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Spatiotemporal Assessment of Groundwater Quality in the Oum Rbia Watershed Using GIS-Pro and Water Quality Indices

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ABSTRACT

Groundwater analysis across the Oum Rbia watershed is currently hampered by technical constraints and high costs. This research aimed to produce comprehensive groundwater quality maps throughout the basin aquifers by integrating the water quality index (WQI) and microbiological quality index (MQI) with GIS-Pro for a spatiotemporal assessment of water quality. Twenty physicochemical parameters, including pH, temperature, conductivity, total dissolved solids, permanganate index, ammonium (NH_4^+), major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, Mn^{2+}), major anions (Cl^-, HCO_3^-, NO_2^-, NO_3^-, CO_3^{2-}, SO_4^{2-}), total hardness (TH), total alkalinity (TAC), and total iron (FeT) concentration were analyzed. Additionally, the microbiological parameters, such as the fecal streptococci, fecal coliforms, and total coliforms were investigated. Fieldwork conducted over twelve campaigns during the 2021 and 2022 seasons involved sample collection from fifty-four locations across the six aquifers of the watershed. The comprehensive database facilitated the calculation of both MQI and WQI. Kriging interpolation was utilized to create spatial estimates of these indices beyond the sampling points, enabling the generation of maps that visualize water quality across the study area. WQI indicated that groundwater in most of the studied basin is of excellent quality, though water quality deteriorates in the areas receiving wastewater discharge from urban, industrial, and agricultural activities. The MQI results revealed significant pathogenic germ contamination across a substantial portion of the watershed, intensifying during the summer due to such factors as temperature, river flow, human activities, and seasonal pollution sources. These maps enhance the understanding of water table information for non-experts as well as aid decision-makers in identifying critical areas and developing effective management strategies. However, complexities in water quality and training data influence the accuracy of ArcGIS-Pro predictions, potentially overlooking key factors if the data is insufficient.

Keywords: water quality modeling, ArcGIS-Pro, interpolation, MQI- modeling, Oum Er-Rabia, groundwater.

INTRODUCTION

Groundwater is one of the most vital sources of drinking water globally, supplying over 50% of the world's potable water [Ali et al., 2022; Erickson et al., 2019; Rao et al., 2019]. In arid and semi-arid regions, rapid population growth and intensive development activities have significantly increased water demand [Ghavidelfar et al., 2017; Ali et al., 2021]. This heightened demand exerts immense pressure on groundwater resources, which are more susceptible to pollution than surface water [Shams et al., 2012]. Urban dwellers often face challenges in accessing potable water, sometimes necessitating long journeys [Dosu and Hanrahan, 2021]. Groundwater contamination presents a severe problem. Pollutants, including nitrogen and heavy metals, degrade water quality and pose significant health risks, such as hypertension, kidney stones, and other serious conditions [Khan et al., 2020; Wang et al., 2022]. Moreover, restoring contaminated groundwater to its original quality is both difficult and costly [Barbieri et al., 2019].

Water quality assessment was once an inaccessible field to the public, only achievable by experts. This was because it required on-site sampling, followed by tedious and time-consuming laboratory analysis. Moreover, these analyses produced a large volume of data that was difficult to interpret and did not necessarily represent the entire study area. The combined use of geographic information systems (GIS), such as Arc GIS-Pro, and water quality indices, such as the microbiological quality index (MQI) and the water quality index (WQI), proves to be a promising approach for modeling and predicting groundwater quality. This methodology offers a valuable tool for the effective and sustainable management of multiple issues related to these precious resources [Ouhakki et al., 2024].

The integration of WQI and MQI with GIS-Pro brings significant advantages and novelty to water quality assessment. Firstly, it enables the visualization of spatial and temporal variations in water quality across large geographic areas, providing a comprehensive overview that traditional methods lack. This integration allows for more accurate and real-time monitoring, facilitating early detection of contamination events and trends. Secondly, the use of GIS technology enhances the interpretation of complex data sets, transforming raw data into actionable insights. By overlaying various data layers, such as land use, pollution sources, and hydrological features, GIS-Pro helps identify potential sources of contamination and areas at risk. Lastly, this approach supports more informed decision-making for resource management and policy development, contributing to the sustainability and protection of water resources. Overall, the novel integration of these indices with GIS-Pro represents a significant advancement in the field of water quality assessment, offering a powerful and efficient tool for researchers, policymakers, and environmental managers. This approach reduces the analysis database into two simple and intuitive indices. Moreover, it allows predicting water quality at any point in the Oum Er Rbia watershed, making it accessible to non-experts. This simplification facilitates the understanding of groundwater quality and enables better decision-making for the sustainable management of this precious resource

Numerous studies have employed the WQI to evaluate the suitability of water for various purposes, including drinking, irrigation, and industrial use [Abbasnia et al., 2019; Dash and Kalamdhad, 2021]. As a powerful and versatile tool, WQI aids decision-makers in selecting the most effective pre-treatment methods to achieve specific water quality objectives. This is accomplished by aggregating the results of multiple water quality parameters, such as pH, dissolved oxygen, turbidity, and concentrations of various contaminants into a single numerical value. This holistic approach simplifies the complex and multifaceted nature of water quality assessment, making it more accessible and actionable for policymakers and water resource managers. The ability of WQI to distill extensive data into an easily interpretable format allows for more informed and timely decisions regarding water treatment processes, ultimately contributing to the protection of public health, the optimization of agricultural practices, and the enhancement of industrial operations [Fard et al., 2019; Giao et al., 2021].

In this sense, the MQI is a vital tool for assessing water quality, particularly in terms of microbial contamination (Hounsinou et al., 2015). By categorizing various microbiological parameters into distinct concentration classes, MQI provides a comprehensive evaluation of water safety and potential health risks (Bousnoubra, 20212). This index helps to identify and quantify the presence of harmful microorganisms, enabling the classification of water quality into clearly defined categories. Such detailed assessments are crucial for ensuring safe drinking water, guiding water management practices, and informing public health decisions (Hounsinou et al., 2015).

This study aimed to investigate the water quality of the Oum Er Rbia region using (WQI and MQI. Additionally, ArcGIS Pro was employed to generate maps that provide a clear visual representation of spatial variations in water quality across the basin. By utilizing ArcGIS Pro for spatiotemporal interpolation of WQI and MQI, this research aspired to develop a comprehensive model of groundwater quality that accounts for both spatial and temporal variations, offering a valuable tool for the assessment and management of groundwater resources in the basin.

MATERIALS AND METHODS

Study area

The experimental station is located in the central Atlantic region of Morocco, within the expansive Oum Er-Rbia watershed. This watershed spans a substantial length of 660 kilometers from east to west, covering an area of 47.032 km^2. Utilizing the Lambert coordinate system for Morocco, the geographical coordinates of the watershed extend from 31° 33' to 33° 32' North latitude and from 5° 06' to 9° 34' West longitude. This corresponds to a longitudinal range of 83.510 km to 306.978 km and a latitudinal range of 127.487 km to 531.050 km.

Turonian Aquifer of Tadla: composed of intensely karstified limestones and dolomitic limestones, the Turonian aquifer varies in thickness from 20 meters at the outcrops to 80 meters to the south, on the edge of the Atlasic domain, and even locally 100 meters (Boutirame et al., 2018). The water table shows significant seasonal variations due to varying recharge rates during wet and dry seasons.

Beni-Amir Aquifer: the Beni-Amir aquifer extends over the irrigated perimeter of Beni-Amir and the "bour" zones constituting its hydraulic continuity to the west over an area of 600 km² (Doubi et al., 2021). The aquifer flows through an alternation of marno-calcareous, lacustrine limestones, and conglomerates with a thickness generally between 50 and 100 meters. Seasonal fluctuations in water levels are notable due to irrigation practices and precipitation differences.

Beni-Moussa Aquifer: the Beni-Moussa aquifer covers an area of 885 km² (Ouatiki, 2021). Groundwater flows through mainly limestone and marl-limestone formations from the Villafranchian and early Quaternary periods, as well as silts and marls, and upper Quaternary sequences with recent Quaternary conglomerates. Differences in groundwater levels between seasons are significant, affecting water availability and quality. Tessaout-aval Aquifer: Covers an area of 500km^2. Groundwater mainly flows within the Plio-Quaternary clay-sandy and conglomeratic infill, which rests on the Eocene marls and transgresses into the Turonian limestones outcropping on the border anticlines. Seasonal variations impact the recharge and discharge rates of the aquifer.

Bahira Aquifer: the Bahira aquifer stretches from east to west over an area of 5.000 km^2 (Elgettafi et al., 2016). The two aquifers of the Bahira aquifer are constituted by secondary and tertiary formations covered by Neogene and Quaternary deposits in the plain. The secondary and tertiary formations outcrop to the north and dip to the south to terminate in a wedge against the Jbilet massif. Seasonal differences significantly affect the water table due to varying rainfall patterns.

Sahel and Doukkala Aquifer: covers an area of 6.000 km^2 along the Atlantic Ocean (Doubi et al., 2021), at the foot of the Rehamna Massif. The aquifer flows through Plio-Quaternary dune formations and Cretaceous limestone formations. Seasonal impacts are observed in the aquifer water levels, influenced by coastal climatic conditions and inland recharge variability.

Measured traits

To assess water quality across the Oum Er-Rbia watershed, the conducted study utilized a substantial dataset of physicochemical and microbiological data collected from groundwater sources. Over a two-year period (2021–2022), twelve bi-seasonal sampling campaigns were conducted at 54 stations, capturing data from both winter and summer months. This comprehensive approach, encompassing 648 water samples, provides a robust foundation for analyzing the water quality of the watershed. The analysis encompassed a range of physicochemical parameters, including pH, temperature (°C), conductivity (µS/cm), total dissolved solids (TDS), permanganate index, ammonium (NH_4^+), major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, Mn^{2+}), major anions (Cl^-, HCO_3^-, NO_2^-, NO_3^-, CO_3^{2-}, SO_4^{2-}), total hardness (TH), total alkalinity (TAC), and total iron (FeT). Additionally, three microbiological parameters were investigated, including: fecal streptococci, fecal coliforms, and total coliforms. Physicochemical analyses adhered to well-established protocols outlined in the AFNOR (1997) and Rodier et al. (1996) standards. The specific sampling locations are depicted in Figure 1. To analyze and visualize the collected data, Microsoft Excel 2010 was employed for data processing and ArcGIS Pro for generating informative maps.

Water quality index

The water quality index simplifies water quality assessment by providing a single score derived from established guidelines, such as

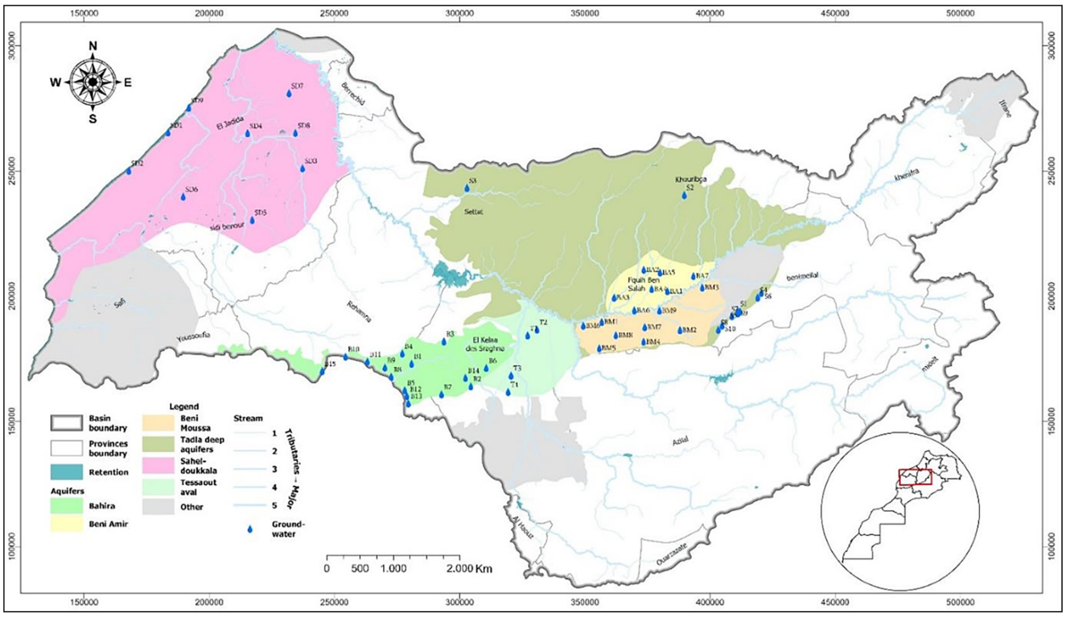

Figure 1. Map of the experimental stations

those from the WHO or national standards. This score, which is calculated using the 20 physicochemical parameters previously mentioned, categorizes water quality into ranges from "excellent" to "very bad," depending on how it aligns with these standards (Kanga et al., 2020). The weighted arithmetic method was employed to compute the WQI, assigning weights to each of the twenty parameters based on Moroccan water quality standards, with units in mg/L for all parameters except pH, temperature, and conductivity (Table 1). To determine the quality index (Qi)

Table 1. Relative weights (Wi) of physicochemical parameters

Parameters	Moroccan standard	S_i (maximum standard value, Morocco)	1/Si	Wi	K
pH	6.5-9.2	9.2	0.1087	0.0078	
T (°C)	20-30	30	0.0333	0.0024	
Cond (µs/cm)	750-2700	2700	0.0004	0.00002657630	
TDS (mg/l)	1000	1000	0.0010	0.0000718	
IP (mg/l)	10	10	0.1000	0.0072	
NH_4^+ (mg/l)	0.1–2	2	0.5000	0.0359	
Na^+ (mg/l)	200	200	0.0050	0.0004	
K^+ (mg/l)	10	10	0.1000	0.0072	
Ca^{2+} (mg/l)	200	200	0.0050	0.0004	
Mg^{2+} (mg/l)	150	150	0.0067	0.0005	1/∑(1/Si)= 0.0717565
Mn^{2+} (mg/l)	0.5	0.5	2.0000	0.1435	
Cl^- (mg/l)	250	250	0.0040	0.0003	
HCO_3^- (mg/l)	500	500	0.0020	0.0001	
NO_2^- (mg /l)	0.1	0.1	10.0000	0.7176	
NO_3^- (mg/l)	< 50	50	0.0200	0.0014	
CO_3^{2-} (mg/l)	500	500	0.0020	0.0001	
SO_4^{2-} (mg/l)	100-250	250	0.0040	0.0003	
TH (f°)	45.5	45.5	0.0220	0.0016	
TAC(f°)	45.5	45.5	0.0220	0.0016	
FeT (mg/l)	1	1	1.0000	0.0718	

for each parameter, its measured concentration was divided by the corresponding standard and then multiplied by 100.

Finally, the overall WQI was obtained by summing the product of each parameter's Qi and its weight:

$$(\Sigma(Q_i \times W_i) / \Sigma W_i) \quad (1)$$

This WQI score then categorizes the water quality into five distinct classes, as explained in Table 2. The relative weight (W_i) for each physicochemical parameter was calculated using the following formula, based on the Moroccan standard for surface water quality (Moroccan Water Quality Standard, 2002):

$$W_i = k/S_i \quad (2)$$

The WQI calculation using the following equation:

$$\frac{\sum_{i=1}^{n} Q_i \times w_i}{\sum_{i=1}^{n} W_i} \quad (3)$$

for the 54 samples collected across the entire study area in the groundwater during winter and summer.

Microbiological quality index

On the basis of the concentration of various microbiological indicators, such as total coliforms, fecal coliforms, and fecal streptococci, MQI is an important metric for water managers and decision-makers, as it allows tracking changes in water microbiological quality and taking corrective measures if necessary. The MQI assessment principle relies on the classification of pollutant values into five classes and the determination of the corresponding class number for each parameter, which are then averaged [Bousnoubra, 2012] (Table 3).

Interpolation modeling in ArcGIS Pro

The water quality modeling relies on interpolation, a technique that estimates values between known data points. This method assumes spatial continuity and requires precise, well-distributed data for accuracy. GIS-based IDW interpolation offers a robust approach compared to traditional methods. To compensate for limitations in data availability, this study employed GIS techniques to generate estimates of water quality throughout the entire watershed. This involved data collection, outlier treatment, interpolation method selection (IDW, Kriging, and Spline), parameter optimization, interpolation execution, and result validation. Finally, by generating thematic maps, spatial water quality patterns were visualized make informed management decisions. Integrating the WQI, MQI, and GIS enhances the accessibility and comprehension of water quality data in the Oum Er-Rabia watershed, even for non-experts (Supardi et al., 2023). This project specifically utilized WQI, (MQI) levels, and GIS to create informative maps that effectively communicate the quality of groundwater across the entire watershed.

Data analyses

To thoroughly evaluate the variations in water quality indices across six experimental stations, a descriptive statistical analysis of the dataset from each station was conducted. This analysis aimed to summarize measures of central tendency and dispersion for each water quality index. Utilizing SPSS v22, an analysis was performed to detect significant differences between the stations. This approach enabled a detailed examination of the variations in physicochemical parameters across the different monitoring sites.

Table 2. WQI scal based on the Yadav et al. [2010]

WQI	0–25	26–50	51–75	76–100	Above 100
Water quality	Excellent	Good	Poor	Very poor	Unsuitable

Table 3. Class numbers corresponding to each parameter used in the determination of the MQI

Parameter	1	2	3	4	5
Total coliforms	< 2000	2000–9000	9000–45000	45000–360000	> 360000
Fécal coliforms	< 100	100–500	500–2500	2500–20000	> 20000
Fécal streptococci	< 5	5–10	10–50	50–500	> 500
MQI	1.0–1.8	1.9–2.6	2.7–3.4	4.3–5.0	4.3–5.0
Contamination	none	low	Moderate	high	very high

RESULTS AND DISCUSSION

Water quality index

The Sahel Doukkala, Tassaout, Bahira, and Tadla aquifers demonstrate water quality ranging from excellent to good throughout both winter and summer seasons. This consistent quality is evident from the WQI observed in the Sahel Doukkala, Bahira, and Beni Moussa aquifers, which exhibit elevated values (Table 4). These elevated WQI values are attributed to the heightened evaporation rates and diminished precipitation, resulting in the increased concentration of pollutants, as corroborated by Bahir et al. [2024].

In contrast, the Beni Amir aquifer experiences elevated pollution levels during winter, while the Beni Moussa aquifer shows higher pollution levels in summer [Barakat, 2020]. This seasonal fluctuation in pollution is predominantly due to the enhanced transport of pollutants driven by agricultural runoff and seasonal rainfall. The spatial distribution of WQI, as illustrated in Figures 2 and 3, was meticulously mapped utilizing GIS technologies, specifically employing the ArcGIS Pro tool. These findings are in agreement with previous research, which has documented similar seasonal variations and influences of climatic factors on groundwater quality across different aquifer systems. For instance, similar patterns of seasonal pollutant variations have been observed in other regions, further validating the observed trends in the present study [Smith et al., 2021; Nguyen et al., 2019].

On the basis of the WQI assessment, the overall water quality within the majority of the watershed ranges from good to excellent. However, significant degradation in water quality has been detected in the Beni Moussa and Beni Amir aquifers, as well as in the downstream section of the Tadla aquifer, specifically between Zawyat Cheikh and Beni Mellal. This deterioration can be attributed to several anthropogenic factors, including uncontrolled landfills, the discharge of untreated wastewater, and the application of manure and poultry farm waste as soil fertilizers, as corroborated by Chaaou et al. [2022]. Similarly, the Tassaout aquifer in the Kelaat Sraghna region exhibits poor water quality near urban centers, with gradual improvement observed at increasing distances from these areas. The groundwater quality of the Tadla aquifer is further compromised by urban waste and the infiltration of wastewater associated with urban activities, as evidenced by the findings of El Hammoumi et al. [2013]. These observations highlight the critical impact of urban and agricultural practices on aquifer water quality, necessitating the

Table 4. WQI values for different analyzed traits

Stations	Values of WQI		Stations	Values of WQI		Stations	Values of WQI	
	Winter	Summer		Winter	Summer		Winter	Summer
B1	11.76	11.11	BA4	191.79	11.700	S6	190.06	10.35
B2	12.49	10.75	BA5	12.99	12.28	S7	19.26	17.55
B3	26.73	19.03	BA6	128.40	19.23	S8	60.61	10.36
B4	41.70	11.08	BA7	44.27	31.17	S9	10.69	10.24
B5	11.90	11.25	BM1	51.29	11.67	S10	10.52	10.72
B6	19.24	52.23	BM2	10.75	10.44	SD1	12.74	15.37
B7	19.36	18.11	BM3	10.86	11.19	SD2	11.96	41.72
B8	11.66	10.68	BM4	18.44	17.88	SD3	28.92	11.94
B9	19.18	10.65	BM5	11.97	564.02	SD4	19.94	12.10
B10	18.80	10.89	BM6	28.33	12.82	SD5	11.59	18.97
B11	12.00	241.60	BM7	19.82	39.94	SD6	12.50	19.67
B12	11.19	11.03	BM8	34.00	11.68	SD7	18.12	25.09
B13	11.26	18.43	BM9	18.37	10.72	SD8	12.4	20.30
B14	20.92	12.21	S1	10.91	10.20	SD9	28.60	49.54
B15	26.17	11.18	S2	12.08	26.09	T1	18.40	10.67
BA1	20.81	83.70	S3	25.71	10.36	T2	11.10	10.77
BA2	71.80	14.30	S4	10.89	10.50	T3	50.24	12.15
BA3	45.21	25.63	S5	17.90	10.32	T4	18.08	10.64

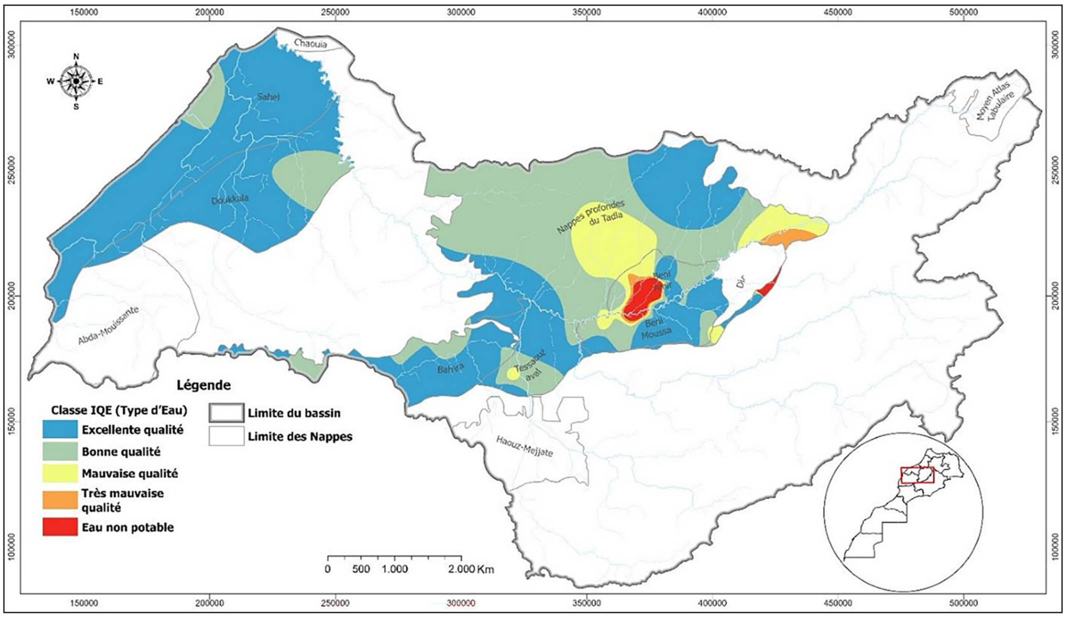

Figure 2. Groundwater quality index (WQI) map during the winter season

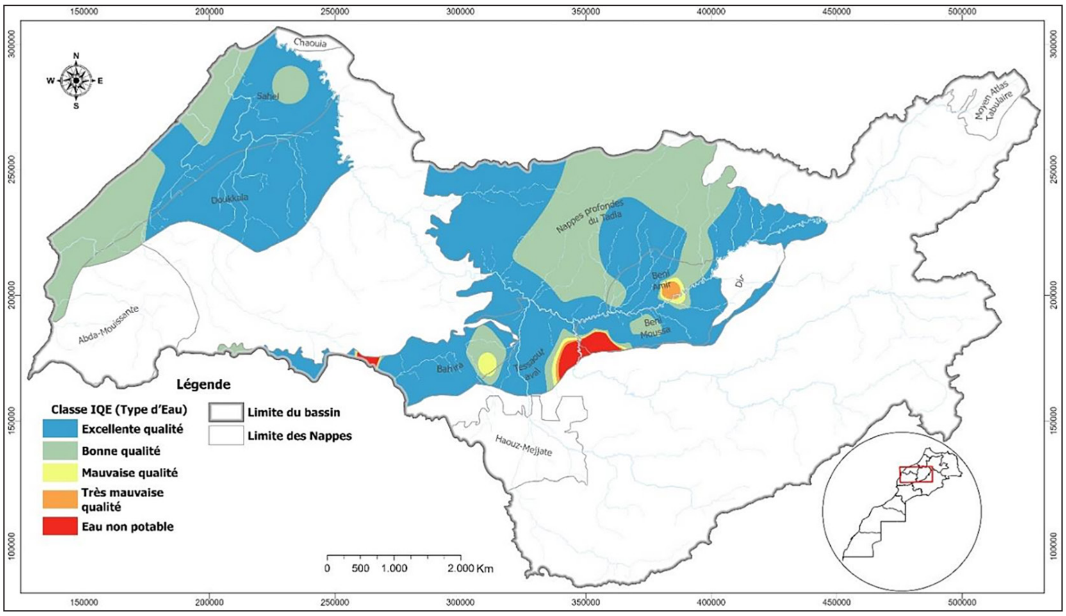

Figure 3. Groundwater quality index (WQI) map during the summer season

implementation of stringent management and remediation strategies. During the summer months, the majority of the Oum Er-Rbia watershed exhibits excellent water quality (Table 5).

However, specific regions experience significant deterioration, notably the northeastern section of the Beni Amir aquifer, the southwestern portion of the Beni Moussa aquifer, and the Tassaout aquifer, predominantly around the city of Kelaat Sraghna. This decline in water quality is primarily attributable to the discharge of urban and industrial wastewater, along with intensive agricultural activities that exert considerable pressure on the watershed integrity. Consequently, these factors culminate in marked water quality degradation. Conversely, the central, western, and northern sectors of the watershed demonstrate low levels of pollution, characterized by minimal concentrations of physicochemical elements that generally adhere to Moroccan drinking water standards. The observed low pollution levels in these regions can be attributed to several factors, including naturally low soil fertilizer loads, agricultural practices that effectively minimize

Table 5. Statistical description of the WQI values in the different aquifers of the Oum Errabia watershed

Aquifer	Bahira		Beni Amir		Beni Moussa		Turonian Of Tadla		Sahel-Doukkala		Tessaout-Aval	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Aver.	18.29	30.69	73.62	28.29	22.65	76.71	36.86	12.67	17.43	23.86	24.48	11.06
Min.	11.19	10.65	12.99	11.70	10.75	10.44	10.52	10.20	11.59	11.94	11.15	10.64
Max.	41.70	241.67	191.79	83.70	51.29	564.02	190.06	26.09	28.92	49.54	50.24	12.15
Stand.	8.13	57.31	59.89	23.59	12.56	172.52	53.07	4.96	6.67	12.41	15.15	0.63

leaching, as well as rigorously controlled urban and industrial wastewater discharge. These findings are consistent with prior research by Elbana et al. [2019], which also reported similar outcomes regarding the influence of agricultural and urban activities on water quality dynamics.

The comparative analysis of the two generated maps reveals a significant seasonal variation in watershed water quality, as measured by WQI, with superior quality observed during the summer months relative to winter. This disparity can be attributed to a complex interplay of environmental factors. In winter, elevated river flows driven by precipitation and snowmelt enhance the transport of pollutants from agricultural runoff and precipitation events, corroborating the findings of Banaszuk et al. [2013]. Concurrently, lower winter temperatures impede the degradation of organic matter, thus promoting pathogen persistence, a phenomenon previously noted by Melek [2012]. Reduced sunlight exposure during the winter months further hinders algal growth, which is essential for oxygenation and water purification, aligning with the observations by Singh and Singh (2015). Additionally, increased heavy rainfall in winter exacerbates wastewater infiltration and soil erosion, contributing to heightened river pollution and subsequent water quality deterioration, as supported by Issaka and Ashraf [2017]. Therefore, the interaction of these environmental variables culminates in markedly lower water quality during winter as compared to summer.

Microbiological quality indices

The calculation of the MQI values for the aquifers of the Oum Er-Rbia watershed, presented in Table 6, and the statistical descriptions

Table 6. IQM values for different analyzed traits

Stations	Values de IQE		Stations	Values de IQE		Stations	Values de IQE	
	Winter	Summer		Winter	Summer		Winter	Summer
B1	3.30	3.30	BA4	2.00	1.70	S6	1.30	1.00
B2	1.00	1.70	BA5	1.00	2.70	S7	2.00	4.70
B3	4.70	2.30	BA6	4.00	4.30	S8	1.70	2.70
B4	1.70	2.00	BA7	4.00	2.70	S9	2.00	3.00
B5	1.70	1.70	BM1	2.00	1.70	S10	1.00	1.70
B6	1.70	5.00	BM2	2.30	1.30	SD1	3.00	1.70
B7	1.70	3.70	BM3	1.00	2.70	SD2	2.30	3.70
B8	1.00	1.70	BM4	2.30	3.30	SD3	3.70	2.00
B9	2.00	2.00	BM5	2.30	3.70	SD4	3.70	4.00
B10	1.30	1.00	BM6	2.70	3.30	SD5	1.70	1.70
B11	1.70	1.70	BM7	2.00	4.00	SD6	1.70	3.70
B12	1.30	3.00	BM8	1.00	3.30	SD7	3.70	3.70
B13	1.00	4.00	BM9	2.00	2.70	SD8	2.30	3.30
B14	1.70	2.00	S1	1.30	1.00	SD9	3.30	4.30
B15	1.00	1.70	S2	3.30	4.00	T1	2.00	4.30
BA1	3.70	4.70	S3	2.30	3.00	T2	1.00	1.30
BA2	1.70	1.30	S4	1.00	3.30	T3	3.00	2.00
BA3	1.70	3.30	S5	2.00	3.70	T4	1.00	1.70

of the mean WQI values for 54 sites across six aquifers during the winter and summer seasons of 2021 and 2022, presented in Table 7, reveal critical insights into groundwater quality variations.

Statistical analysis of MQI values indicates that during winter, the Bahira, Beni Moussa, Tadla, and Tassaout aquifers exhibit low microbiological contamination. In contrast, the Beni Amir aquifer shows moderate contamination, and the Sahel Doukkala aquifer demonstrates the highest level of contamination. In summer, the Bahira and Tassaout aquifers experience moderate microbiological contamination, while other aquifers face high levels of microbial contamination. These findings are consistent with previous research, which identified similar contamination patterns due to seasonal and environmental factors [Ratikane, 2013; Macaulay et al., 2018].

Areas with elevated groundwater contamination typically share common features, such as non-compliant septic tanks and latrines that leak fecal matter into the ground, agricultural zones utilizing manure as fertilizer, and proximity to urban areas. These conditions contribute to groundwater contamination through the discharge of untreated wastewater and solid waste leachate rich in microbes [El Badraoui and Berdai, 2011; Ratikane, 2013].

Figures 4 and 5 illustrate the spatial distribution of the MQI index in the investigated aquifers during the winter and summer seasons. The Sahel Doukkala aquifer, particularly the northern areas around Sidi Benour and Sidi Abd Allah, exhibits significant bacterial contamination in winter due to intense human activities, such as agriculture, agro-industrial operations, and urban wastewater discharge. Conversely, the southern part of the aquifer maintains low microbiological contamination, making the water suitable for various uses, including human consumption. Similar patterns have been reported by other studies [El Badraoui and Berdai, 2011].

In the deep Tadla aquifer, the northern region between Oued Zem, Khouribga, and Bejaad

Table 7. Statistical descriptions of IQE values in the different aquifers of the Oum Er Rbia watershed

Aquifer	Bahira		Beni Amir		Beni Moussa		Tadla		Sahel Doukkala		Tassaout	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Aver.	1.79	2.45	2.59	2.96	1.96	2.89	1.79	2.81	2.82	3.12	1.75	2.33
Min.	1.00	1.00	1.00	1.30	1.00	1.30	1.00	1.00	1.70	1.70	1.00	1.30
Max.	4.70	5.00	4.00	4.70	2.70	4.00	3.30	4.70	3.70	4.30	3.00	4.30
Stand.	0.96	1.07	1.18	1.16	0.55	0.84	0.66	1.18	0.79	0.97	0.83	1.17

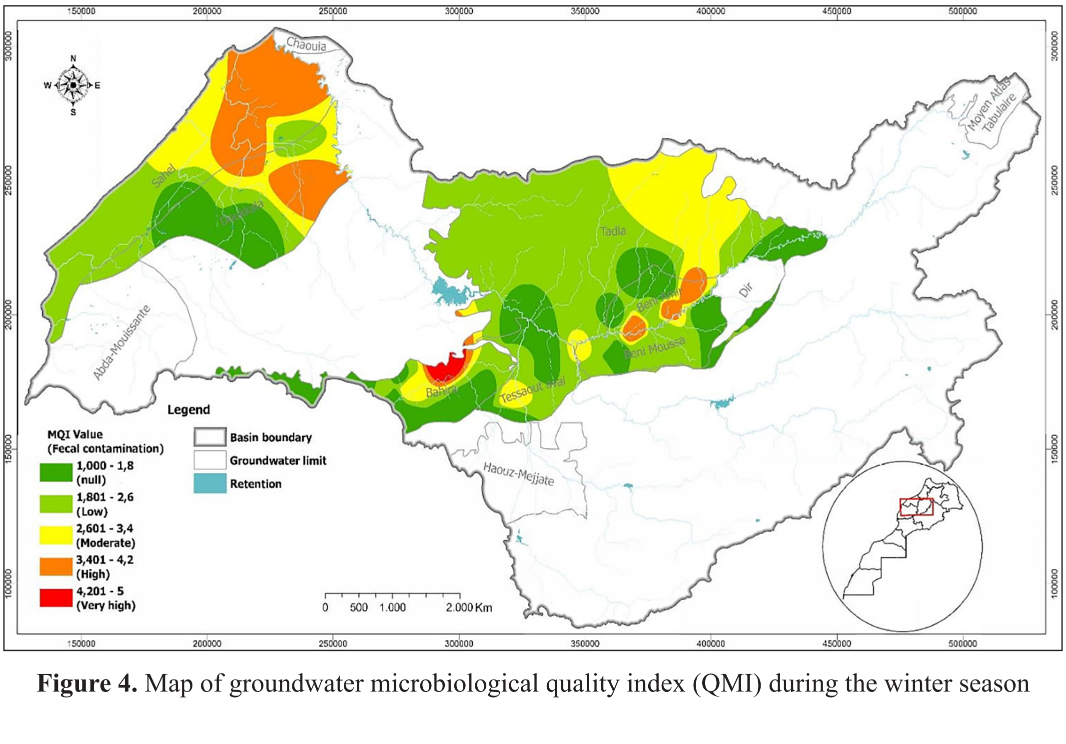

Figure 4. Map of groundwater microbiological quality index (QMI) during the winter season

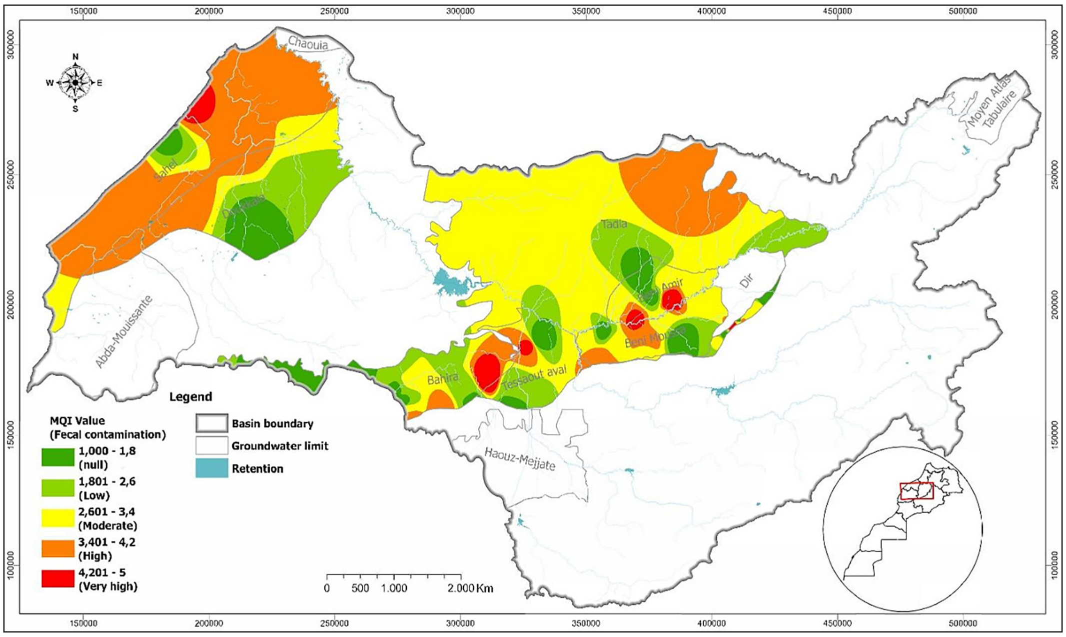

Figure 5. Groundwater microbiological quality index (QMI) map during the summer season

shows moderate water quality, while the area around Kasbat Tadla faces severe water quality issues. This disparity arises from factors such as population density, sources of contamination, and geological characteristics affecting contaminant dispersion. These findings align with the research by Benamar et al. [2019] and Barakat et al. [2016], which highlight the influence of urbanization and industrial activities on groundwater quality.

The water quality of the Beni Moussa aquifer deteriorates around urban centers like Benimelal, improving progressively with distance from the city. Similarly, the Beni Amir aquifer near Fkih Ben Salah and El Borj shows poor microbiological quality due to local contamination sources, corroborated by studies from El Baghdadi et al. [2019] and El Hammoumi et al. [2013]. The Bahira aquifer around Kelaat Sraghna also demonstrates very poor water quality, consistent with findings from Ali et al. [2018].

During the summer, the Sahel Doukkala aquifer remains highly contaminated, particularly in the coastal zones, except for the Doukkala area, which maintains good water quality [Adnani et al., 2020]. The Beni Amir and Beni Moussa aquifers continue to suffer from high bacterial contamination, with only the mountainous regions showing low microbiological levels. The Tadla aquifer around Khouribga and Oued Zem poses a high health risk due to severe contamination. The Bahira and Tassaout aquifers also display increased areas of poor-quality water during summer, reflecting a seasonal contamination pattern.

Winter conditions contribute to lower WQI due to reduced microbial growth from lower temperatures and increased dilution from higher precipitation, which aligns with findings by Al-Afify et al. [2019] and Sprenger et al. [2011]. Reduced human activities further decrease bacterial loads in water [Gerba, 2000]. Conversely, summer conditions, characterized by higher temperatures, lower river flows, and increased human activities, elevate WQI, corroborating the studies by Brock [1970], Pachepsky and Shelton [2011], Nilsson and Renöfält [2008], and Currell et al. [2012]. These seasonal dynamics underscore the significant impact of environmental and anthropogenic factors on groundwater quality in the Oum Er-Rbia basin.

CONCLUSIONS

A comprehensive investigation conducted within the Oum Er-Rbia basin utilizing GIS, WQI, and MQI has produced spatially explicit water quality maps. The WQI results predominantly indicate excellent water quality throughout the majority of the basin. Conversely, MQI reveals pervasive pathogen contamination, particularly accentuated during the summer months, suggesting a seasonal correlation with temperature fluctuations, river discharge rates, and anthropogenic activities. The successful integration of WQI, MQI, and GIS methodologies underscores a robust framework for water resource management, delivering pivotal insights essential for formulating sustainable water policies and enhancing environmental protection measures. The findings from this study suggest several policy implications for groundwater management in the Oum Er-Rbia basin. Firstly, the identification of pathogen contamination hotspots calls for the implementation of targeted sanitation and waste management strategies, particularly in the areas with high anthropogenic activity. Seasonal variations in water quality underscore the need for adaptive management practices that consider temperature fluctuations and river discharge rates.

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