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Assessment of groundwater pollution using PIG index and microbiological indicators in the Angads plain, Morocco

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This study assessed the hydrochemical quality of groundwater in the Angads plain using the pollution index of groundwater (PIG), and microbiological indicators. Two sampling campaigns were carried out in 2023 (wet and dry seasons), with 45 samples taken each year. The analyses revealed that the majority of the ions studied exceeded the limits recommended and authorized by the World Health Organization (WHO). The PIG revealed that over 80% of samples fall into the insignificant and low pollution categories, with pollution levels increasing during the dry season. Microbiological analyses revealed the presence of fecal coliforms (FC), total coliforms (TC), intestinal enterococci (IE) and sulfate-reducing clostridium (SRC) with average levels of 52, 80, 2, and 0 CFU/100 mL during the wet season, while during the dry season these values increased to 79, 120, 3, and 0 CFU/100 mL, respectively. This study offers vital information on groundwater pollution, enabling decision makers, residents, and scientists to better identify safe water sources and areas at risk. The findings highlight the urgency of implementing effective treatment solutions and devising sustainable management plans to preserve these water resources over the long term.

Keywords Groundwater, Microbial water quality, PIG, Angads plain, Morocco

Water resources are a fundamental pillar for economic development and the support of various socio-economic sectors[1,2]. Although water covers around 70% of the surface area on Earth, only 3% of the total is freshwater, which is indispensable to life[3,4]. Among these limited reserves, groundwater stands out for its crucial importance, providing a reliable source of freshwater for around 80% of the planet's population. Around 23% of the world's freshwater reserves are underground, which is essential for drinking water supplies, providing around half the world's drinking water and 43% of the water used to irrigate agricultural land[5].

In arid and semi-arid regions such as Morocco, groundwater is vital for meeting water needs[6]. However, these precious resources are threatened by anthropogenic pollution such as intensive agricultural practices, marked by the excessive use of pesticides, fertilizers and manure, as well as natural degradation, affecting around 31% of Moroccan groundwater[7,8]. More than pollution, the combination of increased water demand and reduced rainfall due to climate change is exerting increasing pressure on these resources. In recent decades, the city of Oujda, located on the Angads plain, has experienced demographic, cultural and industrial growth. Groundwater has become a key resource for meeting the growing water needs of all sectors, with the city currently drawing 63% of its drinking water demand from groundwater. Moreover, most of the inhabitants of the rural communes in the study area are not connected to the water distribution network, which means that groundwater is the main source of water for their consumption.

Assessing groundwater quality is therefore essential to ensure that it remains safe and usable for a variety of applications[9–11]. This assessment is often complex, requiring the analysis of numerous parameters. The water

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quality index approach is particularly useful in this context, as it enables large quantities of data to be synthesized into clear, accessible information for managers and the public[12,13]. Among the most popular indices is the PIG index introduced by[14]to classify groundwater into different pollution zones. Recent studies have combined the PIG index with other indices and techniques to better assess water pollution. In the rural area of Telangana state, India, a study applied the Entropy Weighted water Quality Index (EWQI) with the PIG to assess groundwater[9]. Other studies have sought to improve the PIG by integrating objective weightings (the Entropy-PIG model and the CRITIC-PIG model), enabling more reliable assessments of groundwater quality[15]. While in the Gharb plain in Morocco, a study combined the PIG with multivariate analyses to identify sources of pollution[7]. Although the PIG is a robust method for assessing groundwater pollution, recent research is tending to improve it or combine it with other indices and analytical techniques to obtain more accurate and comprehensive assessments.

Therefore, the current study aims to use a combination of the PIG index with microbiological indicators, since the PIG is based just on physicochemical parameters in its calculation which does not constitute a complete assessment of water quality, to evaluate pollution level and to assess the potential impact on public health for a more comprehensive assessment of groundwater quality. In addition, this study aims to establish a spatial database of water quality using Geographic Information Systems (GIS), which has proven to be a useful means of mapping and analyzing spatial variations in groundwater quality, providing invaluable support for water resource management and informed decision-making for the protection and sustainable use of aquifers. Furthermore, the findings of our research may provide the framework for the future design of predictive groundwater models to quantify the effects of pollutants on groundwater quality.

Materials and methods

Study area

The Angad plain, located in northeastern Morocco (Fig. 1), covers an area of 460 km² and is populated by over 550,000 people. This population density contributes to the specificity of its demographic and socio-economic environment. The climate of the region studied is typically semi-arid to arid Mediterranean. It is characterized by mild to cold, rainy winters and warm summers. The dry season extends from May to September, while the wet season is from October to April. Average annual temperatures range from a minimum of 10.1 °C to a maximum of 27.4 °C. The region receives over 264.5 mm of annual precipitation[16].

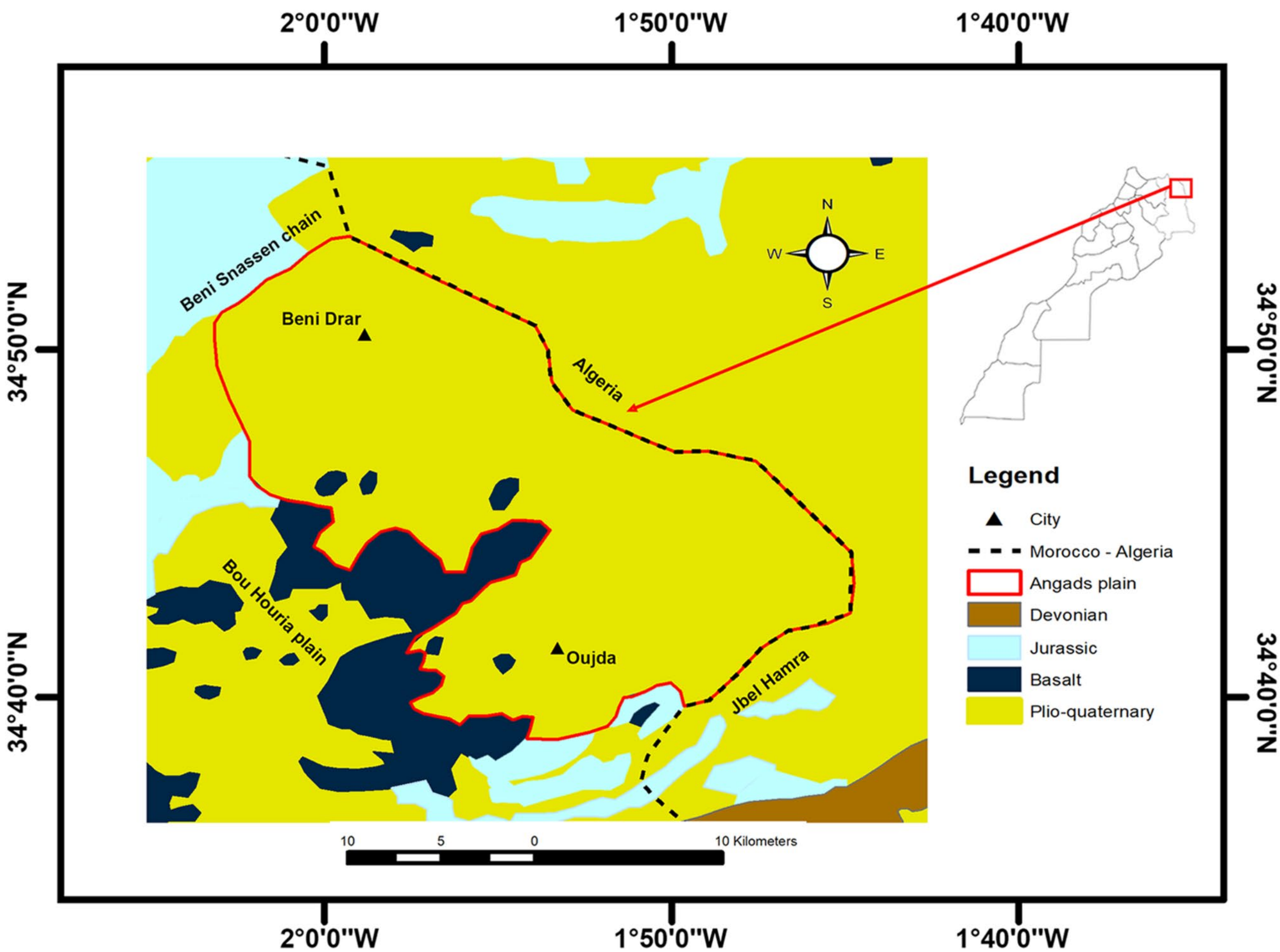

Fig. 1. Map showing study area location and geology (Generated by: ArcGIS 10.8, Link: www.esri.com).

The Angad plain is a vast east-west trough, characterized by two distinct lithostratigraphic units, separated by a marked angular unconformity. The first, of marine origin, is composed of limestones, conglomerates and blue and yellow marls. On the periphery of the depression, these formations evolve towards volcanodetritic or reef facies, with intercalations of basalt flows[17]. This geological unit, rich in fossils, has been dated from the Upper Tortonian to the Messinian. The second, younger unit, of continental origin, consists of fossil-free detrital or volcanodetritic deposits with interbedded basalt flows. Both units rest unconformably on a Mesozoic basement.

In terms of hydrogeology, two main water tables have been identified. The first is found in the shallow Quaternary formations, while the second, deeper and captive, circulates in the Jurassic dolomitic limestones (Fig. 2). The post-Miocene terrain rests on an impermeable base of Upper Miocene marl, which also acts as a cover for the deep aquifers. The aquifers display a high degree of lateral heterogeneity, consisting of various facies such as conglomerates, compact and fissured basalts, silts, basaltic ashes, lacustrine limestones, cinerites and gravels, thus complicating groundwater dynamics in the region[18].

Local rainfall is the main source of aquifer recharge. Rainwater infiltration recharges the aquifers, with a general south-west to north-east flow in the study area[19], underlining the essential role of local climatic conditions in the renewal of groundwater resources.

Groundwater sampling and laboratory analysis

We collected 90 groundwater samples, with 45 samples taken in May 2023 (wet season) and 45 in October 2023 (dry season), at different wells surrounding the study region (Fig. 3). To ensure that the groundwater collected was not stagnant, groundwater samples were collected after 15 to 20 min of continuous drilling. One-liter polypropylene bottles rinsed twice with distilled water and soaked in a 10% HCl solution for 24 h, were used to collect groundwater samples. Samples were stored at 4 °C until analysis. A portable TDS meter, with an accuracy of ± 1%, was used in the field during the groundwater sample to measure total dissolved solids (TDS) values. The procedures described by the American Public Health Association were used to measure the main anions and cations[20]. Each analysis was performed in triplicate to ensure consistent results. The detection methods used for cations and anions analysis are detailed in Table 1.

Bacteriological analyses were carried out in 2023 (wet and dry seasons) on 28 groundwater samples to assess indicators of fecal contamination, including Total Coliforms (TC), Fecal Coliforms (FC), Intestinal Enterococci (IE), *Escherichia coli* (*E. coli*), and Sulfate-Reducing Clostridium (SRC) (Fig. 3). This analysis was based on the

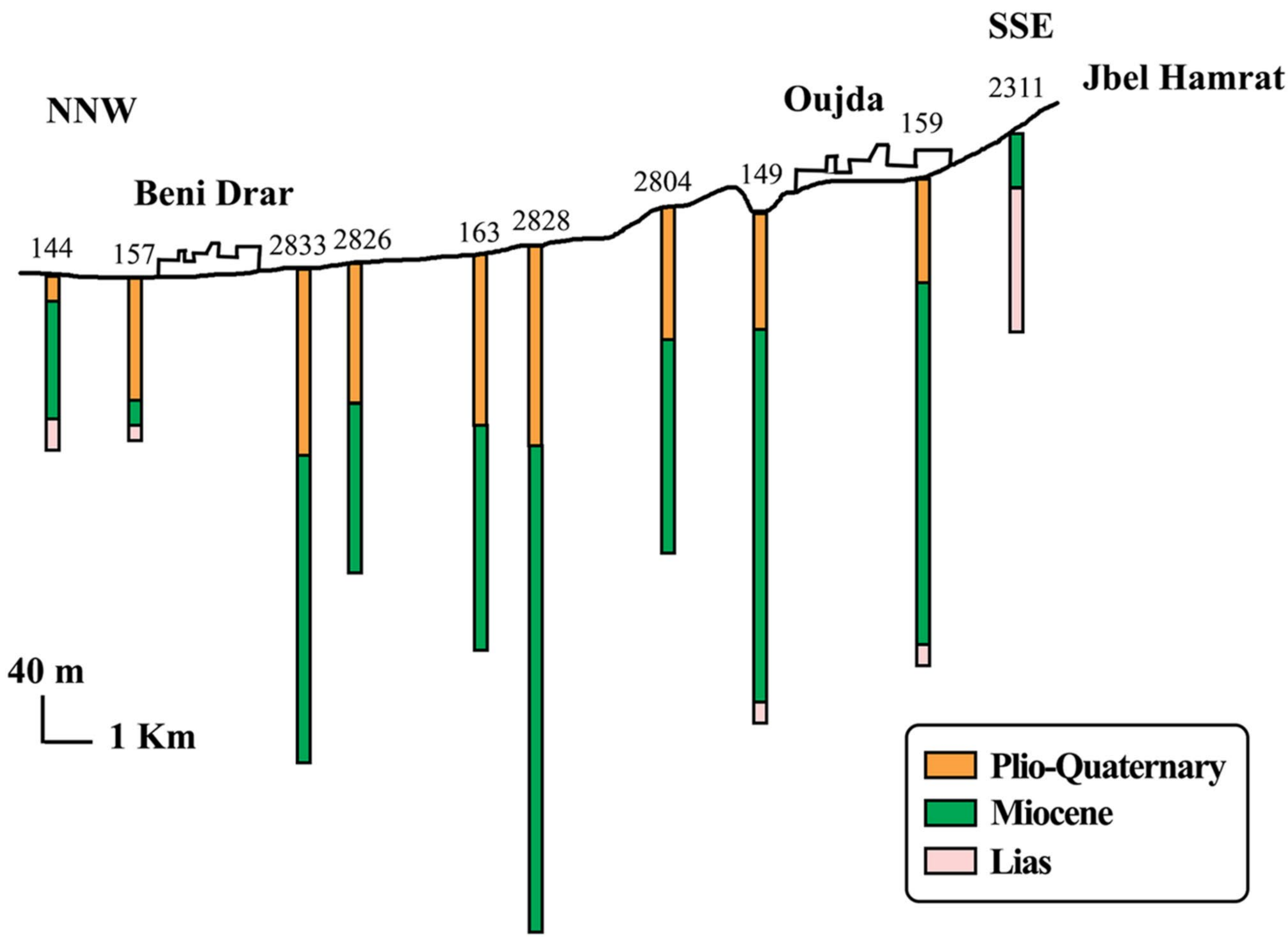

Fig. 2. Hydrogeology of the study area[17].

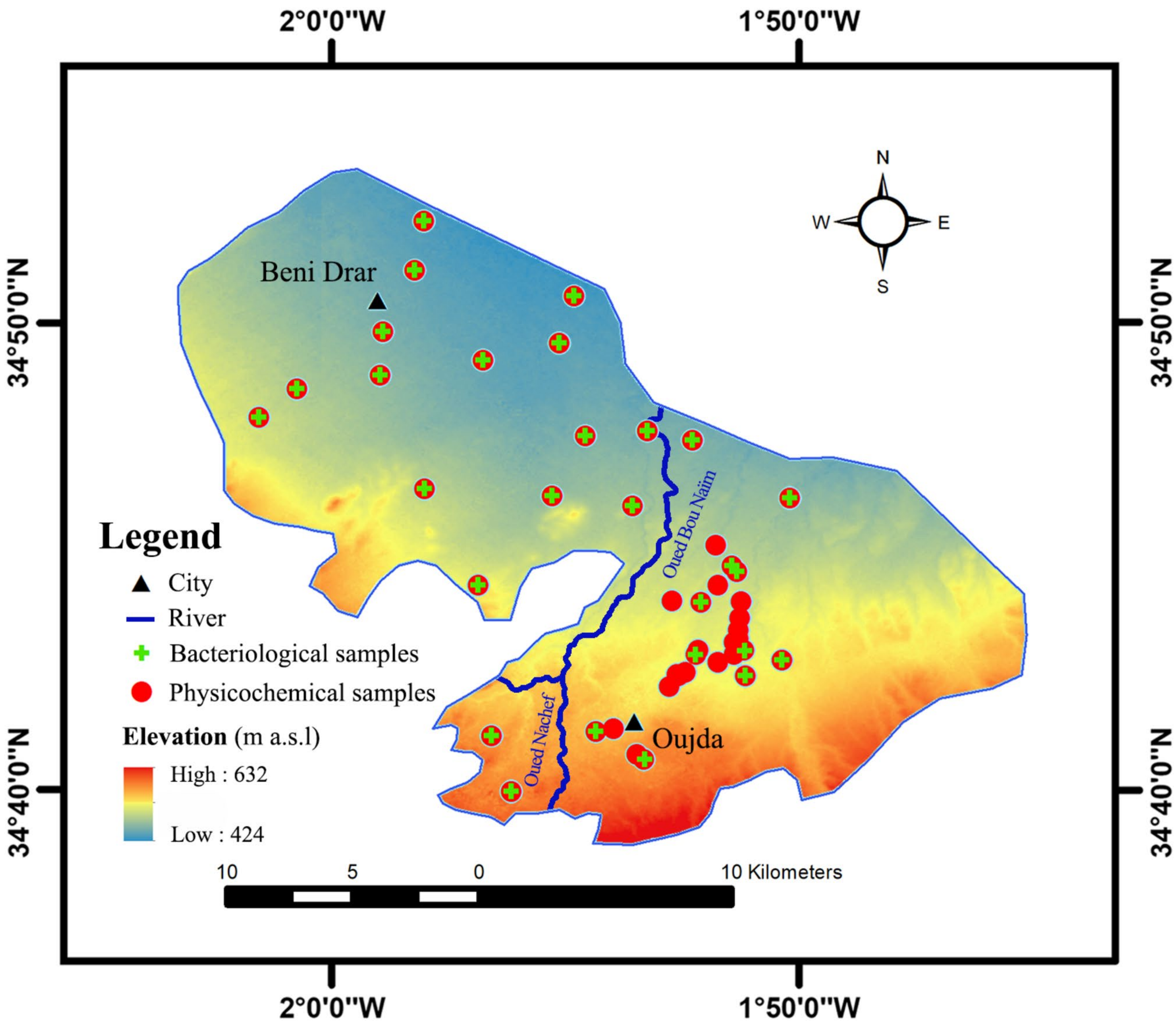

Fig. 3. Location of wells in the study area (Generated by: ArcGIS 10.8, Link: www.esri.com).

Parameter	Analysis method	Reference
Total dissolved solids	TDS meter	[20]
Sodium	Flame photometric	
Potassium	Flame photometric	
Magnesium	Titration using EDTA	
Calcium	Titration using EDTA	
Chloride	Titration using $AgNO_3$	
Bicarbonate	Titration using HCl	
Sulfate	Spectrophotometry	
Nitrate	Spectrophotometry	

Table 1. Physicochemical parameter detection methods.

standard procedures of the Moroccan drinking water quality standard[21]. The membrane filtration method was used: each 100-milliliter sample was filtered through a 0.45 µm cellulose ester membrane for CT, CF, IE, and *E. coli*, while 0.22 µm for SRC. The filters were then placed on selective culture media and incubated at specific temperatures (Table 2). After incubation, the colonies were counted and expressed as colony-forming units (CFU) per 100 ml of sample. Each analysis was performed in triplicate to ensure consistent results.

Parameter	MSMAV	WHO	Incubation T°C	Culture media
FC (ISO 9308-1)	0	0	44	Tergitol 7 and TTC agar
TC (ISO 9308-1)	0	0	37	Tergitol 7 and TTC agar
E. coli (ISO 9308-1)	0	0	37	MacConkey agar
IE (ISO 7899-2)	0	0	37	Slanetz and Bartley agar
SRC (ISO 6461-2)	0	0	37	TSC agar

Table 2. Bacteriological analysis methods. MSMAV : Moroccan standards maximal allowable value (CFU/100 mL)[21]. WHO : World Health Organization standards limit (CFU/100 mL)[22].

Parameter	Unit	WHO guidelines	R_w	W_p
TDS	mg/L	1000	5	0.152
Ca^{2+}	mg/L	200	3	0.091
Mg^{2+}	mg/L	150	3	0.091
Na^{+}	mg/L	200	4	0.121
K^{+}	mg/L	12	3	0.091
Cl^{-}	mg/L	250	4	0.121
SO_4^{2-}	mg/L	250	4	0.121
HCO_3^{-}	mg/L	300	2	0.060
NO_3^{-}	mg/L	50	5	0.152

Table 3. WHO guidelines[22]and weight values[7].

Analysis accuracy

The ion balance error, less than 5% and considered acceptable, was calculated using Eq. (1) to assess the analytical precision of each sample[23].

$$IBE = \frac{\sum Cations - \sum Anions}{\sum Cations + sum\ Anions} \times 100 \quad (1)$$

Pollution index of groundwater (PIG)

Developed by[14], the PIG offers a comprehensive approach to assessing the quality of groundwater, taking into account variations that influence its global quality. In recent years, the use of the PIG has increased[5,24–26]. The PIG was determined in five steps. First, a relative weight (R_w) was attributed to every physicochemical parameter (ranging from 1 to 5), according to its effect on human health (Table 3). Secondly, the parameter weight (W_p) was determined for every physicochemical variable using Eq. (2), making it possible to evaluate its relative contribution to global water quality (Table 3).

$$W_p = \frac{R_w}{\sum R_w} \quad (2)$$

Thirdly, by dividing the concentration of every physicochemical variable (C) in every groundwater sample by its drinking water quality limit (D_c), the concentration status (S_c) was calculated, as shown in the following Eq. (3).

$$S_c = \frac{C}{D_s} \quad (3)$$

Fourthly, the global groundwater quality (O_w) was calculated by multiplying S_c by W_p (Eq. (4)).

$$O_w = W_p \times S_c \quad (4)$$

Finally, the PIG was determined by summing all O_w values, encompassing all physicochemical variables for each water sample as shown in Eq. (5), to obtain an overall view of the impact of contamination on the aquifer.

$$PIG = \sum O_w \quad (5)$$

To evaluate PIG, it is essential to examine the contribution of the physicochemical variables present in each groundwater sample. The PIG is classified into different categories according to value ranges: insignificant pollution is attributed to values below 1.0, low pollution corresponds to values between 1.0 and 1.5, between 1.5 and 2.0 moderate pollution, high pollution is indicated by values ranging from 2.0 to 2.5, and for values above 2.5 very high pollution[14].

Geospatial assessment

ArcGIS is a crucial tool for modeling and predicting the spread of pollutants in aquatic ecosystems. It enables data to be visualized, analyzed, and interpreted, facilitating decision-making in urban planning and environmental management[27]. Using ArcGIS, it is possible to create maps showing the spatial distribution of water quality parameters and pollution indices, clearly illustrating variations in groundwater concentration in the area under study[28,29]. This tool provides an overview of the state of pollutants, enabling current conditions to be assessed, the evolution of pollution to be forecast and its future impact to be anticipated[30,31]. Spatial distribution maps were produced using the inverse distance weighting (IDW) interpolation method.

Results and discussions

Groundwater chemistry

Figures 4 and 5 show the spatial distribution of the main parameters analyzed, while Fig. 6 show the percentage of samples exceeding the WHO standard. According to mean concentrations, the predominant anion is Cl^-, followed by HCO_3^-, SO_4^{2-} and NO_3^-. As for cations, Na^+ is the predominant ion, followed by Ca^{2+}, Mg^{2+}, and K^+.

TDS represents the quantity of inorganic and organic substances dissolved in water, which increases with the presence of dissolved minerals[24]. Water with a TDS concentration greater than 1000 mg/L is classified as unfit for drinking[22]. TDS values range from 812 to 3664 mg/L, with a mean of 1604.4 mg/L for the wet season, and from 933 to 3854 mg/L, with a mean of 1745.1 mg/L for the dry season, which suggests that most of the region's groundwater is highly mineralized. Studies in Morocco have revealed similar results, notably in the Bokoya massif, where mean TDS values of 2019 mg/L have been reported, indicating strong groundwater mineralization[26]. At

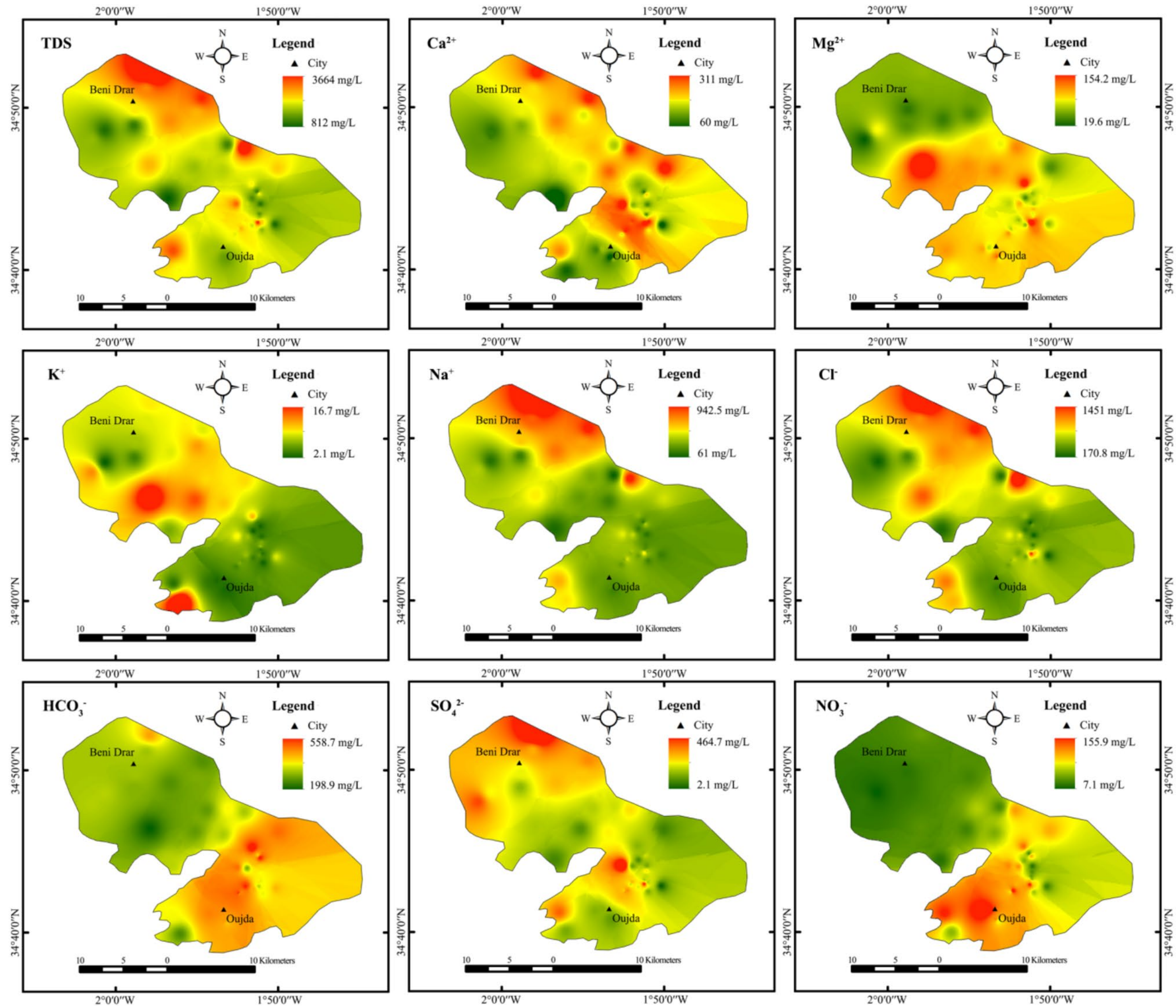

Fig. 4. Spatial distribution of TDS, anions, and cations for the wet season (Generated by: ArcGIS 10.8, Link: www.esri.com).

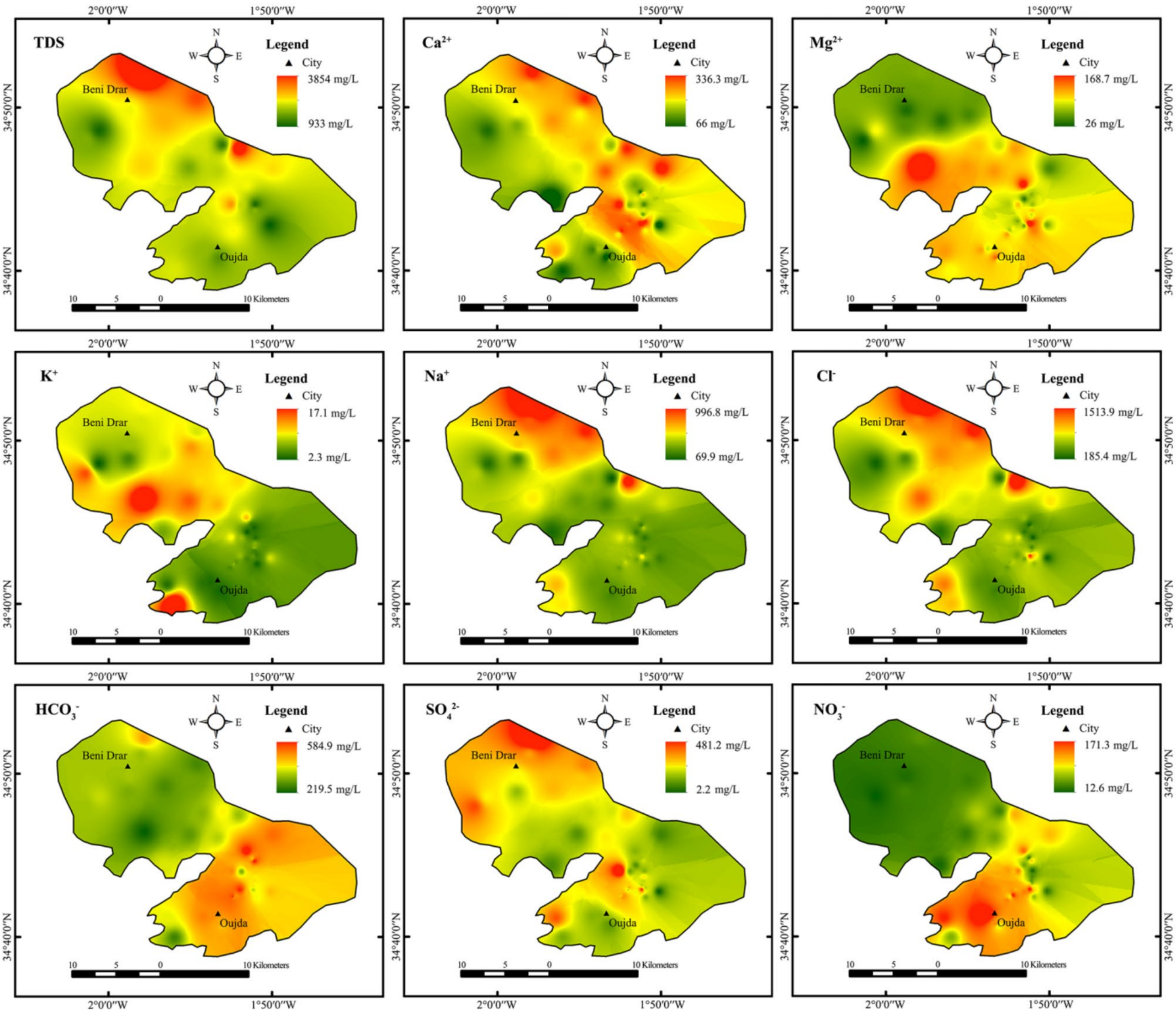

Fig. 5. Spatial distribution of TDS, anions, and cations for the dry season (Generated by: ArcGIS 10.8, Link: www.esri.com).

the international level, a study carried out in India revealed TDS concentrations up to 3295 mg/L in certain agricultural areas, accentuated by intensive irrigation and soil salinization[32]. High concentrations of TDS can alter the taste of water and lead to laxative effects, while also representing a risk for people with kidney disease[22]. The results reveal that over 86% of groundwater samples collected during both periods exceeded the WHO recommended limit, which was located in the northeast of the study area.

Total hardness is one of the most important parameters with a harmful effect on human health, its increase reflects the deposit of Ca^{2+} and Mg^{2+}in water[33]. Groundwater Ca^{2+} and Mg^{2+} concentrations ranged from 60 to 311 mg/L and from 19.6 to 154.2 mg/L in wet season, while in dry season they ranged from 66 to 336.3 mg/L and from 26 to 168.7 mg/L, respectively. The erosion of rocks such as dolomite, calcite, and gypsum mainly influence Ca^{2+}levels in groundwater[26]. High calcium concentrations in groundwater can alter the taste of water and cause abdominal disorders in humans, especially those suffering from kidney disease[33,34]. The values recorded in this study are lower than those reported by Bouaissa[26], where the authors reported that the cause of these concentrations is the dissolution of carbonate rocks. In addition, more than 40% of the samples had Ca^{2+} concentrations exceeding the standard (200 mg/L) recommended by the WHO for both periods. According to the spatial distribution, these samples were taken in the north-east and center of the study area. For Mg^{2+}, almost all groundwater samples (97.8% in both seasons) had concentrations below the WHO recommended standard (150 mg/L).

Potassium levels in groundwater ranged from 2.15 to 16.7 mg/L and from 2.3 to 17.1 mg/L during the wet and dry seasons, respectively. Just 4.4% of samples exceeded the WHO recommended standard, located in the center of the study area. Sodium values ranged from 61 to 942.5 mg/L in wet season and from 69.9 to 996.8 mg/L in dry season. In the northern part of the study area, high sodium levels were observed, exceeding WHO standards

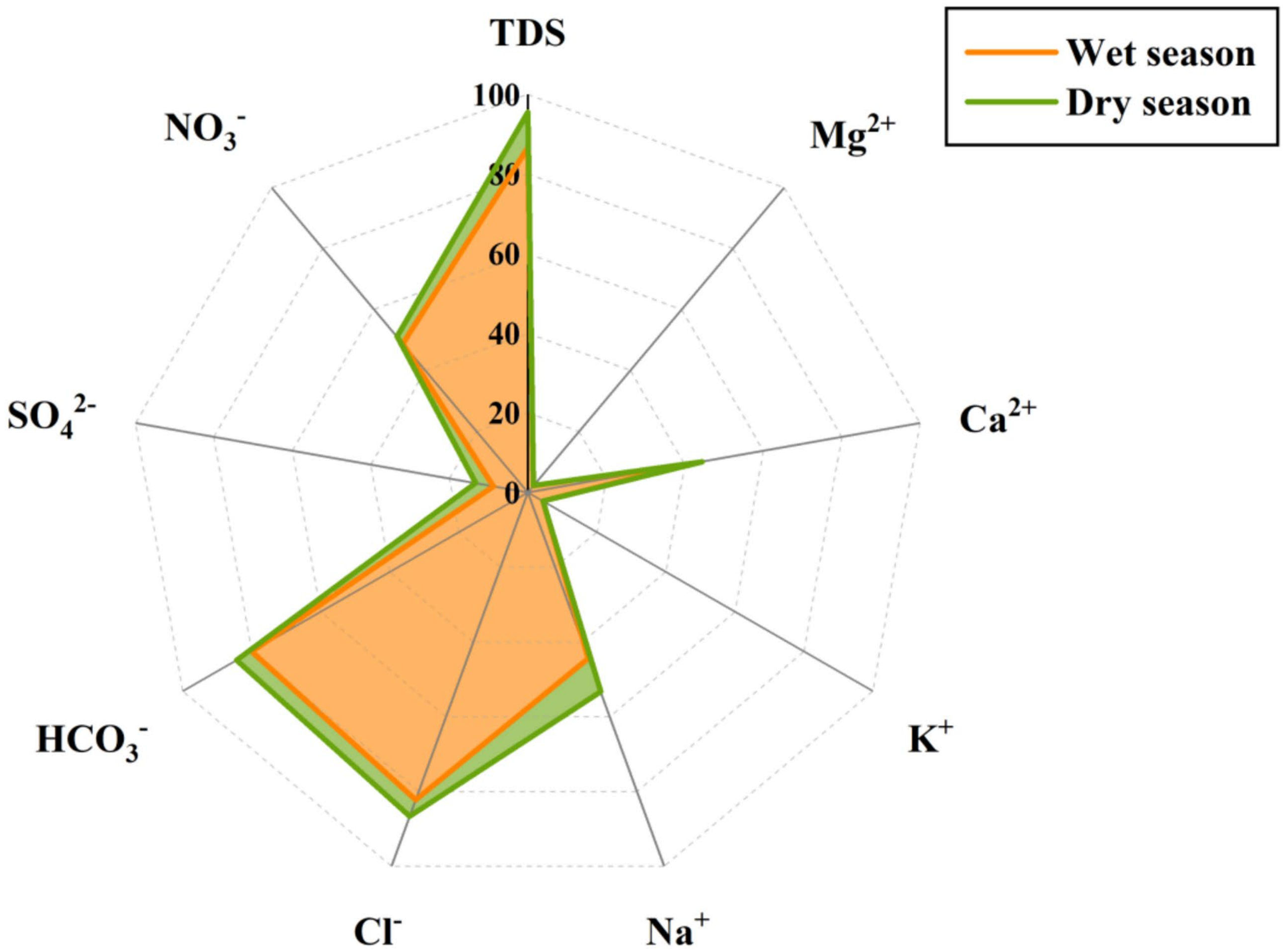

Fig. 6. Percentage of groundwater samples above WHO limits.

(>44% of samples). The sources of Na^+ and K^+in groundwater are due to both natural processes and human activities. It is clear that these compounds are found in aquifers as a result of the dissolution of sodium and potassium rich minerals such as clays and feldspars[35]. The intensive use of potassium fertilizers and infiltration from industrial and agricultural sites all contribute to this pollution[36,37]. Na^+ and K^+ are generally harmless in normal concentrations, but their presence in excess can have adverse effects on health. High blood pressure and cardiovascular disease are linked to high Na^+intake[38,39], while excessive K^+intake can lead to electrolyte imbalances and heart problems for people with kidney disease, although it is beneficial in small doses[16]. Furthermore, a few areas noted situations where high concentrations of Na^+ and K^+in groundwater represented a health hazard, particularly for children[40].

Chloride is generally present in low concentrations in natural water[25]. However, its levels can be significantly higher if the water is classified as saline or brackish, due to seawater intrusion, dissolution of chloride-containing minerals, or anthropogenic sources[41,42]. Chloride values ranged from 170.8 to 1451 mg/L in wet season and 185.4 to 1513.9 mg/L in dry season, or over 82% of samples exceeding the WHO recommended limit. The spatial distribution of chlorides reveals that high concentrations are observed to the northeast of the study area. This distribution is similar to that of TDS, suggesting that the mineralization of these waters is mainly controlled by this ion. One of the processes that may influence chloride ion concentrations is the infiltration of irrigation water, since the study area has a high level of agricultural activity, and the dissolution of salt deposits[43].

HCO_3^- levels ranged from 198.9 to 558.7 mg/L and 219.5 to 584.9 mg/L during the wet and dry seasons, respectively. This evolution could be explained by natural processes such as the increased dissolution of carbonate rocks, like calcite and dolomite, due to the infiltration of water rich in carbon dioxide. Several studies such as[26,44] have reported that these major natural mechanisms increase bicarbonate levels in groundwater. Indeed, over 80% of samples exceeded the WHO limit. The highest levels were found in the southern part of the plain.

SO_4^{2-} concentrations ranged from 2.1 to 464.7 mg/L in wet season, and from 2.2 to 481.2 mg/L in dry season. The high sulfate concentration may be due to the geological composition of the soil and human activity. Studies such as[25,45] have mentioned that gypsum dissolution and intensive agricultural practices may contribute to these levels. Although concentrations reached up to 481.2 mg/L, just 13% of groundwater samples in the central and northern parts of the study area exceeded the WHO maximum permissible limit.

Nitrate concentrations in groundwater samples ranged from 7.1 to 155.9 mg/L in wet season, and from 12.6 to 171.3 mg/L in dry season, indicating that almost half the samples exceed the WHO standard of 50 mg/L located mainly in the south and around the city of Oujda. These results are similar to[46], who recorded a concentration up to 265 mg/l in the groundwater of the Faridkot district in India. The main sources of nitrates in groundwater, according to the authors, are agriculture and industrial activities. Fertilizing chemicals, particularly those containing nitrates, are commonly used in farming methods. However, a fraction of these nitrates can percolate into the soil and groundwater as a result of irrigation or rainfall[16]. Groundwater contamination can also result from leaking sewer systems, wastewater discharges from industry, and the decomposition of organic matter such as animal excrement[47]. There are various effects on human health: high nitrate concentrations in drinking water can be associated with the dangers of methemoglobinemia, a potentially fatal condition known as "blue baby syndrome". In addition, it could increase the risk of digestive cancers and thyroid-related diseases[22]. Respiratory and cardiovascular functions may also be affected by nitrates, particularly in babies and pregnant women[22].

The groundwater chemistry of the study area reveals significant variations in key parameters across the two sampling periods. The observed increases in TDS, chloride, sodium, and sulfate concentrations, particularly in the north part of the study area, highlight intensified salinization processes, which could be exacerbated by factors such as prolonged drought periods, reduced recharge rates, and increased groundwater extraction[8,48]. These processes often result in a concentration of dissolved ions in the aquifer, as evidenced by the rise in TDS levels (from 1604.4 mg/L in wet season to 1745.1 mg/L in dry season).

The predominance of sodium and chloride ions, reflected in the high Na^+ (up to 996.8 mg/L) and Cl^-(up to 1513.9 mg/L) concentrations in the region, may be linked to the combination of anthropogenic activities, such as excessive agricultural irrigation and domestic waste disposal, and natural factors like the dissolution of evaporite, as indicated by previous studies[26]. Furthermore, the increased concentrations of calcium and magnesium in the southern and central parts of the study area suggest the dissolution of dolomite and calcite minerals[44]. This geogenic influence aligns with findings from[7,10], which demonstrate similar mineral-driven water chemistry in semi-arid to arid regions.

Water quality assessment using PIG

A single number that represents the total amount of pollution is obtained by the PIG, a global index that assesses the combined effects of many physicochemical factors on groundwater quality[14]. The PIG was introduced to measure drinking water quality in this study, using 9 physicochemical parameters, including TDS, K^+, Na^+, Mg^{2+}, Ca^{2+}, Cl^-, HCO_3^-, SO_4^{2+}, and NO_3^-. The mean W_p values of the Na^+ (0.151 in wet season and 0.165 in dry season), and Cl^- (0.251 in wet season and 0.268 in dry season) parameters in groundwater are above 0.1, suggesting that these parameters have a major contribution to the increase in PIG values. To validate this contribution, we plotted two-dimensional graphs (PIG vs. Na and PIG vs. Cl). Figure 7 shows a significant correlation between PIG and Na, with a correlation coefficient (R^2) of 0.728 in wet season and 0.720 in dry season, confirming that the Na ion influences groundwater quality. As for chloride, Fig. 7 reveals a strong correlation between PIG and Cl, with an $R^2$of 0.799 in wet season and 0.789 in dry season, confirming the considerable contribution of this ion to groundwater quality. These correlations suggest that the dissolution of evaporite rocks, particularly halite, is a major process influencing water chemistry in the study area. This hypothesis is reinforced by[26], who also highlighted the influence of evaporites on groundwater chemistry based on PIG results. While other studies[13] observed that other parameters control PIG results such as Ca^{2+} and Mg^{2+}, this may be due to the difference in geological characteristics of the study areas.

As shown in Table 4, PIG values vary between 0.51 and 2.44 during the wet season and between 0.58 and 2.57 during the dry season, making it possible to classify water quality in all categories. The results showed that, for the wet season, 37.7% were classified as insignificant pollution, 46.7% as low, 8.9% as moderate, and 6.7% as high, while for the dry season 33.3% were classified as insignificant pollution, 48.9% as low, 11.1% as moderate, 4.5% as high and 2.2% as very high (Fig. 8). These results reflect varying levels of pollution and underline the impact of human activities and natural conditions on water resources. Figure 9 shows the spatial distribution of PIG values, which indicate that insignificant and low pollution zones cover most of the study area. However, moderate and high pollution zones cover a very limited area in the northeast of the study region. PIG spatial distribution maps for both periods show that polluted zones have remained relatively stable, although pollution levels are slightly higher in the dry season.

These results highlight the cumulative impact of multiple physicochemical parameters on water quality. The stronger correlations observed between PIG and chloride in both seasons suggest that chloride ions are becoming a more dominant factor influencing overall water quality. This could be indicative of increasing agricultural runoff, as chloride-based fertilizers and irrigation return flows contribute to groundwater contamination[23]. The spatial stability of polluted zones, despite the slightly elevated PIG values in the dry season, suggests that existing pollution sources, whether geogenic or anthropogenic, persist over time[13]. This stability may also imply insufficient groundwater recharge to dilute these contaminants, emphasizing the need for controlled extraction and sustainable water management practices[5].

Comparison with other studies

To provide an overview of groundwater pollution on an international scale, the results of the PIG index obtained were compared with other regions of the world (Table 5). The minimum and maximum PIG values of groundwater samples from the study area are almost similar to those observed in Telangana state[5], Gangetic basin[49]and Madhya Pradesh[50]in India, as well as in the Gharb plain[7]in Morocco. This indicates that groundwater in these five regions has a comparable level of pollution. The similarity suggests also that the sources of pollution identified in our study are representative of the environmental pressures commonly exerted on groundwater in comparable areas. In contrast, other studies show much higher PIG values, suggesting more severe pollution

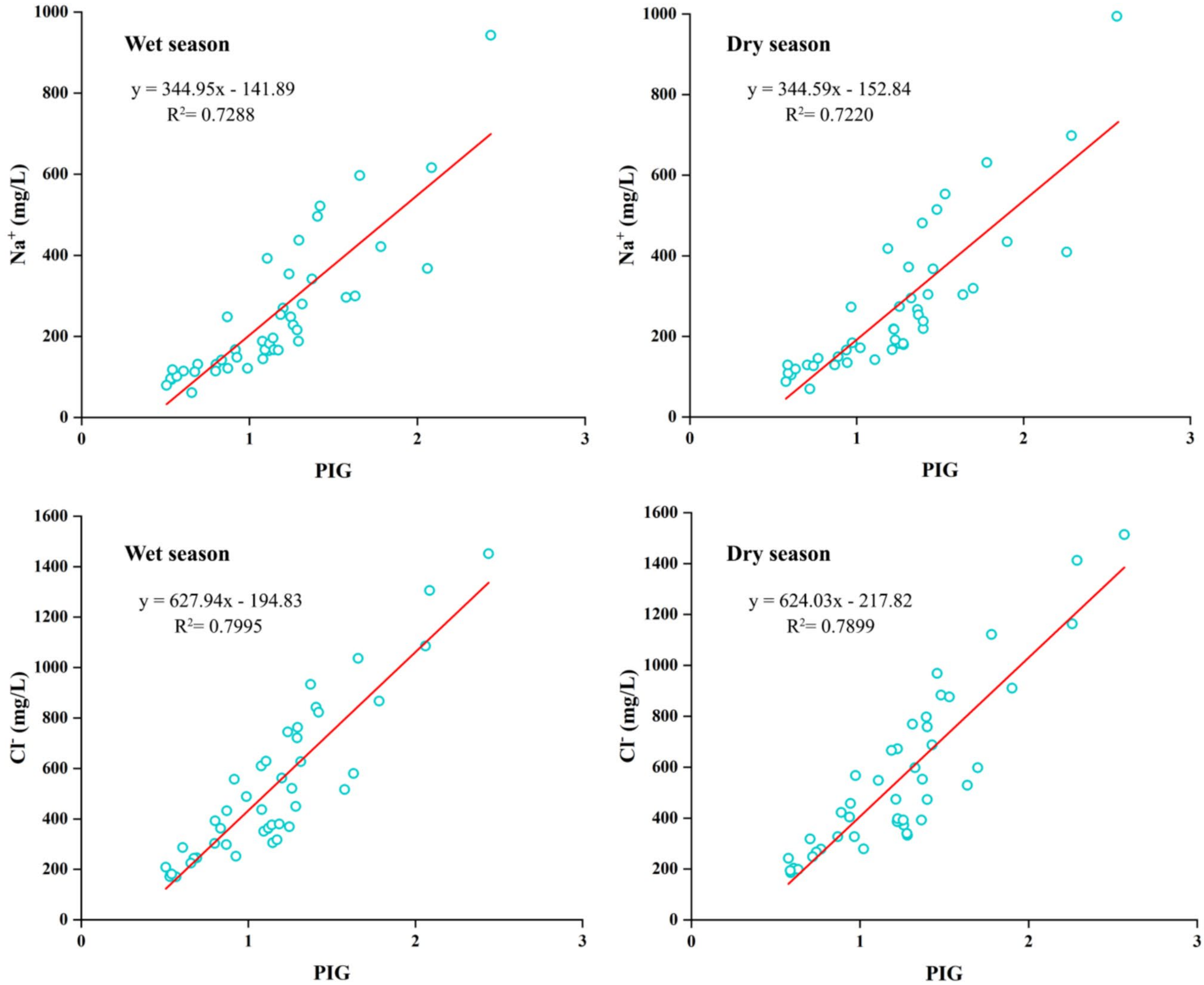

Fig. 7. Correlation between PIG and ions.

in these regions. In Algeria, the maximum PIG value reaches 8.19, mainly due to geogenic and anthropogenic factors, as well as mining activities[50]. In the Bokoya massif, maximum PIG values are 11.40 in the wet season and 13.20 in the dry season, this pollution being attributed to geological features, such as the presence of evaporitic rocks, and sewage leakage, particularly in villages[26]. The groundwater in the town of Sidi Slimane classified as highly polluted (PIG = 10.8) and unfit for consumption, due to the geological characteristics of the study area, which increase salt levels in the water through rock dissolution[10].

Microbiological quality

The quality of groundwater, an essential resource for the supply of drinking water, is currently threatened by microbiological contamination[52]. These waters can be polluted by a variety of biological contaminants from multiple sources, leading to adverse effects and often posing risks to human health[53].

Microbiological analysis of groundwater samples was carried out in wet and dry seasons. The results of analyses of biological contamination indicators (TC, FC, IE, *E. coli* and SRC) are presented in Table 6. The results show significant contamination of groundwater by total and fecal coliforms, with higher concentrations during the dry season (up to 264 CFU/100 mL for total coliforms and 198 CFU/100 mL for fecal coliforms) compared to the wet season (211 CFU/100 mL and 133 CFU/100 mL respectively). In addition, intestinal enterococci were identified in several samples, reaching 21 CFU/100 mL in the dry season and 16 CFU/100 mL in the wet season. The presence of sulfite-reducing anaerobes was occasional (two samples) and mainly detected during the dry season at low concentrations (1 CFU/100 mL), while *E. coli* was not detected in all samples.

In line with MSMAV and WHO drinking water standards, which set the threshold for all germs studied at 0 CFU/100 ml, the majority of groundwater samples analyzed exceeded this limit for CT (92.8% during the wet period and 96.4% during the dry period), CF (85.7% during the wet period and 89.3% during the dry period) and IE (53.6% during the wet period and 64.3% during the dry period), underlining that the majority of groundwater is unfit for human consumption. Whereas for SRC (100% during the wet period and 92.8% during

	Wet season		Dry season	
Sample ID	PIG value	Class	PIG value	Class
GW1	0.80	Insignificant pollution	0.89	Insignificant pollution
GW2	0.83	Insignificant pollution	0.94	Insignificant pollution
GW3	1.25	Low pollution	1.37	Low pollution
GW4	1.26	Low pollution	1.37	Low pollution
GW5	1.63	Moderate pollution	1.70	Moderate pollution
GW6	2.09	High pollution	2.29	High pollution
GW7	1.08	Low pollution	1.22	Low pollution
GW8	0.99	Insignificant pollution	1.11	Low pollution
GW9	0.61	Insignificant pollution	0.70	Insignificant pollution
GW10	0.53	Insignificant pollution	0.61	Insignificant pollution
GW11	0.87	Insignificant pollution	0.97	Insignificant pollution
GW12	1.12	Low pollution	1.26	Low pollution
GW13	1.58	Moderate pollution	1.64	Moderate pollution
GW14	1.09	Low pollution	1.23	Low pollution
GW15	2.06	High pollution	2.26	High pollution
GW16	1.08	Low pollution	1.21	Low pollution
GW17	0.69	Insignificant pollution	0.77	Insignificant pollution
GW18	0.53	Insignificant pollution	0.59	Insignificant pollution
GW19	0.57	Insignificant pollution	0.63	Insignificant pollution
GW20	1.31	Low pollution	1.43	Low pollution
GW21	1.12	Low pollution	1.22	Low pollution
GW22	1.14	Low pollution	1.22	Low pollution
GW23	1.20	Low pollution	1.33	Low pollution
GW24	0.67	Insignificant pollution	0.74	Insignificant pollution
GW25	1.19	Low pollution	1.26	Low pollution
GW26	0.66	Insignificant pollution	0.72	Insignificant pollution
GW27	0.92	Insignificant pollution	0.97	Insignificant pollution
GW28	1.29	Low pollution	1.39	Low pollution
GW29	1.66	Moderate pollution	1.78	Moderate pollution
GW30	1.41	Low pollution	1.48	Low pollution
GW31	1.42	Low pollution	1.53	Moderate pollution
GW32	2.44	High pollution	2.57	Very high pollution
GW33	1.11	Low pollution	1.19	Low pollution
GW34	1.37	Low pollution	1.46	Low pollution
GW35	0.51	Insignificant pollution	0.58	Insignificant pollution
GW36	1.29	Low pollution	1.40	Low pollution
GW37	0.54	Insignificant pollution	0.59	Insignificant pollution
GW38	0.87	Insignificant pollution	0.94	Insignificant pollution
GW39	1.15	Low pollution	1.28	Low pollution
GW40	1.17	Low pollution	1.28	Low pollution
GW41	0.80	Insignificant pollution	0.87	Insignificant pollution
GW42	0.93	Insignificant pollution	1.02	Low pollution
GW43	1.24	Low pollution	1.31	Low pollution
GW44	1.78	Moderate pollution	1.90	Moderate pollution
GW45	1.28	Low pollution	1.40	Low pollution
Min	0.51		0.58	
Mean	1.14		1.24	
Max	2.44		2.57	

Table 4. Groundwater classification based on PIG.

the dry period) and *E. coli* (100% during both periods), almost all samples were within MSMAV and WHO standards.

The presence of CT, CF and EI in water is a worrying indicator, as it can lead to infections such as cholera, gastroenteritis, dysentery and typhoid fever when a person consumes contaminated water. Indeed, the study area is subject to intensive livestock farming, which is a potential source of contamination by animal

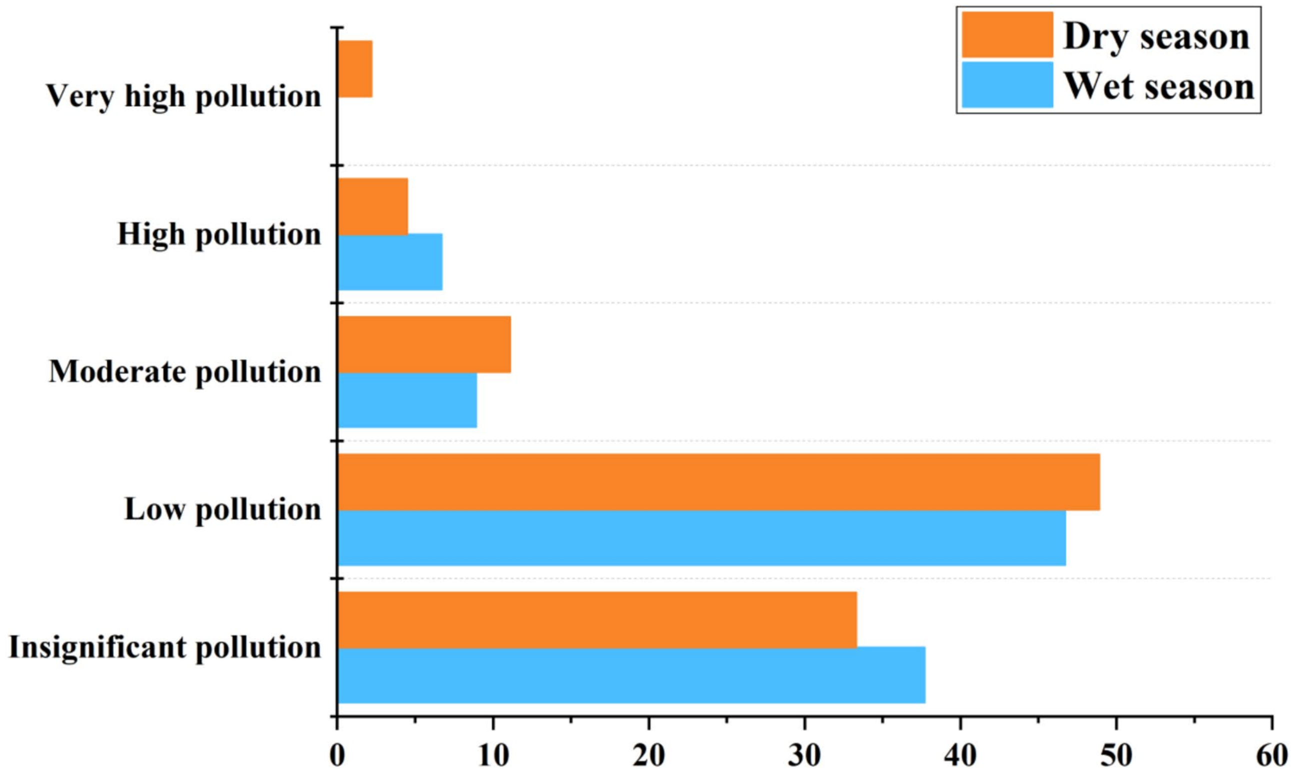

Fig. 8. Percentage of groundwater classification.

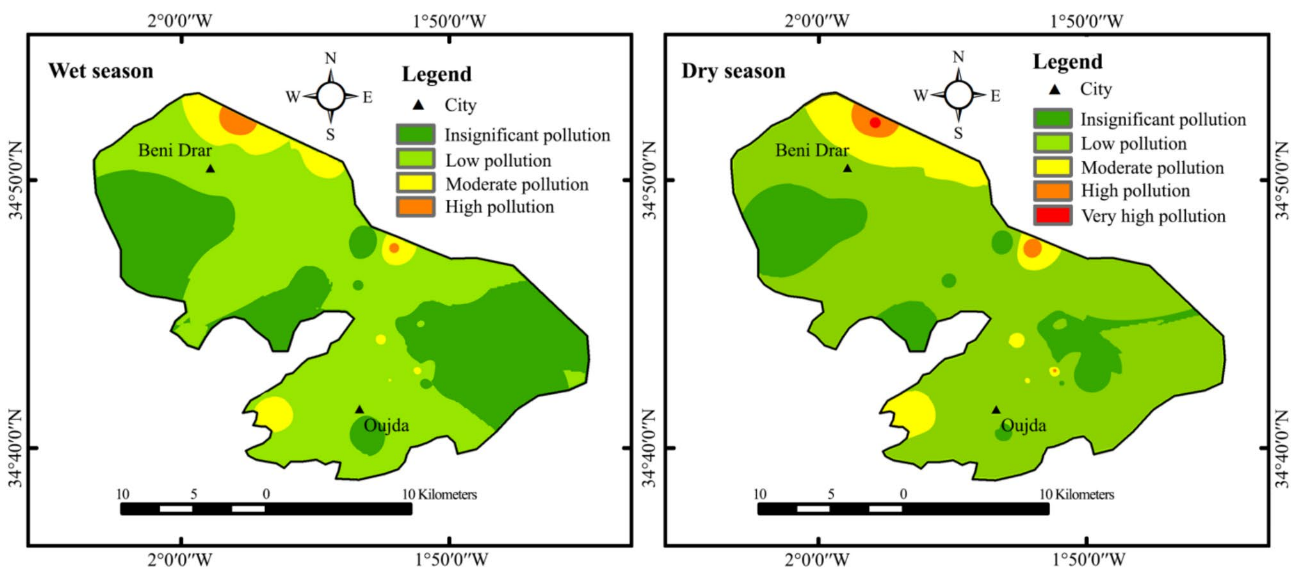

Fig. 9. Spatial distributions of PIG (Generated by: ArcGIS 10.8, Link: www.esri.com).

excrement[54,55]. In addition, the absence of sewage systems in some areas also amplifies the risk of contamination through infiltration of septic tank waste, while a failure in water treatment can favour conditions for bacterial proliferation[56,57].

In terms of seasonal variations, this study highlighted an increase in fecal pollution indicators during periods of drought. This trend could be linked to a reduction in the volumes of water available in reservoirs, a lack of natural dilution and an increase in direct discharges into groundwater[58,59]. These observations are consistent with those of[60], who also found in northern Ghana an increase in germ concentrations during the dry season due to reduced water volumes. Other studies[53] have also shown that seasonal variation and other factors influence directly the microbiological quality of groundwater.

Location	Min	Max	References
Telangana State, India	0.50	1.83	[25]
Tebessa region, Algeria	0.45	8.19	[51]
Gangetic Basin, India	0.63	2.08	[49]
Bokoya massif, Morocco (Wet period)	0.40	11.40	[26]
Bokoya massif, Morocco (Dry period)	0.50	13.20	[26]
Sidi Slimane, Morocco	0.70	10.8	[10]
Gharb Plain, Morocco	0.51	1.92	[7]
Madhya Pradesh, India	0.42	1.67	[50]
Angads plain, Morocco (Wet period)	0.51	2.44	This study
Angads plain, Morocco (Dry period)	0.58	2.57	This study

Table 5. Comparison of PIG with different regions of the world.

	Wet					Dry				
Parameter	Min	Max	Mean	% Fit	% Unfit	Min	Max	Mean	% Fit	% Unfit
TC	0	211	80	7.1	92.9	0	264	120	3.6	96.4
FC	0	133	52	14.3	85.7	0	198	79	10.7	89.3
IE	0	16	2	46.4	53.6	0	21	3	35.7	64.3
E. coli	0	0	0	100	0	0	0	0	100	0
SRC	0	0	0	100	0	0	1	0	92.9	7.1

Table 6. Min, max, and mean of Microbiological parameters.

Comparatively, the levels of contamination observed in this study are lower than those reported in other studies[52], who detected concentrations of up to 4100 CFU/100 ml in the rural commune of Nihit in the Moroccan Anti-Atlas, and[53]who found values of up to 2400 CFU/100 ml in groundwater in Ghana. Other recent research in Morocco, such as[61]observed high concentrations of total coliforms in the Khenifra province, highlighting a major health risk. Similarly[62], reported significant contamination of the Ghis-Nekor aquifer in Al Hoceima, with the presence of total coliforms and intestinal enterococci. At the international scale[63], observed high contamination by *E. coli*and other enteric bacteria in wells and boreholes in Nigeria, increasing the risk of gastrointestinal infections. In addition[64], reported high levels of total coliforms, *E. coli* and sulfite-reducing anaerobes in coastal wetlands in Turkey, with a notable increase during rainy seasons due to river water runoff.

The fecal bacteria detected, notably intestinal enterococci and fecal coliforms, are indicators of fecal pollution and represent a significant risk to human health. Coliforms are often associated with severe gastrointestinal infections such as diarrhea and hemorrhagic colitis[63,65]. Intestinal enterococci can cause urinary tract infections, endocarditis and opportunistic infections[61]. Sulfite-reducing anaerobes, although absent in this study, are generally indicators of past contamination and may signal the presence of persistent pathogenic spores.

These results underline the need for rigorous water management measures, such as the installation of treatment systems (chlorination or disinfection), the regulation of agricultural practices and the improvement of sanitation infrastructures to limit fecal pollution.

Limitation of the study
The main limitation is the absence of a sampling point to the south-east of the study area, due to the difficulty of accessing the private well, which may lead to an underestimation or overestimation of pollution levels in the south-east of the study area.

Sustainable management of groundwater quality
For sustainable management of groundwater quality, it is essential to adopt sustainable agricultural practices by minimizing the use of chemical fertilizers and promoting efficient irrigation with quality-controlled water. Precision farming and the use of salinity-tolerant crops can help reduce the build-up of salts in soils. At the same time, it is crucial to strengthen land-use regulations, notably by imposing building restrictions in areas close to vulnerable groundwater and implementing measures to protect wetlands. The adoption of water resource management technologies, such as controlled artificial recharge and continuous monitoring of salinity levels and bacteriological contamination, is also recommended to balance groundwater extraction and recharge. In addition, the restoration of degraded wetlands is essential to maintain natural groundwater recharge and filtration functions. Finally, raising awareness among farmers and water managers of the impact of agricultural practices on groundwater quality, as well as promoting training programs for sustainable irrigation techniques, will contribute to better management of water resources.

Conclusion

This study examined groundwater quality in the Angads plain by analyzing the pollution level of 45 samples taken in 2023 (wet and dry seasons). According to WHO standards, groundwater quality assessment was carried out to determine its suitability for human consumption. The spatial ion distribution map reveals that some areas of the study are unsuitable for consumption. Application of the PIG index showed that groundwater quality indicates moderate pollution, making the water unsuitable for consumption. In addition, an assessment of bacteriological quality showed that the groundwater from almost all the wells is not fit for drinking. Consequently, this study underlines the importance of appropriate groundwater treatment before use in the region studied. The results obtained will be invaluable to the government, general public, and policy-makers, providing information on the state of groundwater pollution and contributing to the monitoring and management of water resources to reduce their negative impact on human health.

Data availability

All data generated or analyzed during this study are included in this published article.

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Oualid Boukich, Musaab Dauelbait: Conceptualization, Formal analysis, Investigation, Data curation, Methodology, Software, Visualization, Roles/Writing - original draft, Writing – review & editing. Rihab Ben-tahar, Mohammed Bourhia: Conceptualization, Formal analysis, Investigation, Methodology, Roles/Writing - original draft. Elkhadir Gharibi, Mohammed Mahjoub: Validation, Resources, Supervision. Bouchra El Guerrouj: Resources, Visualization. Youssef Smiri, Gamal A. Shazly: Conceptualization, Validation, Project administration, Supervision, Roles/Writing - original draft.

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Declarations

Ethics approval and consent to participate
Not applicable.

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Competing interests
The authors declare no competing interests.

Ethical consideration
Not applicable.

Additional information
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