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# Characterization and pollution assessment of surface water in the Ziz Basin, southeastern Morocco

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## Abstract

Surface-water resources in arid and semi-arid regions are increasingly vulnerable to climatic variability and anthropogenic pressures, including urban expansion, wastewater discharge, agricultural activities, and inadequate waste management. In southeastern Morocco, the Ziz Basin is an important water-resource system, particularly because it is connected with the Hassan Addakhil Dam. Understanding the spatial distribution of water quality and identifying the main pollution sources are essential for protecting these resources and supporting sustainable water management. This study aims to assess the physicochemical and environmental conditions of the surface waters in the Ziz Basin by analyzing monthly water samples collected during two separate 12-month monitoring periods, in 2016 and 2022, at 7 sampling stations. The results showed that the surface waters in the Ziz Basin were contaminated. The pollution is of domestic origin and threatens the basin's water quality. The study methodology utilized principal component analysis of physicochemical parameters to categorize the sampling stations into two types. Upstream of the Hassan Addakhil Dam, stations were characterized by high dissolved oxygen levels and lower values for other parameters, whereas downstream stations showed higher COD, BOD5, total phosphorus, and phosphates. Physicochemical parameters were analyzed using standard methods to assess basin pollution control. Results indicated minimal spatiotemporal variation in pollution, although pollution levels increased significantly during the rainy season. In conclusion, this study highlights the importance of monitoring and managing water quality in the Ziz Basin, particularly regarding the impacts of urban pollution. The findings suggest the need for effective measures to mitigate the anthropogenic impacts on the region's environment.

***Keywords:*** Surface water chemistry; Environment; Urban wastewater; Ziz Basin; Domestic pollution

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## 1. Introduction

Freshwater ecosystems are essential for ecological continuity and sustain critical anthropogenic activities, including municipal drinking water supply, industry, agriculture, and recreation.[1,2] Regrettably, these delicate ecosystems have increasingly borne the brunt of human activities over the past century.[3] Population growth and rapid urbanization have caused considerable disruptions to natural environments.[4] Agricultural prosperity, population expansion, and socioeconomic development activities depend fundamentally on water quantity and quality. Additionally, geographical, geological, pedological, and climatic factors play pivotal roles in this socioeconomic development.[5,6] However, socioeconomic growth, accompanied by the increasing complexity of economic and industrial facilities, can adversely impact the environment, particularly water resources, including surface waters.[7,8] Consequently, engineers and other stakeholders have systematically assessed the quantitative and qualitative status of surface waters, which are heavily utilized for regional food and water supplies in socioeconomic sectors. The primary objective is to protect water resources and propose mitigation measures.[9] The watershed controlled by the Hassan Addakhil Dam has been experiencing strong economic and urban development for several years, posing potential risks to the water resources mobilized by this dam.[10] The geological history of this region has shaped the characteristics of its watershed. Diverse geological formations, ranging from Precambrian to Mesozoic and Cenozoic formations in the Ziz basin, influence the chemical composition of surface water.[11] Economic and urban development have adverse impacts on the water resources of the basin, rendering surface water highly exposed and sensitive to pollutant discharges.[12,13] Furthermore, the hydrological network of the region is characterized by numerous major valleys, although perennial watercourses are rare. The Ziz River, which traverses this basin, is fed by tributaries originating from the summits of the High Atlas. However, these tributaries are highly sensitive to inputs from Jurassic limestone aquifers and precipitation—including snowmelt—which directly modulate the hydrological regime of the Ziz River.[14-16] These geological and hydrological elements substantially contribute to understanding the Ziz basin environment and water quality. This study aims to develop a strategy for safeguarding the quality of water mobilized by the Hassan Addakhil Dam, with a particular focus on re-establishing the protection perimeters of this essential infrastructure. To achieve these goals, the study addresses two primary objectives. Firstly, it aims to systematically identify and assess the negative impacts stemming from various sources of pollution, both natural and human-induced. Secondly, it seeks to identify the major sectors driving pollution and the most polluted areas to map vulnerability and sensitivity zones for surface waters, while defining future protection zones for the Hassan Addakhil Dam.

## 2. Materials and methods

### 2.1. Description of study area

The study area encompasses the entire Ziz Basin up to the Hassan Addakhil Dam, located in the Errachidia Province and Midelt Province. It is crucial to define the protection perimeters for the Hassan Addakhil Dam, particularly due to the ongoing demographic growth, rapid urbanization, and the intensification of socioeconomic activities, primarily industrial, in this region.[12] The Ziz Basin corresponds to the catchment area of the Ziz River. This geographical unit is predominantly located within the Errachidia Province.[17] The arid climate and low vegetation density profoundly influence the soil characteristics in the Drâa-Tafilalet region. As a result, most soils in the area are relatively underdeveloped. Developed soils are rare due to factors such as runoff, wind erosion, and salinization. Most of these developed soils are concentrated in the Errachidia Province. Geographically, the Ziz Region stretches in a meridional direction, covering a distance of approximately 220 km. It extends from Jbel Ayyachi in the north, with an elevation of 3,751 m, to the Hamada of Kem Kem in the south, with an elevation of 850 m. This area is aligned perpendicular to the structural lines of the Eastern High Atlas and the Eastern Anti-Atlas.[18]

From a hydroclimatic perspective, the Ziz Basin belongs to the pre-Saharan arid climatic domain, with a strong continental influence. The climatic conditions are characterized by low, irregular precipitation and high atmospheric evaporative demand. Previous hydroclimatic investigations of the Ziz Basin reported an average annual potential evaporation of approximately 2,500 mm, considerably exceeding the annual precipitation over most of the basin. Hot, dry winds, including the Chergui, further drive high evaporative demand, particularly during the warm season.[19]

The basin operates under a strongly negative climatic water balance over much of its area. At the annual scale, the simplified climatic water balance can be expressed as:

$$D = P - PET \quad (1)$$

where $D$ is the climatic water balance, $P$ is the annual precipitation, and $PET$ is the annual potential evapotranspiration. When $P < PET$, atmospheric water demand exceeds available precipitation, resulting in a climatic water deficit. This condition is particularly pronounced in the downstream and lower-elevation sectors

of the Ziz Basin, where precipitation decreases substantially toward the pre-Saharan and Saharan domains. Limited precipitation and high evaporative demand explain why the basin's water resources strongly depend on episodic rainfall, snowmelt, and upstream runoff. Recent assessments of the Ziz Basin similarly indicate that precipitation represents a major control on water availability, while high *PET* under warm and dry conditions drives groundwater and surface water depletion.[19]

The degree of climatic aridity can be quntitatively represented using the UNEP aridity index, defined as the ratio between mean annual precipitation and mean annual potential evapotranspiration:

$$AI = \frac{P}{PET} \quad (2)$$

Serving as a true ethnic crossroads, the Ziz Region has historically been a connecting point between the Sahara and the rest of Morocco, as well as among various regions of the Moroccan Pre-Sahara. Figure 1 shows the Ziz watershed boundary.[19]

The mean annual temperatures increase from approximately 18.2 °C at Foum Zaâbel in the north to 22.5 °C at Taouz in the south. This region experiences substantial seasonal temperature variations, with hot summers and cold winters. Winter daytime temperatures are low, and nighttime temperatures rarely drop below 0 °C.[20] Notably, the distribution of meteorological stations across this region is uneven. Most stations are concentrated in the High Atlas, while the southeastern and southwestern sectors have fewer stations, resulting in data gaps. Rainfall patterns are also highly variable across the region. Rainfall decreases from approximately 260 mm in the highlands (e.g., Zaouiat Sidi Hamza Station) to approximately 123 mm in the foothills near the Hassan Addakhil Dam. In the southern areas, such as Radier Erfoud Station, annual rainfall is approximately 65.66 mm. The low rainfall in the south can be attributed to the orographic blocking effect of the Atlas Mountains against oceanic influences and the influx of hot air masses from the Sahara.[21] Monthly rainfall data show considerable year-to-year variability, reflecting

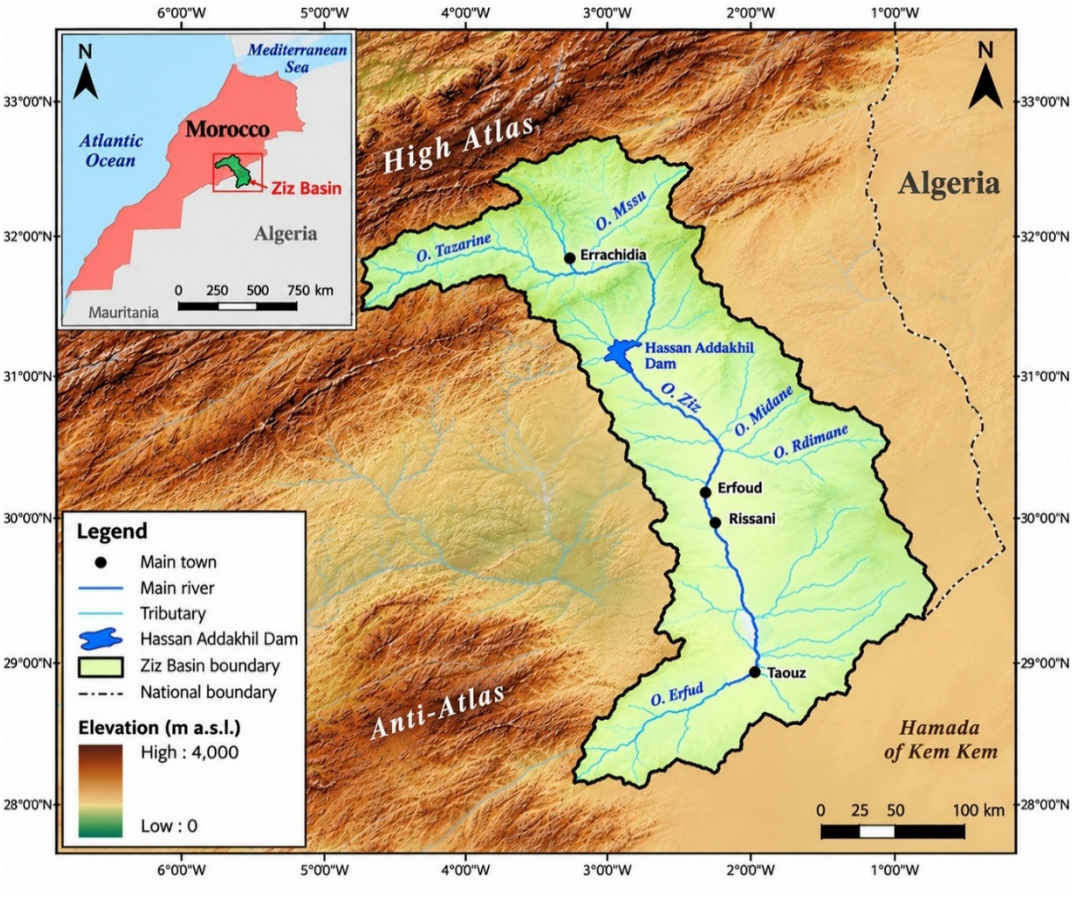


**Figure 1.** Hydrographic system mapping of the Ziz Basin

the irregular precipitation. Mean annual rainfall increases from south to north, ranging from 65.66 mm at Radier Erfoud to 259.33 mm at Zaouiat Sidi Hamza. The annual rainfall pattern features two wet seasons in autumn and spring, separated by a short winter season with relatively low precipitation, and a long, notably dry summer season.[22]

### 2.2. Measurement of physicochemical parameters

Sampling campaigns were conducted from bridges along the rivers, with samples collected from the mid-channel to ensure representative sampling (Figure 2). Water sampling campaigns were conducted during two monitoring periods, in 2016 and 2022, at selected sampling stations throughout the Ziz Basin. These campaigns provided the basis to compare surface water quality between the two study years. Water sampling was performed on the river surface (0 to 10 cm) using a bailer with a 1 L capacity. One end of the bailer is open for filling, while the opposite end features a ball valve to facilitate controlled emptying. The bailer was fitted with a rope to allow easy retrieval after deployment from the bank or a bridge. Some samples were obtained using a sampling rod from the shore at the head of the basin when it was impractical to use a bailer. All collected samples were collected in clean polyethylene bottles, shielded from light, and promptly transported to the laboratory for storage at 4 °C in the dark before analysis.[23]

Ammonium ion ($NH_4^+$) concentrations were determined according to the Nessler method using a HACH DR/2400 spectrophotometer (Hach, United States), which features a detection range of 0 to 2.500 mg/L $NH_4^+$–N.[25] According to this method, ammonium ion concentration is quantified by analyzing the distinctive yellow compound formed via reagent decomposition. Biochemical oxygen demand ($BOD_5$) was determined by measuring initial dissolved oxygen (DO) concentrations and repeating the measurement after 5 days. The $BOD_5$ value represents the difference between these baseline and final oxygen concentrations. Chemical oxygen demand was measured via the dichromate photometric approach using a HI97106 photometer (Hanna Instruments, Italy). Following standardized water analysis procedures, DO concentrations were measured using an oximeter.

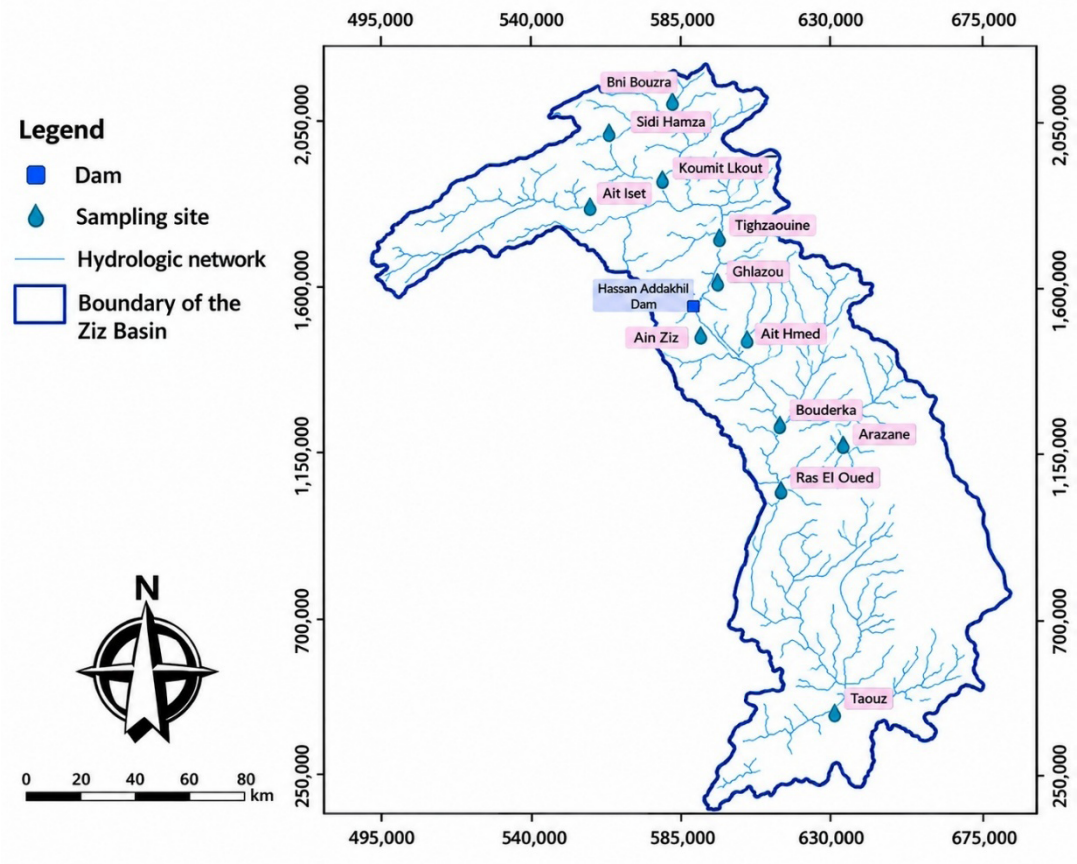


**Figure 2.** Location of the sampling stations in the Ziz Basin

Table 1 summarizes the available information regarding the sampling campaigns, including monitoring periods, sampling locations, sampling frequency, sampling dates and seasons, and physicochemical parameters analyzed.

### 2.3. Anthropogenic impacts, environmental sensitivity, and mitigation measures

The objective of this study is to assess surface water quality in the Ziz Basin, identify the main potential pollution sources, determine the most vulnerable areas, and propose appropriate mitigation measures to protect the water resources of the Hassan Addakhil Dam. To achieve these objectives, field investigations, physicochemical water-quality assessment, spatial analysis using GIS, and identification of anthropogenic activities and pollution sources were conducted.

The identified anthropogenic impacts were assessed for their nature, spatial distribution, magnitude, duration, and frequency. Existing environmental information, field observations, stakeholder consultations, and available spatial data were considered to identify areas with different levels of sensitivity and vulnerability. The results were then used to identify priority areas and propose appropriate mitigation measures for the protection of surface water resources of the Hassan Addakhil Dam.

Once the identification process was complete, major anthropogenic impacts were described in terms of their nature and characteristics. For instance, impacts can be direct or indirect, temporary or permanent, continuous or intermittent, reversible or irreversible, short-term, medium-term, or long-term, with varying degrees of magnitude, correctability, compensation potential, and potential interaction with other impacts. Their criticality was assessed in the context of the local environment and the sensitivity of the watershed's waters.[26]

The proposed mitigation measures in this study are designed to anticipate, correct, repair, or mitigate weak, moderate, or major negative impacts on the biophysical and human environments resulting from anthropogenic activities, products, or services. All these measures are thoroughly described, along with their conditions of application.[27]

## 3. Results and discussion

### 3.1. Natural streamflow contributions within the Ziz Basin

#### *3.1.1. Isohyet map*

The isohyet map was illustrated based on the interannual rainfall averages recorded at the available meteorological stations during 1973–2021 (Figure 3). The precipitation values, expressed in mm, show a clear spatial gradient across the Ziz Basin, with higher rainfall in the northern High Atlas and progressively lower values toward the southern Anti-Atlas. This spatial variability is closely related to the elevation gradient and the continental and Saharan influences affecting the basin. The precipitation distribution is important to understanding the hydrological functions of the Ziz Basin, as rainfall drives surface runoff and streamflow, thereby modulating pollutant dilution and transport. In addition, rainfall events may influence pollutant transfer from surrounding areas into surface waters. Therefore, the isohyet distribution provides an essential climatic context for interpreting the spatiotemporal variations observed in surface water quality.

#### *3.1.2. Hydrographic network*

The Ziz Basin is extensive and characterized by a relatively regular morphology. The hydrographic network comprises numerous prominent valleys, yet displays poorly developed perennial courses; the Ziz River exhibits a hydrological regime with Saharan tendencies (Figure 4).

The main stem of the Ziz River can be divided into

**Table 1. Summary of the surface water sampling campaigns and available hydrological information in the Ziz Basin**

| Sampling period | Sampling sites | Sampling frequency | Season/date | Parameters analyzed |
|---|---|---|---|---|
| 2016 | Surface water stations in the Ziz Basin | Monthly | – | $NH_4^+$, $BOD_5$, COD, DO, TP |
| 2022 | Surface water stations in the Ziz Basin | Monthly | – | $NH_4^+$, $BOD_5$, COD, DO, TP |
| November 2016 | Hassan Addakhil Dam | Monthly | November 2016 | $NO_3^-$, $NH_4^+$, $Cl^-$, TP, DO |

Abbreviations: EC: Electrical conductivity; $BOD_5$: Biochemical oxygen demand; COD: Chemical oxygen demand; DO: Dissolved oxygen; TP: Total phosphorus; TSS: Total suspended solids.

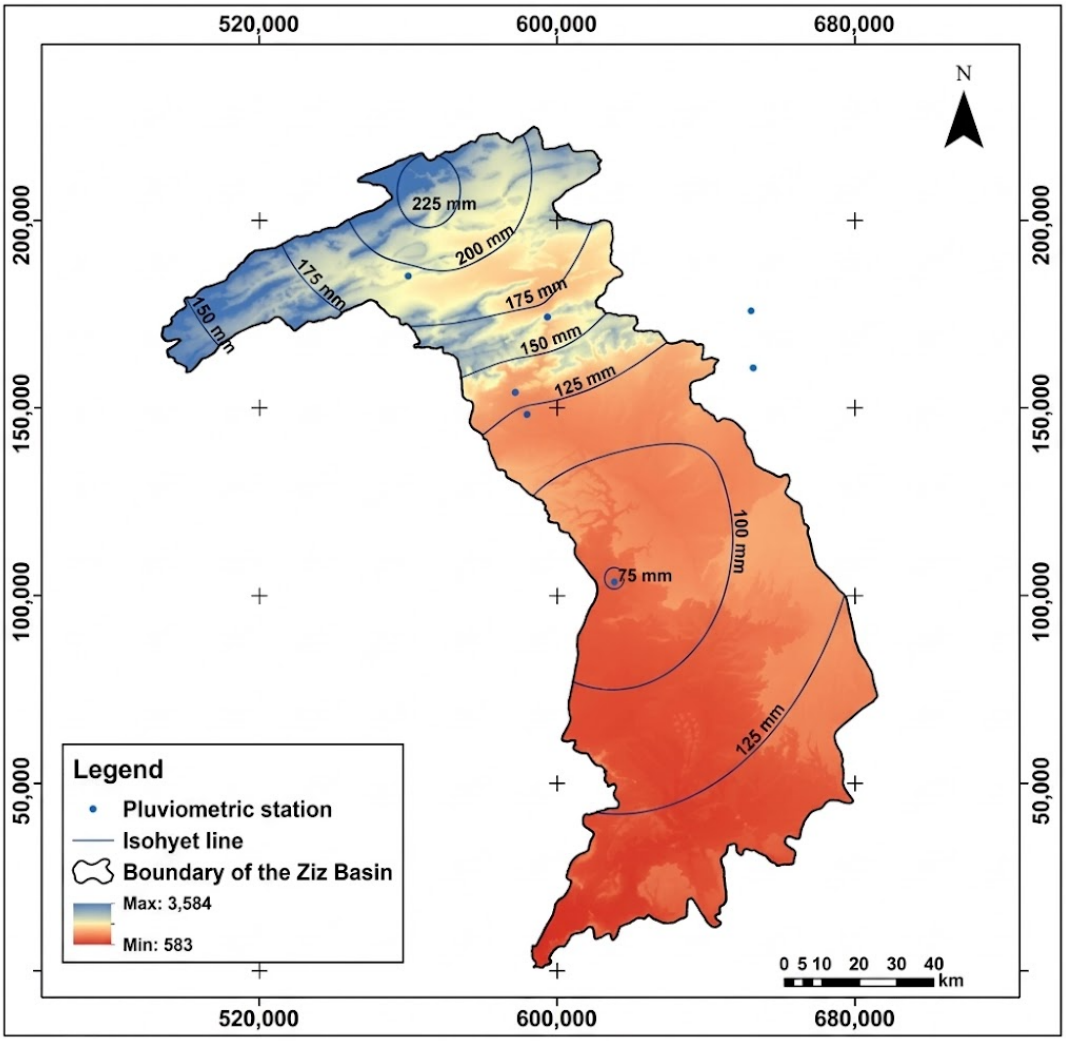


**Figure 3.** Isohyet map of the Ziz Basin

three primary courses. The upper course runs east–west for approximately 122 km before changing to north–south at the Kerrando bend. This course drains the upstream basin of the Ziz River, which is restricted to the south by the Hassan Addakhil Dam. The middle course, generally oriented north to south, collects water from the intermediate basin extending from the Hassan Addakhil Dam to the Erfoud Radier Station. Finally, the lower course follows a north–south direction and crosses the Tafilalet plain. Several tributaries originating from the High Atlas contribute to this section, including Oued Outerbat, Oued Nasla, Oued Talsast, and Oued Sidi Hamza.

On the right bank of the Ziz Basin (intermediate basin), several tributaries flow into the Ziz River only during flash floods/high-magnitude flood events. Conversely, on the left bank, the Ziz River receives two important tributaries: Oued Meski, formed by the confluence of several small wadis, and Oued Aoufous, which exhibits a perennial flow regime due to continuous discharge from its tributaries, the Boubarnous and Rahma wadis, as well as the Aoufous springs.

### *3.1.3. Surface water inputs to the Ziz Basin*

The natural streamflow into the Ziz Basin originates from various sources. Two main tributaries upstream of Rich, Foum Tillicht and Mzizel, contribute approximately 57 $Mm^3$ and 60 $Mm^3$ of water, respectively. The section between the gauging stations of these two tributaries, including Foum Zaâbel, accounts for an additional 46 $Mm^3$ of water. Moving downstream from Foum Zaâbel to the Hassan Addakhil Dam, there is a natural input of 10 $Mm^3$ of water. Based on the available hydrological information

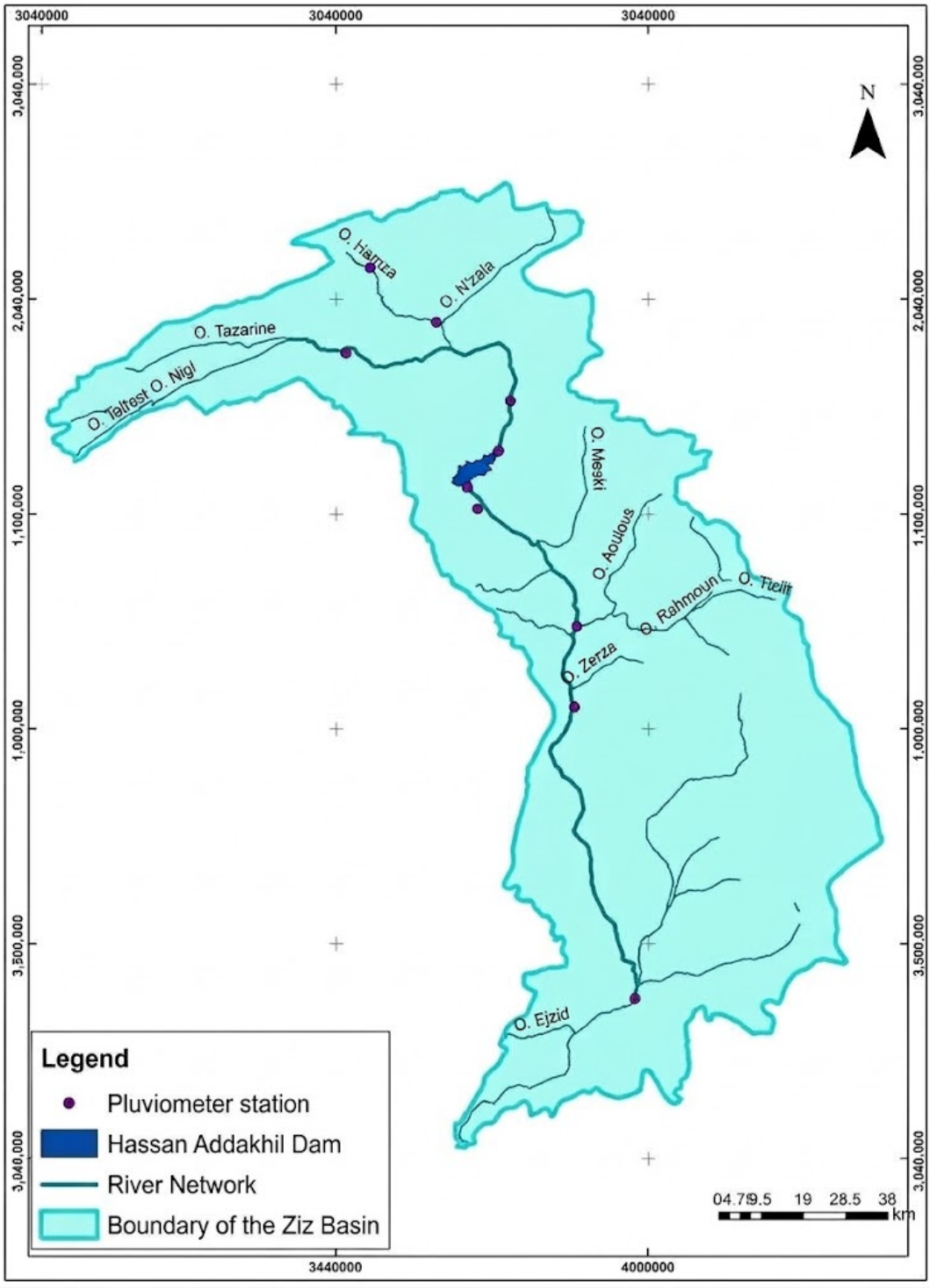


**Figure 4.** Map of the hydrographic network of the Ziz Basin

for the studied period, the natural streamflow contribution in the Ziz Basin approximates 232 $Mm^3$. This value should be interpreted as a period-specific estimate rather than a long-term climatological or hydrological average because streamflow in the basin is strongly influenced by interannual variability in precipitation, snowmelt, temperature, and

other climatic and hydrological processes. Consequently, the relative contributions reported in Table 2 may vary considerably between wet and dry years, and should not be considered representative of the long-term hydrological regime without a sufficiently long time series. The climatic and hydrological characteristics described above should be interpreted in the context of the strong temporal variability in the Ziz Basin. Precipitation, streamflow, temperature, and snowmelt processes can vary considerably between years and may consequently alter the quantity and spatial distribution of water reaching the river network. Therefore, the natural streamflow contributions presented in Table 2 represent estimates for the studied hydrological period and should not be interpreted as fixed long-term values.

### 3.2. Assessment of the overall water quality

#### *3.2.1. Surface water quality in the Ziz Basin*

Assessing surface water quality in the Ziz Basin is critical, requiring thorough scrutiny and continuous monitoring to gain comprehensive insights into the condition of water resources in this region. This evaluation plays a pivotal role in preserving aquatic ecosystem integrity, protecting public health and well-being, and supporting sustainable water resource management. Carefully examining and tracking surface water quality is essential for making informed decisions and implementing measures aimed at its conservation and enhancement. The results of the analysis are presented in Table 3.

The results indicated relatively low nutrient concentrations in most of the investigated wadis. $NH_4^+$ concentrations were generally ≤ 0.37 and ≤ 0.21 mg/L $NH_4^+$–N in 2016 and 2022, respectively, with a notable exception of 3.05 mg/L $NH_4^+$–N at Aval Eroud in 2016. In contrast, total phosphorus remained below 0.01 mg P/L at all reported stations. These values indicate that nutrient enrichment was generally limited at the monitored locations, although localized ammonium enrichment occurred. The relatively low phosphorus concentrations also align with observations reported for Hassan Addakhil Dam, where phosphate concentrations were described as very low or close to negligible.

The comparison with groundwater studies further illustrates the difference between surface water and groundwater quality in the region. Using a national Moroccan database, Miftah *et al.*[28] reported a mixed groundwater quality profile for the Ziz aquifer, noting that 48.84% of sampled sites were suitable for drinking water purposes, while 51.16% were unsuitable. Their analysis identified nitrate contamination and mineralization as important groundwater quality concerns and attributed nitrate occurrence mainly to agricultural practices, wastewater, and septic systems.[28]

Morarech *et al.*[29] provided a more direct spatial comparison with this study by performing surface water assessment upstream of Hassan Addakhil Dam. Their measurements show nitrate concentrations of 1–9.65 mg/L in the Ziz River, with river-water nitrate generally below 10 mg/L. They also reported DO concentrations of approximately 4.5–5.6 mg/L and EC values generally below 750 µS/cm, except at one station where EC achieved 1,350 µS/cm. However, this study does not include nitrate, EC, or DO in the surface water dataset presented in **Table 3**; consequently, direct temporal comparison of these parameters is not possible.

Comparison with previous studies indicates that the water quality of the Ziz Basin is spatially heterogeneous and highly dependent on the specific parameter, hydrological compartment, season, and local pollution source. The present study primarily indicates limited nutrient enrichment with localized ammonium deterioration in the monitored surface waters.

**Table 2. Estimated natural streamflow contributions in the Ziz Basin for the studied hydrological period**

| Basin | Sub-basin | Natural streamflow ($Mm^3$) | Contribution (%) |
|---|---|---|---|
| Ziz | Foum Tillicht | 57 | 9 |
| | Mzizel | 60 | 9 |
| | Foum Zaâbel–Hassan Addakhil Dam | 56 | 9 |
| | Hassan Addakhil Dam–Radier Erfoud (middle Ziz) | 35 | 5 |
| | Taouz and lower Ziz | 24 | 4 |
| Total basin of Ziz | | 232 | 35 |

**Table 3. Surface water quality (wadis) 2016 and 202**

| Sampling station | $NH^{4+}$ concentration (mg/L $NH_4^+$–N) | TP (mg P/L) | Global quality | $NH^{4+}$ concentration (mg/L $NH_4^+$–N) | TP (mg P/L) | Overall water quality |
|---|---|---|---|---|---|---|
| | 2016 | | | 2022 | | |
| Foum Zaâbel | 0.06 | <0.01 | Good | 0.21 | <0.01 | Good |
| Radier Erfoud | 0.02 | <0.01 | Good | – | – | – |
| Amouguer | 0.02 | <0.01 | Good | <0.04 | <0.01 | Good |
| Foum Tillichte | <0.02 | <0.01 | Good | <0.04 | <0.01 | Good |
| Aval Aïn Meski | 0.05 | <0.01 | Good | <0.04 | <0.01 | Moderate |
| Aval Erfoud | 3.05 | <0.01 | Poor | – | – | – |
| Aval Rich | 0.10 | <0.01 | Good | 0.18 | <0.01 | Moderate |
| Aval Aïn Atti | 0.37 | <0.01 | Good | – | – | – |
| Oued Aoufous | 0.02 | <0.01 | Moderate | – | – | – |

Abbreviation: TP: Total phosphorus.

Surface water quality in the Ziz basin does not show a significant improvement trend from 2016 to 2022, with some exceptions at specific points, notably Aval Erfoud. Most sampling points continue to exhibit compromised water quality. An analysis of the basin's water samples revealed that 77.78% were categorized as good quality. Approximately 11.11% of the samples were of average quality, and another 11.11% were classified as bad quality. Only one sample fell into this category, mainly due to its $BOD_5$ measurement (10–25 mg $O_2$/L). According to the 2022 findings, approximately 66.67% of the samples were categorized as good quality, whereas 33.33% were of average quality (Figure 5). Notably, streams within the basin experience temperature variations in response to normal climatic fluctuations. These variations are typically seasonal and, in certain streams, can occur over 24-hour periods. Surface water temperature is influenced by factors such as latitude, elevation, season, time of day, air circulation, cloud cover, flow rate, and water depth. These temperature changes, in turn, impact various physical, chemical, and biological processes within the water bodies, causing fluctuations in the concentrations of multiple variables. As water temperature increases, chemical reaction rates generally increase, while the solubility of dissolved gases decreases. In particular, oxygen, carbon dioxide, nitrogen, and methane all show an inverse relationship between temperature and aqueous solubility. Thus, increased temperatures typically reduce DO concentrations, potentially decreasing oxygen availability for aquatic organisms, while carbon dioxide, nitrogen, and methane also become less soluble and more likely to transfer from water to the atmosphere. Higher temperatures may additionally enhance the evaporation and volatilization of volatile substances. It is essential to consider these temperature-dependent responses when interpreting seasonal variations in surface water quality.

### *3.2.2. Analysis of source water quality*

Source water quality plays a crucial role in meeting the water quality requirements for agricultural and domestic use. In this region, these resources comprise shallow water tables of limited extent that are directly influenced by climatic conditions, as well as deeper, artesian water tables. They are the integral components of the water and subsurface cycle, functioning as reservoirs and flows, similar to surface waters. Their spatial distribution is considerably more continuous than that of surface water and is determined by geological formations, which in turn influence their behavior.[30]

While all analyzed samples from the two sampling points were of good quality in 2016, the 2022 results revealed a shift: 50% of the samples at these same locations dropped to average quality, while the remaining 50% were classified as poor quality (Table 4).

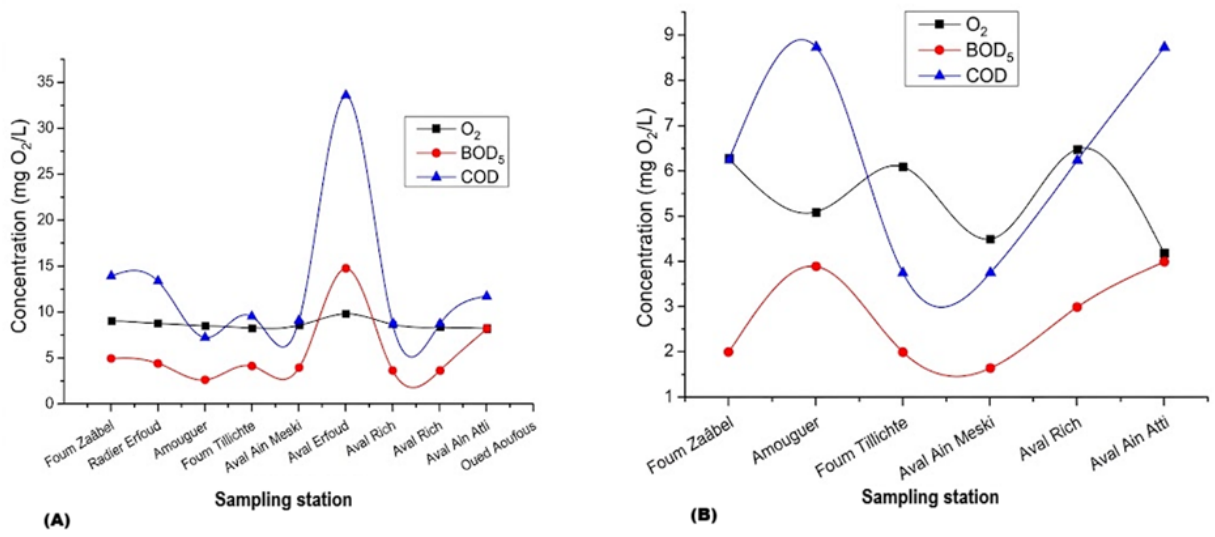


**Figure 5.** Physicochemical quality of surface waters in (a) 2016 and (b) 2022
Abbreviations: $BOD_5$: Biochemical oxygen demand; COD: Chemical oxygen demand; DO: Dissolved oxygen.

**Table 4. Source water quality in 2016 and 2022**

| Sampling station | $NH_4^+$ (mg/L $NH_4^+$–N) | TP (mg P/L) | Global quality | $NH_4^+$ (mg/L $NH_4^+$–N) | TP (mg P/L) | Global quality |
|---|---|---|---|---|---|---|
| | 2016 | | | 2022 | | |
| Meski | 0.04 | <0.01 | Good | 0.04 | <0.01 | Moderate |
| Moulay Hachem | <0.02 | <0.01 | Good | 0.06 | <0.01 | Poor |

Abbreviation: TP: Total phosphorus.

### *3.2.3. Analysis of the reservoir quality (Hassan Addakhil Dam)*

The reservoir quality analysis was based on samples acquired from the waters of the Hassan Addakhil Dam in November 2016. The water quality analysis was conducted according to the methods described by Hamid *et al.*[31] and the recommendations of the World Health Organization.[32] The physicochemical assessment performed for the Hassan Addakhil Dam water quality included nitrate, $NH_4^+$, chloride, total phosphorus, and DO. The analysis results are presented in Table 5 and Figure 6.

The results revealed that one of the reservoir water depth levels exhibits DO levels below the natural threshold of 8 mg/L. The other parameters displayed considerable variations. Moreover, TP concentrations are remarkably low, often approaching negligible thresholds. Collectively, these findings indicate that the reservoir exhibits favorable water quality.[32]

**Table 5. Water quality of the Hassan Addakhil Dam in 2016**

| Sampling location | Level | TP (mg P/L) | Global quality |
|---|---|---|---|
| Hassan Addakhil Dam | 0 | <0.01 | Mesotrophic |
| Hassan Addakhil Dam | 13 | <0.01 | Mesotrophic |
| Hassan Addakhil Dam | 26 | <0.01 | Mesotrophic |

Abbreviation: TP: Total phosphorus.

Overall, the water quality at Hassan Addakhil Dam ranges from good to excellent, primarily due to adequate oxygenation. Both nitrate and TP levels fall within excellent quality thresholds, whereas the $NH_4^+$ level is classified as good to excellent. Trophic status assessment categorizes the dam reservoir as mesotrophic.[33]

Water quality in the Ziz River, as illustrated in Figure 7, is significantly influenced by the geology of the areas through

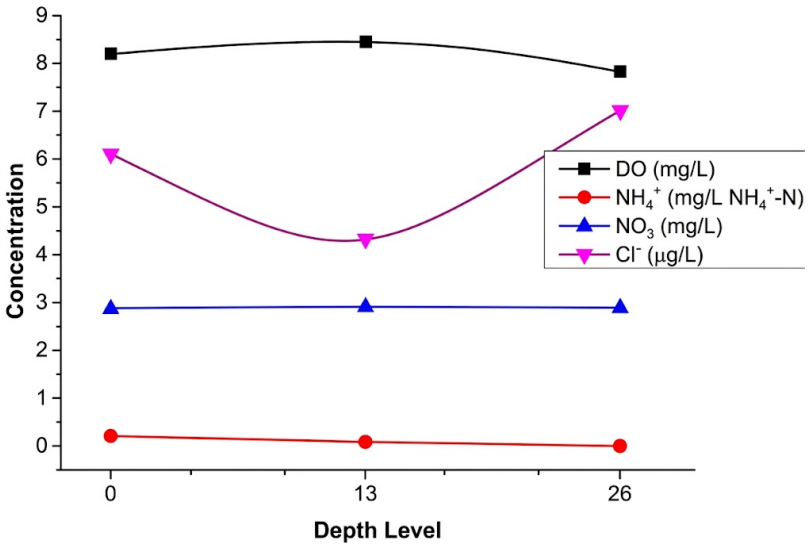


**Figure 6.** Physicochemical characteristics of Hassan Addakhil Dam water in 2016.
Abbreviation: DO: Dissolved oxygen.

which the watercourse flows and the substantial impact of agricultural activities along its banks.[34] However, most of the studied physicochemical parameters do not exceed the relevant Moroccan standards for surface water quality.[35] Compared with the physicochemical contamination levels observed in other Moroccan rivers (e.g., the Sebou and Bounaim) and an international river (the Seine), the Ziz River remains within sustainable limits. This favorable status is likely attributable to the relatively lower level of socioeconomic development in the surrounding region.[36]

### 3.3. Risk assessment, analysis, and hierarchization

To develop a strategy for preserving water quality in the Hassan Addakhil Dam, this study investigated the following aspects.

#### *3.3.1. Impacts of wastewater and mitigation measures*

The impacts of wastewater disposal in the area have been assessed through field surveys conducted in each municipality. The findings indicate that the Rich center is served by a centralized liquid sanitation network, which produces approximately 18,750 $m^3$ of discharges monthly directly into the Ziz River. Similarly, Hammat Moulay Ali Cherif (in the municipality of Guers Tiaalaline) and the Lkheng Barracks (in the municipality of Lkheng) also produce wastewater discharges into the natural environment through septic tanks and cesspools. These discharges pose considerable environmental threats and deteriorate the quality of surface waters in the Ziz River basin upstream of the Hassan Addakhil Dam. One of the mitigation measures taken to address the negative impacts on the water quality of the Hassan Addakhil Dam is the implementation of a wastewater treatment plant in the Rich center as part of the National Program of Liquid Sanitation and Purification.

Urbanization should be considered separately from other anthropogenic pressures because it directly alters both the magnitude and spatial concentration of pollutant loads entering the Ziz hydrological network. Population growth and the expansion of urban and emerging centers increase domestic water consumption and wastewater production, while insufficient wastewater collection and treatment infrastructure can result in direct or indirect discharges to wadis. This pressure is particularly relevant upstream of the Hassan Addakhil Dam, where the field survey identified direct wastewater discharge from the Rich center, as well as discharges through septic tanks and cesspools in other settlements. Urban expansion may also increase impervious surfaces and alter runoff pathways, facilitating the rapid transfer of accumulated contaminants from populated areas toward surface waters during rainfall events.

#### *3.3.2. Impacts and mitigation measures for solid waste and leachate*

Landfills are also a source of diffuse pollution where pollutant flows are difficult to estimate. Leachate represents a regular source of degradation for surface waters, especially during rainy periods when water running through the waste becomes loaded with pollutants and contaminates surface waters. The Ziz Basin is characterized by the proliferation of uncontrolled landfills. These landfills are

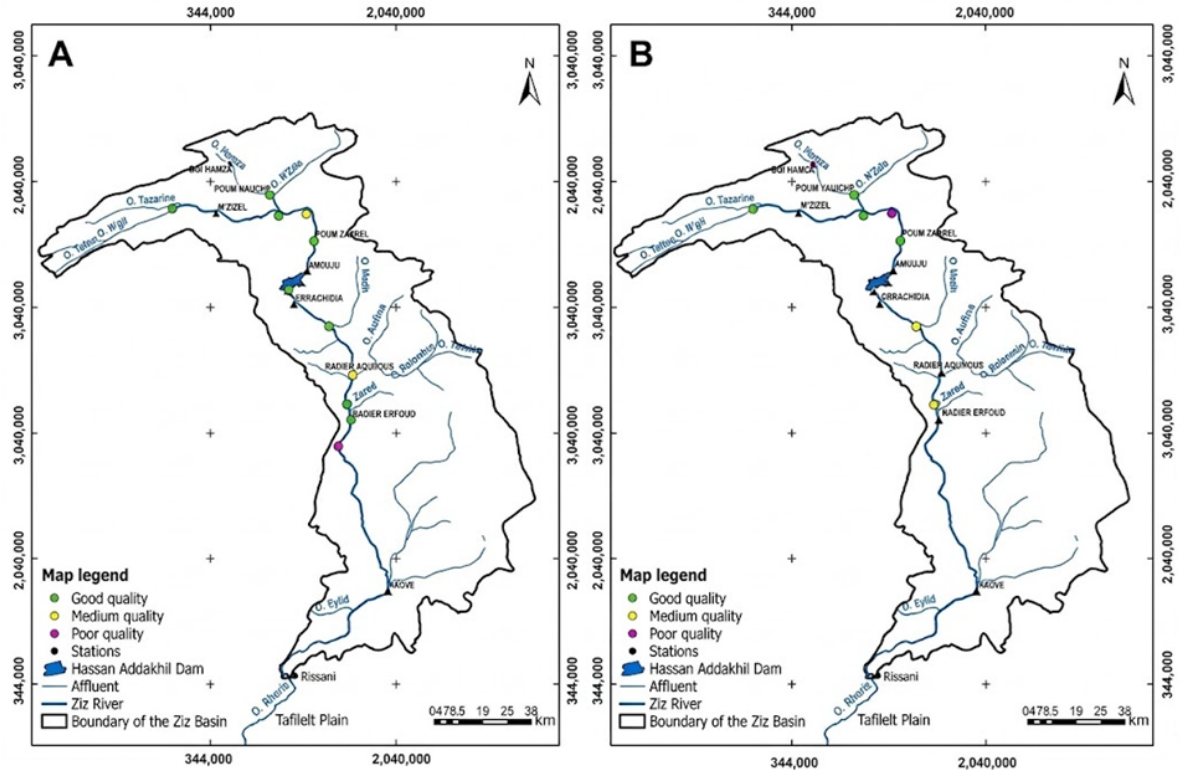


**Figure 7.** The quality of the surface water of the Ziz River: (A) 2016 and (B) 2022

one of the sources of contamination for surface water in the basin via leachate runoff.

To mitigate the negative impacts of solid waste, the establishment of controlled landfills is urgently required to minimize these impacts on surface waters (the most vulnerable to pollution), the surrounding environment, and public health. Consolidating waste management into a single, regional controlled landfill represents a highly effective and logistically viable environmental solution.

### *3.3.3. Impacts of industrial activities and mitigation measures*

Wastewater from industrial units is typically highly polluted with contaminants including heavy metals, detergents, and olive mill wastewater (margines). In the absence of pretreatment systems, these industrial effluents are discharged indiscriminately into the natural environment.[37]

In the present study area, the main industrial units inventoried are olive oil mills. These industrial units are distributed across nearly the entire basin. These are traditional industrial units that typically produce high yields. In addition to oil and pomace, olive oil mills produce significant quantities of margines. The survey of olive oil mills within the study area revealed a lack of dedicated drying tanks for pomace, which is consequently spread directly onto bare soil.

Several corrective and preventive measures can be adopted to mitigate the negative impacts of the preexisting industries in the studied watershed, such as:

- to enforce regulatory compliance for the olive oil mill owners to build sufficient basins with geomembranes to limit the impact of the margines on the environment;
- to provide a small controlled and open-air landfill within these units for proper management of solid waste, especially plastic and organic waste;
- to construct storage and drying basins for pomace;
- to collect and treat liquid waste, utilizing at least secondary containment or small-scale decantation basins.

A preliminary impact study is mandatory for future and ongoing industrial activities that are likely to generate, directly or indirectly, negative impacts on the waters of the studied watershed.

#### *3.3.4. Negative impacts of agricultural and farming activities*

Agricultural activities represent a considerable cause of soil erosion and soil alteration. The negative impacts manifest as deteriorated soil quality—characterized by a loss of fertility, soil crusting, and the formation of non-aggregated, prismatic structures—as well as water resource pollution through increased sediment loads, suspended solids, siltation, and eutrophication. Consequently, these processes adversely affect downstream technological infrastructure, raw water treatment processes, regional water supplies, and the operational lifespan of the Hassan Addakhil Dam and its associated hydraulic works. The excessive use of nitrogenous fertilizers, agricultural salts, and pesticides within the market gardening sector presents a high risk of water contamination through nitrogen, phosphorus, potassium, and pesticide residues.[38] Consequently, these contaminants complicate the water purification process and pose severe risks to public health.

Agricultural residues from large cereal fields can also cause water contamination through organic matter. Accordingly, several mitigation measures can be implemented to minimize the adverse environmental impacts generated by the agricultural sector, such as:

- limiting the usage of nitrogenous fertilizers, agricultural salts, and pesticides according to the crop requirement and soil capacity;
- prohibiting the use of chicken manure, especially on agricultural plots located near the reservoir and on the banks of the wadis;
- encouraging the conversion of agricultural waste into biochar via controlled pyrolysis, providing a beneficial soil amendment.

Additionally, livestock in the study area generate several negative impacts, which can be summarized as follows:

- Fowl droppings, which subsequently produce leachate with a high mineral, organic, and microbiological load. Poultry facilities have been identified within the upstream part of the studied watershed, with several facilities located just a few dozen meters from adjacent wadis. This proximity indicates a considerable risk of water contamination driven by the leaching of high-load organic pollutants.
- Poor storage of animal manure causes diffuse contamination of water mainly through nitrogen compounds, consequently resulting in eutrophication of the water reservoir.
- Overgrazing destroys the vegetation cover and leaves the soil bare and vulnerable to erosion, increasing the risk of soil erosion.

Poultry manure is characterized by a high concentration of trace elements (Table 6). These elements, particularly nitrogen and phosphorus, infiltrate water resources (surface water and groundwater) through leaching of soluble compounds or particle runoff. When these nutrient inputs exceed the natural assimilation capacities of local ecosystems, surface waters undergo eutrophication, resulting in excessive algal proliferation and a subsequent loss of biodiversity.[39]

Elevated nitrate content also poses a considerable barrier to utilizing raw groundwater or surface water for human consumption and food industry applications. In addition to these elements, animal husbandry operations introduce risks related to the dissemination of pathogens and residues from veterinary hygiene and healthcare products.[40,41]

To mitigate these negative impacts, the following measures can be considered:

- Prohibit any discharge and deposit of poultry droppings on the banks of the wadis and the reservoir, while requiring facilities to conduct comprehensive environmental impact assessments as a prerequisite for regional zoning and operation permits. Each extensive livestock facility (e.g., sheep, goats, cattle, horses,

**Table 6. Average composition of poultry manure**

| Type of farm waste | Composition (g/kg of raw product) | | | | |
|---|---|---|---|---|---|
| | Nitrogen, N | Phosphate, $P_2O_5$ | Potash, $K_2O$ | Calcium oxide, CaO | Magnesium oxide, MgO |
| Manure from the broiler | 29 | 25 | 20 | 14.5 | 3.7 |
| Manure from the turkey house | 27 | 27 | 20 | 23.5 | 3.7 |

and rabbits) must be preceded by an environmental impact study before its installation, followed by strict monitoring of compliance clauses once environmental clearance has been granted.
- For existing facilities, it is essential to encourage the adoption of good environmental management practices for waste handling, mandating disposal at a centralized municipal facility located safely away from the basin boundary.
- Prohibit the installation of any livestock facility near the reservoir and the wadis upstream of the Hassan Addakhil Dam.
- Restrict all operational activities and transport workflows of existing facilities to within their designated properties, and enforce a strict setback radius of at least 300 meters from adjacent wadi banks; additionally, establish a reforested riparian buffer zone along these perimeters to enhance watershed protection.

#### *3.3.5. Impacts related to the mining sector*

The four types of mining-associated impacts that affect water quality are discussed below.

Acid rock drainage is a natural process where sulfuric acid is produced when rock-bound sulfides are exposed to atmospheric oxygen and water. Acid mine drainage represents the exact same chemical pathway, but is drastically amplified by mining operations. When large amounts of sulfide-bearing rock are dug into open pits, the rock reacts with water and oxygen to create sulfuric acid. When the water reaches a certain level of acidity, a natural bacterium, *Thiobacillus ferrooxidans*, facilitates the oxidation and acidification process by leaching out additional metals from the mining waste. This acidification and leaching process persists continuously as long as the host rock remains exposed to atmospheric oxygen and water, continuing until the reactive sulfides are entirely depleted. This process can take hundreds or even thousands of years. Acid mine drainage migrates off mine sites through rainwater or drainage and seeps into waterways such as rivers, lakes, and groundwater. It severely degrades water quality, destroys aquatic life, and renders water resources unsuitable for any use.

Heavy metal contamination is caused by the leaching of heavy metals such as arsenic, cobalt, copper, cadmium, lead, silver, and zinc in exposed rock at underground mines upon contact with water. The metals are leached out when the water used to clean the top of the rocks during mining operations moves downstream. Although metals are stabilized at neutral pH levels, low pH conditions such as acid mine drainage accelerate the leaching process.

Chemical pollution occurs when chemicals such as cyanide or sulfuric acid used to separate minerals from the ores are discharged or leached into nearby water bodies. These chemicals are highly toxic to wildlife.

Mineral development disturbs rock and soil structures during road construction and maintenance, open-pit operations, and the deposition of mining waste. Without proper prevention and control strategies, soil erosion can produce discharge into streams, rivers, and lakes. Excessive sediment discharge can block rivers, smother vegetation, and destroy terrestrial and aquatic life.

Safeguarding water quality against unsustainable mining development is imperative for the well-being of present and future generations. Implementing better prevention strategies is essential to avoid potential pollution. Finally, it is critical to recognize that certain ecologically sensitive zones must be excluded from mineral extraction activities due to the severe risks they pose to vital environmental resources.

Figure 8 shows the pollution hot spots identified in the areas surrounding the Hassan Addakhil Dam.

The combination of all these factors—including the characteristics of the pollutants (such as quantity, intrinsic properties, transport, and transformation mechanisms), surface water (flow rate and renewal rate), runoff soil (constant variable given the clayey nature of all the substrates), and the focus of contamination (such as situation, nature, and pollution flow to the water)—allows us to assess the vulnerability, sensitivity, and degradation risks of the surface waters studied. Thus, several conclusions can be drawn, as summarized below.

The most and moderately vulnerable, most and moderately sensitive, and most exposed to hazards areas, spatiotemporally, are located around the Hassan Addakhil Dam with an average distance of 20 km at the level of the main wadis. Several contamination sources have been discussed above, which can be classified according to their generated flows and incurred risks: the margines from olive oil mills, domestic discharges from cities and emerging centers, transportation (development of cities and dualling of the Route Nationale 13), erosion, and agriculture.

The least vulnerable sectors and areas with low sensitivity to hazards occupy the remaining portion of the studied watershed. The areas of contamination and degradation have been discussed above and can be classified according to the flows generated and the risks involved: erosion, agriculture and livestock, and construction. Figure 8 illustrates the vulnerability, sensitivity, and associated risks of the studied surface waters to different threatening activities and pollution sources.

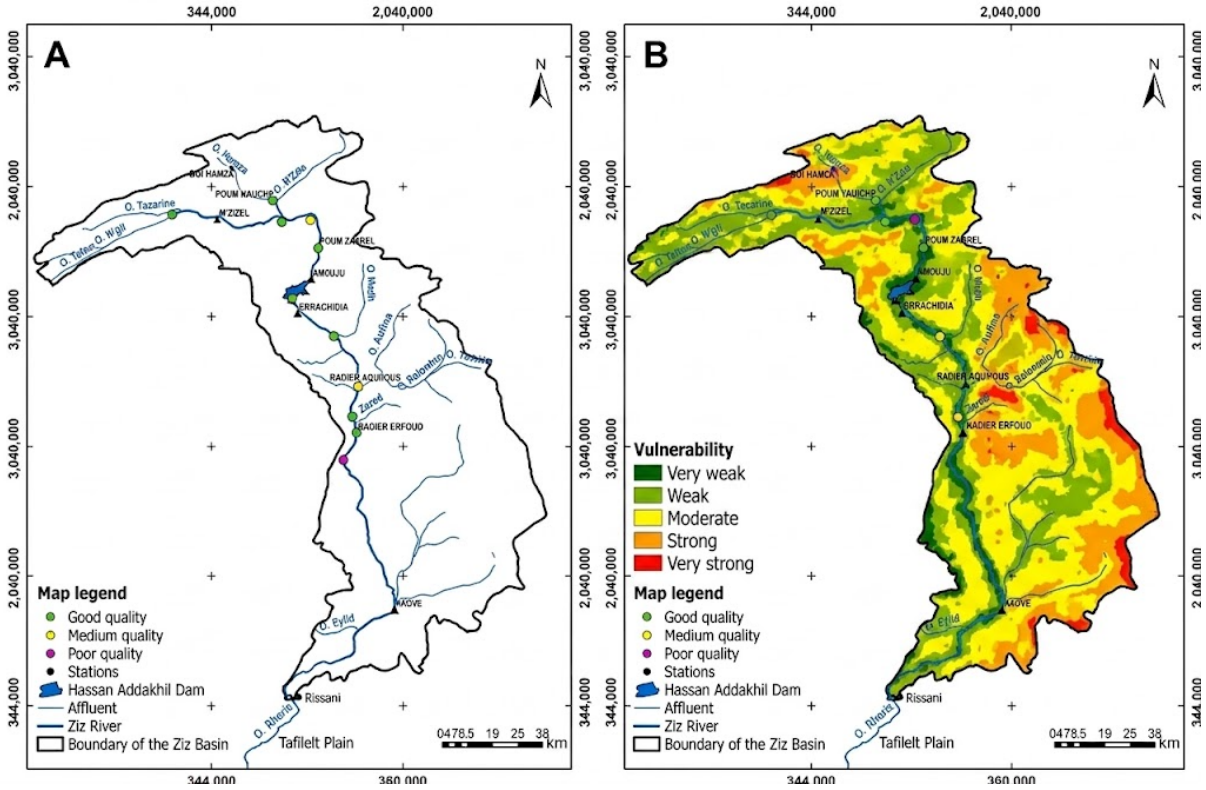


**Figure 8.** Spatial distribution of pollution zones and vulnerability across the Ziz Basin: (A) pollution zone mapping and (B) vulnerability mapping

Within this context, the spatial relationship between human settlements and hydrological hazards is also evaluated. Based on a global analysis of flood events between 2000 and 2018, Wang *et al.*[42] showed that changes in human–flood distance constitute an important indicator of population exposure and adaptation to flood-prone environments. Their results indicate substantial geographical differences in settlement responses to flood risk, identifying Morocco as one of the African countries characterized by relatively low flood-protection levels where populations tend to move closer to flood-affected areas. Although human–flood distance represents an indicator of flood exposure rather than a direct measure of water pollution, these findings highlight the importance of considering the spatial relationship between expanding settlements, flood-prone areas, and river systems when assessing urban pressures on water resources. In the Ziz Basin, such spatial interactions are particularly relevant during rainfall and flood events, when elevated surface runoff may increase hydrological connectivity between populated areas and receiving waters.

The main limitation of the present study is the temporal length of the available water-quality dataset. Although the observations provide useful information on the spatial distribution of pollution and allow comparison among the available sampling periods, they do not constitute a continuous multidecadal record. Consequently, the results should not be interpreted as the long-term hydrological and climatic behavior of the Ziz Basin. Natural processes such as precipitation, streamflow, temperature, and snowmelt exhibit substantial interannual and low-frequency variability, which may influence both water quantity and quality. A longer monitoring period, ideally spanning several decades, would be required to characterize these natural fluctuations, identify persistent trends, and separate long-term changes from short-term variability. Future studies should therefore combine continuous water-quality monitoring with long-term hydrological and meteorological records, as well as apply appropriate time-series approaches, including analyses of long-term persistence and the Hurst phenomenon.

## 4. Conclusion

Our study reveals that anthropogenic activities significantly impact the surface water quality in watershed aquatic systems. Within the Ziz Basin, watercourses play a pivotal role in transporting and purifying municipal and industrial wastewater—subject to varying degrees of treatment—

as well as managing runoff from agricultural land. Physicochemical characteristics of the waters in the basin and Hassan Addakhil Dam are consistent with established water quality standards and the results from previous research on rivers and water bodies. Notably, the basin shows no significant pollution from chemical substances stemming from anthropogenic activities, including waste management discharges, biomedical waste, leaching, and domestic wastewater effluents along its banks.

However, the surface water quality in the Ziz Basin exhibits spatiotemporal heterogeneity. These variations may reflect the combined influence of anthropogenic pressures as well as natural climatic and hydrological variability, including changes in precipitation, streamflow, temperature, and snowmelt. Because the present assessment is based on observations available for specific sampling periods, these relationships should not be interpreted as long-term trends. Multidecadal monitoring is necessary to characterize the long-term variability of the basin and to distinguish persistent trends from interannual and low-frequency fluctuations. For instance, variations in water temperature are often seasonal but occur within 24-hour cycles in certain watercourses, carrying far-reaching implications. Water temperature, influenced by diverse elements such as latitude, altitude, season, time of day, air circulation, cloud cover, water flow, and depth, impacts multiple physical, chemical, and biological processes in aquatic ecosystems. As water temperatures rise, chemical reactions tend to accelerate, and substances in the water become more prone to evaporation and volatilization. Furthermore, higher temperatures lead to reduced gas solubility in water, affecting oxygen, carbon dioxide, nitrogen, and methane solubility. These dynamics underline the need for comprehensive monitoring and management of water quality.

Despite these challenges, the data indicate a generally positive trend in the Ziz Basin water quality. Most sampled points pose no significant water quality issues, with 77.78% of the samples categorized as good quality. Approximately 11.11% exhibit moderate quality, and another 11.11% fall under the poor quality category. The 2022 analyses show encouraging results, with approximately 66.67% of samples classified as good quality, and the remaining 33.33% categorized as moderate quality. Urbanization and population growth constitute a distinct pressure on surface water quality in the Ziz Basin, particularly through the generation of domestic wastewater and expansion of settlements near the river network. The field investigations identified direct and indirect wastewater discharges from several urban and emerging centers upstream of the Hassan Addakhil Dam, indicating that inadequate wastewater management remains a major pathway for urban pollution. This pressure may be particularly substantial during rainy periods, when runoff can elevate the pollutant transfer from urbanized areas to surface waters. Therefore, urbanization should be evaluated independently of other anthropogenic pressures when assessing the main factors affecting water quality in the basin.

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## Conflict of interest

The authors declare they have no competing interests.

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## Availability of data

The data are available from the corresponding author upon reasonable request.

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