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Evaluating Ecosystem Health in the Zarqa River Through Biological Indicators, Jordan

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ABSTRACT

The Zarqa River has long served as a critical source of surface water in Jordan, originating from a spring in Amman and sustained by numerous large springs and seasonal floods as it flows toward the lower Jordan River. However, rapid urban expansion, industrial activities, and the continuous discharge of treated and untreated wastewater have severely degraded its ecological integrity. This study utilizes biological indicators, specifically macroinvertebrates and aquatic plant assemblages, to assess the river's condition and provide a clearer, evidence-based picture of long-term water quality. Pollution-tolerant species such as Tubificinae, *Physa acuta*, and *Chironomus* (red larvae) were found in high numbers in heavily polluted sections of the river, while moderately polluted zones still support species like *Baetis monnerati*, blackflies (Simuliidae), and Hirudinea (leeches). In contrast, pollution-sensitive organisms such as Melanopsis gastropods and Trichoptera caddisflies were only observed in relatively clean areas, but notably, Theodoxus gastropods were entirely absent. Similarly, plant communities reflected pollution levels: Herbaceous plants like Eruca, Rumex, and Amaranthus thrive in degraded areas. Species such as *Phragmites*, *Tamarix*, *Eucalyptus*, *Nicotiana*, *Nerium*, and *Cardaria* tolerate a wide range of water qualities, from clean to polluted. However, their presence alone doesn't reliably indicate water quality without supporting macroinvertebrate data. *Spergularia* cf. *diandra*, associated with *Asteriscus* and *Pteranthus* plant assemblage, indicates saline and alkaline conditions. Plants indicate salinity levels, but macroinvertebrates provide a better measure of water quality, distinguishing clean from polluted conditions more reliably. This assessment shows that aquatic plants and animals are effective, low-cost indicators for monitoring river health and are especially important in water-scarce Jordan. Alongside scientific monitoring, stronger enforcement of environmental laws is urgently needed to prevent pollution, protect public health, and ensure the Zarqa River's long-term sustainability.

1. INTRODUCTION

The Zarqa River is an important source of fresh surface water in Jordan, which rises from a spring in Amman City Center and flows into the Lower Jordan River. The river has two main branches, Wadi Al-Dhuleil from the northeast and the Zarqa River from the west, which meet at Sukhna and continue westwards into the Jordan Valley. Over the past decades, the river has been increasingly influenced by human activities, including urbanization, industrialization, wastewater discharge, and irrigation return flows. The construction of King Talal Dam (KTD) in 1977 and the discharge of treated wastewater from As-Samra Wastewater Treatment Plant have further altered the river's flow regime and water quality. Today, the Zarqa River faces severe challenges due to reduced natural base flow, population growth in the Amman–Zarqa basin (hosting ~35% of Jordan's population), and increasing pressure on already scarce water resources. Protecting the Zarqa River is thus not only an ecological necessity but also a humanitarian priority for water security in Jordan.

The ecological changes in the Zarqa River are reflected in the assemblage of aquatic macroinvertebrates and plants, whose presence or absence offers valuable insights into environmental health. Aquatic organisms respond sensitively to pollution, making them excellent bioindicators [1, 2]. Unlike chemical and physical tests, monitoring these organisms provides an efficient way to detect ecological change. Globally, macroinvertebrates are widely recognized as reliable indicators of freshwater ecosystem integrity [3, 4]. In Jordan, pioneering studies [5, 6] linked biological communities to water quality, while later research extended bioindicator approaches to rivers and springs [7-10]. However, previous work has often focused on either aquatic plants or invertebrates separately, and on limited numbers of sites, with little integration into the legal and management framework of Jordan's water sector.

The present study addresses this gap by: (1) surveying a larger number of sites along the Zarqa River, (2) combining both aquatic macroinvertebrates and riparian plants as complementary bioindicators, and (3) linking ecological findings with the national legal framework and water quality standards. This integrated approach provides new insights into how biological assemblages reflect pollution gradients and recovery potential along the river, while also demonstrating the practical implications of using bioindicators in Jordan's environmental monitoring and law enforcement.

2. METHODOLOGY

2.1 Study area

This study is conducted along 50 kilometers stretch of the Zarqa River, beginning at the KS and extending downstream to the Abu Zighan Weir at a few km east of Deir Alla (Figure 1). The study area features diverse topographic, geologic, environmental, and hydrologic conditions. The elevation drops significantly along this route from approximately 550 meters above sea level (masl) at KS to about 200 meters below sea level (mbsl) near Zighan Weir. Historically, the base flow of the ZR consisted of natural springs. However, during the last three decades, the ZR in the downstream area of the KS WWTP has mainly consisted of the treated wastewater of the largest treatment facility in Jordan.

Sites capture key influences, including treated wastewater (Site 1), geothermal input (Site 2), mixing of river and effluent (Site 3), dam-regulated flow (Site 4), natural hypersaline spring (Site 5), and cumulative upstream impacts near Abu Zighan Weir (Site 6).

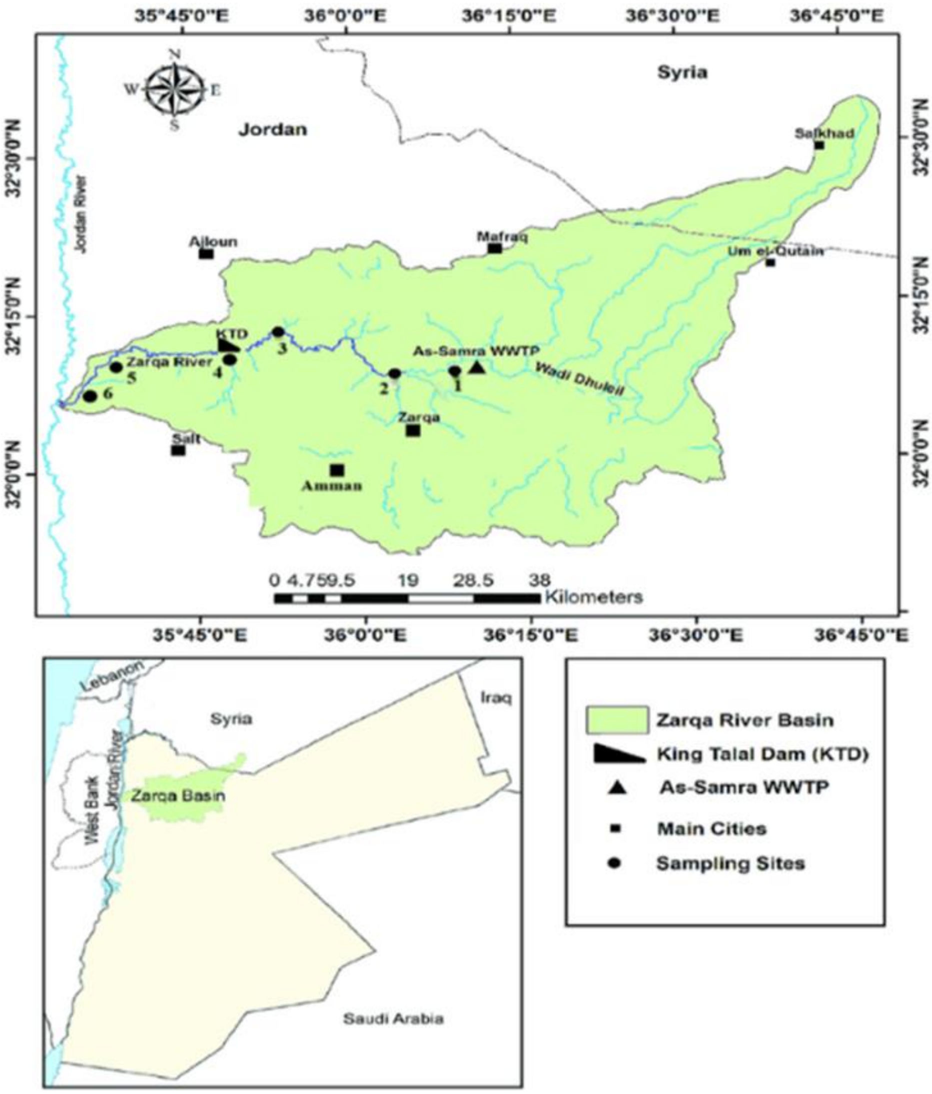


Figure 1. Study area map of the Zarqa River showing six sampling sites along a 50 km stretch

To investigate the aquatic organisms and environmental variability along the Zarqa River, six sampling sites were selected along a 50-kilometer stretch of its course. Site 1, located immediately downstream of the KS WWTP, reflects the direct impact of treated effluent on water quality (32.150060° N, 36.148890° E). Site 2, situated at the Thermal Romani Hamam spring around 500 m upstream of Jarash Bridge, offers insight into the influence of geothermal inputs (32.167141, 36.012335). Site 3, near the Jarash Bridge, represents a key mixing zone where the river's natural flow merges with discharged wastewater, often resulting in noticeable changes in water chemistry (32.224816, 35.893035). Site 4, located at the outlet of KTD, provides data on the influence of stored and regulated water releases from the dam on downstream conditions (32.189911, 35.801131). Site 5, near the gypsum quarry, is affected by a natural hypersaline spring, adding a layer of geochemical complexity to the river system (32.194851, 35.647940). Finally, Site 6, located near the Abu Zighan Weir, illustrates the cumulative impact of all upstream inputs, including treated wastewater, natural salinity, and agricultural runoff, making it a crucial point for assessing the overall ecological condition of the river (32.098163, 35.583914).

2.2 Methodology

To assess the environmental changes along the Zarqa River using biological communities, six sampling sites were selected along a 50-kilometer stretch of the river. These sites were chosen based on observed changes in aquatic biological assemblages, including both faunal and floral communities. The study also considers ecological transitions influenced by natural factors, such as geothermal and saline springs, as well as human impacts, including treated wastewater discharges, urban runoff, and agricultural activities. Sampling was conducted twice, during the spring seasons (March–April) of 2021 and 2022. At each site, water and biological samples were collected during the spring seasons of 2021 and 2022. Macroinvertebrates larger than 0.5 mm were collected using hand nets with a 500 µm mesh size from fast- and slow-flowing areas, as well as from still water habitats. Organisms attached to rocks or aquatic vegetation were carefully dislodged by hand or with brushes.

Aquatic plants were also sampled and recorded both in the field and in the laboratory, to assess the riparian and aquatic vegetation as indicators of environmental quality. In the study area, a diverse species of aquatic fauna was observed, representing various taxonomic groups. Insect larvae were notably present, including Ephemeroptera (mayflies), Diptera, specifically Simuliidae (blackfly larvae), Hirudinea (leeches), Trichoptera (caddisflies), and Chironomidae (red *Chironomus*). Gastropods were also abundant, with species such as *Physella acuta* (Family: Physidae) and Melanopsis (Melanopsidae). Additionally, tube-dwelling worms (Tubificida, Annelida) were prevalent, contributing to the benthic community. All observed biological species were classified to the lowest possible taxonomic level, providing a comprehensive understanding of the aquatic biodiversity in the study area. Physical and chemical parameters were measured in situ using portable equipment, including temperature, pH, electrical conductivity (EC), salinity, total dissolved solids (TDS), and dissolved oxygen (DO). Additional water samples were collected and analysed in the laboratory for biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrates (NO_3^-), ammonium (NH_4^+), phosphates (PO_4^{3-}), chlorides (Cl^-), alkalinity, hardness, and selected heavy metals such as zinc (Zn), copper (Cu), lead (Pb), and strontium (Sr). In the laboratory, macroinvertebrates were preserved in ethanol and identified under a Leica S6 D stereomicroscope (6.3x–40x magnification), using regional identification keys and global taxonomic databases. The collected biological data were then compared with the physicochemical parameters to examine how environmental gradients influence the structure, diversity, and abundance of aquatic life.

3. FIELD OBSERVATIONS AND LABORATORY RESULTS

To evaluate the ecological and chemical health of the Zarqa River, six representative sampling sites were selected along its course. These sites reflect a range of environmental conditions, from natural springs to zones affected by treated wastewater, saline inflows, and agricultural runoff. At each site, detailed physicochemical parameters (Tables 1 and 2) and biological observations were recorded to better understand the cumulative impact of natural and anthropogenic influences on the river's water quality, biodiversity, and habitat integrity.

Table 1. Common water quality parameters of the studied sites along the Zarqa River

Site	EC (µS/cm)	Temp (℃)	Ph	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NO_3
1	2100	20.2	7.86	5.18	4.69	9.06	0.84	5.30	11.98	2.55	1.41
2	3100	30.5	6.30	9.18	4.77	10.17	1.28	4.80	13.57	4.80	0.00
3	2000	21.3	7.86	5.03	4.60	9.10	0.80	5.22	11.00	2.40	1.31
4	2000	22.2	7.30	4.80	3.85	9.40	0.80	4.86	11.86	.53	1.04
5	14370	35.2	6.19	15.3	10.25	142	2.88	34.8	112.3	21.50	0.02
6	1880	22.0	8.40	4.85	2.83	9.48	0.70	4.34	10.0	3.39	0.66

Note: Ionic concentrations are in meq/L.

Table 2. Nutrients, organics, and trace elements

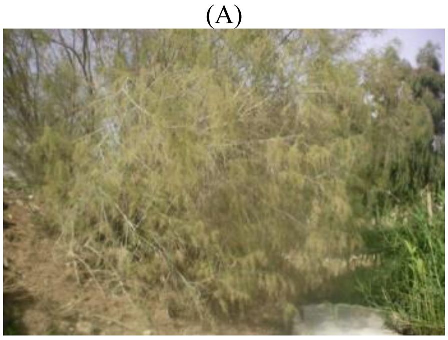
Site	PO_4	COD	BOD	Fe	Pb	Zn	Mo	Cu	Mn	Sr	Ba	Br	F
1	0.354	65.90	25.06	14	<10	<10	<10	<10	<10	301	<10	600	440
2	0.2	5.00	0.0	1.778	45	64		64	135	na	na	na	na
3	0.140	45.90	15.06	0.010	<0.01	<0.01	<10	<10	152	2.850	<10	629	451
4	0.300	15.04	5.00	0.014	<0.01	<10	<10	<10	50	4.49	<10	1.038	0.35
5	0.049	4.79	1.0	120	<10	nm	Na	192	100	34.1	40	643	3200
6	0.260	50.83	21.63	210	<10	<10	<10	<10	Na	na	na	na	na

Note: PO_4, COD, and BOD are reported in ppm; all other elements are in ppb. na = not analyzed.

Site 1: Downstream of Khirbet As-Samra Wastewater Treatment Plant (KS-WWTP)

This site is located just downstream of the KS WWTP and is heavily affected by the continuous discharge of treated effluent. The advanced treatment processes employed are not designed to remove all nutrients and organic matter. The electrical conductivity (EC) is high at 2100 µS/cm, indicating a large concentration of dissolved ions, while the chemical oxygen demand (COD) and biological oxygen demand (BOD) are significantly elevated at 66 ppm and 25 ppm, respectively, reflecting substantial organic content. Nutrient enrichment is also evident with phosphate at 0.354 ppm and nitrate at 1.412 meq/L. The habitat is visibly degraded, characterized by foamy, brownish water with a strong organic odor, silty substrates, floating debris, and poor oxygenation (Figure 2(A)). Vegetation along the riverbanks includes *Tamarix* and *Phragmites australis*, along with herbaceous species such as Eruca, Rumex, Amaranthus, and *Cardaria*, while wetter zones support plants like Papaver, Ranunculus, Calendula, and Matricaria (Figures 2(B) and 3). The fauna is dominated by pollution-tolerant macroinvertebrates, including Tubificinae worms, *Physa acuta* snails, and Chironomidae midge larvae, with abundant cyanobacteria and filamentous algae, thriving in the nutrient-rich conditions (Figure 4). Overall, despite the wastewater treatment efforts, this site experiences strong ecological stress, as indicated by the high organic loads and the prevalence of species tolerating it.

(A)



(B)

Figure 2. (A) Brownish water with surface foam at the outlet of the Khirbet As-Samra Wastewater Treatment Plant; (B) Zarqa River spring with *Tamarix* and *Phragmites australis* growing nearby

These species are present along the river down to the Jordan Valley.

Figure 3. Rim of *Cardaria* along the river and *Matricaria* rooted almost in the water

(A) (B)

Figure 4. (A) Red *Chironomus* larvae (Chironomidae) are found in large numbers in the sediments of the Zarqa River, where high nitrate levels are found (Site 1), (B) *Physa* acuta with their eggs are heavily present in the same site

Site 2: Roman Hamam Thermal Spring

Site 2, located at the Roman Hamam Spring, is primarily influenced by a natural geothermal spring with minimal direct human impact. The spring discharges warm, mineral-rich water directly into the Zarqa River, altering its chemical profile. Electrical conductivity is notably high at 3100 µS/cm, and the water temperature reaches 30°C. The pH is slightly acidic at 6.3. The trace element concentrations are Fe: 1.778, Zn: 20.0, Cu: 6.4, Pb: 45, and Mn: 135 µg/L, reflecting their dissolution in a slightly acidic environment. In addition, the spring water smells of H_2S. The habitat is rocky and shaped by geothermal activity, with clear water and little turbidity. Aquatic life is largely absent, possibly as a result of H_2S and iron and manganese precipitation along the spring's short flow to the Zarqa River, although reed vegetation such as *Phragmites australis* and *Juncus* species grow along the banks (Figure 5). These stable but mineral-rich and warm conditions create a niche environment that supports only a few highly adapted plant species, limiting overall biological diversity.

Figure 5. Different types of reeds represented by *Phragmites australis* and *Juncus* species growing in the Zarqa River

Site 3: Jarash Bridge

(A) (B)

Figure 6. (A) The floral assemblage at this site includes *Phragmites australis*, *Tamarix* spp., growing along the riverbank, (B) Example of faunal species, *Baetis monnerati* (mayfly), present at the same site

Site 3, located near the Jarash Bridge, represents a transitional zone where treated wastewater from upstream begins to mix with the river's natural flow. This creates turbulent conditions and dynamic shifts in water chemistry. The electrical conductivity is moderate at 2000 µS/cm, but the water still shows signs of organic pollution, with COD at 45.9 ppm and BOD at 15.06 ppm. Nutrient levels remain elevated, with nitrate at 1.31 meq/L and phosphate at 0.140 ppm. The habitat is characterized by unstable substrates made up of mixed gravel and silt, with frequent flow variations that contribute to habitat instability. Vegetation along the banks includes *Phragmites*, *Tamarix*, and *Nerium oleander*, while wetter seep zones support species like *Salix* and *Nicotiana* (Figure 6). A slight increase in biological diversity is observed here, with the presence of both pollution-tolerant species and more sensitive organisms such as *Simuliidae* (blackfly larvae), *Baetis monnerati* (mayfly), *Hirudinea* (leeches), as well as frogs, fish, and crabs (Figure 7). Overall, this site signals the beginning of partial ecological recovery, although the fluctuating conditions from water mixing still pose environmental challenges.

(A) (B)

Figure 7. (A) Frog larvae are present at this site, (B) Filamentous algal mats in the Zarqa River at the site

Site 4: Downstream of King Talal Dam

Site 4, located just downstream of King Talal Dam, is strongly influenced by the dam's regulated outflow, which helps stabilize water flow and improves some aspects of water quality. Electrical conductivity remains moderate at 2000 µS/cm, and the pH is slightly lower at 7.30. Organic pollution has decreased compared to upstream locations, with BOD at 5.0 ppm and COD at 15.04 ppm, while nitrate levels are moderate at 1.04 meq/L. The habitat is characterized by a steady, uniform flow, with few natural features such as riffles or pools, limiting overall habitat complexity and diversity. Algal mats are visibly present on the water surface near the dam, indicating localized eutrophication driven by residual nutrient enrichment. The riverbanks are lined with dense riparian vegetation, including *Phragmites australis*, *Nerium oleander, Salix* (willows), and large *Eucalyptus* trees (Figure 8). Signs of biological recovery are evident with the presence of *Simuliidae* (blackfly larvae), *Melanopsis* gastropods, and occasional mayflies. However, the overall ecological improvement remains constrained by the simplified habitat structure and the ongoing effects of nutrient enrichment, as seen in the algal growth.

Figure 8. Site 4: Downstream of King Talal Dam
The riverbanks support dense riparian vegetation dominated by *Phragmites australis*, *Salix* (willows), and mature *Eucalyptus* trees.

Site 5: Saline Well Near Gypsum Quarry, East of Abu Zighan

Site 5 is located near a gypsum quarry and a hypersaline well, creating one of the extreme environments along the Zarqa River. The water emerging from this well is exceptionally saline, with electrical conductivity reaching 14,370 µS/cm. It is also slightly acidic, with a pH of 6.19, and has an elevated temperature of 35.2℃. The chemical analysis reveals extremely high concentrations of sodium (3,260 mg/L), chloride (3,930 mg/L), sulfate (1,050 mg/L), and bicarbonate (2,155 mg/L), all indicative of the strong geochemical influence from the Jurassic gypsum beds. Organic pollution is minimal, as shown by very low BOD (1.00 ppm) and COD (4.79 ppm) values, while nitrate is nearly absent (0.020 meq/L).

The habitat is dominated by white salt crusts and a stark, mineral-rich substrate, with little to no vegetation in the immediate water zone. However, some highly salt-tolerant plant species, such as *Spergularia* cf. *diandra*, *Asteriscus*, and *Pteranthus*, are found thriving in the dry, saline soil nearby (Figures 9 and 10). No macrofauna were observed at this site, likely due to the extreme salinity and harsh chemical conditions. Overall, this site represents a naturally stressed environment, where biodiversity is extremely limited, and only highly specialized halophytic species can survive.

(A) (B)

Figure 9. (A) Plants were observed growing in saline well seepage areas at Site 5, (B) *Asteriscus* plants were found growing in alkaline and saline soils

(A) (B)

Figure 10. (A) Site 5 dominated by *Spergularia* cf. *diandra*, (B) Close-up view of *Spergularia* cf. *diandra* at the same site

Site 6: Near Abu Zighan Diversion Weir

Site 6, located near Abu Zighan Weir, at a few kilometers east of the entrance of Zarqa River into the Jordan Valley, represents the downstream end of the study area, where the cumulative influence of all upstream inputs, including treated wastewater, saline spring discharges, and agricultural runoff, is present. Water quality indicators reflect these mixed influences, with an electrical conductivity of 1880 µS/cm and a slightly alkaline pH of 8.40. Nutrient levels are moderate, with nitrate at 45 mg/L and phosphate at 0.260 mg/L, while organic content remains noticeable. COD is 50.8 mg/L, and BOD is 21.6 mg/L, indicating continued but reduced organic loading.

The habitat here is characterized by a broader, slower-flowing river with a diverse range of sediment types and a more developed riparian structure. Vegetation is diverse and includes *Tamarix*, *Salix* (willows), *Typha*, *Eucalyptus*, and *Cardaria draba* (Figure 11). This mix reflects a recovering riparian zone with improving stability and ecological complexity. This site also exhibits the highest macroinvertebrate diversity observed in the study area, including *Melanopsis* gastropods, caddisflies, *Baetis monnerati* (mayflies), *Simuliidae* (blackfly larvae), and Hirudinea (leeches), as well as frogs and small fish.

Despite being subjected to a mix of anthropogenic and natural stressors, Site 6 shows strong signs of ecological resilience. The increase in both habitat complexity and biodiversity indicates that the river system, while impacted, is capable of partial recovery and biological regeneration.

Figure 11. The floral community is diverse, featuring *Tamarix*, *Salix* (willows), *Typha*, *Eucalyptus*, and *Cardaria draba* along the riverbank in Abu Zighan

4. DISCUSSION

4.1 Summary of the core ecological gradient patterns

The Zarqa River, one of Jordan's most vital surface water sources, flows through landscapes shaped by a complex interplay of natural processes and escalating human pressures. This study assessed six key sites along a 50-kilometer stretch and revealed a clear ecological gradient, where water quality and biological communities are influenced both by natural inputs, such as thermal and saline springs, and by anthropogenic impacts, including domestic and industrial wastewater discharges, and agricultural runoff. The river faces significant environmental challenges, particularly from pollution sources such as untreated or partially treated domestic wastewater, effluents from textiles, battery production, and oil industries, and agricultural return flows.

Along the river course, chemical and biological changes are evident. Treated effluent often mixes with natural waters, while untreated sewage enters at multiple points, leading to heterogeneous water quality. Natural processes, such as aeration and self-purification, particularly in King Talal Reservoir, help mitigate pollution to some extent, but nutrient accumulation can trigger eutrophication. Historically, the Zarqa River issued from Ras El Ain springs in Amman; however, groundwater extraction has reduced base flows, leaving only floodwater and local runoff to feed the stretch from Ras El Ain to Sukhna, which is now primarily used for irrigation. For the past two decades, the river effectively begins near Khirbet As-Samra, flowing westward through King Talal Dam, then reaching Abu Zighan Weir before entering the Jordan Valley. It receives floodwater from major tributaries, including Wadi Al-Dhuleil and the western branch from Amman, both converging near Sukhna. Since 1985, treated wastewater from As-Samra has been discharged into Wadi Dhuleil, joining the Zarqa River a few kilometers downstream. The river's catchment area supports about 35% of Jordan's population, which intensifies environmental stress on this critical water resource.

4.2 Effectiveness of biological indicators

Biological indicators, particularly macroinvertebrates, proved highly effective for long-term water quality assessment [7, 11]. Along the Zarqa River, clear gradients in ecological conditions were observed across the six studied sites:

- Site 1 exhibited high pollution, dominated by tolerant taxa such as Tubificinae worms, *Physa acuta* snails, and red *Chironomus* larvae, reflecting significant organic contamination and nutrient enrichment [7, 12]. Riparian vegetation was limited, with *Tamarix* and *Phragmites australis*, while invasive herbaceous species like *Eruca*, *Rumex*, and *Amaranthus* thrived in the degraded environment [8].
- Site 2 showed slight improvement, with mixed communities of tolerant and moderately sensitive taxa, including blackfly larvae (Simuliidae) and leeches (Hirudinea). Riparian vegetation remained dominated by *Tamarix* and *Phragmites*, indicating some resilience despite ongoing pollution [7, 8].
- Site 3 represented a transitional zone with moderate pollution, where mayflies (*Baetis monnerati*), caddisflies (Trichoptera), and leeches became more frequent. Plant species such as *Phragmites australis*, *Nicotiana glauca*, and *Nerium oleander* increased in density, suggesting partial ecological recovery [7, 13].
- Site 4 showed further improvement, with sensitive macroinvertebrates including caddisflies, mayflies, and moderate-tolerant worms indicating higher water quality. Riparian vegetation, including *Tamarix*, *Phragmites australis*, *Cardaria draba*, and willows, became denser, supporting a more diverse ecosystem [7, 8].
- Site 5 was highly saline, dominated by salt-tolerant plants such as *Spergularia* cf. *diandra*, *Asteriscus*, and *Pteranthus*, with very limited macroinvertebrate diversity due to extreme environmental conditions. These plants are well adapted to alkaline and high-salinity soils, marking a sharp ecological contrast along the river [8].
- Site 6, downstream near Wadi Abu Zighan, represented the recovery zone, where sensitive species such as *Melanopsis* snails, caddisfly larvae, and mayflies were abundant, reflecting cleaner and less disturbed habitats. Riparian vegetation remained dense with *Tamarix*, *Phragmites*, and *Cardaria draba*. Although some pollution-sensitive taxa like Theodoxus gastropods were still absent, water quality improved due to natural filtration, dilution from groundwater, and reduced anthropogenic pressures [7, 11, 12]. Biological indicators, especially macroinvertebrates, remain highly effective for long-term monitoring of water quality, capturing cumulative pollution impacts that are not apparent in snapshot chemical analyses [3, 7]. Plants such as *Tamarix* and *Phragmites australis*, abundant along the river, show adaptability to diverse habitats, from freshwater to brackish marshes and mineral-rich springs, including Zarqa Ma'in and Maqarin [7, 8]. While earlier studies suggested these species indicate high-quality water [6], they persist across a wide spectrum of

conditions, even downstream of wastewater discharges.

4.3 Key environmental drivers

The distribution and abundance of biological communities along the Zarqa River are strongly shaped by several key environmental drivers, including organic pollution, high salinity, and elevated water temperatures. At certain sites near the gypsum quarry, chemical analysis reveals very high levels of sodium, chloride, sulfate, and bicarbonate, reflecting strong geochemical influence from Jurassic gypsum beds. These interacting factors influence species composition, ecosystem stability, and ecological recovery potential.

In sections near the As-Samra treatment plant, *Physa acuta*, Tubificinae worms, and red *Chironomus* larvae confirm organic and nitrate enrichment, consistent with nutrient-rich, eutrophic environments and high BOD and COD concentration [7, 11]. Cyanobacteria and filamentous algae mats in slower-flowing stretches further highlight eutrophication from untreated wastewater and agricultural runoff. Downstream toward Jarsh Bridge, partial recovery is evident, with mayflies, blackflies, leeches, frogs, and crabs appearing in areas receiving diluted treated wastewater, although agricultural runoff and domestic sewage still affect these habitats.

Hydrogeological influences contribute to localized ecological variability. Thermal springs sourced from deep Kurnub Formation aquifers and artesian saline springs in the lower Zarqa Valley support specialized, salt-tolerant plant communities, including *Spergularia*, *Pteranthus*, and *Asteriscus*, which thrive under high salinity, elevated trace elements, and anaerobic soils [8]. In contrast, downstream areas near Wadi Abu Zighan exhibit improved water quality and biodiversity, reflecting the combined effects of natural filtration, groundwater inputs, and dilution.

Overall, the Zarqa River demonstrates a clear ecological gradient from heavily polluted upstream reaches to partially recovered downstream zones. Macroinvertebrates provide the most reliable bioindicators along this gradient, while plant assemblages indicate broader environmental conditions. Effective river management requires integrated pollution control, protection of freshwater springs, and long-term biological monitoring to conserve biodiversity and ensure sustainable use of this vital water resource [7, 8, 11, 14, 15].

Numerous studies worldwide have demonstrated that the structure and composition of riverine biological communities are strongly controlled by interacting environmental factors, particularly organic pollution, nutrient enrichment, salinity, temperature, and hydrological alteration. Elevated organic loads and nutrient inputs have been shown to favor pollution-tolerant macroinvertebrates and algal blooms, while reducing sensitive taxa and overall biodiversity. Similarly, increased salinity and thermal inputs, whether of natural or anthropogenic origin, significantly alter species distributions by selecting for stress-tolerant organisms and specialized plant assemblages. Hydrological modification and wastewater discharge further influence ecological processes by changing flow regimes, oxygen availability, and habitat connectivity. These patterns have been consistently reported in river systems across Europe, North and South America, Africa, and arid and semi-arid regions, highlighting the universal applicability of biological indicators for assessing cumulative environmental stress and ecosystem health under diverse climatic and geochemical settings [16-20].

4.4 Management and legal implications

Pollution of the Zarqa River represents a clear violation of several Jordanian laws related to environmental protection, water quality, public health, and agriculture. Article 19 of the Environmental Protection Law No. 6 of 2017 prohibits the discharge of any waste that may pollute surface water without proper treatment and prior approval from the Ministry of Environment. Likewise, Article 24 of the Water Law No. 18 of 2020 forbids the discharge of pollutants into rivers and valleys without adequate treatment. Additionally, Article 52 of the Public Health Law No. 47 of 2008 classifies any water pollution that threatens human health as a public-health offense, while Article 115 of the Agriculture Law No. 20 of 2002 prohibits the use of polluted water for irrigation. National assessments, such as the 2025 Jordanian Sustainability Lab report, confirm that nearly 70% of the river's water is heavily polluted due to untreated industrial and domestic wastewater discharges, posing major risks to ecosystems, groundwater, and public health.

The Waste Management Law No. 16 of 2020 further strengthens environmental protection by prohibiting improper handling of hazardous waste under Article 8, while Article 10 holds industrial waste producers fully responsible for ensuring safe disposal through licensed treatment facilities. Penalties for severe environmental violations may reach up to 50,000 JOD and imprisonment. Under tort liability principles, any party whose unlawful actions contribute to environmental damage is required to compensate for the resulting harm.

Environmental oversight under the Environmental Protection Law (2017) and the Waste Management Law (2020) is carried out through routine and surprise inspections and water sampling conducted by the Ministry of Environment and municipalities. The law prohibits direct discharge of untreated wastewater into waterways and grants authorities the power to impose fines, require treatment, or close violating facilities. Due to the multiple and overlapping sources of pollution, Jordanian law applies the "probability and approximation" principle when determining liability, assigning responsibility to each contributing party based on its share of harm, supported by scientific reports and field data that link polluting activities to environmental damage. This approach strengthens accountability and enhances mechanisms for protecting the Zarqa River.

5. CONCLUSIONS

This study demonstrates the value of biological indicators, particularly macroinvertebrates and aquatic plants, in monitoring the ecological health of the Zarqa River in Jordan. In water-scarce regions where chemical testing is costly and provides only snapshots, biological monitoring offers an integrated, continuous, and cost-effective approach to assess water quality and habitat health over time.

Distinct patterns emerge along the river: pollution-tolerant taxa, such as Tubificinae worms, *Physa acuta* snails, and red *Chironomus* larvae, dominate heavily polluted sections near wastewater discharges, indicating significant organic pollution. Moderately tolerant species, including mayflies (*Baetis monnerati*) and blackfly larvae, occur in transitional zones where water quality begins to improve. Sensitive organisms, such as *Melanopsis* snails and caddisfly larvae, are restricted to cleaner sections, reflecting healthier conditions. Plant communities also respond to stressors: invasive herbs like Eruca, Rumex, and Amaranthus thrive in degraded zones, whereas *Phragmites australis*, *Tamarix*, *Eucalyptus*, *Nicotiana*, *Nerium oleander*, and *Cardaria draba* tolerate a range of water qualities. Specialized plants such as *Spergularia* cf. *diandra*, *Asteriscus*, and *Pteranthus* indicate saline or alkaline conditions.

Biological indicators integrate the cumulative effects of pollution, habitat changes, and flow variations, providing a dynamic picture of ecosystem health beyond what chemical tests can capture. Identifying key macroinvertebrates to the species level enhances sensitivity in detecting ecological changes.

These findings provide a baseline for ongoing monitoring and management. Regular biological assessments can inform policymakers, guide restoration efforts, and detect emerging threats early. Integrating bioindicators into Jordan’s water monitoring programs and enforcing environmental laws are essential for protecting the Zarqa River, safeguarding biodiversity, and ensuring sustainable water use in one of the world’s most water-stressed regions.

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