piezometric" network to monitor groundwater levels and quality.

Moreover, the team coordinated with the Ministry of Local Governance, which the ministry provided valuable insights into the current state of groundwater resources and the socio-economic impacts of the crisis.

3. RESULTS

3.1 Basin's Topography:

Using the downloaded DEM, it has been found that most parts of the basin are characterised by low relief and gentle slopes. The Wadi Majer basin's elevation values range from 0 to 206 meters above sea level, and can be divided into eight categories as illustrated in Figure 7 and as follows:

- **Category One:** Elevation between 0-32 meters, covering an area of 164.64 km^2 (15.59% of the total basin area). This category consists of very gentle slopes extending over a wide area in the northern part of the basin, overlooking the sea. It includes areas experiencing groundwater discharge (Al-Nashia, Al-Mantarha, Al-Baza, and Al-Rumaiah), which are at the lowest elevation within the basin, making them conducive to groundwater rise.
- **Category Two:** Elevation between 32-56 meters, covering 103.93 km^2 (10.5% of the basin area). This category extends into some coastal areas, primarily in the northern basin south of the previous category.
- **Category Three:** Elevation between 56-79 meters, covering 136.61 km^2 (12.93% of the basin area).
- **Category Four:** Elevation between 79-100 meters, with an area of 152.25 km^2 (14.41% of the basin area).
- **Category Five:** Elevation between 100-118 meters, covering 164.12 km^2 (15.54% of the basin area).
- **Category Six:** Elevation between 118-135 meters, covering 200.20 km^2 (18.96% of the basin area). This is the largest category in terms of area, extending into the southern parts and the eastern and western edges of the central valley.
- **Category Seven:** Elevation between 135-158 meters, covering 92.02 km^2 (8.71% of the basin area). This category extends into the southern, eastern, and western parts of the basin.
- **Category Eight:** Elevation between 158-206 meters, covering 35.12 km^2 (3.82% of the basin area), primarily found in the southern regions.

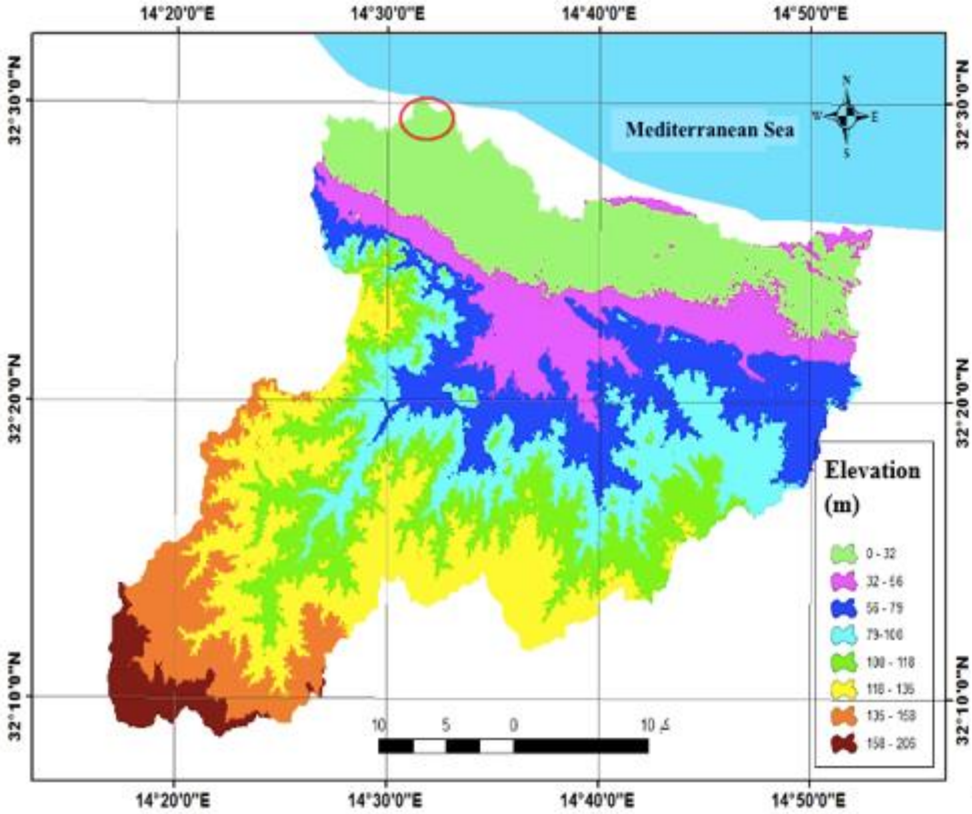

Figure 7. Elevation Categories Based on the DEM (created by the authors using ArcGIS)

Figure 7 shows that the damaged area of Zliten is located at the lowest elevation 0-32 m above sea level.

3.2 Geological Structure

The drainage pattern of the basin varies according to the types and characteristics of the rocks present, and the basin's area is closely linked to geological formations. The area tends to increase in regions characterised by soft, less erosion-resistant rocks, particularly if these areas are subjected to tectonic movements that lead to a decrease in base levels (Mustafa, 1989).

The geological structure of the region, like other areas in North Africa, has undergone significant tectonic and climatic influences throughout its long history. These influences included periods of marine dominance, particularly during the Tertiary and Quaternary periods, when marine influence gradually receded. A subsidence event resulted in the flooding of the entire region, and by the onset of the Pleistocene epoch, most of the layers that were widespread over the area were exposed as dry land.

The geological structures in the study area are relatively uncomplicated, dominated by Quaternary geological formations that are prevalent across most of the region, which constitute its primary tectonic framework. Additionally, climatic conditions at different times have played a role in shaping the geomorphological features of the area. The geological map of the basin reveals a variety of geological formations that were developed during different periods, the oldest being from the second period, which appears in multiple layers throughout most of the basin. The third period is represented by the Khums formation, while the fourth period encompasses various sections of the basin with diverse. Figure 8 illustrates the geological formation of the Wadi Mager Basin.

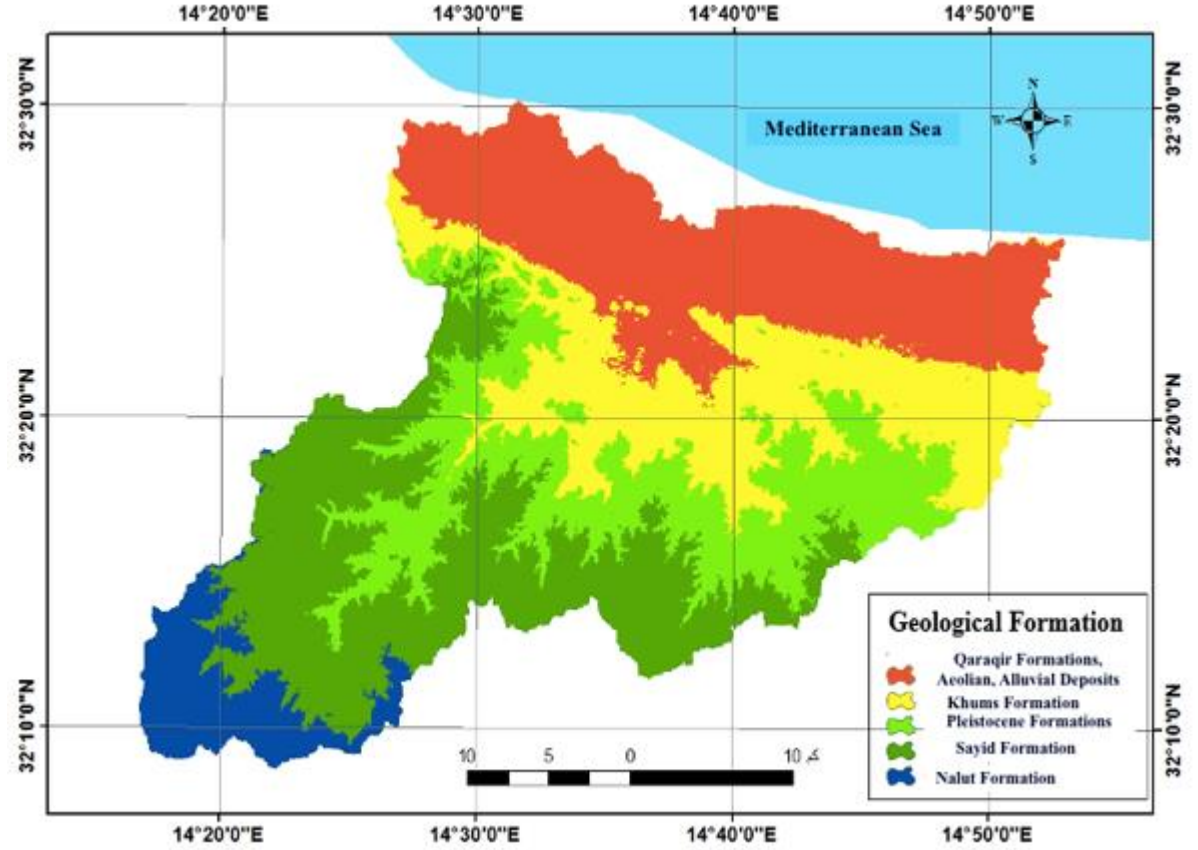

Figure 8. Geological formation of Wadi Majer (created by the authors using ArcGIS)

The main geological formations generally include sedimentary rocks, igneous rocks, metamorphic rocks, unconsolidated deposits, structural, erosional landforms, and volcanic and glacial formations. Zliten area has a rich geological structure that offers a fascinating glimpse into the region's ancient history dominated by formations from the fourth geological period, the Quaternary Period, which began approximately 2.58 million years ago and continues to the present day. These formations can be observed in various locations, often covered by sandy formations or recent sediments. The region also boasts formations from the third geological period (Gefli, 1976). This period spans from approximately 541 million years to 252 million years. It was a time of significant diversification of life on Earth, with the emergence and evolution of many major animal and plant groups.

The geological composition of Zliten's land varies across its constituent stages. The northern parts of the region are covered with the Pleistocene formation, dating back to the fourth geological time. These rocks are overlaid with Celtic sands from the excavator formation, accompanied by layers of limestone rocks parallel to the seashore. The coastal strip and the borders of the study area consist of rocks from the Qarqarash Formation, which date back to the fourth geological time. These sands primarily comprise quartz and lime (Rashed & Farag, 2016).

Moving further back in time, the Zliten region is also home to rocks from the Upper Cretaceous period, dating back to the second geological time. These rocks, representing the oldest geological formations in the area, can be found in the southwestern parts of Zliten, particularly in the Wadi Majer area (Shusan, 2017; Shushan & Abdeljalil, 2017).

Based on the geological map, Figure 4, the affected areas are situated within two distinct geological formations that share some physical characteristics. These formations include:

Kargash Formation: This formation consists of marine-origin sandy deposits located near the coast. It is characterised by its strong cohesion, containing proportions of silt and sandy clay. This formation allows for significant percolation of rainwater, leading to accumulation near the surface. It rests on an impermeable clay layer, which undoubtedly facilitates the rise of groundwater levels. Historical data also indicate that the area was characterised by the proximity of freshwater sources in the mid-20th century.

Water and Wind Deposits: These deposits result from both aeolian and hydrological erosion, forming layered sediments in the valley channels and at their mouths, creating alluvial fans and sand dunes. Approximately 98% of these deposits have been removed, which previously covered much of the affected area. They also exhibit high porosity, confirming that geological formations are key contributors to rising groundwater levels by absorbing surface water and retaining a portion of rainwater.

Moreover, the Ministry of Water Resources (MoWR) is the main responsible body for geological and hydrological works through the Directorate of Research and Study. Three geological sectors, 1-1*, 2-2*, and 3-3*, were performed in March-May 2024, as shown in Figure 9.

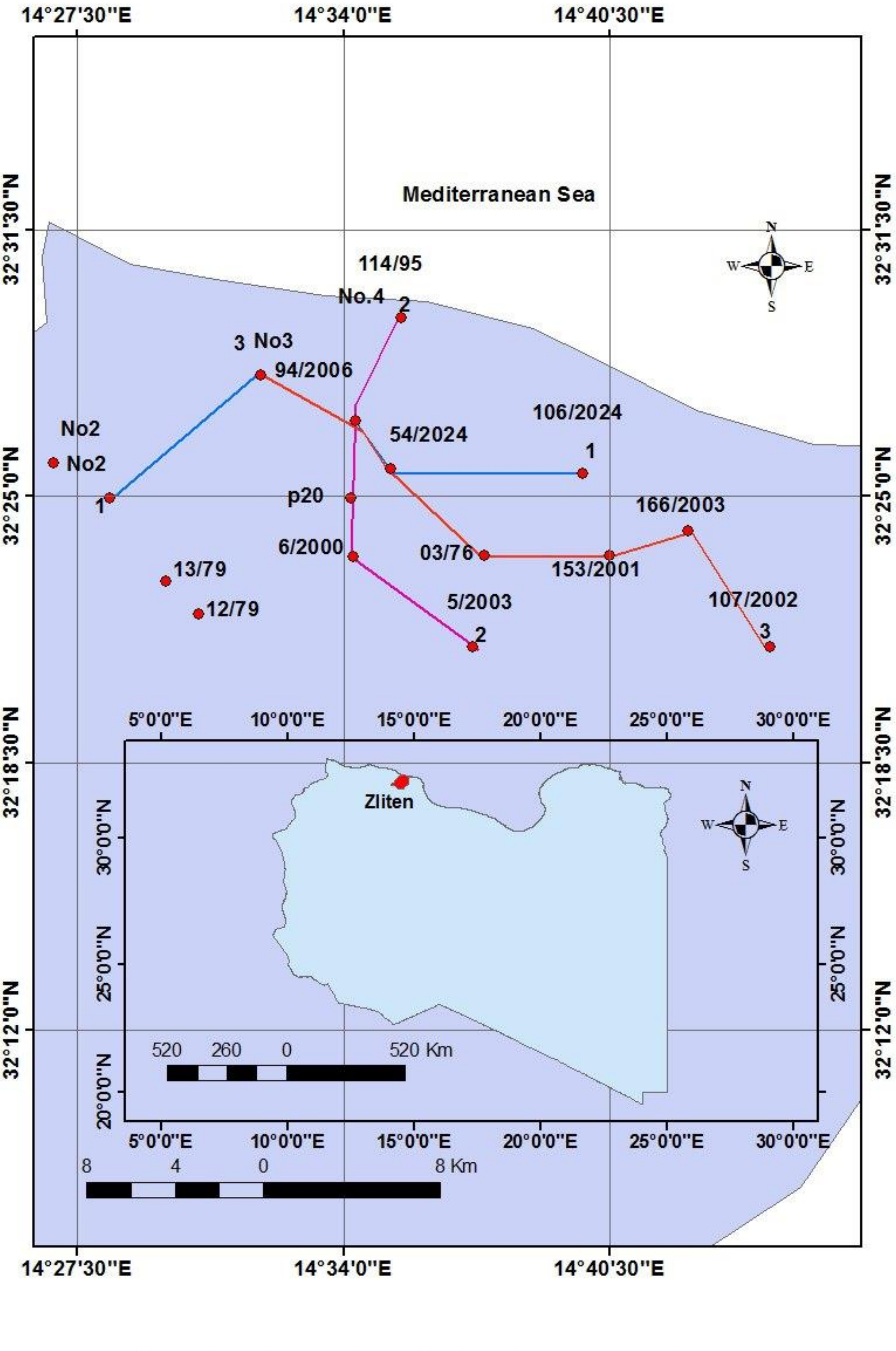

Figure 9. The Sections of the Geological Surveys (created by the authors using ArcGIS)

Based on these surveys, the surface layers are permeable and covered by sand and sediments. Some areas near the coasts have rocks. The deeper layers are primarily impermeable, with mudstones that prevent groundwater from flowing downward.

3.2 Rainfall

3.3.1 Rainfall

The rainfall in the study area follows a Mediterranean climate pattern, with precipitation beginning in the autumn. The rainy season in the region extends from October to March, peaking in winter during December. Table 1 presents annual rainfall rates between 1980 and 2024.

Table 1. Average annual rainfall from 1981 to 2024.

Period	Rainfall (mm)
1981-1990	255
1991-2000	168
2001-2010	216
2011-2020	226
2021-2023	214
2024-2024	226

Looking at the monthly rainfall between 2019 and 2024, Figure 10, man can notice that in 2019 there were two extreme rainfall events in December and February, then the next extremes came in 2022. Moreover, looking at the average annual rainfall between 1981 and 2024, confirms the increase in rainfall in 2019 and 2022, Figure 11, which might have contributed to the saturation of the aquifers in the area.

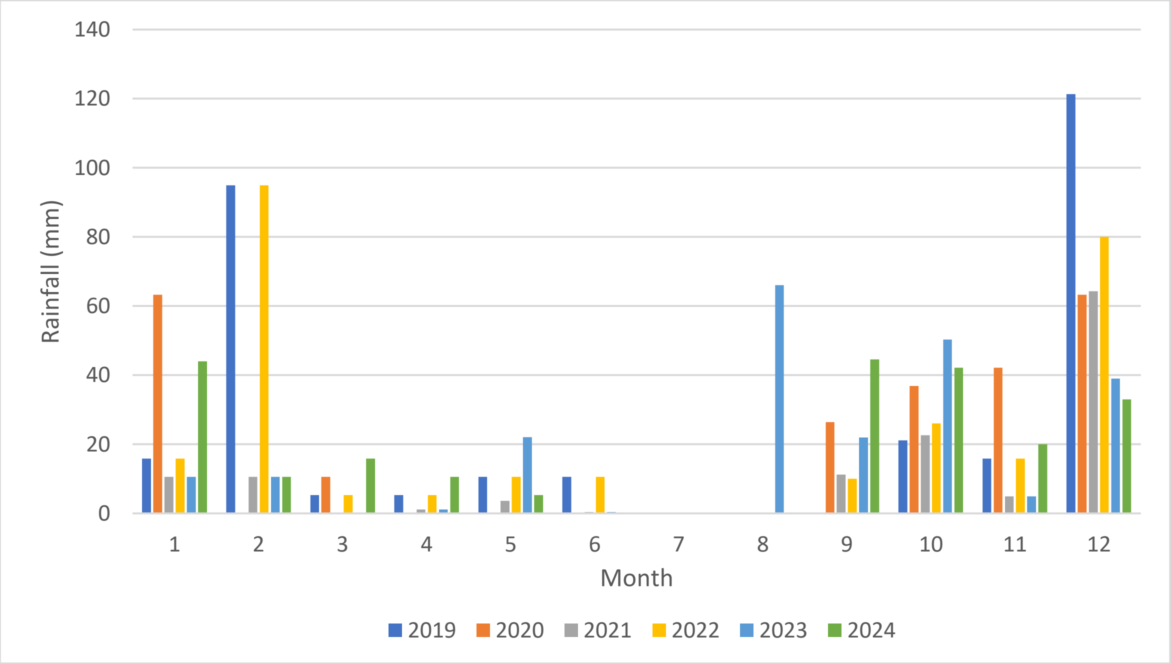

Figure 10. Monthly Rainfall Between 2019 and 2024 (created by the authors)

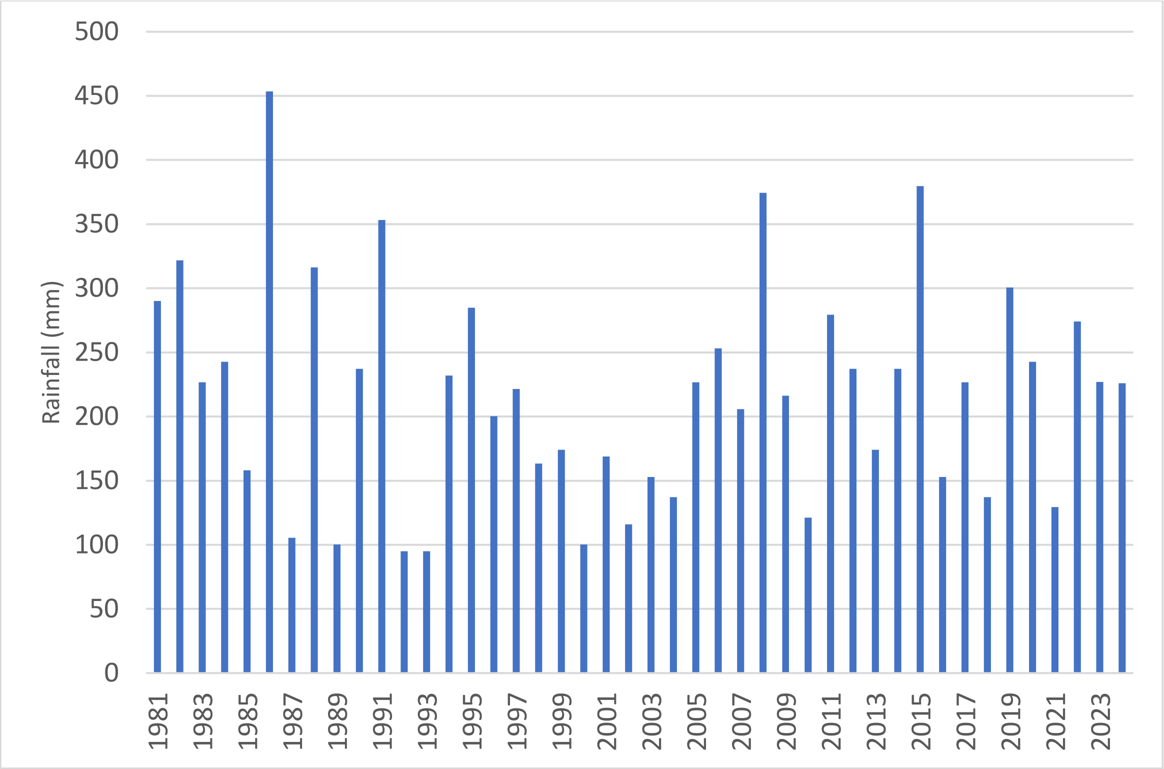

Figure 11. Annual Rainfall Between 1981 and 2024 (created by the authors)

The total average rainfall in the study area amounts to 267.1 mm, including affected regions that have repeatedly experienced heavy rainstorms in recent years. These storms have led to a significant rise in groundwater levels, with increases of over 30 cm in the monitoring wells during the period from 2020 to 2024.

3.4 Water Balance

Estimating water resources and demands of the six groundwater basins in 2010 showed that only the Jifara basin was under water scarcity, as shown in Figure 12 (Brika, 2019). Zliten is located in the Al-Hamada groundwater basin.

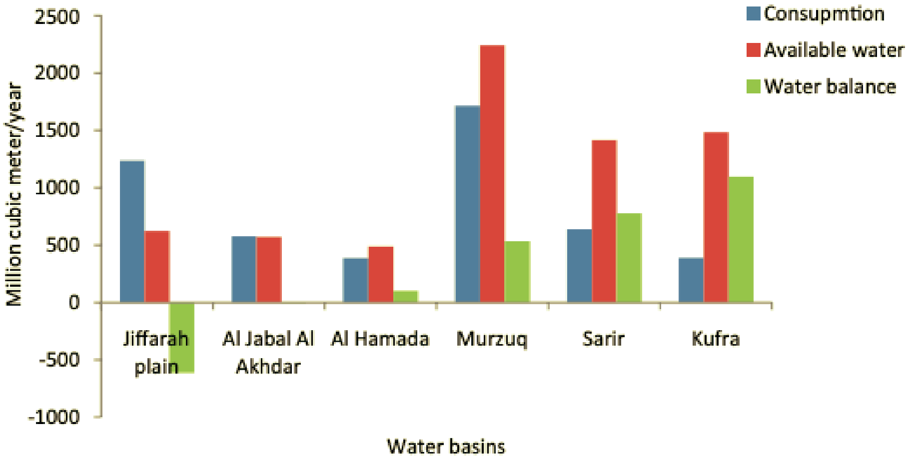

Figure 12. Water Resources Use and Balance in Underground Water Basins in 2010 (created by the authors)

On the other hand, the MoWR estimated the daily water supply, demand and balance in the urban areas of Zliten in January 2024, as shown in Table 2. It is worth saying that all water supplies come from groundwater resources. These estimates ignore industrial and agricultural water uses and do not include nonconventional waters, as all wastewater is discharged directly to the aquifer through illegal septic tanks. Thus, the calculations resulted in a water deficit, unmet demand, of 23,250 m^3/day.

Table 2. Water Supply, Demand and Balance in Zliten for January 2024 (m^3/day)

Population	Service centre	Wells		MMRP	Water supply	Water Demand	Water Balance
		Working	Discharge				
327,433	Zliten city	14	6,300	14,000	41,744	65,000	-23,250
	Al Jumaa	20	10,500				
	Thalatha	10	4,500	144			
	Majer	12	6,300				
TOTAL		56	27,600	14,144			

3.5 Initial Hydrological Assessment

Zliten, with an area of 2,743.25 Km2, was considered an agricultural area as houses occupied only 6.7 km^2 in 1984. At that time, 100,000 people lived in Zliten, and most people worked in agriculture. The farmland was divided into irrigated land of 530 km^2 using groundwater resources and rainfed land of 677 Km^2. However, due to population growth and urbanisation, Zliten had 335,371 people on 31 December 2023, and housing areas have increased and occupied 236 Km^2 of the agricultural lands, which reduced the farmland to 970 Km^2.

In 1984, people mainly used groundwater to cover their domestic and agricultural demands. In 2012, the Man-Made River Project MMRP started to supply Zliten with water for agricultural, industrial and domestic purposes. This led to a stop using local groundwater resources, an increase in urbanisation, and an increase in industrial activities. This unmonitored increase in socioeconomic, farming and industrial activities has led to water abundance and pollution. The following are the main potential reasons behind groundwater crises in Zliten:

1) The overuse of water coming from MMRP. The MMRP is used to supply Zliten with 14000 from 50,000 m^3/day. However, there is no actual metering and one sudden metering in 2020 showed that the flow was about 63,000 m^3/day.

2) The absence of a proper sewage system in the city. Thus, all consumed water is returned to the aquifer through open septic tanks, which leads to recharging groundwater with domestic and industrial wastewater.

3) Mismanaging agriculturally polluted return flows, which are full of pesticides and chemical pollutants, has increased chemical contaminants in groundwater.

4) Looking at the contour map of Zliten, as shown in Figure 13, one can notice that the area is almost flat, with an average elevation of 10 m AMSL, which reduces the possibility of water flowing outside it.

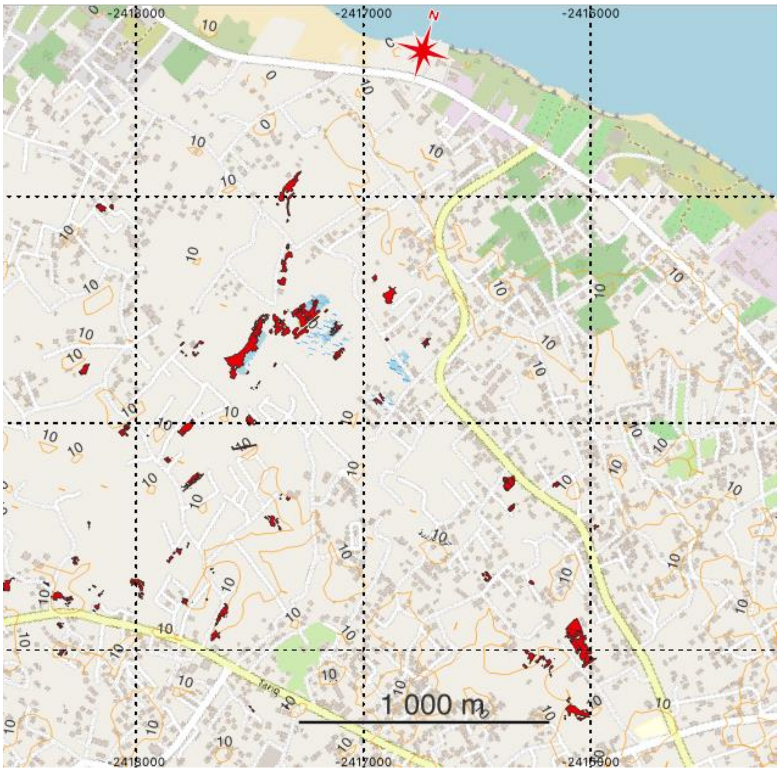

Figure 13. The Contour Map and Affected Areas Are in Red (created by the authors using ArcGIS)

5) According to the geological survey conducted by the Ministry of Water Resources, Zliten is situated above a shallow surface aquifer, which is confined and about 30 m deep, followed by a mudstone layer of 50 m, which prevents deep groundwater recharge. Thus, all used water and rainfall have saturated the shallow aquifer with polluted water, so groundwater flow from and to the surface aquifer is not feasible. However, modern modelling and geological surveys are needed to confirm this assumption: "the possibility of groundwater flow from deep aquifers towards the surface aquifer".

Before the construction of the MMRP, the primary water resources in Zliten were groundwater, a seawater desalination plant, and a surface dam. However, after the MMRP was built, farmers stopped using groundwater, and the desalination plant ceased operating. As a result, the primary water sources became the MMRP, local wells, and some surface waters. The increase in groundwater levels is typically due to more significant groundwater recharge. Before the MMRP, the water cycle in Zliten was closed, as people used and recharged the groundwater, supplemented by rainfall and surface waters. But after 2012, people stopped pumping groundwater and started using around 17,000 m^3/day from the new MMRP, introducing about 6.2 million cubic meters per year of polluted water to recharge the groundwater. The accumulation of this contaminated water in the upper confined aquifer has led to rising groundwater tables, exacerbated by the lack of adequate drainage and sewage systems. The obvious solution is to construct proper drainage and sewage infrastructure to collect agricultural runoff, domestic wastewater, and industrial effluent and treat it before discharging it for further use or into the ocean.

3.6 Comparison with Global Case Studies

In Zliten, rising groundwater levels and contamination were due to uncontrolled MMRP supply and lack of centralised wastewater management, rapid urbanisation, conversion of agricultural land, and inadequate drainage infrastructure. The crisis has caused damage to homes and infrastructure, health risks, and agricultural impacts. Similar groundwater issues have impacted some other areas, as shown in Table 3.

Table 3. Similar Groundwater Crisis in Egypt and Saudi Arabia.

Area	Primary Issue	Contributing Factors	Similarities to Zliten	Differences from Zliten
Cairo, Egypt	Rising groundwater levels are leading to structural damage, archaeological site degradation, and health concerns	Over-irrigation, leakage from ageing water and wastewater pipes, industrial discharge, and Nile River seepage (El-Arabi et al., 2014; Sefelnasr et al., 2019).	Both cities face challenges related to rapid urbanisation and inadequate wastewater infrastructure, contributing to rising groundwater.	Cairo's issue is exacerbated by Nile River seepage, a natural factor less prominent in Zliten. The source of excess water in Zliten (MMRP) is more readily controllable than the multiple sources in Cairo.
Jeddah, Saudi Arabia	Depletion of coastal aquifers due to over-abstraction for domestic and industrial use, leading to seawater intrusion. Also, localised flooding due to inadequate drainage during rainfall events (Al-Amri et al., 2015; Sherif et al., 2012).	High population density, limited surface water resources, and rapid development.	Both cities are coastal and face challenges related to rapid development and water management.	Jeddah primarily faces groundwater depletion and seawater intrusion, while Zliten faces rising groundwater levels. Jeddah's challenges are primarily related to demand exceeding supply, while Zliten's are linked to oversupply and inadequate wastewater management.
Riyadh, Saudi Arabia:	Depletion of non-renewable fossil aquifers due to over-abstraction for agriculture and urban use (Al-Assaf et al., 2017; Edgell, 2012).	Arid climate, high population growth, and water-intensive agricultural practices.	Both cities are located in arid regions and face water management challenges related to human activities.	Riyadh faces groundwater depletion, while Zliten faces rising levels. Riyadh's challenges are primarily related to unsustainable abstraction of a finite resource, while Zliten's relate to oversupply and contamination of a renewable resource.

3.7 Adaptation Measures

3.7.1 Ongoing Measures

The local authorities in Zliten have started handling the crisis by implementing urgent solutions/ measures:

The General Company for Water and Sanitation operates a work team that removes approximately one million litres of contaminated water daily from farms and residential areas in Zliten. The team utilises trucks to transport and discharge the collected water into the Mediterranean Sea. This operation is carried out continuously from the early morning until midnight with limited resources for this colossal work (Libyan News Agency, 2024 January). However, the collected water discharges into the sea without treatment, which poses significant environmental and public health impacts, mainly:

- Deterioration of marine water quality due to the introduction of organic matter, nutrients, suspended solids, and contaminants like heavy metals and chemicals. This can lead to eutrophication, oxygen depletion, and toxic substances, harming sensitive marine ecosystems, disrupting food webs, and accumulating in commercially critical aquatic resources.
- Degradation of coastal water quality can impact local livelihoods and tourism activities.
- Public health concerns arise from the potential exposure to waterborne pathogens and contaminants through the consumption of contaminated seafood or direct contact with polluted waters, as well as the risk of groundwater and surface water contamination.
- The continuous discharge of wastewater can result in the long-term and cumulative deterioration of the marine environment, with irreversible impacts on the ecosystem.

Thus, it will be better to construct a comprehensive wastewater treatment system in the Zliten region, including installing appropriate treatment facilities, enforcing environmental regulations, and adopting sustainable water and waste management practices.

In February 2024, the Zliten Municipality started the construction of drainage channels to divert the extra groundwater from the affected areas to the sea, Figure 14, as an "urgent solution" to reduce the water level (Alwasat, 2023).

Figure 14. Excavation Work of the Drainage Channel (Alwasat, 2023)

The MoWR drilled 31 monitoring boreholes in the neighbourhood of Zliten and developed the “piezometric” network systems to monitor groundwater table level and groundwater quality (Eye of Libya, 2024).

In the second half of April 2024, the MMRP's General Management stopped pumping water to Zliten from the sound field area of the "Al-Hasawna—Jefara Plain" system to the city except on Tuesdays every week, based on a recommendation from the crisis committee (On January 23, 2024, the Prime Minister issued Resolution No. 39 of 2024 regarding the formation of a committee to monitor the situation in Zliten Municipality resulting from the rise in groundwater levels (Prime Minister of Libya, 2024)). There was also an exception for Eid Aludah Week (Libyan News Agency, 2024 June).

The issue of rising groundwater in Zliten, Libya, has prompted the establishment of a high-level technical committee to address this phenomenon, as outlined in the Prime Minister's decision No. 39 of 2024 and the Minister of Local Governance's decision No. 227 of 2024, dated February 8, 2024. This committee is tasked with monitoring and managing the impacts of groundwater overflow, which has become increasingly problematic in the region. The government's response highlights the urgency of the situation, as rising water levels threaten infrastructure and the safety of residents, necessitating coordinated efforts to mitigate the crisis effectively.

3.7.2 Proposed measures

Short-, medium-, and long-term measures can be used to lower the groundwater table and reduce groundwater contamination in Zliten.

Short-term measures: The following are some possible short-term measures:

- Utilise methods such as pumping, treatment, and drainage channels to protect affected areas.
- Mitigate the ongoing contamination of groundwater.
- Ensure coordination and collaboration among relevant governmental agencies, water authorities, and national and international experts from various fields to develop comprehensive and innovative solutions.
- Encourage civil society participation in the decision-making process and the implementation of groundwater management initiatives.
- Implement public awareness campaigns to educate the local community about the causes, impacts, and mitigation strategies related to rising groundwater levels.

Medium-term measures: Implementing medium-term measures requires coordination among local authorities, water management agencies, environmental regulators, and the community. In general, water management in Libya faces many challenges (Alatrash & Shebani, 2017), thus, continuous monitoring, evaluation, and adaptation to the strategies will be necessary to address the evolving challenges and ensure the long-term sustainability of groundwater resources in Zliten (Abdullatif & Mokhtar, 2013). The following are some possible medium-term measures that can be considered:

- Establish an integrated monitoring system of groundwater and artificial river water that will provide correct data from the levels of water, the quality, and the flow for early warnings.
- Environmental legislation on treating industrial wastewater before it reaches the environment by decentralised systems should be legislated.
- The detailed hydrogeological investigations have to be performed in order to study groundwater movement, the structure of the aquifer, the causes of rise of the levels of groundwater, and the dynamics.
- This means that farmers should be provided with both technical and financial assistance to adapt agricultural practices that reduce pesticide pollution, hence transitioning towards more sustainable and resilient agricultural systems by using effective irrigation techniques that conserve water and grow crops with a higher degree of tolerance to saline and water-stressed conditions.
- Improve the technical and institutional capacity at local water authorities and other relevant government agencies to manage groundwater resources.
- Provide training and support to government staff and local authorities for policy and regulation development in the field of water wastage and pollution reduction, and their implementation mechanisms.
- Stimulate scientific research targeting problems to enhance local knowledge and share as a basis of evidence-informed decision-making and policy formulation.

Long-term measures: Long-term measures should address the rise of polluted groundwater, improve groundwater quality, and ensure the sustainable use of this vital water resource. However, the successful implementation of long-term measures requires continuous monitoring, policy enforcement, and stakeholder engagement. The following are some possible medium-term measures that could be considered:

- Construct sewage systems and treatment facilities to protect groundwater and improve the quality of effluent discharged into the environment.
- Develop and implement an Integrated Water Resources Management plan, considering surface water, groundwater, and wastewater in a holistic manner.
- Incorporate management considerations of groundwater in urban planning and distribution systems, especially in areas of saturation and salinisation, to restrict or regulate land use activities that may further worsen the problem in groundwater.
- Design or adapt infrastructure, including buildings, roadways, and storm drainage systems, to be resistant and resilient to the effects of increasing groundwater levels.

3.8 Challenges of Implementing IWRM

3.8.1 Institutional and Governance Challenges

- Fragmented water management responsibility poses a significant challenge to effective water governance in Libya. The absence of a unified, central authority for water resources management has led to overlapping mandates, unclear responsibilities, and a lack of coordination among various government agencies and local actors (El-Naas & Abu-Rizaiza, 2010). This fragmentation hinders the implementation of integrated water management strategies, particularly in addressing complex issues like the groundwater crisis in Zliten. The institutional framework for water management in Libya has been further weakened by years of political instability and conflict, exacerbating existing challenges and hindering progress towards sustainable water resource management (World Bank, 2018). A clear delineation of roles and responsibilities, coupled with enhanced inter-agency cooperation and capacity building, is crucial for effective water governance and addressing Libya's pressing water challenges (GWP-Med, 2013).
- Weak capacity: Effective IWRM requires skilled personnel and robust institutions. Capacity limitations in technical expertise, data management, and financial resources can hinder implementation (UN-Water, 2006). Weak institutional capacity poses a significant obstacle to effective IWRM implementation in Libya. Limited technical expertise within government agencies, coupled with a lack of trained personnel in water management practices, hinders the development and enforcement of effective water policies (Legrouri, 2019). Furthermore, weak institutional coordination and fragmented responsibilities among different government bodies create inefficiencies and hinder integrated planning efforts. Capacity-building initiatives, including training programs, knowledge transfer, and institutional strengthening, are essential for empowering local authorities and enabling them to effectively manage water resources under the IWRM framework. Developing strong institutional capacity is crucial for overcoming these challenges and ensuring the long-term success of IWRM in Libya.
- Lack of political will: IWRM can require difficult policy choices and trade-offs between competing water users. Lack of political will and commitment can stall implementation, especially when it involves challenging established practices or powerful interests (GWP, 2000). The lack of sustained political will presents a significant obstacle to implementing Integrated Water Resources Management (IWRM) in Libya. While there may be rhetorical support for IWRM principles, translating this into concrete action and policy implementation has been challenging (Bhattacharya, 2010). This lack of political will often stems from competing priorities, limited resources, and the perceived complexity of IWRM implementation. Furthermore, the protracted political instability and conflict in Libya have diverted attention and resources away from long-term water management planning, further hindering progress towards IWRM (World Bank, 2018). Building political will requires demonstrating the tangible benefits of IWRM, fostering a shared vision among stakeholders, and creating a stable political environment conducive to long-term planning and investment (Biswas, 2004). Successfully implementing IWRM in Libya necessitates strong leadership, sustained commitment from decision-makers, and effective communication of the long-term benefits of integrated water management to the public and policymakers alike.

3.8.2 Financial Challenges

Implementing Integrated Water Resources Management (IWRM) in Libya faces significant financial hurdles. The country's water infrastructure requires substantial investment to address ageing systems, expand wastewater treatment capacity, and improve water quality monitoring (Sadr et al., 2019). Securing adequate funding for these investments remains a challenge, particularly given the fluctuating oil revenues and competing demands for public funds in other sectors (World Bank, 2021). Furthermore, establishing sustainable cost-recovery mechanisms for water services is crucial but politically sensitive, requiring careful consideration of affordability and social equity (OECD, 2012). Mobilising domestic resources, exploring innovative financing mechanisms, and attracting international development assistance are essential to overcome these financial constraints and enable successful IWRM implementation in Libya.

3.8.3 Social and Cultural Challenges

Implementing Integrated Water Resources Management (IWRM) in Libya encounters social and cultural complexities. Traditional water management practices, often deeply ingrained in local customs and tribal structures, can sometimes clash with the principles of IWRM (El-Naas & Abu-Rizaiza, 2010). Furthermore, raising public awareness about the importance of water conservation and responsible water use remains a challenge. Effective community engagement and participation are crucial for successful IWRM, requiring culturally sensitive communication strategies and inclusive stakeholder involvement (UNEP-DHI, 2015). Addressing these social and cultural factors is essential for building public support, fostering a sense of shared responsibility for water resources, and ensuring the long-term sustainability of IWRM initiatives in Libya. Therefore, Further research exploring the specific socio-cultural dynamics surrounding water management in different regions of Libya would be beneficial.

3.8.4 Technical Challenges

Implementing Integrated Water Resources Management (IWRM) in Libya faces various technical challenges. The country's water infrastructure suffers from ageing systems, inadequate maintenance, and limited monitoring capacity, hindering effective water management (World Bank, 2018). Data scarcity and a lack of reliable hydrological information pose significant challenges for planning and decision-making. Furthermore, the technical expertise required for implementing advanced water management technologies and practices may be limited, necessitating capacity building and training programs (GEF, 2017). Addressing these technical challenges requires investing in infrastructure upgrades, strengthening data collection and analysis capabilities, and developing local technical expertise to ensure the successful implementation of IWRM in Libya.

4. CONCLUSIONS

Groundwater resources are the most reliable for freshwater use in many arid and semi-arid areas. However, responsible authorities should be aware of groundwater levels, quality and recharge zones to protect this valuable resource. This paper provides compelling evidence that the worsening groundwater crisis in Zliten is primarily due to anthropogenic causes, i.e., the uncontrolled water supply of the Man-Made River Project (MMRP) and the inefficient wastewater management system. Though natural climatic and geological fluctuations cause the overall water balance, their contribution to increased groundwater levels and contamination noted is negligible compared to that of anthropogenic activities. The effectiveness of the current means of mitigating, e.g., water extraction and drainage conduits, appears to be small, suggesting more holistic and sustainable approaches are required.

The findings highlight the imperative for an immediate paradigm shift towards Integrated Water Resources Management (IWRM) in Zliten. Implementing IWRM, however, will require overcoming some of the challenges, including institutional fragmentation, capacity limitations, access to finance, public participation, and addressing the evolving impacts of climate change. Its implementation depends on strong political will, inter-agency collaboration, and public participation. Specifically, we recommend the following measures:

1. Controlled MMRP Supply: Create a robust monitoring and control system of MMRP water supply to Zliten that guarantees supply to meet demand and prevent oversupply.
Wastewater Treatment Infrastructure: Invest in a central wastewater treatment facility and network to prevent aquifer contamination in the future.
2. Increased Monitoring Network: Implement an extensive groundwater monitoring network to track water levels, quality, and potential sources of contamination that facilitates data-driven adaptive management.
3. Community Participation and Awareness: Implement public awareness programs to educate the inhabitants about the water conservation steps and the correct disposal of wastewater.
4. IWRM Framework Development: Formulate an integrated IWRM system for Zliten based on the inputs provided by the stakeholders and addressing the challenges recognised within this study. The system shall identify the tasks, the schedule of implementation, and performance targets.

By adopting these recommendations, Zliten will find it possible to shift towards a more sustainable and resilient water management system, lessening the ongoing crisis and safeguarding this precious resource for generations to come. This research serves as an important foundation upon which to make decisions and is a guide to action. Additional research should address a more precise quantification of MMRP's impact, using hydrological simulation and hydrological models, investigation of new wastewater treatment technologies applicable to the local conditions, and formulation of complete feasibility studies and cost-benefit analyses for the suggested measures.

AUTHOR CONTRIBUTIONS

Khaldoon A. Mourad: Writing the initial draft, conducting a desk review, performing formal analysis, proposing measures, and finalising the manuscript,
Abd Rahman Issa Al-Ghafoud: Data collection, GIS mapping and field visits.
Mohammed Ali Husyin: Engaging in consultations with national stakeholders and conducting data collection.

DECLARATIONS

The authors report there are no competing interests to declare.

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